文章编号：1674－2869(2026)01－0075－07

生物可降解微塑料对植物-土壤系统的影响

洪鑫成，樊昊心*
武汉工程大学环境生态与生物工程学院，湖北 武汉 430205

摘 要：在全球塑料污染问题日益加剧的背景下，生物可降解塑料作为传统塑料的重要替代材料受到广泛关注，但生物可降解塑料在环境降解过程中可能在较短时间内产生大量微塑料，其潜在生态风险尚未得到充分认识，尤其是其对植物－土壤生态系统的影响仍缺乏系统性总结。综述了近年来微塑料，特别是生物可降解微塑料，对植物生长与生理过程的研究进展，重点归纳其对植物形态、生理代谢、营养吸收及植物－土壤相互作用的影响机制，并分析当前研究中存在的不足与争议。旨在为深入理解生物可降解微塑料在植物-土壤系统中的环境行为及生态效应提供理论依据，为相关环境风险评估与后续研究提供参考。

关键词：微塑料；植物-土壤生态系统；微生物群落
中图分类号：　　**文献标识码**：A　　**DOI**：10.19843/j.cnki.CN42-1779/TQ.202405017

Impact of biodegradable microplastics on plant-soil ecosystems

HONG Xincheng, *FAN Haoxin**
School of Environmental Ecology and Biological Engineering, Wuhan Institute of Technology, Wuhan 430205, China

Abstract: In the context of increasingly severe global plastic pollution, biodegradable plastics have attracted great attention as a promising alternative to conventional plastics. However, biodegradable plastics may generate substantial amounts of microplastics within a relatively shorter period during environmental degradation, and their potential ecological risks—especially their impacts on plant-soil ecosystems—are not yet fully understood and remain systematically underexplored. This review summarized recent research progress on the effects of microplastics, especially biodegradable microplastics, on plant growth and physiological processes, focusing on the mechanisms by which they influence plant morphology, physiological metabolism, nutrient uptake, and plant-soil interactions. It also analyzed current research gaps and controversies in the field. This review aims to provide a theoretical basis for an in-depth understanding of the environmental behavior and ecological effects of biodegradable microplastics in plant-soil systems and to offer insight for related environmental risk assessments and future research.

Keywords: microplastics; plant-soil ecosystem; microbial community

塑料材料广泛应用于我们日常生活的各个方面，包括各类包装材料、农业覆膜，建筑和制造[1]。全球塑料年产量从1950年的150万t增至2020年的3.7亿t[2]。目前，已经在各个不同的生态环境中发现塑料，例如土壤[3]、空气[4]、淡水系统（即河流和湖泊）和海洋[5-6]。塑料产品通过各种途径进入环境中，并在各种物理、化学或生物的作用力下逐渐分解成更小的塑料碎片，对生态环境体系及人体生命健康造成潜在的危害[7]。

由于产生大量难以生物降解的塑料产品，微塑料污染已经成为全球关注的问题。目前，学术界将直径小于5 mm的细小塑料碎片和颗粒定义

收稿日期：2024-05-26
基金项目：国家自然科学基金（4207039）
作者简介：洪鑫成，硕士研究生。Email：2449256847@qq.com
***通信作者**：樊昊心，博士，副教授。Email：haoxin.fan@wit.edu.cn
引文格式：洪鑫成，樊昊心. 生物可降解微塑料对植物-土壤系统的影响[J]. 武汉工程大学学报，2026，48(1)：75-81.

为“微塑料”[8]。微塑料由初级和次级微塑料组成。初级微塑料是指直接产生的塑料颗粒,包括来自纺织品的微珠、微球和微纤维、化妆品和制造产品[9];而次级微塑料是塑料废物经紫外线辐射、风化、高温、氧化、冻融循环和生物降解后的碎片[8-10]。

随着全球塑料污染的日益严重,微塑料作为塑料污染的重要组成部分,其环境效应已成为全球关注的热点问题。特别是生物可降解微塑料,作为一种潜在的环境友好型材料,其在自然环境中的降解过程和对生态系统的影响引发了广泛的研究兴趣。理想情况下的生物可降解塑料是一种性能优异、降解速度快的聚合物材料,可以通过自然发生的微生物矿化作用100%转化为二氧化碳和水,最终作为碳循环的一部分存在于自然界。植物-土壤系统是陆地生态系统的重要组成部分,对维持地球生态平衡和人类生存具有重要意义。因此,探究生物可降解微塑料对植物-土壤系统的影响,不仅有助于我们深入理解微塑料在环境中的行为,也为微塑料的环境风险评估和生态修复提供了科学依据。

1 土壤生态系统中微塑料的来源

土壤生态系统是全球生态系统中的重要环节,连接着大气、水、岩石等环境系统。它对营养循环和能量流动极其重要。因此,土壤容易受到各种污染物的降解,包括新出现的污染物,如微塑料[11]。

土壤中微塑料主要来自人类活动,包括施肥、塑料覆膜以及生活垃圾。特别是在农业土壤类型中,最常见的是地膜,但也通过灌溉水,街道径流,洪水,污水污泥,农业堆肥和空气等方式产生微塑料[12-15]。土壤中微塑料的另一个重要来源是路边附近空气中微塑料的沉积,源自轮胎与道路之间摩擦产生[16]。已经有研究发现轮胎橡胶颗粒可负面影响植物生长并改变土壤的生物地球化学性质,从而导致芽和根生长减少以及土壤pH水平升高[17]。微塑料因其种类多、吸附能力强、易迁移、疏水性强、存在时间长等特点,可广泛存在于大气、水、土壤等环境介质中[18-19]。类似地,微塑料广泛存在于不同类型的土壤环境中,包括农业土壤、工业土壤、城市土壤以及未使用的土壤中[20-22]。

2 微塑料对土壤生态系统的影响

2.1 微塑料对土壤理化性质的影响

土壤pH值是影响土壤理化性质的主要非生物因素之一,如矿物质和土壤有机碳(soil organic carbon, SOC)的结合能力、营养元素的生物利用度、污染物的吸附以及土壤微生物群落的组成和活性[23]。微塑料在进入土壤环境后,在分解降解过程中释放出化合物,影响土壤pH值,微塑料还可能通过改变微生物群落结构,引起微生物分泌物的变化,间接影响土壤pH值。pH值变化的具体程度取决于土壤环境。目前,Yang等[24]发现了质量分数1%和10%聚乳酸(polylactic acid, PLA)和高密度聚乙烯(high density polyethylene, HDPE)微塑料的存在显著增加了土壤pH。多项研究表明聚乙烯(polyethylene,PE)微塑料提高了土壤pH值[24-26]。同样地,Lozano等[27]发现质量分数0.4%聚醚砜(polyether sulfone, PES)微塑料增加了土壤pH值。但并不是所有的微塑料类型都引起土壤pH的增加,例如Feng等[28]发现质量分数2% PE和聚苯乙烯(polystyrene, PS)微塑料则引起了土壤pH的下降,但在质量分数0.2%的浓度下土壤pH没有发生改变。Dong等[29]发现质量分数0.2%PS微塑料同样引起了土壤pH的下降。Boots等[29]比较了分别暴露于衣物纤维、PLA和HDPE微塑料30 d后土壤pH值的变化,发现HDPE微塑料显著降低了pH值,但是PLA微塑料和衣物纤维没有引起显著影响。这些情况说明不同浓度、类型的微塑料对土壤pH的影响是不确定的。而土壤pH值不确定变化可能会进一步导致土壤养分的可用性和植物生长,以及农作物生产力的改变。

对于土壤中养分,质量分数1%聚氯乙烯(polyvinyl chloride, PVC)微塑料污染的稻田土壤中,土壤中有效氮的含量降低了10%~13%[30]。Chen等[31]发现,在低碳条件下,PLA微塑料显著增加土壤NO_3^--N含量,但降低了NH_4^+-N含量。此外,微塑料本身就可作为碳库,成为土壤环境中的碳来源之一。研究发现土壤细菌具有将微塑料转化为土壤可溶解性有机碳(dissolved organic carbon,DOC)的能力,Wang等[32]的研究发现DOC含量随着微塑料浓度的提高而增加。目前有几种机制解释微塑料对土壤养分的影响。首先是一些微塑料含有含氮、磷的抗氧化添加剂,最终在矿化后将这些元素释放到土壤中[33]。其次,由于微塑料较强的吸附能力,导致微塑料能直接吸附营养物质,从而改变其有效性。

2.2 微塑料对土壤酶活的影响

土壤环境中的酶主要是土壤动物、植物以及

微生物群落的代谢分泌物。同时,土壤酶活是反映土壤质量和肥力的重要指标[34]。微塑料主要是由含碳聚合物组成,可以为土壤微生物群落提供碳源,促进关键酶的产生。同时微塑料浸出的有毒化合物也有可能抑制相关微生物的生存,从而导致土壤酶活性的下降[35]。不同类型的微塑料对酶活的影响也不同,Machado等[33]发现PA、HDPE和PES微塑料增加了荧光素二乙酸水解酶酶活,但PET、PP和PS微塑料对该酶酶活没有显著影响。另一项研究发现,3种不同的微塑料对脲酶、脱氢酶和碱性磷酸酶具有不同的影响[36]。150 d的土壤培养实验中发现,PE微塑料抑制了6种胞外酶活性[34]。Chen等[31]发现,尽管单独添加PLA微塑料对土壤酶活性没有显著影响,但在用秸秆残留物改良的土壤中,PLA微塑料暴露显著降低了β-葡萄糖苷酶、脲酶和过氧化氢酶的活性。有机物质的添加刺激土壤团聚体的形成,导致土壤团聚体中存在大量微塑料,降低团聚体的稳定性,从而负面影响酶活性[21]。综上所述,不同的微塑料对不同的土壤酶活的影响不同。目前,对微塑料如何诱导土壤性质和酶活性能变化仍不清楚。

2.3　微塑料对土壤微生物群落的影响

微塑料可以为微生物群落提供能量来源,改变微生物群落结构和功能。微塑料还可以通过有毒和有害化学物质的沥滤或土壤性质的间接变化来影响微生物群落组成和活性[37]。研究发现不同类型、剂量、大小、形状的微塑料对土壤细菌的组成和功能的影响不同[11, 38-40]。在一项长期密集PE塑料覆盖实践的农田中,发现多种微生物定殖于地膜的微塑料表面,并且微生物群落结构与周围的土壤环境的微生物群落结构显著不同[41]。Zhou等[42]发现微塑料添加的土壤中碳和养分周转显著增加,可能因为微塑料圈中独特的细菌群落结构以及可生物降解微塑料引起的微生物生物量和活性的增加。在具有低pH和低磷含量,但高氮含量的农业土壤环境中,添加PE和PVC微塑料(质量比1%和5%)降低了土壤细菌群落的多样性和丰富度并且PE的影响更加严重[43]。Yan等[30]则发现在0.1%和1.0%(质量分数)浓度下的PVC微塑料污染不影响土壤细菌总体的多样性和组成,但改变了一些特定细菌的分类群的相对丰度。

土壤真菌是产生孢子的真核生物,包括霉菌、酵母和藻类细菌,它们不同于土壤动物、植物和其他真核生物。研究发现土壤真菌同样也可以降解微塑料,甚至其降解能力比放线菌等细菌具有更强的降解能力[44]。微塑料同样也能改变土壤真菌群落的结构和多样性[45]。Lehmann等[46]发现,在干旱和浇水充足的条件下,微塑料的存在增加了土壤真菌的定殖,而另一项研究发现,PES和PP微塑料增加了土壤真菌对洋葱根的定殖,但PET微塑料减少了土壤真菌对洋葱的根定殖[33]。最后,土壤微塑料还能成为植物病原菌的载体[41, 47]。例如,残存的微塑料污染增加了黄单胞菌属(*Xanthomonas*)的相对丰度,其中一些为植物病原菌[39],可能为植物生长发育带来潜在的风险。

微塑料能吸引特定的微生物类群定殖,甚至是潜在病原微生物,从而改变植物根际微生物组成和活性,进而影响到植物的正常生长发育。但是不同类型、大小、形状等方面的微塑料对土壤微生物群落结构的影响不同。因此,微塑料对土壤微生物群落的影响仍然有待进一步的研究。

3　微塑料对植物的影响

微塑料可以通过与根际直接的相互作用影响农作物,也可以通过改变土壤性质间接影响农作物。植物根际系统是独特的、综合的和动态的,连接着植物、非生物体和生物组分[48]。微塑料影响植物根对营养物质的吸收转化,导致生物量和微生物活性的下降以及组成和根际特征的改变[49]。此外,微塑料表面各种的官能团也能吸附大量其他类型的污染物,导致有毒物质对植物的间接或直接伤害[50]。

根据报道,土壤中的微塑料能影响植物发芽率、芽高以及生物量[51-52]。Meng等[53]发现LDPE微塑料(质量分数0.5%~2.0%)不会影响菜豆的芽、根和豆类生物量,但添加聚对苯二甲酸己二酸丁二烯(polybutylene adipate terephthalate, PBAT)微塑料(质量分数2%)的处理显著降低了菜豆茎、根和豆类生物量。但同时另一方面,Tang等[54]发现PE和PVC微塑料增加了水稻的地上生物量,同时降低了水稻的地下生物量。不同类型的塑料、土壤环境和植物物种的结果不同。Liu等[55]发现PBAT微塑料严重破坏了拟南芥的光合系统,提高了药物转运相关途径的基因表达水平,还提高了块状土壤和根际土壤中慢生根瘤菌属、噬氢菌属和节杆菌属细菌的丰度,并抑制拟南芥的生长。微塑料还能引起植物的多种生理反应。PS和聚四氟乙烯微塑料在水稻根中引起氧化爆发和细胞损伤[53],还能增加拟南芥中的活性氧[56]。Zhao

等[57]发现了PS和PP微塑料增强了玉米根系对重金属的镉的吸收。Abbasi等[58]发现PET微塑料可以作为载体将重金属转移到小麦根际，影响小麦生长并显著降低作物产量。这些结果表明微塑料不仅能够直接影响植物生理，还能够通过释放有毒的降解产物和改变污染物的生物有效性来间接地影响植物生理状态。但另一方面，PS微塑料能够促进小麦生长、增加根长、显著提高植株的碳、氮含量以及生物量[59]。具体案例见表1。

表1 微塑料对植株生长生理的影响

Table 1 Effects of microplastics on plant growth and physiology

微塑料类型	微塑料浓度(质量分数)	植株	具体影响	参考文献
PLA	0.1%、1.0%	大豆(*Glycine max* L.)	枝条长度增加，根长减小并对叶片抗氧化系统有显著负面影响。	[60]
PLA	0.2%	燕麦(*Avena sativa* L.)和大豆(*Glycine max* L.)	燕麦和大豆的生长不受微塑料的影响。	[61]
PLA	1.0%	蒲公英(*Taraxacum mongolicum* Hand.-Mazz.)	降低了植株生物量。	[62]
PLA	1.0%、10.0%	花生(*Arachis hypogaea* L)	两种浓度均显著增加了植株株高，并且增加了叶绿素a和b的含量	[63]
PBAT	1.0%	水稻(*Oryza sativa* L.)	叶片叶绿素含量减少，下调氮转运蛋白基因干扰水稻植株生长。	[64]
PBAT	0.5%、1.0%、2.0%	拟南芥(*Arabidopsis thaliana* (L.)Heynh.)	严重破坏了拟南芥的光合系统。	[55]
PBAT	0.5%、1.0%、1.5%、2.0%、2.5%	菜豆(*Phaseolus vulgaris* L.)	降低了植株生物量。	[53]
PE	/	玉米(*Zea mays* L.)	减少了植株生物量和植株对氮的吸收利用。	[65]
PE	0.1%	玉米(*Zea mays* L.)	减少了植株生物量。	[66]
PE	0.2%	小麦(*Triticum aestivum* L.)	显著降低了植株的生物量和高度。	[67]
PS	/	海草(Cymodocea nodosa)	对植株光合作用机制有负面影响，增加了海草的氧化应激反应并影响了苯酚的产生。	[68]
PS	/	水稻(*Oryza sativa* L.)	微塑料会抑制根系活性并引发氧化应激，破坏细胞结构。	[52]
PVC	0.1%、0.2%、0.4%、0.8%、1.6%	甜瓜(*Cucumis melo* L.)	显著降低了甜瓜种子的发芽率和植株干重。	[69]
LDPE	0.02%、0.20%、0.40%	大麦(*Hordeum vulgare* L.)	减少了植株对氮的吸收，但对生物量和茎高无影响。	[70]

4 结论与展望

植物是陆地生态系统的基本组成部分。微塑料在土壤中的普遍存在导致它们不可避免地与陆地植物相互作用。由于植物在陆地生态系统中的重要作用以及微塑料的持续释放，微塑料对陆地植物的潜在影响正引起越来越多的关注。

生物可降解微塑料在土壤中的降解过程受到多种因素的影响，包括土壤类型、微生物群落结构、环境条件等。其次，生物可降解微塑料对植物-土壤系统的影响具有复杂性和多样性，既可能带来正面的生态效应，如改善土壤结构、促进植物生长等，也可能产生潜在的生态风险，如影响土壤微生物群落结构、改变营养元素循环等。因此，在推广和应用生物可降解微塑料时，需要充分考虑其环境效应和生态风险，并采取相应的防控措施。未来，需要进一步加强对生物可降解微塑料在环境中的行为、生态效应和风险评估的研究，为微塑料的环境管理和生态修复提供更为科学、有效的指导。

参考文献

[1] CHAE Y，AN Y J. Current research trends on plastic pollution and ecological impacts on the soil ecosystem：a review [J]. Environmental Pollution，2018，240：387-395.

[2] GEYER R, JAMBECK J R, LAW K L. Production, use, and fate of all plastics ever made [J]. Science Advances, 2017, 3(7): e1700782.

[3] CHOI Y R, KIM Y N, YOON J H, et al. Plastic contamination of forest, urban, and agricultural soils: a case study of Yeoju City in the Republic of Korea [J]. Journal of Soils and Sediments, 2021, 21(5): 1962-1973.

[4] TRAINIC M, FLORES J M, PINKAS I, et al. Airborne microplastic particles detected in the remote marine atmosphere [J]. Communications Earth & Environment, 2020, 1: 64.

[5] BELLASI A, BINDA G, POZZI A, et al. Microplastic contamination in freshwater environments: a review, focusing on interactions with sediments and benthic organisms [J]. Environments, 2020, 7(4): 30.

[6] WANNER P. Plastic in agricultural soils-a global risk for groundwater systems and drinking water supplies? -a review [J]. Chemosphere, 2021, 264: 128453.

[7] GAN Q, CUI J W, JIN B. Environmental microplastics: classification, sources, fates, and effects on plants [J]. Chemosphere, 2023, 313: 137559.

[8] THOMPSON R C, OLSEN Y, MITCHELL R P, et al. Lost at sea: where is all the plastic? [J]. Science, 2004, 304(5672): 838.

[9] Van CAUWENBERGHE L, DEVRIESE L, GALGANI F, et al. Microplastics in sediments: a review of techniques, occurrence and effects [J]. Marine Environmental Research, 2015, 111: 5-17.

[10] BLETTLER M C M, ULLA M A, RABUFFETTI A P, et al. Plastic pollution in freshwater ecosystems: macro- , meso- , and microplastic debris in a floodplain lake [J]. Environmental Monitoring and Assessment, 2017, 189(11): 581.

[11] WANG F Y, WANG Q L, ADAMS C A, et al. Effects of microplastics on soil properties: current knowledge and future perspectives [J]. Journal of Hazardous Materials, 2022, 424: 127531.

[12] De SOUZA MACHADO A A, LAU C W, TILL J, et al. Impacts of microplastics on the soil biophysical environment [J]. Environmental Science & Technology, 2018, 52(17): 9656-9665.

[13] PÉREZ-REVERÓN R, GONZÁLEZ-SÁLAMO J, HERNÁNDEZ-SÁNCHEZ C, et al. Recycled wastewater as a potential source of microplastics in irrigated soils from an arid-insular territory (Fuerteventura, Spain) [J]. Science of the Total Environment, 2022, 817: 152830.

[14] ROLF M, LAERMANNS H, KIENZLER L, et al. Flooding frequency and floodplain topography determine abundance of microplastics in an alluvial Rhine soil [J]. Science of the Total Environment, 2022, 836: 155141.

[15] SALEHI Z, HASHEMI S H, FLURY M. Micro- and mesoplastics in farmlands with different irrigation water sources [J]. Water, Air, & Soil Pollution, 2023, 234(4): 267.

[16] KOLE P J, LÖHR A J, VAN BELLEGHEM F G A J, et al. Wear and tear of tyres: a stealthy source of microplastics in the environment [J]. International Journal of Environmental Research and Public Health, 2017, 14(10): 1265.

[17] LEIFHEIT E F, KISSENER H L, FALTIN E, et al. Tire abrasion particles negatively affect plant growth even at low concentrations and alter soil biogeochemical cycling [J]. Soil Ecology Letters, 2022, 4(4): 409-415.

[18] DELANGIZ N, ALIYAR S, PASHAPOOR N, et al. Can polymer-degrading microorganisms solve the bottleneck of plastics' environmental challenges? [J]. Chemosphere, 2022, 294: 133709.

[19] ZHAO T T, LOZANO Y M, RILLIG M C. Microplastics increase soil pH and decrease microbial activities as a function of microplastic shape, polymer type, and exposure time [J]. Frontiers in Environmental Science, 2021, 9: 675803.

[20] GUO Q Q, XIAO M R, ZHANG G S. The persistent impacts of polyester microfibers on soil bio-physical properties following thermal treatment [J]. Journal of Hazardous Materials, 2021, 420: 126671.

[21] LIANG Y H, YANG M C. Move-on-modify: an efficient yet crash-consistent update strategy for interlaced magnetic recording [C]//2021 58th ACM/IEEE Design Automation Conference (DAC). San Francisco, CA, USA: IEEE, 2021: 97-102.

[22] WAN Y, WU C X, XUE Q, et al. Effects of plastic contamination on water evaporation and desiccation cracking in soil [J]. Science of the Total Environment, 2019, 654: 576-582.

[23] ROUSK J, BÅÅTH E, BROOKES P C, et al. Soil bacterial and fungal communities across a pH gradient in an arable soil [J]. The ISME Journal, 2010, 4(10): 1340-1351.

[24] YANG W W, CHENG P, ADAMS C A, et al. Effects of microplastics on plant growth and arbuscular mycorrhizal fungal communities in a soil spiked with ZnO nanoparticles [J]. Soil Biology and Biochemistry, 2021, 155: 108179.

[25] YA H B, XING Y, ZHANG T, et al. LDPE microplastics affect soil microbial community and form a unique plastisphere on microplastics [J]. Applied Soil Ecology, 2022, 180: 104623.

[26] QI Y L, OSSOWICKI A, YANG X M, et al. Effects of plastic mulch film residues on wheat rhizosphere and soil properties [J]. Journal of Hazardous Materials, 2020, 387: 121711.

[27] LOZANO Y M, AGUILAR-TRIGUEROS C A, ONANDIA G, et al. Effects of microplastics and drought on soil ecosystem functions and multifunctionality [J]. Journal of Applied Ecology, 2021, 58(5): 988-996.

[28] FENG X Y, WANG Q L, SUN Y H, et al. Microplastics change soil properties, heavy metal availability and bacterial community in a Pb-Zn-contaminated soil [J]. Journal of Hazardous Materials, 2022, 424: 127364.

[29] DONG Y M, GAO M L, QIU W W, et al. Effect of microplastics and arsenic on nutrients and microorganisms in rice rhizosphere soil [J]. Ecotoxicology and Environmental Safety, 2021, 211: 111899.

[30] YAN Y Y, CHEN Z H, ZHU F X, et al. Effect of polyvinyl chloride microplastics on bacterial community and nutrient status in two agricultural soils [J]. Bulletin of Environmental Contamination and Toxicology, 2021, 107(4): 602-609.

[31] CHEN H P, WANG Y H, SUN X, et al. Mixing effect of polylactic acid microplastic and straw residue on soil property and ecological function [J]. Chemosphere, 2020, 243: 125271.

[32] WANG J, PENG C, LI H Y, et al. The impact of microplastic-microbe interactions on animal health and biogeochemical cycles: a mini-review [J]. Science of the Total Environment, 2021, 773: 145697.

[33] DE SOUZA MACHADO A A, LAU C W, KLOAS W, et al. Microplastics can change soil properties and affect plant performance [J]. Environmental Science & Technology, 2019, 53(10): 6044-6052.

[34] TAN X P, NIE Y X, MA X M, et al. Soil chemical properties rather than the abundance of active and potentially active microorganisms control soil enzyme kinetics [J]. Science of the Total Environment, 2021, 770: 144500.

[35] VITHANAGE M, RAMANAYAKA S, HASINTHARA S, et al. Compost as a carrier for microplastics and plastic-bound toxic metals into agroecosystems [J]. Current Opinion in Environmental Science & Health, 2021, 24: 100297.

[36] YI M L, ZHOU S H, ZHANG L L, et al. The effects of three different microplastics on enzyme activities and microbial communities in soil [J]. Water Environment Research, 2021, 93(1): 24-32.

[37] GAO B, YAO H Y, LI Y Y, et al. Microplastic addition alters the microbial community structure and stimulates soil carbon dioxide emissions in vegetable-growing soil [J]. Environmental Toxicology and Chemistry, 2021, 40(2): 352-365.

[38] SUN Y Z, LI X F, CAO N, et al. Biodegradable microplastics enhance soil microbial network complexity and ecological stochasticity [J]. Journal of Hazardous Materials, 2022, 439: 129610.

[39] QIAN H F, ZHANG M, LIU G F, et al. Effects of soil residual plastic film on soil microbial community structure and fertility [J]. Water, Air, & Soil Pollution, 2018, 229(8): 261.

[40] REN X W, TANG J C, LIU X M, et al. Effects of microplastics on greenhouse gas emissions and the microbial community in fertilized soil [J]. Environmental Pollution, 2020, 256: 113347.

[41] ZHANG M J, ZHAO Y R, QIN X, et al. Microplastics from mulching film is a distinct habitat for bacteria in farmland soil [J]. Science of the Total Environment, 2019, 688: 470-478.

[42] ZHOU J, GUI H, BANFIELD C C, et al. The microplastisphere: biodegradable microplastics addition alters soil microbial community structure and function [J]. Soil Biology and Biochemistry, 2021, 156: 108211.

[43] FEI Y F, HUANG S Y, ZHANG H B, et al. Response of soil enzyme activities and bacterial communities to the accumulation of microplastics in an acid cropped soil [J]. Science of the Total Environment, 2020, 707: 135634.

[44] BONKOWSKI M, VILLENAVE C, GRIFFITHS B. Rhizosphere fauna: the functional and structural diversity of intimate interactions of soil fauna with plant roots [J]. Plant and Soil, 2009, 321(1): 213-233.

[45] WANG F Y, ZHANG X Q, ZHANG S Q, et al. Interactions of microplastics and cadmium on plant growth and arbuscular mycorrhizal fungal communities in an agricultural soil [J]. Chemosphere, 2020, 254: 126791.

[46] LEHMANN A, LEIFHEIT E F, FENG L S, et al. Microplastic fiber and drought effects on plants and soil are only slightly modified by arbuscular mycorrhizal fungi [J]. Soil Ecology Letters, 2022, 4(1): 32-44.

[47] HUANG Y, ZHAO Y R, WANG J, et al. LDPE

microplastic films alter microbial community composition and enzymatic activities in soil [J]. Environmental Pollution, 2019, 254: 112983.

[48] BOUAICHA O, MIMMO T, TIZIANI R, et al. Microplastics make their way into the soil and rhizosphere: a review of the ecological consequences [J]. Rhizosphere, 2022, 22: 100542.

[49] WANG J, COFFIN S, SUN C L, et al. Negligible effects of microplastics on animal fitness and HOC bioaccumulation in earthworm Eisenia fetida in soil [J]. Environmental Pollution, 2019, 249: 776-784.

[50] ZHANG Y Y, CAI C, GU Y F, et al. Microplastics in plant-soil ecosystems: a meta-analysis [J]. Environmental Pollution, 2022, 308: 119718.

[51] BOOTS B, RUSSELL C W, GREEN D S. Effects of microplastics in soil ecosystems: above and below ground [J]. Environmental Science & Technology, 2019, 53(19): 11496-11506.

[52] DONG Y M, GAO M L, SONG Z G, et al. Microplastic particles increase arsenic toxicity to rice seedlings [J]. Environmental Pollution, 2020, 259: 113892.

[53] MENG F R, YANG X M, RIKSEN M, et al. Response of common bean (Phaseolus vulgaris L.) growth to soil contaminated with microplastics [J]. Science of the Total Environment, 2021, 755: 142516.

[54] TANG X Y, CHEN M J, LI M Z, et al. Do differentially charged nanoplastics affect imidacloprid uptake, translocation, and metabolism in Chinese flowering cabbage? [J]. Science of the Total Environment, 2023, 871: 161918.

[55] LIU J X, WANG P Y, WANG Y F, et al. Negative effects of poly (butylene adipate-co-terephthalate) microplastics on Arabidopsis and its root-associated microbiome [J]. Journal of Hazardous Materials, 2022, 437: 129294.

[56] SUN X D, YUAN X Z, JIA Y B, et al. Differentially charged nanoplastics demonstrate distinct accumulation in Arabidopsis thaliana [J]. Nature Nanotechnology, 2020, 15(9): 755-760.

[57] ZHAO M, XU L, WANG X X, et al. Microplastics promoted cadmium accumulation in maize plants by improving active cadmium and amino acid synthesis [J]. Journal of Hazardous Materials, 2023, 447: 130788.

[58] ABBASI S, MOORE F, KESHAVARZI B, et al. PET-microplastics as a vector for heavy metals in a simulated plant rhizosphere zone [J]. Science of the Total Environment, 2020, 744: 140984.

[59] REN X W, YIN S, WANG L, et al. Microplastics in plant-microbes-soil system: a review on recent studies [J]. Science of the Total Environment, 2022, 816: 151523.

[60] LING N, WANG T T, KUZYAKOV Y. Rhizosphere bacteriome structure and functions [J]. Nature Communications, 2022, 13: 836.

[61] CHU J C, ZHOU J, WANG Y, et al. Field application of biodegradable microplastics has no significant effect on plant and soil health in the short term [J]. Environmental Pollution, 2023, 316: 120556.

[62] LI X F, ZENG G N, DU X Y, et al. Effects of polyethylene and biodegradable microplastics on the physiology and metabolic profiles of dandelion [J]. Environmental Pollution, 2024, 352: 124116.

[63] WANG Q L, FENG X Y, LIU Y Y, et al. Response of peanut plant and soil N-fixing bacterial communities to conventional and biodegradable microplastics [J]. Journal of Hazardous Materials, 2023, 459: 132142.

[64] YANG C, GAO X H. Impact of microplastics from polyethylene and biodegradable mulch films on rice (*Oryza sativa* L.) [J]. Science of the Total Environment, 2022, 828: 154579.

[65] URBINA M A, CORREA F, ABURTO F, et al. Adsorption of polyethylene microbeads and physiological effects on hydroponic maize [J]. Science of the Total Environment, 2020, 741: 140216.

[66] FAJARDO C, MARTÍN C, COSTA G, et al. Assessing the role of polyethylene microplastics as a vector for organic pollutants in soil: ecotoxicological and molecular approaches [J]. Chemosphere, 2022, 288: 132460.

[67] GUO A Y, PAN C R, SU X M, et al. Combined effects of oxytetracycline and microplastic on wheat seedling growth and associated rhizosphere bacterial communities and soil metabolite profiles [J]. Environmental Pollution, 2022, 302: 119046.

[68] MENICAGLI V, CASTIGLIONE M R, BALESTRI E, et al. Early evidence of the impacts of microplastic and nanoplastic pollution on the growth and physiology of the seagrass Cymodocea nodosa [J]. Science of the Total Environment, 2022, 838: 156514.

[69] LI Z Y, ZENG X L, SUN F H, et al. Physiological analysis and transcriptome profiling reveals the impact of microplastic on melon (Cucumis melo L.) seed germination and seedling growth [J]. Journal of Plant Physiology, 2023, 287: 154039.

[70] REAY M K, GREENFIELD L M, GRAF M, et al. LDPE and biodegradable PLA-PBAT plastics differentially affect plant-soil nitrogen partitioning and dynamics in a Hordeum vulgare mesocosm [J]. Journal of Hazardous Materials, 2023, 447: 130825.

本文编辑：张　瑞