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GUO Rong, SHEN Yating. A Review on the Impacts of Microplastics and Environmental Pollutants on Soil Microorganisms[J]. Rock and Mineral Analysis, 2024, 43(1): 1−15. DOI: 10.15898/j.ykcs.202209180175.

土壤中微塑料与环境污染物的复合作用及其对微生物的影响

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摘要: 随着塑料制品在工农业和生产生活中的广泛使用，大量微塑料被释放到土壤中，带来不可忽视的生态环境与健康风险。长久以来，人们更关注微塑料本身的生态毒性，对微塑料与环境中的其他化学污染物的联合作用及其环境效应研究较少。由于土壤微生物在微塑料降解过程中起着关键作用，认识土壤微塑料是如何通过影响土壤环境而直接或间接影响土壤中微生物群落和土壤生态功能的微观机理，已成为未来推进微塑料的降解和科学认识微塑料生态系统风险的关键。本文综述了近年来微塑料在土壤中吸附和迁移机理，以及微塑料的吸附程度和位置对其迁移行为的影响。总结了微塑料与土壤中有机污染物和重金属的复合作用的进展，探讨了这些复合作用对土壤环境风险的影响，包括污染物的毒性、生物利用度和迁移性的变化。评述了微塑料对土壤微生物群落的影响及作用机制，微塑料对微生物的物种丰富度、活性和结构的影响，以及微塑料表面的定殖和选择性富集能力。建议未来应该加强以下三方面的研究：①深入探索微塑料与环境污染物的复合作用及其生态毒理作用的微观机理；②认识土壤中微塑料对土壤微生物群落结构改变的微观机制；③探索通过科学调控土壤理化特性、特异性微生物在微塑料表面的定殖与富集能力等途径来控制土壤中微塑料及微塑料-其他环境污染物复合污染的可能性。

关键词: 微塑料；微生物群落结构；有机污染物；重金属；复合作用

要点:

(1) 微塑料在土壤中吸附迁移受到微塑料性质、土壤性质、动植物活动等多种因素的影响。

(2) 微塑料与土壤中有机污染物和重金属的复合作用可能改变污染物的环境风险、迁移、降解和生物可利用度，这取决于微塑料和土壤的特性及环境因素。

(3) 微塑料可增加或降低土壤微生物丰富度和多样性，该影响受土壤理化性质、微生物定殖和复合污染等多重机制调控。

中图分类号: S151.93　　**文献标识码:** A

微塑料 (Microplastics, MPs) 是一种持久性环境污染物[1-2]，通常尺寸或粒径在 100 ~ 5mm 之间，可通过光氧化降解或环境中的机械磨损向更小粒径 (<100nm) 分解。根据微塑料的生物可降解特征分为: ①生物难降解的微塑料，如聚乙烯 (Polyethylene, PE) 和聚丙烯 (Polypropylene, PP) 等; ②生物可降解型微塑料，如聚乳酸 (Polylactic acid, PLA) 和聚-β-羟丁酸 (Polyhydroxybutyrate, PHB) 等。微塑料具有粒径小、光降解能力弱，并可在土壤和沉积物等介质中富集等特性有机污染物。不同种类的微塑料聚合物官能团、结构特征、带电性、化学链排列紧密程度不同，可影响微塑料的比表面积、疏水性及其降解能力，

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进而影响到微塑料在土壤环境中的环境行为[3]。目前,在土壤、水体、空气等多种环境介质中均发现微塑料的存在[4-6],微塑料还具有长距离迁移性,如在人类活动较少的偏远沙漠[7]以及北极地区[8]等均有检出。环境中微塑料的累积甚至可能会加速北极冰雪圈的升温和冰雪融化[9],影响全球气候变化[10]。微塑料已在人类血液、尿液及粪便中被发现[11-12],对人体消化系统、神经系统、免疫及生殖系统等器官和组织产生毒害作用[13]。吸入微塑料颗粒会导致呼吸道疾病和癌症[14]。当中性粒细胞(哺乳动物血液中最主要的一种白细胞)摄取微塑料后,诱发内皮炎症[15],导致氧化应激和引发炎症反应的细胞因子持续释放。此外,微塑料中有害添加剂的释放会影响人体生长发育过程[16]。

微塑料可在土壤中发生吸附与迁移行为[17-18],微塑料可作为载体改变土壤中的有机污染物和重金属在土壤环境中的迁移性和生物利用度[19-21]。然而,微塑料与污染物之间的详细相互作用机制仍需深入研究。微塑料对土壤微生物群落的影响是微塑料研究的另一个关键领域。最新研究发现,微塑料导致土壤微生物多样性、生物量及功能基因表达发生变化。微塑料的微观特性可能是导致微生物与之相互作用的关键因素。尽管已取得一些进展,但仍存在亟待解决的科学问题。例如,不同土壤类型和环境条件下微塑料的吸附和迁移机制需深入研究。微塑料与有机污染物、重金属的复合作用机理需要更全面的解析。微塑料对土壤微生物的具体影响机制及其生态效应仍需深入挖掘。这些问题的解答将有助于更全面地理解微塑料在土壤中的行为及其对生态系统的潜在影响。

本文综述了微塑料在土壤环境中的吸附迁移、与其他有机污染物及重金属形成复合污染特征和风险,以及微塑料对于土壤环境中微生物的影响及作用。在此基础上,总结了微塑料对微生物群落结构作用的特征和微观机理,为深入了解土壤环境中的微塑料污染,增强对微塑料的微生物和生态健康危害的认识。

1　微塑料在土壤环境中的吸附与迁移

微塑料在土壤中的吸附与其迁移密切相关。土壤吸附机制,如静电作用和物理滞留,直接影响微塑料在土壤中的附着和分布。微塑料的吸附程度和位置会影响其在土壤中的迁移。因此,微塑料的吸附特性有助于理解微塑料在土壤中的迁移行为。

1.1　土壤对微塑料的吸附

微塑料可以滞留在土壤中的一个重要原因是,土壤对微塑料的吸附能力。土壤吸附微塑料的主要机制是静电作用和物理滞留[22]。微塑料表面上的电荷可与环境中阴阳离子相互作用从而影响微塑料在土壤环境中吸附滞留。首先,某些微塑料表面本身的疏水性和官能团可影响土壤对不同种类微塑料的吸附效果。以高岭土吸附微塑料为例[23],吸附主要以疏水性和氢键吸附作用为主,聚酰胺(Polyamide, PA)含有的极性酰胺基团,可提高微塑料与高岭土的吸附亲和力。同时,在环境中,物理、化学和光降解均可导致微塑料的物理化学性质变化,一般来说,塑料带有正电荷(MPs^+)[24],而在环境风化作用下,微塑料表面出现羰基从而带有负电荷(MPs^-)[25]。正因为如此,土壤环境的改变会影响土壤对微塑料的吸附作用,例如,土壤 pH 可显著影响土壤对 MPs^+的吸附[22]。

1.2　微塑料在土壤中的迁移

微塑料可以在土壤环境中发生迁移[26]。首先,不同微塑料的迁移性存在差异,例如,纤维状微塑料的迁移性强于农膜碎片和碎片状微塑料[27]。低密度微塑料更容易在土壤或水环境中通过自然作用力水平迁移[28]。耕作田的表层土壤中直径为 3.7μm 的聚酯微纤维(PMF)可通过生物活动或在雨水下渗作用沿土壤孔隙向 70cm 的深层土壤中迁移[29]。

影响微塑料在土壤中迁移的主要因素有:①土壤经反复干缩和湿胀会影响微塑料迁移速度[30]。②动物对其周围沉积颗粒所进行的搅动、混合和破坏会影响微塑料在土壤中迁移[16, 31-32]。土壤中的小动物如蚯蚓[32]和跳虫[33]可通过凿洞、排泻和皮肤粘附等方式提高微塑料的迁移。③植物通过根系扩张和吸水作用对土壤中微塑料运移产生影响,例如植物向上吸收可使微/纳米塑料从土壤下层转移到上层[34]。④灌溉、排水和翻耕等人类活动也会干扰微塑料在土壤中的迁移[27]。

2　微塑料与土壤中有机污染物和重金属的复合作用

微塑料与有机污染物和重金属之间会发生吸附与释放、固定与迁移等复合作用。在环境因素变化时,吸附在微塑料上的污染物会发生吸附、解吸、迁移等作用也会发生变化,从而带来突发性污染物浓度、形态等发生改变[35]。

2.1　微塑料对土壤中有机污染物的复合作用

土壤中微塑料与有机污染物的复合作用, 到底增加还是减小了土壤中污染物的环境风险尚存争议。一方面, 有研究认为, 微塑料与有机污染物的复合作用降低了土壤中污染物的环境风险。例如, 有研究显示微塑料 [聚乙烯 (PE)、聚丙烯 (PP)] 可通过吸附有机污染物从而降低环境中有害物质的自由态, 从而降低土壤环境中有机污染物的毒性[36-37]。老化的 PA-MPs 较难释放已吸附的卤代基有机磷阻燃剂 [磷酸三 (1, 3-二氯-2-丙基) 酯, TDCIPP], 从而阻止了 TDCIPP 的解吸[38], 使得其在土壤环境风险减少。另一方面, 研究发现, 微塑料易于吸附有机污染物, 从而增加土壤中有机污染物残留量, 例如微塑料使得土壤中农药残留比例从 4% 上升到 15%[39]。

2.1.1　环境因素对微塑料吸附和解吸附有机污染物的影响

土壤中微塑料具有较大比表面积和疏水性[40], 是疏水性有机物 (HOCs) 等的重要载体。非极性聚乙烯 (PE) 和聚丙烯 (PP) 可通过范德华力吸附有机污染物, 聚苯乙烯 (Polystyrene, PS) 中苯环取代基通过 Π-Π 作用, 增强其吸附芳香族化合物如多环芳烃 (PAHs) 和多氯联苯 (PCBs) 的能力[41]。微塑料对有机污染物的吸附和解吸作用受到复杂的环境因素影响。

第一, 微塑料对有机污染物的吸附受到土壤中有机质(SOM)的影响。微塑料与 SOM 对 HOCs 存在显著的竞争吸附关系。例如, 土壤中微塑料会通过影响 SOM, 而间接地影响土壤 PAHs 的分布和生物利用度[42]。腐植酸浓度增加可占据微塑料更多的表面吸附位点, 从而使得微塑料吸附多溴联苯醚 (PBDEs) 的能力减弱[43]。生物炭与聚乙烯 (PE) 共存有助于吸附环境中的菲, 共存时的吸附能力大于单一颗粒物的吸附能力, 其吸附效果不仅受颗粒物表面性质及粒径大小的影响, 还受溶解性有机碳的影响[44]。

第二, 微塑料对有机污染物的吸附还受到微塑料本身结构及老化程度的影响。聚乙烯 (PE)、聚苯乙烯 (PS)、聚酰胺 (PA) 土壤中吸附四环素能力依次减弱[45]。老化作用使得聚苯乙烯 (PS) 表面增加的羧基和酯羰基与土霉素形成氢键而增强其吸附作用力[46]。老化的 PE-MPs 表面积增加从而更有利于其对四溴双酚 A 的吸附[47]。

第三, 温度、pH、盐度、离子强度等因素可影响微塑料吸附有机物。例如, 溴系阻燃剂——四溴双酚 A(TBBPA) 在聚乙烯 (PE) 上吸附是自发放热的过程, 温度越低越有利于聚乙烯 (PE) 对 TBBPA 的吸附[47]。聚苯乙烯 (PS) 对三氯生的吸附与其粒径及环境中 pH 值有关, 而温度、离子强度和重金属离子对该过程影响较小[48]。

2.1.2　微塑料对有机污染物降解的影响

由于有机污染物的降解以微生物降解为主, 随着微生物和有机污染物在微塑料表面的吸附和降解能力的差异, 有机污染物的降解也会发生变化[49]。影响微塑料降解有机污染物降解的因素和微观机理包括: ①微塑料本身。由于土壤中微塑料本身对有机污染物的吸附, 减少了它们与被微生物降解的几率, 在一定程度上可使得土壤中有机污染物的化学降解速率减慢。②土壤有机质。如微塑料与生物碳共同作用有助于 PAHs 和邻苯二甲酸酯 (PAEs) 去除, 其中聚乙烯 (PE) 与生物炭对有机污染物去除率大于可降解微塑料与生物炭的作用[50]。③土壤 pH 的改变。有报道显示, 在酸性农田土中, 无论灭菌与否, PE-MPs 的加入量与四环素 (TC) 的降解无显著相关性[51]; 而在碱性土壤中, 添加 1% 的 PE-MPs 可显著降低抗生素环丙沙星 (CIP) 降解率[52], 即碱性条件下, 微塑料的存在显著抑制了 CIP 的降解, 并且微塑料和 CIP 的联合作用导致土壤的微生物多样性下降大于微塑料或 CIP 的单独作用的影响[52]。

2.2　微塑料与土壤中重金属的复合作用

2.2.1　微塑料与土壤中重金属的复合作用对土壤生态系统的影响

微塑料与土壤中的重金属的复合作用对土壤生态系统, 尤其是对土壤-植物体系存在影响。有研究发现微塑料加剧了植物对重金属的吸收。与单独重金属处理相比, 0.1% 的 PE-MPs-重金属联合处理使得油菜中 Cu 和 Pb 的积累增加了 10% 和 8%[53], PE-MPs 增加了土壤中 Cd 的生物利用度 (8.59% ~ 40.5%) 和生菜中 Cd 的积累 (9.5% ~ 61.4%)[54], 即微塑料可通过增加重金属的生物有效性, 提高重金属在植物中的富集方式, 从而抑制植物生长[53, 55-58]。但是, 对微塑料和重金属复合作用对土壤植物体系的影响机理尚值得探索。例如, 有研究认为, 微塑料本身对植物造成的物理损伤加剧了重金属对植物的毒性[58]。也有研究表明并未发现微塑料对植物吸收重金属存在影响, 例如高密度的 PE-MPs 和聚酯 (PES) 微纤维并不影响玉米[59] 和莴苣[60] 中 Cd 的积累。因此, 关注复杂环境条件下微塑料对植物吸收重金属的促进和抑制作用, 并且探讨其中的微观

机理，对正确认识微塑料与重金属复合作用对土壤体系的生态风险显得尤为重要。

2.2.2　微塑料与土壤中重金属的吸附-解吸附作用机理

微塑料与重金属之间的吸附-解吸附行为同时存在，微塑料具有从周围环境中吸附 Cu、Pb、Zn、Fe、Co、Ni、Cr、Cd、Ag 及 As 等重金属/类金属的能力[61-69]。微塑料可使得重金属物质局部富集，不利于在重金属污染物质土壤溶质迁移，一定程度上防止了重金属污染物在土壤环境中的迁移转化，但一定程度上也加剧局部土壤污染[70]。吸附到微塑料上的重金属也会随着环境条件的改变发生解吸附。

微塑料对土壤中重金属的吸附与表面电荷、pH、微塑料表面的有机质及微塑料本身有关。①微塑料表面的电荷可影响对重金属的吸附作用。例如，微塑料磨损过程中会使其表面带有电荷，金属阳离子或络合物可与微塑料表面的带电位点或中性区域相互作用，并与水合氧化物共沉淀或吸附[66]。②微塑料的类型、粒径、比表面积、分子极性及组成等可影响对重金属的吸附。例如，聚氯乙烯 (PVC) 和聚丙烯 (PP) 相比聚酰胺 (PA) 对重金属 Pb 吸附量大 1 倍 (吸附量分别为 1.32μg/g 和 0.63μg/g)[71]。③微塑料对重金属吸附能力受 pH 影响。酸性土壤中，H^+导致微塑料表面质子化，产生静电排斥，使得微塑料表面吸附的 Hg^+[54]、Cd^{2+}[72]、Cu^{2+}和 Zn^{2+}[73]重新解吸。含有巯基和含氧基团对重金属的亲和以及重金属离子在微塑料表面竞争吸附可导致部分重金属解吸附[54]。pH 为 3～11 时，随着 pH 升高，PS-MPs 对 As 的吸附趋势整体呈降低趋势[74]。④土壤中有机物质会对微塑料表面改性，从而可能影响微塑料对土壤中重金属吸附。PS-MPs 可通过氢键作用吸附三价砷，并在腐植酸存在的情况下，吸附量大大增加[75]。⑤微塑料所添加的催化剂、颜料及稳定剂中含 Pb、Cd、Ba 和 Sn 等[62, 76]，是微塑料毒性的重要来源[77]，且老化或脆性微塑料释放添加剂的速度更快。例如，$BaSO_4$ 是聚丙烯 (PP) 和聚酰胺 (PA) 中常见塑料添加剂之一，被微塑料污染的土壤中 Ba 含量比对照土壤高 10^3 数量级[49]。⑥微塑料分解使得其极性或表面积增加，从而提高其对金属吸附能力，如微塑料经紫外光照射 1h 老化处理，可增加微塑料对 Cu 和 Zn 吸附量[68]。

3　微塑料对土壤微生物的影响与作用机制

微塑料会影响土壤中微生物的物种丰富度、活性和微生物群落结构。优良的微生物群落配置状况能提高群落的结构稳定性，从而决定微生物生态功能的特性。

3.1　微塑料对土壤微生物群落的影响

微塑料对土壤微生物群落的影响是近年来土壤微生物的研究热点之一，然而，该领域的研究结论存在较多争议。

首先，研究发现微塑料对土壤微生物的影响主要表现为：微塑料的存在可增加某些微生物群落的丰富度和多样性[10, 78]，微塑料可增加拟杆菌属和亚硝酸螺菌属的丰度[79-80]。微塑料处理的土壤中，参与硝化作用的硝化螺旋杆菌基因丰度增加，增强了硝化作用，从而降低了 NH_4^+-N 含量[81]。聚乙烯 (PE) 和聚氯乙烯 (PVC) 可促进膜转运功能相关的微生物群落的丰度[51, 82]。微塑料可增加沉积物中抗生素抗性基因的丰度，且抗生素抗性基因可随着微塑料在环境中的迁移转化[83]，从而增加抗性基因对环境介质的生态影响[84]。

但是，也有研究显示微塑料也会降低土壤中某些微生物的丰富度、多样性和稳定性[81-82, 85]。农田中残留的薄膜微塑料使得土壤细菌群落演替加剧，降低土壤细菌群落结构的稳定性并影响土壤功能[86]。聚苯乙烯-纳米微塑料(PS-NPs)显著降低了真菌群落中子囊菌门和壶菌门的相对丰度，PE-MPs(＜13μm 和 0.03mm 的 PE；50mg/L) 导致子囊菌门的相对丰度降低[10, 87-88]，与细菌相比，真菌群落对 PE-MPs 的添加更敏感[88]。聚乙烯 (PE) 和聚氯乙烯 (PVC) 降低了氨基酸代谢、碳水化合物代谢等一些基本代谢功能的微生物群落丰度[51, 82]。低密度聚乙烯(LDPE)可促进微生物物种的消除和替代，导致土壤中细菌群落演替差异越来越大，从而降低微生物群落的稳定性[86]。

同时，也有研究显示，微塑料对微生物的丰富度、均匀性和多样性的影响不显著。例如，添加了 2% 及 7% 的 LDPE-MPs 的土壤中，土壤细菌群落相关指标均未受到显著影响[89]。

3.2　微塑料影响土壤微生物群落的微观作用机理

要正确地认识微塑料对土壤微生物群落的影响，需要深入探索微塑料对微生物影响的微观作用机制。

3.2.1　微塑料通过改变土壤理化性质改变影响微生物

微塑料可通过改变土壤的团聚、容重、比重、通气性、透水性、养分状况等性质从而影响微生物群落和功能[90-92]，这对土壤温室气体排放产生影响。微

塑料通过改变土壤的含水量和孔隙率, 从而影响 O_2 的利用率, 扰动反硝化微生物, 导致反硝化过程不完全[93], 降低微生物活性及丰度, 从而降低 N_2 有效性, 有研究显示土壤中聚乙烯 (PE) 微塑料 (5%, *w*/*w*) 可减少 N_2O 排放, 从而降低全球温度升高的潜势[10]。

3.2.2　不同微生物在微塑料表面的定殖和选择性富集能力存在差异

微生物在土壤中的群落结构的改变, 主要取决于不同微生物在微塑料表面的黏附、生长和繁殖等定殖和选择性富集能力的差异。

首先, 微生物可以在微塑料表面定殖形成生物膜, 以聚合物或添加剂为碳源进行生存和繁殖[94]。土壤环境中生物膜表面的微生物群落组成、结构及遗传与周围土壤环境相比具有显著差异[95-96]。变形菌门被认为是一种共营养细菌 (生活在碳和营养丰富的环境中), 由 PS-NPs 作为外源碳可使得变形菌门丰度升高[97]。PLA 及 PHB 等生物可降解微塑料及其降解所产生的中间体可被某些异样微生物作为额外碳源所利用, 从而直接影响微生物群落[98]。

其次, 微塑料表面对土壤中微生物本身具有选择性富集的特征[81]。土壤中微生物进化出多种吸附机制, 为更好地适应环境变化及所接触微塑料特性的不同[49]。有研究表明, 微塑料表面的物种丰富度和多样性高于周围的环境样品[99]。环境中少见的细菌群可出现于塑料碎片表面, 例如弧菌科和假丝酵母科[100]。已使用聚乙烯 (PE) 地膜超过 30 年的新疆棉田中, 微塑料表面上的放线菌和拟杆菌显著高于周围土壤中的比例, 而变形菌、芽单胞菌及酸杆菌与之相反[48]。聚乙烯 (PE)、LDPE 及聚苯乙烯 (PS) 等生物降解性低的微塑料表面对塑料降解菌和病原体均有明显富集[48, 79, 86]。同时, 菌类可产生胞外多糖或其他代谢物, 可进一步促进生物膜形成[101]。

此外, 某些微生物表现出在微塑料表面的选择性排斥特征。例如潘阳湖沉积物中[102], 薄膜类 [聚乙烯 (PE)] 和碎片类 [聚丙烯 (PP)] 微塑料表面细菌和真菌物种丰富度指数与周围沉积物中的无显著差异, 而纤维类 [聚丙烯 (PP)] 和发泡类 (PS) 微塑料表面的细菌丰富度和纤维类 [聚丙烯 (PP)] 表面真菌的丰富度显著低于周围沉积物。

3.2.3　微塑料与重金属和有机污染物的复合作用可能改变土壤微生物群落

微塑料吸附的重金属可影响微生物。例如, 微塑料可通过改变重金属利用率, 从而影响微生物相对丰度。例如, 土壤中绿弯菌门 (*Chloroflexi*) 的细菌可代谢有机卤化物[103], 它们对重金属有较强的抗性, 是重金属污染土壤中的优势种群[104]。高剂量的聚苯乙烯 (PS) 增加了绿弯菌门 (*Chloroflexi*) 的相对丰度, 且其丰度与二乙烯三胺五乙酸提取 Pb 有效态(DTPA-Pb)含量呈负相关[81]。土壤微塑料表面细菌群落与土壤环境因子 (如: 速效磷、pH、总氮、速效氮、SOM、总磷及重金属含量等) 具有相关性, 例如在不同地方采集的微塑料表面 *Pedomicrobium* 属与土壤中速效磷呈显著正相关[49]。

微塑料与有机污染物的复合作用会影响土壤中的微生物。例如, 抗生素环丙沙星 (CIP) 的联合作用可导致土壤中微生物多样性下降[52]。在大量使用有机肥农田中, 抗生素与微塑料形成复合污染较为常见[105], 微塑料可选择性地富集抗生素耐药基因[106]。微塑料中所含有的 PAEs 可进入土壤环境, 土壤中 PAEs 浓度随塑料膜残留量的增加而增加[107], 土壤微生物活性因 PAEs 和双酚 A(BPA) 而抑制, 因此使得微生物滋生增殖受到影响[107-108]。邻苯二甲酸二丁酯 (DBP) 是环境中典型的增塑剂, 随着其在土壤环境浓度增加, 微生物群落多样性和丰富度将下降[108], 并使得具有降解 DBP 的细菌相对丰度增加 (例如: 德氏菌属、红球菌属和梭菌属), 而使有利于土壤健康的菌属 (例如: 庞氏杆菌、芽孢杆菌、泥炭杆菌等) 的相对丰度降低。在黑土环境体系中, 二甲基邻苯二甲酸酯 (DMP) 可影响其相关降解基因的表达, 进而影响土壤肥性维持[109]。

4　结论与展望

土壤中微塑料对有机污染物的吸附和解吸作用, 受到多种环境因素的影响。微塑料与土壤有机物质、微塑料本身结构及老化程度、温度、pH、盐度、离子强度等因素都会影响其对有机污染物的吸附。同时, 微生物和有机污染物在微塑料表面的吸附和降解能力的差异也会影响有机污染物的降解。微塑料本身、土壤有机质和土壤 pH 的改变等因素会影响微塑料对有机污染物的降解。微塑料可以增加土壤中重金属的生物有效性, 提高重金属在植物中的富集方式, 从而抑制植物生长。微塑料与重金属之间的吸附-解吸附行为同时存在, 微塑料可从周围环境中吸附重金属, 并将其局部富集在土壤中。吸附到微塑料上的重金属也会随着环境条件的改变发生解吸附。微塑料对重金属的吸附与表面电荷、pH、微塑料表面

的有机质及微塑料本身有关。微塑料可以增加某些微生物群落的丰富度和多样性，但也会降低某些微生物的丰富度、多样性和稳定性，微塑料通过改变土壤理化性质来影响微生物群落和功能，不同微生物在微塑料表面的定殖和选择性富集能力存在差异。微塑料与重金属和有机污染物的复合作用可能改变土壤微生物群落。然而，该领域的研究结论存在较多争议，需要进一步深入探索。

对土壤微塑料的研究，未来需要关注以下问题：①微塑料与其他有机污染物和重金属复合污染的影响及其对土壤微生物群落结构的作用机制；②探索微生物对促进微塑料的安全降解的途径及其应用，促进微生物安全去除环境中的微塑料；③探索通过科学调控土壤理化特性、特异性微生物在微塑料表面的定殖与富集能力等途径来改善土壤中的微生物群落结构，从而更安全地调控与降解土壤中微塑料以及微塑料和其他环境污染物复合污染。

A Review on the Impacts of Microplastics and Environmental Pollutants on Soil Microorganisms

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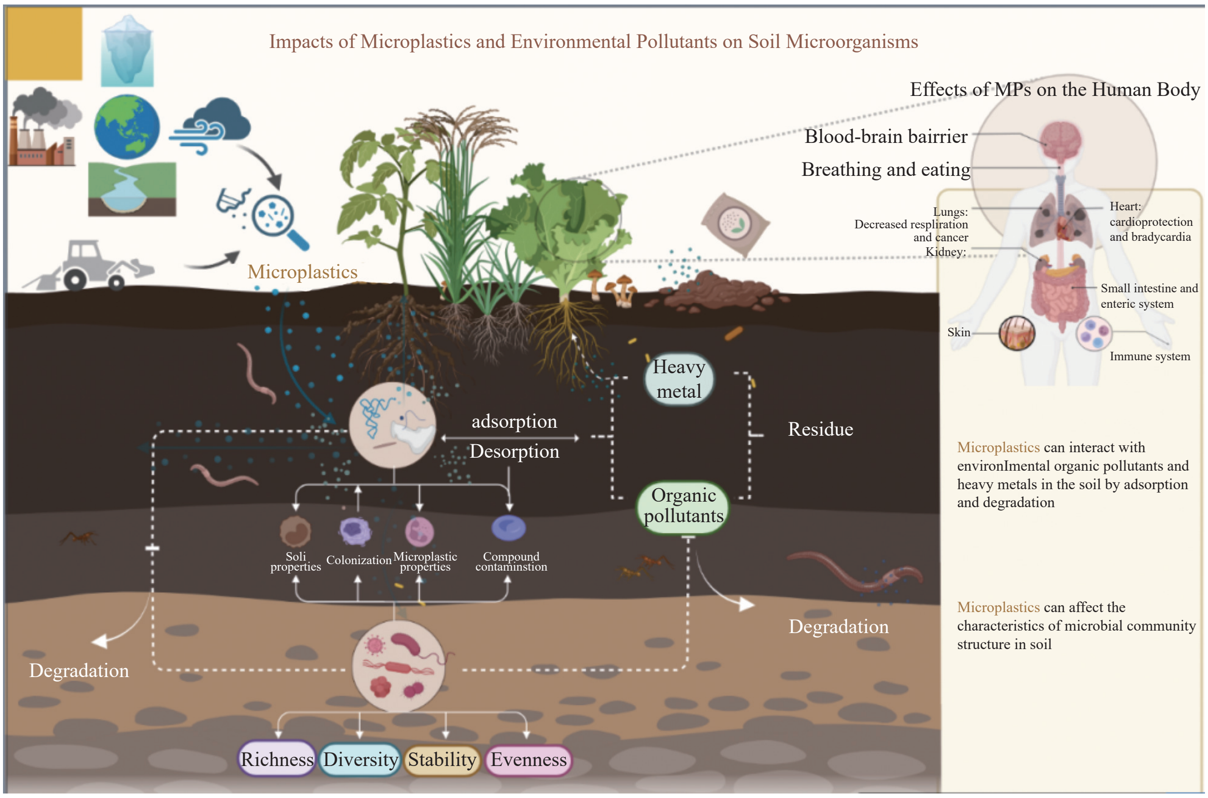
HIGHLIGHTS

(1) The adsorption and migration of microplastics in soil are influenced by various factors such as the properties of microplastics, soil, and flora and fauna activities.

(2) The combined effects of microplastics with organic pollutants and heavy metals in soil could alter the environmental risks, mobility, degradation, and bioavailability of pollutants. This alteration is contingent upon the characteristics of microplastics, soil, and environmental factors.

(3) Microplastics can either increase or decrease the richness and diversity of soil microorganisms, affecting them through multiple mechanisms regulated by soil physicochemical properties, microbial colonization, and composite pollution.



ABSTRACT: The extensive use of plastic results in a significant release of microplastics into the soil, posing risks to ecosystems and human health. Research on the interaction between microplastics and pollutants and their combined effects is sparse. Understanding how soil microplastics affect microbial communities is crucial for assessing ecological risks. This comprehensive review examines the adsorption and migration mechanisms of microplastics, with a specific focus on their impact on migration. It explores the combined effects of microplastics with organic pollutants and heavy metals, leading to changes in toxicity, bioavailability, and mobility. Additionally, the review investigates how microplastics influence soil microbial communities, revealing alterations in species richness, activity, and structure. The findings of this review highlight the significant impact of microplastics on pollutants, the modifications in toxicity, bioavailability, and mobility of combined pollutants, as well as their influence on soil microbial communities. To comprehensively assess the environmental impact, it is essential to understand how microplastics interact with pollutants. The review underscores the need to comprehend their influence on soil microbes and functions in order to effectively address ecological risks. Future research should prioritize exploring microscale mechanisms and developing strategies to mitigate soil microplastics and associated pollution. The BRIEF REPORT is available for this paper at http://www.ykcs.ac.cn/en/article/doi/10.15898/j.ykcs.202209180175.

KEY WORDS: microplastics; microbial community structure; organic pollutants; heavy metals; synergistic effects

BRIEF REPORT

Understanding the impact of microplastics (MPs) is crucial due to their persistent presence in the environment and global consequences[1-2]. Ranging from 100 to 5mm, these pollutants undergo processes that can break them down into smaller sizes (<100nm) through mechanisms like photodegradation or environmental wear. The intricate ecological effects of microplastics are evident in diverse environmental media, including soil, water, and air[4-6]. The urgency for investigation is highlighted by the prevalence of microplastics in remote areas like the Arctic and their identification in human blood, urine, and feces[7-12]. The environmental impact of microplastics extends to potentially accelerating Arctic ice melting[9], posing significant health risks to multiple human organ systems[13-14]. Concerns also arise from harmful additives released by microplastics, potentially disrupting normal human growth and development[16]. In soil environments, microplastics display adsorption and migration behaviors[17-18], acting as carriers that influence the mobility and availability of organic pollutants and heavy metals[19-21]. However, a detailed understanding of the interaction mechanisms between microplastics and pollutants requires further exploration. Another critical research area involves investigating the impact of microplastics on soil microbial communities, with recent studies indicating alterations in microbial diversity, biomass, and functional gene expression due to microplastic exposure.

Addressing scientific gaps is imperative for a holistic understanding. Exploring the adsorption and migration mechanisms of microplastics under various soil types and environmental conditions, comprehensively deciphering the synergistic effects between microplastics and organic pollutants or heavy metals, and unraveling the specific mechanisms and ecological implications of microplastics on soil microorganisms are essential. This comprehensive review aims to shed light on the characteristics and microscopic mechanisms of microplastics, advancing our comprehension of their implications for soil health and ecology.

1. Adsorption and migration of microplastics in a soil environment

Microplastics interact with soil primarily through electrostatic forces and physical retention[22]. Their surface charge influences adsorption and retention, affecting interactions with environmental ions. For example, when adsorbing onto kaolin clay[23], hydrophobic interactions and hydrogen bonding dominate, especially with polyamide's polar amide groups. Initially positively charged (MPs^+)[24], microplastics weather to develop a negative charge (MPs^-)[25]. Changes in soil conditions may alter soil adsorption capacity, potentially enabling microplastic migration[26].

The migratory behavior varies among different types of microplastics. Fibrous microplastics exhibit stronger migration compared to agricultural film fragments and fragmented microplastics[27]. Additionally, low-density microplastics are more susceptible to lateral migration in soil or water, influenced by natural forces[28]. Environmental changes in soil conditions[30], disturbances caused by flora and fauna[16,31-32], and anthropogenic activities[27] collectively influence the intricate process of microplastic migration in soil.

2. Interaction of microplastics with organic contaminants and heavy metals in soil

The complex interplay between microplastics, organic pollutants, and heavy metals in soil has generated ongoing debates regarding its impact on environmental risk. Microplastics, such as polyethylene (PE) and polypropylene (PP), have been shown to adsorb organic contaminants, potentially reducing the free fraction of these pollutants and mitigating soil toxicity[36-37]. However, microplastics can also increase the overall residue levels of organic contaminants in soil, exemplified by a rise in pesticide residues from 4% to 15% due to microplastic presence[39].

The effectiveness of microplastics in adsorbing organic pollutants is influenced by soil factors. With a high specific surface area and hydrophobic properties, microplastics efficiently carry hydrophobic organic compounds (HOCs)[40]. Soil organic matter (SOM) also affects their adsorption capacity, indirectly influencing the distribution and bioavailability of soil polycyclic aromatic hydrocarbons (PAHs)[42]. Additionally, microplastics' structural composition and aging impact their adsorption abilities, showing varied capacity among different types[45-47]. Environmental factors like temperature, pH, salinity, and ion strength further modulate organic compound adsorption by microplastics[47-48]. Their impact on contaminant degradation relies on complex microorganism, pollutant, and microplastic surface interactions[49].

In the context of the interaction between microplastics and heavy metals in soil, studies have shown that joint treatment with 0.1% PE-microplastics and heavy metals can lead to increased accumulation of certain heavy metals in plants, such as Cu and Pb in rapeseed[53]. Additionally, PE-microplastics can enhance the bioavailability of Cd in soil, affecting its accumulation in lettuce[54]. However, it is important to note that microplastics may physically damage plants, exacerbating the toxicity of heavy metals[58]. Nevertheless, some studies have not found significant effects of microplastics on the absorption of heavy metals by plants[59-60].

The adsorption-desorption mechanisms between microplastics and heavy metals in soil are complex, with microplastics capable of adsorbing various heavy metals from their surroundings[61-69]. Factors like surface charge, pH, organic matter on microplastic surfaces, and the type of microplastic all influence this process[66-71]. Additionally, the competitive adsorption of heavy metal ions on microplastic surfaces can lead to partial desorption of some heavy metals[54].

In summary, the interaction of microplastics with organic pollutants and heavy metals in soil is multifaceted, influenced by various environmental factors and the specific properties of microplastics. Understanding these interactions is crucial for assessing their impact on soil contamination and ecosystem health.

3. Impacts and mechanisms of microplastics on soil microbial communities

Microplastics have emerged as influential agents affecting soil microbial communities, with profound implications for biodiversity and ecosystem functions.

Enhancement effects: Microplastics have been observed to augment the abundance and diversity of specific microbial communities[10,78]. Notably, genera like *Pseudomonas* and *Nitrospira* exhibit increased abundance in the presence of microplastics[79-80]. Within microplastic-treated soils, a significant increase in the gene abundance of *Nitrospira*, crucial for nitrification, results in a reduction in NH_4^+-N content[81]. Polyethylene (PE) and polyvinyl chloride (PVC) microplastics promote the proliferation of microbial communities associated with membrane transport functions[51,82].

Detrimental effects: Contrarily, studies have also highlighted adverse impacts of microplastics on soil microbial communities. For instance, residual film microplastics in agricultural soils intensify bacterial community succession, destabilizing the microbial community structure and compromising soil functions[86]. Specific microplastic types, like polystyrene nanoparticles (PS-NPs) and certain polyethylene microparticles (PE-MPs), have shown to significantly alter fungal community compositions, with fungi being more sensitive to microplastic presence than bacteria[10,87-88].

Mechanistic insights: The interaction between microplastics and soil microbial communities is underpinned by alterations in soil physicochemical properties, such as aggregation, bulk density, and nutrient status, directly influencing microbial colonization and enrichment[90-92]. Soil biofilm-associated microbial communities exhibit marked differences in composition and genetics compared to adjacent soil environments[95-96]. This suggests that microplastics may selectively enrich specific microbial taxa. Furthermore, microorganisms have evolved diverse adsorption mechanisms to adapt to the presence of microplastics, underscoring the dynamic nature of soil-microplastic interactions[49].

Concluding remarks: While certain studies report no significant impacts of microplastics on soil bacterial communities under specific conditions[89], the overarching consensus underscores the intricate interplay between microplastics and soil microbial dynamics, necessitating further research to elucidate long-term ecological consequences.

This streamlined overview encapsulates the multifaceted relationship between microplastics and soil microbial communities, emphasizing both their beneficial and detrimental impacts, while highlighting the need for continued academic exploration.

4. Future perspectives

Future research should prioritize: (1) Investigating the impact of microplastic co-pollution with contaminants (organic pollutants, heavy metals) on soil microbial communities. (2) Exploring microbial pathways for safe microplastic degradation, with potential applications for environmentally sound removal. (3) Developing strategies to improve soil microbial community structures by regulating physicochemical properties, specifically focusing on microbe colonization and enrichment on microplastic surfaces. This aims to facilitate safer regulation and degradation of microplastics, particularly in scenarios of compound pollution with other contaminants.

参考文献

[1] Law K L, Thompson R C. Microplastics in the seas[J]. Science, 2018, 345(6193): 144−145.

[2] 高文杰, 卫新来, 吴克. 环境中微塑料的研究进展[J]. 塑料科技, 2021, 49(2): 111−116.
Gao W J, Wei X L, Wu K. Research progress of microplastics in the environment[J]. Plastics Science and Technology, 2021, 49(2): 111−116.

[3] 王一飞, 李淼, 于海瀛, 等. 微塑料对环境中有机污染物吸附解吸的研究进展[J]. 生态毒理学报, 2019, 14(4): 23−30.
Wang Y F, Li M, Yu H Y, et al. Research progress on the adsorption and desorption between microplastics and environmental organic pollutants[J]. Asian Journal of Ecotoxicology, 2019, 14(4): 23−30.

[4] Moller J N, Loder M G J, Laforsch C. Finding microplastics in soils: A review of analytical methods[J]. Environmental Science & Technology, 2020, 54(4): 2078−2090.

[5] Bergmann M, Wirzberger V, Krumpen T, et al. High quantities of microplastic in Arctic deep-sea sediments from the HAUSGARTEN Observatory[J]. Environmental Science & Technology, 2017, 51(19): 11000−11010.

[6] Wright S L, Ulke J, Font A, et al. Atmospheric microplastic deposition in an urban environment and an evaluation of transport[J]. Environment International, 2020, 136: 105411.

[7] Zylstra E R. Accumulation of wind-dispersed trash in desert environments[J]. Journal of Arid Environments, 2013, 89: 13−15.

[8] Obbard R W, Sadri S, Wong Y Q, et al. Global warming releases microplastic legacy frozen in Arctic Sea ice[J]. Earth's Future, 2014, 2(6): 315−320.

[9] Evangeliou N, Grythe H, Klimont Z, et al. Atmospheric transport is a major pathway of microplastics to remote regions[J]. Nature Communication, 2020, 11(1): 3381.

[10] Ren X, Tang J, Liu X, et al. Effects of microplastics on greenhouse gas emissions and the microbial community in fertilized soil[J]. Environmental Pollution, 2020, 256: 113347.

[11] Leslie H A, van Velzen M J M, Brandsma S H, et al. Discovery and quantification of plastic particle pollution in human blood[J]. Environment International, 2022, 163: 107199.

[12] Zhang N, Li Y B, He H R, et al. You are what you eat: Microplastics in the feces of young men living in Beijing[J]. Science of the Total Environment, 2021, 767: 144345.

[13] 曹腾瑞, 屈艾彬, 郭会彩, 等. 微塑料毒性的研究进展[J]. 河北医科大学学报, 2021, 42(1): 107−111.
Cao T R, Qu A B, Guo H C, et al. Research progress on the toxicity of microplastics[J]. Journal of Hebei Medical University, 2021, 42(1): 107−111.

[14] Gupta S, Kumar R, Rajput A, et al. Atmospheric microplastics: Perspectives on origin, abundances, ecological and health risks[J]. Environmental Science and Pollution Research, 2023, 30(49): 107435−107464.

[15] Cao Y, Vlacil A K, Bänfer S, et al. Polystyrene microplastic particles induce endothelial activation[J]. PLoS ONE, 2021, 16(11): e0260181.

[16] 刘沙沙, 付建平, 郭楚玲, 等. 微塑料的环境行为及其生态毒性研究进展[J]. 农业环境科学学报, 2019, 38(5): 957−969.
Liu S S, Fu J P, Guo C L, et al. Research progress on environmental behavior and ecological toxicity of microplastics[J]. Journal of Agro-Environment Science, 2019, 38(5): 957−969.

[17] Leitao I A, van Schaik L, Ferreira A J D, et al. The spatial distribution of microplastics in topsoils of an urban environment—Coimbra City case-study[J]. Environmental Research, 2023, 218: 114961.

[18] Tran T K A, Raju S, Singh A, et al. Occurrence and distribution of microplastics in long-term biosolid-applied rehabilitation land: An overlooked pathway for microplastic entry into terrestrial ecosystems in Australia[J]. Environmental Pollution, 2023, 336: 122464.

[19] Beriot N, Zornoza R, Lwanga E H, et al. Intensive vegetable production under plastic mulch: A field study on soil plastic and pesticide residues and their effects on the soil microbiome[J]. Science of the Total Environment, 2023, 900: 165179.

[20] Selonen S, Jemec K A, Benguedouar H, et al. Modulation of chlorpyrifos toxicity to soil arthropods

by simultaneous exposure to polyester microfibers or tire particle microplastics[J]. Applied Soil Ecology, 2023, 181: 104657.

[21] Liu Y, Cui W, Li W, et al. Effects of microplastics on cadmium accumulation by rice and arbuscular mycorrhizal fungal communities in cadmium-contaminated soil[J]. Journal of Hazardous Materials, 2023, 442: 130102.

[22] Zhou Y, Sun F, Wu X, et al. Formation and nature of non-extractable residues of emerging organic contaminants in humic acids catalyzed by laccase[J]. Science of the Total Environment, 2022, 829: 154300.

[23] 胡桂林. 微塑料与土壤介质相互作用机制的研究[D]. 淮南: 安徽理工大学, 2019: 1-49.
Hu G L. Interaction mechanism between microplastics and soil media[D]. Huainan: Anhui University of Science and Technology, 2019: 1-49.

[24] Larue C, Sarret G, Castillo-Michel H, et al. A critical review on the impacts of nanoplastics and microplastics on aquatic and terrestrial photosynthetic organisms[J]. Small, 2021, 17(20): 2005834.

[25] 吴小伟, 黄何欣悦, 石妍琦, 等. 水环境中微塑料的光老化过程及影响因素研究进展[J]. 科学通报, 2021, 66(36): 4619−4632.
Wu X W, Huang-He X Y, Shi Y Q, et al. Progress on the photo aging mechanism of microplastics and related impact factors in water environment[J]. Chinese Science Bulletin, 2021, 66(36): 4619−4632.

[26] 胡婷婷, 陈家玮. 土壤中微塑料的吸附迁移及老化作用对污染物环境行为的影响研究进展[J]. 岩矿测试, 2022, 41(3): 353−363.
Hu T T, Chen J W. A review on adsorption and transport of microplastics in soil and the effect of ageing on environmental behavior of pollutants[J]. Rock and Mineral Analysis, 2022, 41(3): 353−363.

[27] Zhang G S, Liu Y F. The distribution of microplastics in soil aggregate fractions in Southwestern China[J]. Science of the Total Environment, 2018, 642: 12−20.

[28] Zhang S, Liu X, Hao X, et al. Distribution of low-density microplastics in the mollisol farmlands of Northeast China[J]. Science of the Total Environment, 2020, 708: 135091.

[29] 张飞祥. 聚酯微纤维对土壤物理性质的影响[D]. 昆明: 云南大学, 2019: 1-36.
Zhang F X. Effect of polyester microfibers on soil physical properties[D]. Kunming: Yunnan University, 2019: 1-36.

[30] O’connor D, Pan S, Shen Z, et al. Microplastics undergo accelerated vertical migration in sand soil due to small size and wet-dry cycles[J]. Environmental Pollution, 2019, 249: 527−534.

[31] Blasing M, Amelung W. Plastics in soil: Analytical methods and possible sources[J]. Science of the Total Environment, 2018, 612: 422−435.

[32] Rillig M C, Ziersch L, Hempel S. Microplastic transport in soil by earthworms[J]. Scientific Reports, 2017, 7: 1362.

[33] Maass S, Daphi D, Lehmann A, et al. Transport of microplastics by two collembolan species[J]. Environmental Pollution, 2017, 225: 456−459.

[34] 吕一涵, 周杰, 杨亚东, 等. 微塑料对农田生态系统的影响: 研究现状与展望[J]. 中国生态农业学报 (中英文), 2021, 30(1): 1−14.
Lyu Y H, Zhou J, Yang Y D, et al. Microplastics in agroecosystem: Research status and future challenges[J]. Chinese Journal of Eco-Agriculture, 2021, 30(1): 1−14.

[35] Lu J, Wu J, Wu J, et al. Adsorption and desorption of steroid hormones by microplastics in seawater[J]. Bulletin of Environmental Contamination and Toxicology, 2021, 107(4): 730−735.

[36] 姬庆松, 孔祥程, 王信凯, 等. 环境微塑料与有机污染物的相互作用及联合毒性效应研究进展[J]. 环境化学, 2022, 41(1): 70−82.
Ji Q S, Kong X C, Wang X K, et al. The interaction and combined toxic effects of microplastics and organic pollutants in the environment: A review[J]. Environmental Chemistry, 2022, 41(1): 70−82.

[37] Wang T, Wang L, Chen Q, et al. Interactions between microplastics and organic pollutants: Effects on toxicity, bioaccumulation, degradation, and transport[J]. Science of the Total Environment, 2020, 748: 142427.

[38] Zhang X, Zhao J, Gan T, et al. Aging relieves the promotion effects of polyamide microplastics on parental transfer and developmental toxicity of TDCIPP to Zebrafish offspring[J]. Journal of Hazardous Materials, 2022, 437: 129409.

[39] Sunta U, Prosenc F, Trebse P, et al. Adsorption of acetamiprid, chlorantraniliprole and flubendiamide on different type of microplastics present in alluvial soil[J]. Chemosphere, 2020, 261: 127762.

[40] Liu X, Xu J, Zhao Y, et al. Hydrophobic sorption behaviors of 17β-estradiol on environmental microplastics[J]. Chemosphere, 2019, 226: 726−735.

[41] Huffer T, Hofmann T. Sorption of non-polar organic compounds by micro-sized plastic particles in aqueous

solution[J]. Environmental Pollution, 2016, 214: 194−201.

[42] 钟名誉, 陈卓, 贾晓洋, 等. 焦化污染土壤有机质不同组分中多环芳烃分布及其生物有效性分析[J]. 环境科学学报, 2021, 41(8): 3349−3358.
Zhong M Y, Chen Z, Jia X Y, et al. The analysis in distribution and bioavailability of polycyclic aromatic hydrocarbons in organic matter components of coking contaminated soil[J]. Acta Scientiae Circumstantiae, 2021, 41(8): 3349−3358.

[43] 徐鹏程, 郭健, 马东, 等. 新制和老化微塑料对多溴联苯醚的吸附[J]. 环境科学, 2020, 41(3): 1329−1337.
Xu P C, Guo J, Ma D, et al. Sorption of polybrominated diphenyl ethers by virgin and aged microplastics[J]. Environmental Science, 2020, 41(3): 1329−1337.

[44] 迟杰, 邢海文, 张海彤, 等. 不同粒径生物炭和微塑料共存对菲吸附的影响[J]. 农业环境科学学报, 2021, 41(3): 616−621.
Chi J, Xing H W, Zhang H T, et al. Effects of the coexistence of biochar and microplastic in different particle sizes on phenanthrene sorption[J]. Journal of Agro-Environment Science, 2021, 41(3): 616−621.

[45] 许佰乐. 土水环境中微塑料对有机污染物的吸附行为及机理[D]. 杭州: 浙江大学, 2020: 1-110.
Xu B L. Sorption of organic contaminants by microplastic in water and soil: Behavior and mechanisms[D]. Hangzhou: Zhejiang University, 2020: 1-110.

[46] Zhang H, Wang J, Zhou B, et al. Enhanced adsorption of oxytetracycline to weathered microplastic polystyrene: Kinetics, isotherms and influencing factors[J]. Environmental Pollution, 2018, 243: 1550−1557.

[47] 黄皖唐. 四溴双酚 A 在 PE 微塑料影响下的人体暴露风险及其生物降解机理研究[D]. 广州: 华南理工大学, 2020: 1-86.
Huang W T. Study on human exposure risks of tetrabromobisphenol a under the influence of polyethylene microplastics and its biodegradation mechanism[D]. Guangzhou: South China University of Technology, 2020: 1-86.

[48] Zhang M, Zhao Y, 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.

[49] 柴炳文, 尹华, 魏强, 等. 电子废物拆解区微塑料与周围土壤环境之间的关系[J]. 环境科学, 2021, 42(3): 1073−1080.
Chai B W, Yin H, Wei Q, et al. Relationships between microplastic and surrounding soil in an E-waste zone of China[J]. Environmental Science, 2021, 42(3): 1073−1080.

[50] Ren X, Tang J, Wang L, et al. Combined effects of microplastics and biochar on the removal of polycyclic aromatic hydrocarbons and phthalate esters and its potential microbial ecological mechanism[J]. Frontiers in Microbiology, 2021, 12: 647766.

[51] 费禹凡. 酸性农田土壤微塑料污染的微生物生态效应[D]. 临安: 浙江农林大学, 2020: 1-62.
Fei Y F. Microbial ecological effects of microplastic pollution in an acidic paddy soil[D]. Lin’an: Zhejiang A & F University, 2020: 1-62.

[52] Wang J, Liu X, Dai Y, et al. Effects of co-loading of polyethylene microplastics and ciprofloxacin on the antibiotic degradation efficiency and microbial community structure in soil[J]. Science of the Total Environment, 2020, 741: 140463.

[53] Jia H, Wu D, Yu Y, et al. Impact of microplastics on bioaccumulation of heavy metals in rape (Brassica napus *L.*)[J]. Chemosphere, 2022, 288: 132576.

[54] Wang F, Wang X, Song N. Polyethylene microplastics increase cadmium uptake in lettuce (Lactuca sativa *L.*) by altering the soil microenvironment[J]. Science of the Total Environment, 2021, 784: 147133.

[55] Dong Y, Gao M, Qiu W, et al. Uptake of microplastics by carrots in presence of As(Ⅲ): Combined toxic effects[J]. Journal of Hazardous Materials, 2021, 411: 125055.

[56] Wang F, Zhang X, Zhang S, et al. Effects of co-contamination of microplastics and Cd on plant growth and Cd accumulation[J]. Toxics, 2020, 8(2): 36.

[57] 顾馨悦, 徐修媛, 咸泽禹, 等. 老化聚氯乙烯微塑料与镉对小麦的联合毒性[J]. 环境化学, 2021, 40(9): 2633−2639.
Gu X Y, Xu X Y, Xian Z Y, et al. Joint toxicity of aged polyvinyl chloride microplastics and cadmium to the wheat plant[J]. Environmental Chemistry, 2021, 40(9): 2633−2639.

[58] Dong Y, Gao M, Song Z, et al. Microplastic particles increase arsenic toxicity to rice seedlings[J]. Environmental Pollution, 2020, 259: 113892.

[59] Wang F, Zhang X, Zhang S, et al. Interactions of microplastics and cadmium on plant growth and arbuscular mycorrhizal fungal communities in an agricultural soil[J]. Chemosphere, 2020, 254: 126791.

[60] Zeb A, Liu W, Meng L, et al. Effects of polyester

microfibers (PMFs) and cadmium on lettuce (Lactuca sativa) and the rhizospheric microbial communities: A study involving physio-biochemical properties and metabolomic profiles[J]. Journal of Hazardous Materials, 2022, 424: 127405.

[61] Brennecke D, Duarte B, Paiva F, et al. Microplastics as vector for heavy metal contamination from the marine environment[J]. Estuarine, Coastal and Shelf Science, 2016, 178: 189−195.

[62] Godoy V, Blazquez G, Calero M, et al. The potential of microplastics as carriers of metals[J]. Environmental Pollution, 2019, 255(3): 113363.

[63] Massos A, Turner A. Cadmium, lead and bromine in beached microplastics[J]. Environmental Pollution, 2017, 227: 139−145.

[64] Turner A, Holmes L A. Adsorption of trace metals by microplastic pellets in fresh water[J]. Environmental Chemistry, 2015, 12(5): 600−610.

[65] Rochman C M, Hentschel B T, Teh S J. Long-term sorption of metals is similar among plastic types: Implications for plastic debris in aquatic environments[J]. Plos ONE, 2014, 9(1): e85433.

[66] 李文华, 简敏菲, 刘淑丽, 等. 鄱阳湖湖口—长江段沉积物中微塑料与重金属污染物的赋存关系[J]. 环境科学, 2020, 41(1): 242−252.

Li W H, Jian M F, Liu S L, et al. Occurrence relationship between microplastics and heavy metals pollutants in the estuarine sediments of Poyang Lake and the Yangtze River[J]. Environmental Science, 2020, 41(1): 242−252.

[67] 宫婉婷, 李万海, 邹继颖, 等. 聚乙烯醇微塑料对溶液中 Cu^{2+}的吸附[J]. 化学试剂, 2021, 43(11): 1561−1568.

Gong W T, Li W H, Zou J Y, et al. Adsorption of Cu^{2+} in solution by polyvinyl alcohol microplastic[J]. Chemical Reagents, 2021, 43(11): 1561−1568.

[68] Bandow N, Will V, Wachtendorf V, et al. Contaminant release from aged microplastic[J]. Environmental Chemistry, 2017, 14(6): 394−405.

[69] Dong Y, Gao M, Song Z, et al. Adsorption mechanism of As(Ⅲ) on polytetrafluoroethylene particles of different size[J]. Environmental Pollution, 2019, 254: 112950.

[70] 宋佃星, 马莉, 王全九. 宝鸡地区典型农田土壤中微塑料赋存特征及其环境效应研究[J]. 干旱区资源与环境, 2021, 35(2): 170−175.

Song D X, Ma L, Wang Q J. Occurrence characteristics and environmental effects of microplastics in typical farmland soils in Baoji area[J]. Journal of Arid Land Resources and Environment, 2021, 35(2): 170−175.

[71] 高丰蕾, 李景喜, 孙承君, 等. 微塑料富集金属铅元素的能力与特征分析[J]. 分析测试学报, 2017, 36(8): 1018−1022.

Gao F L, Li J X, Sun C J, et al. Analysis on ability and characteristics of microplastics to enrich metal lead[J]. Journal of Instrumental Analysis, 2017, 36(8): 1018−1022.

[72] 韩宾. 微塑料对土壤中重金属吸附、解吸的影响[D]. 青岛: 青岛科技大学, 2020: 12-14.

Han B. Effects of microplastics on adsorption and desorption of heavy metals in soil[D]. Qingdao: Qingdao University of Science & Technology, 2020: 12-14.

[73] 范秀磊, 常卓恒, 邹晔锋, 等. 可降解微塑料对铜和锌离子的吸附解吸特性[J]. 中国环境科学, 2021, 41(5): 2141−2150.

Fan X L, Chang Z H, Zou Y F, et al. Adsorption and desorption properties of degradable microplastic for Cu^{2+} and Zn^{2+}[J]. China Environmental Science, 2021, 41(5): 2141−2150.

[74] 周瑛, 徐博凡, 王萍亚, 等. 微塑料对水体中痕量砷、铅的吸附[J]. 浙江工业大学学报, 2019, 47(6): 648−653.

Zhou Y, Xu B F, Wang P Y, et al. Study on the adsorption of trace arsenic and plumbum ion by microplastics[J]. Journal of Zhejiang University of Technology, 2019, 47(6): 648−653.

[75] Dong Y, Gao M, Qiu W, et al. Adsorption of arsenite to polystyrene microplastics in the presence of humus[J]. Environmental Science Processes & Impacts, 2020, 22(12): 2388−2397.

[76] Fahrenfeld N L, Arbuckle-Keil G, Naderi B N, et al. Source tracking microplastics in the freshwater environment[J]. Trends in Analytical Chemistry, 2019, 112: 248−254.

[77] Catrouillet C, Davranche M, Khatib I, et al. Metals in microplastics: Determining which are additive, adsorbed, and bioavailable[J]. Environmental Science Processes & Impacts, 2021, 23(4): 553−558.

[78] Yi M, Zhou S, Zhang 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.

[79] Huang Y, Zhao Y, Wang J, et al. LDPE microplastic films alter microbial community composition and enzymatic activities in soil[J]. Environmental Pollution,

2019, 254: 112983.

[80] Ng E L, Lin S Y, Dungan A M, et al. Microplastic pollution alters forest soil microbiome[J]. Journal of Hazardous Materials, 2021, 409: 124606.

[81] Feng X, Wang Q, Sun Y, 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.

[82] Fei Y, Huang S, Zhang H, 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.

[83] 黄福义, 杨凯, 张子兴, 等. 微塑料对河口沉积物抗生素抗性基因的影响[J]. 环境科学, 2019, 40(5): 2234−2239.

Huang F Y, Yang K, Zhang Z X, et al. Effects of microplastics on antibiotic resistance genes in estuarine sediments[J]. Environmental Science, 2019, 40(5): 2234−2239.

[84] 周昕原, 王言仔, 苏建强, 等. 微塑料对河水抗生素抗性基因的影响[J]. 环境科学, 2020, 40(9): 4076−4080.

Zhou X Y, Wang Y Z, Su J Q, et al. Microplastics-induced shifts of diversity and abundance of antibiotic resistance genes in river water[J]. Environmental Science, 2020, 40(9): 4076−4080.

[85] Hou J, Xu X, Yu H, et al. Comparing the long-term responses of soil microbial structures and diversities to polyethylene microplastics in different aggregate fractions[J]. Environment International, 2021, 149: 106398.

[86] Wang J, Huang M, Wang Q, et al. LDPE microplastics significantly alter the temporal turnover of soil microbial communities[J]. Science of the Total Environment, 2020, 726: 138682.

[87] Zou Z, Li S, Wu J, et al. Effects of nanopolystyrene addition on nitrogen fertilizer fate, gaseous loss of N from the soil, and soil microbial community composition[J]. Journal of Hazardous Materials, 2022, 438: 129509.

[88] Li H Z, Zhu D, Lindhardt J H, et al. Long-term fertilization history alters effects of microplastics on soil properties, microbial communities, and functions in diverse farmland ecosystem[J]. Environmental Science & Technology, 2021, 55(8): 4658−4668.

[89] Rong L, Zhao L, Zhao L, et al. LDPE microplastics affect soil microbial communities and nitrogen cycling[J]. Science of the Total Environment, 2021, 773: 145640.

[90] 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.

[91] Qian H, Zhang M, Liu G, et al. Effects of soil residual plastic film on soil microbial community structure and fertility[J]. Water, Air, & Soil Pollution, 2018, 229(8): 261.

[92] Judy J D, Williams M, Gregg A, et al. Microplastics in municipal mixed-waste organic outputs induce minimal short to long-term toxicity in key terrestrial biota[J]. Environmental Pollution, 2019, 252: 522−531.

[93] Jiang T, Ma X, Tang Q, et al. Combined use of nitrification inhibitor and struvite crystallization to reduce the NH_3 and N_2O emissions during composting[J]. Bioresource Technology, 2016, 217: 210−218.

[94] Oberbeckmann S, Löder M G J, Labrenz M. Marine microplastic-associated biofilms—A review[J]. Environmental Chemistry, 2015, 12(5): 551−562.

[95] Jiang P, Zhao S, Zhu L, et al. Microplastic-associated bacterial assemblages in the intertidal zone of the Yangtze Estuary[J]. Science of the Total Environment, 2018, 624: 48−54.

[96] Dussud C, Meistertzheim A L, Conan P, et al. Evidence of niche partitioning among bacteria living on plastics, organic particles and surrounding seawaters[J]. Environmental Pollution, 2018, 236: 807−816.

[97] 李汶璐, 王志超, 杨文焕, 等. 微塑料对沉积物细菌群落组成和多样性的影响[J]. 环境科学, 2022, 43(5): 2606−2613.

Li W L, Wang Z C, Yang W H, et al. Effects of microplastics on bacterial community composition and diversity in sediments[J]. Environmental Science, 2022, 43(5): 2606−2613.

[98] 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.

[99] Frere L, Maignien L, Chalopin M, et al. Microplastic bacterial communities in the bay of Brest: Influence of polymer type and size[J]. Environmental Pollution, 2018, 242: 614−625.

[100] Tender C, Devriese L, Haegeman A, et al. Bacterial community profiling of plastic litter in the Belgian Part of the North Sea[J]. Environmental Science & Technology, 2015, 49(16): 9629.

［101］ Sharma G, Burrows L L, Singer M. Diversity and evolution of myxobacterial type Ⅳ pilus systems［J］. Frontiers Microbiology, 2018, 9: 1630.

［102］ 刘淑丽, 简敏菲, 邹龙, 等. 鄱阳湖白鹤保护区微塑料表面微生物群落结构特征［J］. 环境科学, 2021, 43(3): 1447−1454.

Liu S L, Jian M F, Zou L, et al. Microbial community structure on microplastic surface in Grus leucogeranus reserve of Poyang Lake［J］. Environmental Science, 2021, 43(3): 1447−1454.

［103］ 张耀之, 金慧娟, 李秀颖, 等. 1, 2, 3-三氯丙烷降解机制与污染场地修复技术研究进展［J］. 生物工程学报, 2021, 37(10): 3578−3590.

Zhang Y Z, Jin H J, Li X Y, et al. Advances in degradation mechanisms of 1, 2, 3-trichloropropane and remediation technology of contaminated sites［J］. Chinese Journal of Biotechnology, 2021, 37(10): 3578−3590.

［104］ Burges A, Fievet V, Oustriere N, et al. Long-term phytomanagement with compost and a sunflower-tobacco rotation influences the structural microbial diversity of a Cu-contaminated soil［J］. Science of the Total Environment, 2020, 700: 134529.

［105］ Zhou B, Wang J, Zhang H, et al. Microplastics in agricultural soils on the coastal plain of Hangzhou Bay, East China: Multiple sources other than plastic mulching film［J］. Journal of Hazardous Materials, 2020, 388: 121814.

［106］ Wang J, Qin X, Guo J, et al. Evidence of selective enrichment of bacterial assemblages and antibiotic resistant genes by microplastics in urban rivers［J］. Water Research, 2020, 183: 116113.

［107］ Wang J, Lv S, Zhang M, et al. Effects of plastic film residues on occurrence of phthalates and microbial activity in soils［J］. Chemosphere, 2016, 151: 171−177.

［108］ Kong X, Jin D, Jin S, et al. Responses of bacterial community to dibutyl phthalate pollution in a soil-vegetable ecosystem［J］. Journal of Hazardous Materials, 2018, 353: 142−150.

［109］ Wang Z G, You Y M, Xu W H, et al. Dimethyl phthalate altered the microbial metabolic pathways in a mollisol［J］. European Journal of Soil Science, 2018, 69(3): 439−449.