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·综 述·

微塑料与土壤环境中微生物互作研究进展

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摘 要：作为环境中广泛存在的污染物，微塑料(microplastics)的相关研究备受关注。基于已有研究，本文综合分析了微塑料与土壤微生物(soil microorganisms)的互作关系，微塑料会通过直接或间接的方式影响微生物群落结构与多样性，影响的程度取决于微塑料的类型、剂量和形状。土壤微生物会通过形成表面生物膜和群落选择效应来适应微塑料这一外来物所引起的变化。本文还特别关注了微塑料的生物降解机理，同时探究了影响这一过程的因素，微生物首先会定殖在微塑料表面，分泌多种胞外酶在特定位点发挥作用，将聚合物转化成低聚物或单体，解聚的小分子进入胞内进一步分解代谢，而影响这一降解过程的因素除了分子量、密度、结晶度等微塑料自身理化性质，还包括一些生物因素和非生物因素对相关微生物生长代谢和酶活性的作用。未来研究应注重与实际环境的联系，在深入探究微塑料生物降解研究的同时，开发解决微塑料污染问题的新技术。

关键词：微塑料；土壤微生物；生物膜；生物降解机理

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Interaction between microplastics and microorganisms in soil environment: a review

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Abstract: As a widespread pollutant in the environment, research on microplastics have attracted much attention. This review systematically analyzed the interaction between microplastics and soil microorganisms based on existing literatures. Microplastics can change the structure and diversity of soil microbial communities directly or indirectly. The magnitude of these effects depends on the type, dose and shape of microplastics. Meanwhile, soil microorganisms can adapt to the changes caused by microplastics through forming surface biofilm and selecting population. This review also summarized the biodegradation mechanism of microplastics, and explored the factors affecting this process. Microorganisms will firstly colonize the surface of microplastics, and then secrete a variety of extracellular enzymes to function at specific sites, converting polymers into lower polymers or monomers. Finally, the depolymerized small molecules enter the cell for further catabolism. The factors affecting this degradation process are not only the physical and chemical properties of the microplastics, such as molecular weight, density and crystallinity, but also some biological and abiotic factors that affect the growth and metabolism of related microorganisms and the enzymatic activities. Future studies should focus on the connection with the actual environment, and develop new technologies of microplastics biodegradation to solve the problem of microplastic pollution.
Keywords: microplastics; soil microorganisms; biofilm; biodegradation mechanism

塑料自问世以来在多个行业大量使用，随着全球生产率的不断提高，人类进入了“塑料时代”[1]，质轻和耐用等特性使塑料制品广泛应用于工业、农业和医药等多个领域，塑料产业得以迅速发展[2]。人们着眼于经济效益的同时忽视了塑料背后的严重问题，大量生产和快速消耗产生的塑料垃圾由于回收和管理不当，加上塑料自身降解缓慢，造成塑料垃圾大量积累[3]。大多数塑料碎片会在环境中经过长期的物理、化学及生物作用进一步破碎、裂解成较小颗粒[4]，通常将尺寸小于 5 mm 的塑料颗粒定义为微塑料(microplastics, MPs)[5]。凭借体积小、迁移快等特性，MPs 在水体、土壤和大气等环境中均有分布，由于化学性质稳定且不易分解，MPs 可在环境中长久存在[6]。有研究表明 MPs 会进入食物链，在各个营养级之间发生转移[7]。2022 年的一项研究首次在人体血液中检测到 MPs[8]，虽然关于微塑料是否一定会危害人体健康，尚无确

切的试验证明[9]，但较多研究已证实了 MPs 对不同生物体消化[10]、呼吸[11]、神经[12]、遗传[13]和生殖[10]各个方面的毒性作用，各生物体间是密切联系的[14]，这些毒性最终很有可能在人类身体上得到显现验证。

早在 1972 年就在水体中发现了微塑料[15]，但微塑料这一概念在 2004 年才被明确定义[16]，之后开展了水生环境中 MPs 的相关问题研究，直到 2012 年 Rillig[17]提出“土壤微塑料”的概念，土壤微塑料的相关研究相继展开。截至 2022 年 6 月 10 日，微塑料相关研究论文已有 12 145 篇(Web of Science 核心合集，检索词 TS=(microplastic*)；中国知网数据库，检索词：微塑料)。关于水生系统中的 MPs，特别是海洋环境中的研究已较为成熟[18-19]，而土壤中 MPs 的研究仍处于初步阶段(图 1)，通过统计 1995−2022 年发表的相关文献可以看出，土壤中 MPs 的研究只在近几年才略有涨幅，共计 1 826 篇(Web of Science 核心合集，检索词 TS=(microplastic*) AND TS=(soil*)；中国知网数据库，检索词：土壤微塑料)。

陆地环境中的 MPs 可能是海洋中的 4−23 倍[20]，MPs 可以通过农业生产(农用地膜残留、污泥和有机肥使用)、生活污水排放和工业生产中产生的废气沉降进入土壤[21]。据估计每年进入土壤环境中的 MPs 已经超过 43 万 t[22]，大量塑料碎片堆积在土壤中，改变土壤的理化性质、结构和功能，同时影响微生物群落[23]。我们在 SCI 核心合集[检索词：TS=(microplastic*) AND TS=(microorganism OR bacteria OR fungi)]和中国知网数据库[检索词：(主题=“微塑料”) AND (主题=“微生物”)]检索到微塑料与微生物相关研究文章 744 篇，使用 CiteSpace V 5.7.R2 绘制了土壤微塑料研究的关键词网络图谱，如图 2 所示，当前 MPs 与微生物的研究关键词包括：biodegradation、生物膜、biofilm formation、environment、microbial community 等，针对 MPs 污染这一问题，相关学者开展了大量 MPs 与微生物相互作用关系的研究。鉴于土壤环境的复杂性和影响机制的不确定性，开展更深入广泛的研究显得尤为重要。当 MPs 进入土壤后，会对土壤微生物产生怎样的影响，这些影响是否存在差异，而微生物又是如何应对 MPs 这一外来物的。基于此，本文着

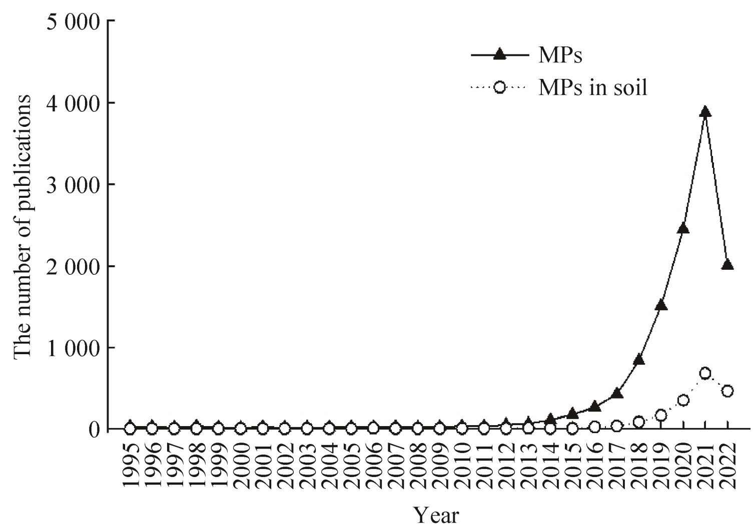

图 1　基于 SCI 数据库和 CNKI 数据库的微塑料发文量研究

Figure 1　Publications related to microplastics based on SCI database and CNKI database.

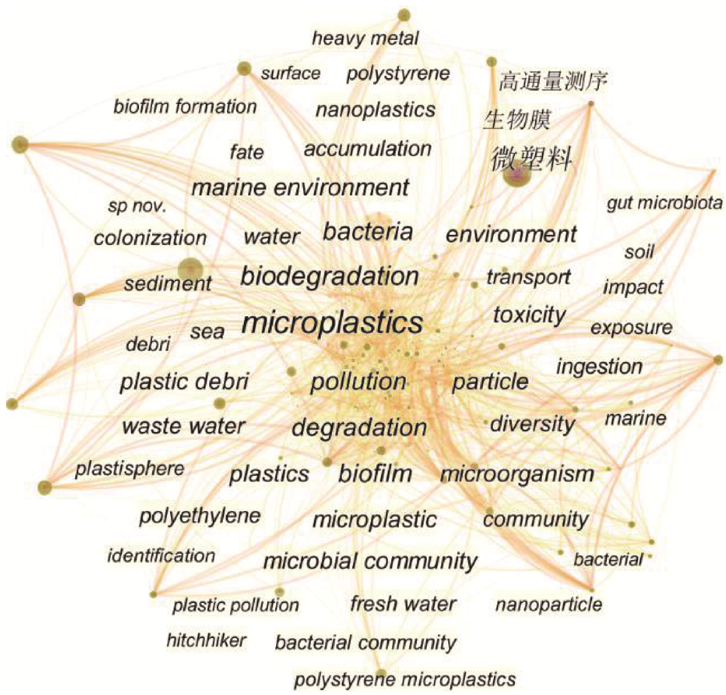

图 2　微塑料与微生物相关研究的关键词共现图

Figure 2　Co-occurrence map of keywords in microplastics and microorganisms related research.

重于探讨土壤 MPs 如何影响土壤微生物以及土壤微生物对微塑料的响应，就二者的互作关系，进一步分析微生物降解 MPs 的机理及影响这一降解过程的因素，以期为未来研究提供参考。

1　MPs 对土壤微生物的影响

近年来，MPs 对微生物的影响受到了广泛关注。Feng 等[24]通过研究 2 种剂量(0.2%和 2%，质量分数)下 6 种不同 MPs 成分对微生物的影响，发现剂量为 2%时，会明显降低细菌群落的丰度和多样性，并改变微生物群落组成。一般情况下高浓度 MPs 对微生物群落的影响更显著，不仅改变微生物群落组成和相关的代谢途径，还会导致特定分类群和功能基因的富集[25]。一项在中国黄土高原采集的黄土中添加不同水平 MPs 的研究发现，MPs 的添加会刺激酶活性，并增加可溶性有机 C、N 和 P[26]。这些种种迹象表明，土壤微生物会受到 MPs 的影响，但影响正面还是负面尚不确定(表 1)。

1.1　对土壤微生物的直接影响

由于氢键、静电相互作用和范德华力等机制，塑料自身就具有较强的吸附和富集环境有害污染物(例如重金属和有机污染物)的能力，这可能会影响土壤微生物群落[33]。值得注意的是，外来 MPs 很可能成为土壤微生物的独特栖息地[34]，研究发现土壤 MPs 表面的凹陷和裂缝处存在着大量微生物，这些微生物群落结构不同于周围土壤、植物凋落物的[35]。我们猜测与水生环境类似，土壤 MPs 表面也会形成生物膜，而生物膜的存在可能会增强 MPs 吸附重金属和污染物的能力[36-37]。Wang 等[38]通过 16S rRNA 基因的高通量测序探究重金属吸附前后生物膜中微生物群落多样性的变化，结果表明低浓度的铜会增加生物膜的群落多样性，相反铅会降低，原始生物膜的微生物群落与重金属吸附

表 1 不同类型 MPs 对土壤微生物的影响

Table 1 Effects of different types of MPs on soil microbes

Polymer (s)	Dose (*W*/*W*)	Size and shape (μm)	Experiment duration (d)	Effects	Reference
Polyethylene (PE), polyester (PS), polybutylene succinate (PBS) and polylactide (PLA)	1%	Particles; 150–180	60	PE and PS altered the taxonomic diversity, which may be attributed to the higher DOC contents. While PBS and PLA only altered the functional diversity	[27]
Polyethylene (PE)	5%	Films; <150	30	Actinobacteria replaced Proteobacteria as the dominant phylum in microplastics soil	[28]
Polystyrene (PS)	100 and 1 000 ng	Nano-particle	28	The significant decrease in microbial biomass was observed	[29]
Polyethylene (PE) (ultra-high-molecular weight)	1%	Particles; 40–48	3, 15, 100	MPs promoted the activities of organic C and N hydrolase enzymes to promote SOM decomposition and provide energy and nutrients for microbial growth	[30]
Polyethylene (PE)	0.5%, 1%	–	–	MPs had an obvious effect on soil microbial community composition and species diversity	[31]
Polyvinyl chloride (PVC, with plasticizer, 24.2% DBP)	0.5%	Fragments; <1 000	15, 30, 60	PVC significantly shaped soil microbiota into a microbial system with more nitrogen-fixing microorganisms	[32]

–: The content was not described in detail.

后的明显不同。此外，有研究在水环境 MPs 表面生物膜上检测到 2 种人类致病菌蒙氏假单胞菌(*Pseudomonas monteilii*)和门多萨假单胞菌(*Pseudomonas mendocina*)，这些病原菌会随着 MPs 迁移到不同环境，给土壤微生物造成未知影响[39-40]。

1.2 对土壤微生物的间接影响

MPs 会通过改变土壤理化性质间接影响土壤微生物群落。作为一类人工合成的高分子聚合物，塑料含有多种化学添加剂，当有害添加剂释放到环境中时，可能改变土壤化学性质，进而影响微生物群落[32]。而一些塑料碎片也会顺势进入土壤孔隙[41]，破坏土壤孔隙间的连续性，进而影响土壤孔隙度[42]，土壤孔隙变化会影响水分循环[43]。孔隙度和水分循环的变化会改变土壤氧通量，从而影响土壤中厌氧或好氧微生物的群落组成比例[44]。MPs 诱导的土壤结构(如团聚体和容重)的变化会影响根际微生物群落[45]。研究表明高密度聚乙烯和聚乳酸会改变水稳性土壤团聚体的形态，大团聚体(>2 000 μm)和小团聚体(<63 μm)显著减少，中团聚体(63−250 μm)显著增加[46]，土壤环境中的微生物可能从而受到影响。此外，土壤 pH 可能会显著影响塑料表面特征及其对污染物的吸附力，从而影响土壤塑料圈中细菌群落的多样性[47-48]。而较高的聚己二酸/对苯二甲酸丁二醇酯(polyadipate/butylene terephthalate, PBAT)微塑料施加量会降低土壤硝态氮和总磷的含量[49]，对土壤养分的影响关系到土壤微生物的生长繁殖[50]。Chae 等[51]在研究塑料污染物对植

物和动物生理的不利影响时，发现土壤中的塑料碎片会转移到绿豆的叶片中，还会在该环境下的蜗牛体内富集，这可能会造成蜗牛摄食和排泄的减少[52]，那么 MPs 对植物和土壤动物的影响是否会影响土壤微生物，其影响机制又是什么，仍有待进一步研究。

2 微生物对 MPs 的响应特征

在海洋和淡水生态系统里，具有疏水性的 MPs 表面会快速形成由基质表面有机和无机物质组成的“调节膜”，细菌、古生菌、真菌、病毒、原生生物及其他微生物会通过形成菌毛、黏附蛋白或分泌胞外多聚物等方式定殖在其表面，随后微生物进一步增殖，不同微生物之间相互影响、相互作用，最终形成“塑料圈”，也就是我们所说的生物膜[53-56]。研究发现弧菌科(Vibrionaceae)和假交替单胞菌科(Pseudoalteromonadaceae)能够在土壤 MPs 表面大量繁殖，相反周围环境中却很少存在[57]。基于形成的这些独特微生物群落，我们猜测与水生环境中发育完整的生物膜[58]类似，在自身理化性质和周围土壤理化性质共同作用下，微塑料表面会产生新的生态位[59]，进而形成不同于周围土壤的微生物群落。

孙玮鸿[60]的研究证实了暴露在环境中的聚酰胺(polyamide, PA)塑料膜表面可以形成生物膜，不同的微生物群落会堆积、分散或缠绕形成不同形态的生物膜。微生物对塑料聚合物的化学成分可能存在选择性。一些可降解的塑料微薄膜，如聚己内酯(polycaprolactone, PCL)、PBAT、聚羟基脂肪酸酯(polyhydroxyalkanoate, PHA)、聚乳酸(polylactic acid, PLA)上存在大量的曲霉、镰孢菌和青霉等特定真菌属[61-62]。一项针对不同类型微塑料，如聚乙烯(polyethylene, PE)、聚氯乙烯(polyvinyl chloride, PVC)、聚氨酯(polyurethane, PU)和 PLA 的附着微生物群落研究发现，PVC 上 Desulfobacteraceae 和 Desulfobulbaceae 等细菌会显著增加[63]。一项在红树林生态系统中进行为期 3 个月的不同类型 MPs 暴露试验发现，在 PE 和 PVC 表面都观察到了生物降解痕迹，而且这些 MPs 生物膜上优势细菌的组合是不同的，这可能与聚合物的特定基团有关[64]。塑料表面特定群落微生物群落形成生物膜，是 MPs 生物降解的重要前提[65]。PE 表面的破碎程度与其表面生物膜的生长成正比，随着低密度聚乙烯(low density polyethylene, LDPE)表面生物膜的形成，微生物群落数量会迅速增加并侵入表面，导致膜的完整性丧失，随之 PE 网络疏松并导致薄膜破碎[66]。而且定殖在微塑料表面的这些微生物会释放酶作用于 MPs 化学键，诱导发生系列反应，从而破坏 MPs 结构[67-68]。

3 MPs 的微生物降解

3.1 微生物降解菌

在探索减少微塑料污染方法的过程中，回收、填埋、焚烧等方法或多或少对环境存在影响[69]。微生物降解为解决这一问题提供了新思路，研究发现环境中长期存在的 MPs 会被一些特定的微生物降解[70]，而一些天然或合成的塑料可以被真菌、细菌等微生物在适宜的条件下降解，即生物降解，这一方法可以在不损害环境的情况下缓解塑料污染问题，是一个环境安全且很有前途的方法，对修复自然生物和净化自然生态系统也有一定的促进作用[68]。作为环境中数量庞大的群体，真菌和细菌的降解能力被广泛研究(表 2)。微生物降解试验多数是通过重量损失、分子质量、拉伸强度、中间过程产物、酶活性等指标对其效果进行评价[43,71]。当前关于微塑料降解的研究更多转向实际环境中

表 2 降解微塑料的真菌和细菌
Table 2 Bacteria and fungi that degrade microplastics

Plastics	Fungi/Bacteria	Strain	Degradation effect	Culture time	Reference
PE	Fungi	*Aspergillus sydowii* PNPF15/TS	The tensile strength of PE decreased by (94.44±2.41)%, and the surface of PE appeared cracks and holes	60 d	[72]
LDPE	Bacteria	*Bacillus cereus* A5	LDPE weight loss was (35.72±4.01)%, and intermediate products were detected	16 weeks	[73]
PVC	Fungi	*Phanerochaete chrysosporium* PV1	Molecular weight of the PVC film showed significant reduction and the structure also changed	10 months	[74]
PLA	Bacteria	*Arthrobacter sulfonivorans*	On the PET film, changes in surface structure were observed in the form of bumps, dulling, or traces of mycelium	6 months	[75]
PBSA	Fungi	*Aspergillus terreus* HC	PBSA weight loss 47.5%, hyphae were observed on the surface of the plastic film. After removing the hyphae, several cracks and cavities were observed on the surface	30 d	[76]
PP	Bacteria	*Bacillus* sp. 27	The weight loss of PP was 6.4%, the strain can colonize, modify and utilize PP microplastics as carbon source	40 d	[77]
PBAT	Bacteria	*Pseudomonas aeruginosa* RD1-3	The degradation rate of PBAT was (6.88±0.06)%, and a large number of gullies, pits and folds appeared on the surface of PBAT plastic surface and significantly reduced the hydrophobicity of the plastic surface	8 weeks	[78]
PUR	Fungi	*Aspergillus* sp. S45	The weight loss of PUR was 20%, and strain could grow with PUR as the sole carbon source	28 d	[79]
	Bacteria	*Bacillus* sp. S10-2	The weight loss of PUR was 19%, and strain could grow with PUR as the sole carbon source	60 d	[80]
PET	Bacteria	*Ideonella sakaiensis* 201-F6	The strain adhered to the surface of PET, and traces of degradation were observed on the film surface	60 h	[81]

存在的塑料碎片污染问题，不仅仅是 MPs，而 MPs 的生物降解本质上与塑料碎片无差别，所以无论是塑料薄膜还是 MPs，筛选分离的降解菌株二者均适用[40]。

3.2 降解机理

3.2.1 微生物在 MPs 表面定殖

真菌会产生疏水蛋白参与菌丝、子实体等结构的形成，进而附着在塑料的疏水表面定殖，由于细菌没有菌丝等结构，其在塑料表面的附着更多取决于塑料表面特性[82-84]。定殖过程中真菌可以通过定向菌丝生长延伸寻找目标，接触到塑料聚合物后穿透并留下裂纹[85-86]。而细菌只有接触到塑料表面，定殖才会发生[43,67]。此外土壤环境可能会影响微生物的定殖。当土壤中氮含量有限时，相较于细菌，真菌受影响程度可能较小，一方面真菌生长所需氮量较低，

另一方面真菌可以借助菌丝将氮从含量高的地方引导到聚合物表面的细胞，缓解氮素限制问题[67,87]。因此，在不同环境条件下，不同的真菌和细菌定殖策略可能存在差异。

3.2.2 MPs 骨架的解聚

定殖开始后，微生物会分泌多种胞外酶作用于 MPs 的特定位置，将聚合物转化为低聚物或单体[88-89]。按化学键结构可将塑料分为聚烯烃类塑料，如 PE、PVC、聚丙烯(polypropylene, PP)、PU 等和聚酯类塑料，如聚对苯二甲酸乙二醇酯(polyethylene terephthalate, PET)、PLA、PBAT 等[90]。前者主链由性质稳定的 C–C 键组成，其在解聚前需要通过调节环境因素(如氧气、温度等)氧化 C–C 键以便进一步分解[91-92]。而聚酯类塑料因其主链中含有可水解化学键，可被微生物分泌的水解酶降解[93]。由于种种因素的影响，MPs 的生物降解难易程度存在差异，需要结合实际情况具体分析[94]。以 PET 代谢途径为例，PET 水解酶(polyethylene terephthalate hydrolase, PETase)会水解 PET 生成主要中间产物单(2-羟乙基)对苯二甲酸酯[mono(2-hydroxyethyl) terephthalic acid, MHET]和对苯二甲酸(terephthalic acid, TPA)，MHET 水解酶[mono(2-hydroxyethyl) terephthalic acid hydrolase, MHETase]将 MHET 水解为 TPA 和乙二醇(ethylene glycol, EG)，TPA 会通过相关转运蛋白和结合蛋白进入细胞质，然后经一系列作用进一步分解[81,94-95]。PU 可通过红曲霉(*Monascus ruber*)、血红红曲霉(*Monascus sanguineus*)分泌蛋白酶和酯酶来降解[96]。漆酶、锰过氧化物酶和木质素过氧化物酶参与了 PE、PVC 的生物降解[91,97]。虽然当前已发现一些对聚烯烃类塑料生物降解有促进作用的酶，但其是否能完全降解仍需进一步研究。

3.2.3 微塑料在微生物胞内的矿化和积累

解聚的小分子会被微生物表面的受体识别从而穿过质膜进入微生物胞内，经微生物胞内代谢氧化为 CO_2、N_2、CH_4 和 H_2O 等小分子化合物，这是理想的降解过程[75]。值得注意的是，实际环境中微塑料很难被完全降解，更小的纳米级微塑料(nanoplastics, NPs)可能会涉及比 MPs 更复杂的生物降解过程。有研究表明 NPs 可以通过内吞作用或作物根部裂纹进入动物细胞或植物组织[21,98]。虽然没有研究证实 NPs 会进入细胞，但我们猜测存在这一可能性，因此，需要更加深入地研究以此来全面了解 MPs 的微生物降解途径。

3.3 影响 MPs 生物降解的因素

根据作用对象和作用方式，影响因素主要从微塑料和微生物 2 个方面考虑。一方面是，分子量、密度、官能团、结晶度和表面疏水性等微塑料自身理化性质对其表面生物膜的形成起一定的决定作用[72,99]。另一方面，对聚烯烃类塑料生物降解的研究多数会通过物理或化学作用预处理进而促进降解[100]。在评估绵毛嗜热丝孢菌(*Thermomyces lanuginosus*)对低密度聚乙烯薄膜(LDPE)的降解能力时，对 LDPE 进行了紫外线照射、加热和酸化预处理，1 个月后相较于未经预处理的，预处理后的 LDPE 重量减少得更多，表面形态也有较大变化[101]。采用组合物理、化学和生物处理结合的方法测定高密度聚乙烯(high density polyethylene, HDPE)的降解效果，经紫外线(UV)和高锰酸钾/盐酸($KMnO_4$/HCl)处理，同时添加土曲霉，观察到了 HDPE 的高效降解。

我们也意识到这一过程中外界因素对相关微生物生长代谢和酶活性的促进作用。Satti 等[102]探究一定条件下聚乳酸(PLA)薄膜的生物降解，发现使用 0.2%乳酸钠刺激天然微生物群落后，PLA 的矿化率显著提高。同样，使用聚氨酯(PU)分散剂进行生物刺激可使 PU 生物

降解从 45%增加到 62%[96]。Chien 等[76]进行的土壤掩埋试验中，夏季和冬季土壤环境中土曲霉(*Aspergillus terreus* HC)的降解率分别超过 90%和 75%。在冬季土壤中添加高剂量的 *A. terreus* HC 菌丝体后，聚丁二酸-己二酸丁二酯(PBSA)的降解效果进一步提高。使用超高温堆肥技术去除污泥中聚苯乙烯微塑料(polystyrene-microplastics, PS-MPs)时，降解率可达 43.7%，主要是由于其中的超嗜热细菌通过优异的生物氧化性能加速了 PS-MPs 的生物降解[103]。而添加一些蛋白质材料(弹性蛋白、明胶和部分氨基酸等)在一定程度上可以通过促进微生物的酶分泌进而提高降解速率[104]。

对于非生物因素促进作用的研究主要集中在培养温度和 pH 值 2 个方面。目前广泛研究了培养温度对聚合物降解速率的影响。在 7 °C、23 °C、37 °C 和 44 °C 条件下观察铜绿假单胞菌降解聚乙烯的效果，发现 44 °C 条件下培养 30 d，聚乙烯达到了最高重量损失百分比 6.25%[105]。而鉴于降解 PET 的 PETase 是在温和条件下(40 °C)发挥作用，为了提高其降解效率，研究人员找到了另一种具有 PET 水解特性的替代酶 LCC 突变体(ICCG)，这种酶可以在高达 80 °C 的温度下工作，更有利于 PET 的降解[106]。而 pH 值会通过调节微生物的存活和活性来影响微塑料的降解，进而影响微生物种群结构、酶活性和降解率[79,107]。当 PET 在高 pH 值条件下用碱性菌株处理时，与中性条件下的生物催化剂相比，降解产物浓度更高，PET 颗粒尺寸显著减小[72]。可以看出，MPs 生物降解过程受多种因素影响，这些因素之间的相互作用显著影响着 MPs 的降解[66]。

4 展望

当前环境中微塑料的相关研究越来越多，在逐步的探索中人们也意识到微塑料的生态影响远比之前认知到的更加复杂[108]，现有研究不能全面揭示其污染问题以及其在环境中的作用机制，还需要进一步深入挖掘微塑料的生态风险并进行相关研究。未来微塑料主要的研究方向建议如下。

(1) 根据实际情况调整室内试验。实际土壤环境中微塑料的最大重量仅有 6.7%，大多试验设计的微塑料用量远超这一比例，除了剂量，还需注意不同形状和类型微塑料存在的影响。同时要综合实际情况考虑到植物在微塑料与微生物互作中的作用。此外，多数研究的试验周期一般都是几周或几个月，得到的结果只反映了短期内对微塑料影响[109]。

(2) 微塑料生物降解问题的深入探究。目前已有大量研究证实了微生物的生物降解潜力，要注重微生物群落的联合作用，同时需要考虑这些筛选菌株应用到实际环境的情况，而且还应高度重视塑料是否能完全被代谢降解，因为不完全或部分降解会导致更小的塑料污染及生态毒理学问题[110]。微塑料生物降解是受多种因素影响的，因此，未来有必要进一步探索这些因素之间的关系，通过综合评价确定 MP 降解的最佳条件，这将有助于 MP 在各种环境中的降解[70]。而对于菌株的分离筛选工作存在一定难度问题，可以考虑从污染部位直接分离和鉴定有效的微生物群落[110]。

(3) 综合考虑土壤微塑料的生态效应。与水生环境相比，微塑料在土壤中的环境行为也更加复杂[111]。在评估土壤中微塑料的影响时还要额外考虑到微塑料对土壤中其他污染物的吸附作用，这种吸附可能导致污染物在微塑料上富集，增加土壤的局部浓度或产生联合效应[112]，因此分析土壤微塑料的生态效应时要综合考虑

微塑料可能产生的影响。

(4) 解决塑料污染问题新技术的研发应用。有研究验证了光照射对微塑料降解的有效性，不同类型土壤的微塑料降解速率存在差异，可能是由于微塑料与土壤表面的静电作用不同[113]。Cao 等[114]通过研究光催化剂为降解塑料污染提供了极好的方案，他们成功研制一系列 MXene/Z_xC1-$_x$S 光催化剂，可以实现与微塑料降解相结合并高效产氢。此外，针对环境中污染物，广泛使用的消除或降解方法是植物修复，其主要通过植物刺激或根际生物活动来实现[115-116]。相关研究发现，在去除土壤污染问题上，同时引入生物和植物的修复技术比单独使用二者之一的修复效果更有效[117]。未来可以考虑将这些技术手段综合起来，用于土壤微塑料污染的治理。

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