中国生态农业学报(中英文)
Chinese Journal of Eco-Agriculture

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中国生态农业学报(中英文) 2022 年 1 月 第 30 卷 第 1 期
Chinese Journal of Eco-Agriculture, Jan. 2022, 30(1): 1−14

DOI: 10.12357/cjea.20210442

吕一涵, 周杰, 杨亚东, 臧华栋, 胡跃高, 曾昭海. 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), 2022, 30(1): 1−14
LYU Y H, ZHOU J, YANG Y D, ZANG H D, HU Y G, ZENG Z H. Microplastics in agroecosystem: Research status and future challenges[J]. Chinese Journal of Eco-Agriculture, 2022, 30(1): 1−14

微塑料对农田生态系统的影响: 研究现状与展望*

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摘 要: 近年来, 微塑料污染成为全球关注的热点问题。在农田生态系统中地膜覆盖、灌溉用水、有机肥施用等措施在提升作物产量的同时, 都会导致塑料残留。因耕作和紫外线辐射, 残留塑料逐步破碎降解, 形成微塑料 (直径<5 mm), 进入土壤、作物与食物链系统, 威胁生态系统健康。本文系统总结了农田微塑料的来源、丰度、迁移特点和检测方法, 重点关注了微塑料在农田生态系统中对作物生长发育、微生物活性、土壤养分循环及温室气体排放等方面的影响。微塑料对作物-土壤-微生物系统产生的主要影响为: 1) 微塑料含有的毒性添加剂 (即增塑剂) 与携带的有害物质 (如有机污染物、重金属和病原体) 随塑料颗粒在土壤中迁移, 可改变土壤理化性质, 并为微生物提供新生态栖息地, 对作物生长、土壤酶和微生物活性造成影响; 2) 微塑料含有大量碳 (通常约为 90%), 影响其他元素 (如氮和磷) 循环, 进而影响微生物活性。土壤性质改变也间接影响 CO_2、N_2O 和 CH_4 形成。由于聚合物类型、大小、形状和浓度的高度可变性, 微塑料对作物生产和土壤生物地球化学过程的影响及其机制有待深入探究。本文还展望了未来农田生态系统微塑料的研究方向和重点。

关键词: 微塑料; 农田生态系统; 作物; 微生物; 土壤养分循环

中图分类号: X53 **开放科学码(资源服务)标识码(OSID):**

Microplastics in agroecosystem: Research status and future challenges*

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Abstract: Microplastics (MPs) pollution has attracted global attention in recent years. Despite the remarkable benefits arising from the production of plastic for film mulching, irrigation, and organic fertilizer application, there are increasing concerns associated with the vast amount of plastic entering the agroecosystems and its subsequent potential environmental problems. More specifically, MPs (particles<5 mm in size), typically formed from the disintegration of larger plastic debris by tillage and UV radiation, accumulate in agroecosystems and eventually enter the food chain, threatening human and animal health. On the basis of the current evidence, we summarized the source, abundance, mitigation, and detection methods of MPs in agroecosystems. We evaluated the potential ecological risks of MPs to crop growth, microbial activity, soil nutrient cycling, and greenhouse gas emissions. It is found that MPs could either directly or indirectly impact the plant-soil-microbe interactions once incorporated into soil, through the following mechanisms: First, owing to their chemical inertia and structural characteristics, MPs have been recognized as carriers of hazardous substances (e.g., organic pollutants, heavy metals, and pathogens), in addition to their toxic additives (i.e., plasticizers). After making contact

* 现代农业产业技术体系建设专项资金 (CARS-07-B-5) 资助
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收稿日期: 2021-07-10 接受日期: 2021-09-24

* This work was supported by the Earmarked Fund for China Agriculture Research System (CARS-07-B-5).
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Received Jul. 10, 2021; accepted Sep. 24, 2021

with the soil, the migration of plastic particles likely facilitates the transport of sorbed contaminants and contributes to a great ecological risk for crop growth, enzyme activity, and microbial activity. MPs could also alter soil physicochemical properties, that is, they may change the soil aggregation stability, bulk density, and water holding capacity, resulting in diverse effects on microbial functions and plant growth. MPs could also serve as a novel ecological habitat for microorganisms living at the soil-plastic interface (i.e., microplastic spheres), allowing the formation of unique microbial communities. The second mechanism involves the fact that MPs are particles that contain a high carbon content, typically around 90%, making them relatively unique in relation to other pollutants as they can drive diverse consequences for other element cycles (e.g., nitrogen and phosphorus). Direct effects are likely to be minimal because MPs contain mostly negligible amounts of nitrogen and phosphorus. However, alterations in soil structure and physicochemical properties would be expected to change microbial processes, including the nitrogen and phosphorus related enzymes, since soil properties indirectly control soil oxygen availability, which in turn influences CO_2, N_2O, and CH_4 formation. Due to the high degree of variability in polymer type, size, shape, and concentration, the impacts of MPs on soil biogeochemical processes and their underlying mechanisms remain unclear, and further detailed research is therefore needed. Thus, we propose some research priorities regarding the future challenges of MPs in agroecosystems.

Keywords: Microplastics; Agroecosystems; Crops; Microorganisms; Soil nutrient cycle

塑料是应用广泛的有机合成高分子材料, 其优良的物理和化学性能给我们日常生活带来了极大便利, 但废弃塑料带来的“白色污染”也不容小觑。统计结果显示, 全球塑料产量及废弃量逐年增加, 1950—2015 年间总产量累计达 78 亿 t (中国约占 30%), 其中仅有约 9% 得以回收。残留塑料被填埋或遗弃在环境中, 危害生态环境健康[1-2]。

进入环境中的塑料经过物理破碎、化学分解或生物降解作用, 逐渐形成塑料碎片或颗粒[3]。当这些碎片或颗粒直径小于 5 mm 时, 称为微塑料[4]。微塑料具有体积小、比表面积大、吸附污染能力强等特性, 对部分土壤组分具有更强吸附性和反应活性, 是造成土壤污染的重要载体[5]。研究表明, 微塑料在世界各地土壤中已广泛分布[6-7]。

土壤微塑料污染问题被列为环境与生态领域的第二大科学问题[8]。研究表明, 我国农田土壤中塑料颗粒浓度在 7100~42 900 个·kg^{-1} 间 (平均 18 760 个·kg^{-1})。其中 0.05~1 mm 粒径的微塑料占 95%, 远高于墨西哥 (2770 个·kg^{-1}) 和瑞士 (593 个·kg^{-1}) 土壤微塑料浓度[9-11]。土壤微塑料对作物的负面影响效应广泛, 包括降低叶面积、抑制株高、延迟分蘖、降低结实率和减少生物量等[12]。2012 年德国科学家 Rillig[13] 首次提出微塑料积累将影响土壤性质和生物多样性, 微塑料污染遂引起人们重视。有关微塑料对土壤微生物群落的影响, 特别是其与植物、土壤和微生物间的相互作用尚不清晰, 有待进一步研究。

本文通过总结、归纳国内外相关研究进展, 系统梳理了农田土壤中微塑料来源、丰度、迁移特点和鉴定方法, 重点关注微塑料对作物及农田土壤微生物和养分循环的影响, 提出了农田微塑料污染的未来潜在研究方向。

1 微塑料的来源、丰度、迁移与鉴定方法

1.1 农田生态系统中微塑料的来源和丰度

农田生态系统中微塑料主要有以下 3 个来源, 即城市源、农业源和大气源[14]。在城市中, 污水处理厂和垃圾填埋场是微塑料的主要来源路径, 过滤、干燥、杀菌、堆肥等污泥处理过程均不会消除微塑料。因此, 当污泥最终以干化焚烧、制复合肥、卫生填埋等方式处理时, 微塑料会输入到农田中并造成土壤污染[15]。据估算, 欧洲每年有 6.3 万~43 万 t 的微塑料通过农用污泥进入土壤中, 北美地区约为 4.4 万~30 万 t[16]。He 等[17] 在 12 个渗滤液样本中检测到 17 种微塑料, 其中超过 99% 来源于垃圾填埋场塑料垃圾的碎片化。此外, 汽车轮胎磨损、道路涂料和交通安全设施材料等也是城市源微塑料的重要来源[18]。研究表明, 堆肥和生物废弃物发酵产生的有机肥普遍含微塑料, 其中粒径>1 mm 的微塑料含量为 14~895 个·kg^{-1} [19], 粒径>0.5 mm 的塑料碎片含量为 2.4~180 mg·kg^{-1}[20]。我国农田土壤中, 每年由于有机肥施用带入的微塑料量为 52.4~26 400 t[21]。此外, 由于地膜覆盖具有控制杂草、保持水分、改善土壤温度等优点, 在干旱和半干旱地区得到广泛应用[22-24]。据统计, 2015 年我国农用地膜使用量达到 145.5 万 t[25], 但回收率不足 60%, 导致大量地膜残留, 带来严重的微塑料污染[26]。在对杭州湾覆膜和未覆膜土壤的研究显示, 覆膜和未覆膜土壤的微塑料含量分别为 571 个·kg^{-1} 和 263 个·kg^{-1} [27]。基于我国多省调查也表明微塑料含量随覆膜年限延长而升高[28]。在地膜覆盖广泛的新疆地区, 土壤地膜残留物最高含量可达 324.5 kg·hm^{-2} [29], 旱区地膜覆盖的 5 年到 30 年间, 粒径>2 mm 的微塑料浓度也从 91.2 mg·kg^{-1} 增加到 308.5 mg·kg^{-1} [30]。另外, 也有部分微塑料通过大气沉降进入农田生态系统, 巴黎的一项研究表明, 大气沉

降物中微塑料可达每天每平方米 280 颗[31]。可见, 微塑料可以通过地膜残留、有机肥施用、灌水、大气沉降等多种渠道进入农田土壤。

1.2　农田生态系统中微塑料的迁移

因微塑料化学性质稳定且能够长期存在, 进入土壤的微塑料会随着自然条件或人类活动而发生迁移 (图 1)[32]。土壤的多孔特性使小颗粒微塑料通过重力沉降和降水渗透进入地下水循环, 同时生物扰动 (如通过动物的活动沿土壤剖面运输) 和耕作等还会导致更大粒径的微塑料颗粒在农田土壤中运移[20,33-34]。Rillig 等[34] 观察到微塑料可以黏附在蚯蚓上随其移动而发生迁移, 认为蚯蚓的外部附着是微塑料迁移的一种运输机制。农业措施 (如耕作) 会引起表层和深层土壤的交换, 进而促进表层土壤中的微塑料向深层土壤迁移。此外, 当微塑料不断分解形成纳米颗粒 (<0.1 μm), 植物根系吸收能使纳米塑料转移到土壤上层, 经无脊椎动物或昆虫吞食后又被鸡等动物捕食, 最终沿着食物链传递, 不仅威胁农田生态系统健康, 还可能会对人体消化系统、呼吸系统、免疫系统等产生潜在危害[10,35-36]。

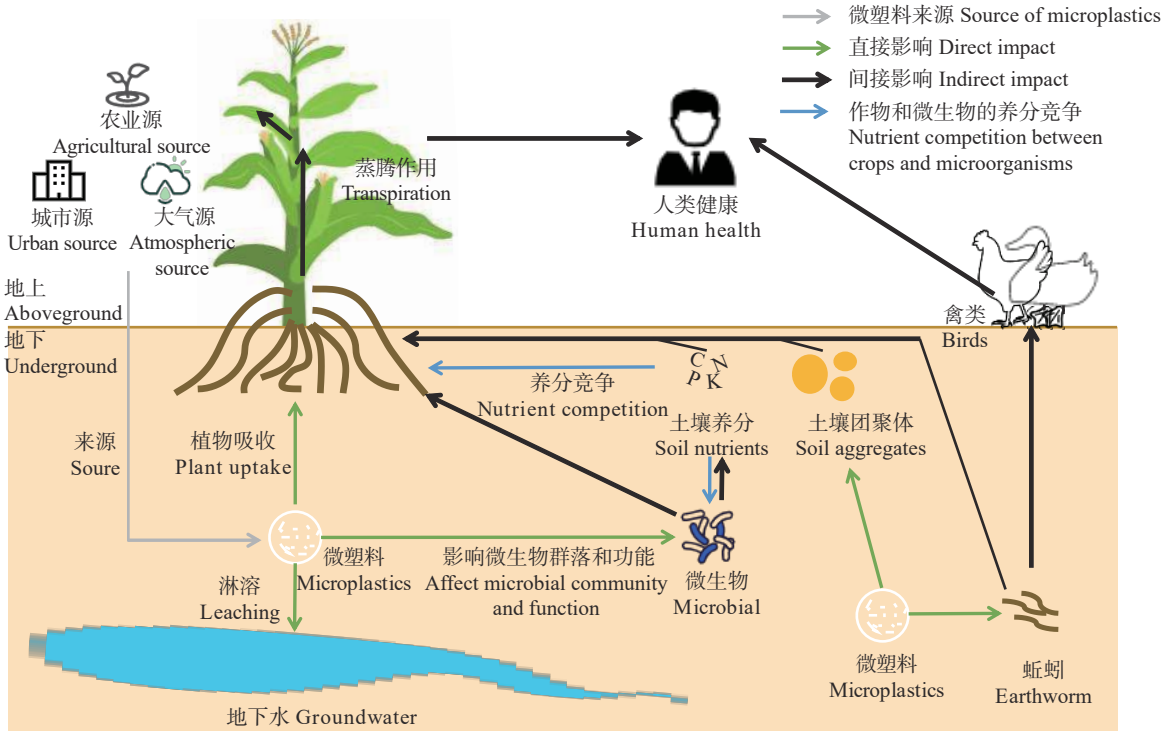

图 1　农田生态系统中微塑料的来源及其迁移过程

Fig. 1　Source and migration process of microplastics in agroecosystems

1.3　农田土壤中微塑料的鉴定

关于水生系统中微塑料的分离与鉴定已有不少研究[37-38], 但农田生态系统中微塑料的分离和鉴定一直是研究的难点与热点[20]。常见的分离鉴定过程如下: 首先, 人工去除肉眼可见的其他废弃物与大块塑料 (>5 mm)[30,39], 然后运用密度分离法将微塑料进行分离, 最后实现对微塑料含量的测定[40]。微塑料颗粒能够在 40 倍显微镜下被识别、计数和分类[41-42], 如 Kim 等[43] 通过高清摄像机、10~80 倍立体显微镜和红外光谱测量了单个微塑料颗粒的形态特征和聚合物特性。Birch 等[44] 运用稳定同位素质谱、显微拉曼光谱 (μ-Raman)、紫外 (UV) 光和热模拟风化条件等方法追踪塑料在环境中的地理起源和变化。同时, 消化处理和荧光染色也有利于微塑料的检测[45]。虽然物理 (如显微镜) 和化学 (如光谱) 分析的结合被广泛用于微塑料测定[46], 但微塑料检测仍受到土壤组分复杂程度以及检测方法本身的限制。因此, 根据试验目的合理选择分析技术的同时, 还亟需加强研究并制定出土壤微塑料检测方法标准[47-48]。

2　农田微塑料污染对作物生长的影响

作物是农田生态系统的基本组成部分, 了解微塑料对作物生长发育的影响至关重要。目前, 已有研究报道了微塑料对小麦 (*Triticum aestivum* L.)、水稻 (*Oryza sativa* L.)、玉米 (*Zea mays* L.)、多年生黑麦草 (*Lolium perenne* L.) 等作物的影响。连加攀等[49] 研究了乙烯-乙酸乙烯酯共聚物 (EVA)、线性低密度聚乙烯 (LLDPE) 和聚甲基丙烯酸甲酯 (PMMA) 对小麦种

子发芽的影响, 结果表明微塑料对小麦种子发芽的影响表现为低浓度 (<500 mg·L^{-1}) 时抑制高浓度 (1000 mg·L^{-1}) 时促进作用。然而, Judy 等[50] 的研究发现高密度聚乙烯 (HDPE)、聚氯乙烯 (PVC) 和聚对苯二甲酸乙二醇酯 (PET) 对小麦出苗无显著负面影响。因此, 微塑料对作物的影响可能因其自身特性 (比如剂量、形状、粒径)、作物种类、土壤类型的差异而有所不同。

2.1 微塑料对作物的直接作用

为了满足不同应用需要, 在塑料生产过程中会添加增塑剂 (邻苯二甲酸酯, PAEs)、防火剂 (双酚 A, BPAs; 多溴联苯醚, PBDEs) 等化学组分。这些添加剂 (如高浓度的塑化剂) 在微塑料的降解过程中会被释放, 产生生态毒性进而抑制作物生长[51]。已有研究证明, 邻苯二甲酸二丁酯 (DBP) 对辣椒 (*Capsicum annuum* L.) 果实中的维生素 C 和辣椒素含量以及大白菜 [*Brassica pekinensis* (Lour.) Rupr.] 中的叶绿素含量均产生了负面影响[52-53]。Kong 等[54] 采用气相色谱-质谱联用仪分析了天津市郊区农田、菜地、果园和荒地中 6 种 PAEs 的分布, 结果表明总 PAEs 在 0.05~10.4 μg·g^{-1} 范围内, 4 种土壤中 PAEs 的含量依次为菜地>荒地>农田>果园, 农用地膜能提高土壤中 PAEs 的含量。此外, 作物细胞壁孔洞约 5~50 nm, 介于此粒径的微塑料更容易吸附在种子表皮或根系细胞壁孔洞, 堵塞种子囊中的孔, 扰乱种子或根系对水分、营养的正常吸收或运输, 进而抑制作物生长[55-56]。李连祯等[35] 通过荧光标记和激光共聚焦扫描电镜观察到微塑料在作物体内的分布情况和运输过程, 发现亚微米级聚苯乙烯 (PS) 微珠能够通过质外体运输聚集在小麦根部, 进入中柱后, 随蒸腾作用向作物地上部移动。上述过程均会对作物生长发育产生直接影响, 但仍需在不同地区对更多微塑料种类和作物种类等进行研究, 以证实其普遍性。

2.2 微塑料对作物的间接作用

由于微塑料的密度通常小于土壤, 微塑料污染会改变土壤容重和保水能力。微塑料能够影响土壤团聚体结构, 降低土壤的通气性和透水性, 阻挡根系对水分及养分的有效吸收, 进而影响作物生长[57-58]。有研究表明, 5 μm 的 PS 纤维 (0.3%) 添加到土壤中有利于土壤团聚体的形成, 增大土壤孔隙率, 降低土壤持水能力[59], 加快水分蒸发[60]。相反, 18 μm 的聚丙烯 (PP) 纤维 (0.4%) 和 8 μm 的 PS 纤维 (0.4%) 添加降低了土壤水稳性团聚体, 导致土壤退化[61]。此外, 微塑料含碳量相对较高, 会导致土壤碳氮比增加, 促进微生物的氮固定能力, 进而抑制其他土壤微生物和植物的生长及养分吸收, 尤其是可降解微塑料[62]。土壤性质的改变还能促使作物根际微生物 (如固氮菌、丛枝菌根真菌等) 的活性变化[63], 土壤孔隙度和水分运输状态的改变也可能造成氧含量变化, 改变土壤中厌氧和好氧微生物的相对分布[64], 进而对微生物多样性和作物生长产生影响 (表 1)。

3 农田微塑料污染对土壤微生物的影响

土壤微生物对农田生态系统至关重要, 微生物活性的增强会促进碳、氮、磷等营养元素的释放[70]。微塑料可以为微生物提供吸附位点, 使其长期吸附形成生物热点, 改变土壤微生物的生态功能[71-72]。如添加聚乙烯 (PE) 促使放线菌门 (Actinobacteria) 取代变形菌门 (Proteobacteria) 成为土壤优势微生物类群[73], 并增加了土壤中与固氮作用有关细菌的丰度[74]。由于微塑料比表面积较大, 其表面会吸附重金属和有机污染物等[75], 这些污染物随微塑料一起发生迁移, 进而改变土壤微生物群落和生物多样性[1]。另外, 微塑料也可能成为致病菌等有害微生物的运输载体, 影响土壤健康[76]。Fei 等[74] 对浙江临安农田表层土壤的研究显示, 微塑料 (PE 和 PVC) 污染导致土壤细菌群落活性和 α 多样性下降。Zang 等[65] 研究表明加入 PE 和 PVC 微塑料增加了土壤微生物的生物量和磷脂脂肪酸总量。Zhou 等[77] 通过加入可生物降解的 3-羟基丁酯酸和 3-羟基戊酸脂的共聚物 (PHBV) 发现, 其能增加微生物活性、生物量和 α 多样性。此外, 丁峰等[78] 研究发现低分子量 (2000) 聚乙烯能够显著降低土壤中细菌和真菌的丰度, 而高分子量 (100 000) 聚乙烯具有相反的影响。虽然上述结果表明添加微塑料会影响土壤微生物的组成和生物量, 但也有一些研究发现, 添加微塑料对土壤微生物群落组成和多样性无显著影响。如 Huang 等[76] 对细菌 16S rRNA 的测序结果表明, LDPE 微塑料处理对土壤微生物群落 α 多样性 (丰富度、均匀度和多样性) 无明显影响; Chen 等[79] 研究表明聚乳酸 (PLA) 微塑料在高碳和低碳条件下对土壤细菌群落组成和优势类群的相对丰度均无显著影响; Blöcker 等[80] 也发现添加低密度聚乙烯 (LDPE) 和 PP 微塑料对土壤微生物活性无明显的不利影响 (表 2)。总之, 微塑料的存在会干扰土壤微生物群落, 然而其潜在危害还需进一步研究。

土壤酶活性反映了微生物活性及其对底物的利用情况, 是调控土壤养分循环的关键[83-85]。Fei 等[74]

表 1　微塑料污染对作物生长的影响

Table 1　The impact of microplastics pollution on crop growth

微塑料 Microplastics				作物 Crop	指标 Index	效应 Effect	地点 Location	参考文献 Reference
种类 Type	形状 Shape	大小 Size	浓度 Concentration					
PE	/	125 μm	1%, 5%, 10%, 20% (*w*/*w*)	小麦 Wheat	微塑料剂量依赖性 Dose-dependent impact of microplastics	−	英国威尔士格温内思郡 Gwynedd, Wales, England	[65]
HDPE	颗粒 Pellets	<2 mm	0.1%, 0.25%, 0.5%, 1% (*w*/*w*)	小麦 Wheat	种子萌发、生物量 Seedling emergence, biomass	=	澳大利亚新南威尔士州 New South Wales, Australia	[50]
	颗粒 Pellets	102.6 μm	0.1% (*w*/*w*)	多年生黑麦草 Perennial ryegrass	地上部生物量(干重)、叶绿素a和叶绿素b含量 Shoot biomass (dry weight), chlorophyll a and b contents	=	北爱尔兰韦斯特兰 Westland, Northern Ireland	[66]
	颗粒 Pellets	102.6 μm	0.1% (*w*/*w*)	多年生黑麦草 Perennial ryegrass	根系生物量、叶绿素a与叶绿素b含量的比值 Dry biomass of roots, chlorophyll a/b	+	北爱尔兰韦斯特兰 Westland, Northern Ireland	[66]
PVC	/	125 μm	1%, 5%, 10%, 20% (*w*/*w*)	小麦 Wheat	微塑料剂量依赖性 Dose-dependent impact of microplastics	−	英国威尔士格温内思郡 Gwynedd, Wales, England	[65]
	颗粒 Pellets	<2 mm	0.01%, 0.1%, 0.25%, 0.5%, 1% (*w*/*w*)	小麦 Wheat	种子萌发、生物量 Seedling emergence, biomass	=	澳大利亚新南威尔士州 New South Wales, Australia	[50]
	薄膜 Films	L: 0.5 mm; W: 0.5 mm; T: 0.008 mm	/	水稻 Rice	生物量、分蘖数 Biomass, tillers number	−	中国海南省海口市 Haikou City, Hainan, China	[67]
PS	颗粒 Pellets	87 nm	10 mg·L^{-1}	小麦 Wheat	叶片Cd和丙二醛含量、超氧化物歧化酶活性 Cd and malondialdehyde contents, and superoxide dismutase activity in leaves	−	/	[68]
	颗粒 Pellets	87 nm	10 mg·L^{-1}	小麦 Wheat	过氧化氢酶和过氧化物酶活性 Catalase and peroxidase activies	=	/	[68]
	颗粒 Pellets	87 nm	10 mg·L^{-1}	小麦 Wheat	Cd胁迫下叶片中长寿自由基的形成、碳水化合物和氨基酸代谢、种子萌发 Formation of long-lived radicals in leaves after exposure to Cd, carbohydrate and amino acid metabolisms, seedling emergence	+	/	[68]
PLA	颗粒 Pellets	65.6 μm	0.1% (*w*/*w*)	多年生黑麦草 Perennial ryegrass	发芽率、株高 Germination percentage, plant height	−	北爱尔兰韦斯特兰 Westland, Northern Ireland	[66]
	颗粒 Pellets	65.6 μm	0.1% (*w*/*w*)	多年生黑麦草 Perennial ryegrass	地上部生物量(干重)、叶绿素a和叶绿素b含量 Shoot biomass (dry weight), contents of chlorophyll a and b	=	北爱尔兰韦斯特兰 Westland, Northern Ireland	[66]
	颗粒 Pellets	65.6 μm	0.1% (*w*/*w*)	多年生黑麦草 Perennial ryegrass	叶绿素a与叶绿素b含量的比值 Chlorophyll a/b	+	北爱尔兰韦斯特兰 Westland, Northern Ireland	[66]
	颗粒 Pellets	100~154 μm	0, 0.1%, 1%, 10% (*w*/*w*)	玉米 Maize	生物量、叶片叶绿素含量 Biomass, chlorophyll content of leaves	−	中国青岛即墨区 Jimo District, Qingdao, China	[69]
PET	颗粒 Pellets	<2 mm	0.1%, 0.25%, 0.5%, 1% (*w*/*w*)	小麦 Wheat	种子萌发、生物量 Seedling emergence, biomass	=	澳大利亚新南威尔士州 New South Wales, Australia	[50]

“+”表示添加微塑料具有正效应; “−”表示添加微塑料具有负效应; “=”表示添加微塑料无效应; “/”表示文献中无该栏信息。“L”表示长度; “W”表示宽度; “T”表示厚度; 未标字母为粒径。PE: 聚乙烯; HDPE: 高密度聚乙烯; PVC: 聚氯乙烯; PS: 聚苯乙烯; PLA: 聚乳酸; PET: 聚对苯二甲酸乙二醇酯。“+” “−” and “=” mean microplastics addition has a positive, negative, and no effect, respectively. “/” means no information in the literature. “L”: length; “W”: width; “T”: thickness; unmarked letters mean particle size. PE: polyethylene; HDPE: high-density polyethylene; PVC: polyvinyl chloride; PS: polystyrene; PLA: polylactic acid; PET: polyethylene terephthalate.

发现在酸性土壤中 PE 和 PVC 微塑料添加抑制了荧光素二乙酸酯水解酶 (FDAse) 的活性, 但是促进了脲酶 (URE) 和酸性磷酸酶 (ACP) 的活性; 与 PVC 处理相比, PE 处理对土壤有更大的负面影响。Huang 等[76]通过添加 LDPE 发现其能显著提高土壤 URE 和过氧化氢酶 (CAT) 活性。也有研究表明, 添加 7% 和 28%

表 2 微塑料污染对土壤微生物的影响

Table 2 The impact of microplastics pollution on soil microorganisms

微塑料 Microplastics				微生物 Microorganisms	指标 Index	效应 Effect	地点 Location	参考文献 Reference
种类 Type	形状 Shape	大小 Size	浓度 Concentration					
PE	/	125 μm	1%, 5%, 10%, 20% (*w*/*w*)	微生物 Microbial	生物量、碳利用效率 Biomass, carbon utilization efficiency	+	英国威尔士格温内思郡 Gwynedd, Wales, England	[65]
	颗粒 Pellets	678 μm	1%, 5% (*w*/*w*)	细菌 Bacteria	丰富度、多样性 Richness, diversity	−	中国浙江省临安市 Lin'an, Zhejiang, China	[74]
	颗粒 Pellets	0.15~0.20 mm	2.12 g·kg^{-1} (2000分子量) 2.12 g·kg^{-1}(2000 molecular weight)	细菌、真菌 Bacteria, fungi	丰富度 Richness	−	/	[78]
	颗粒 Pellets	0.15~0.20 mm	2.12 g·kg^{-1} (>100 000分子量) 2.12 g·kg^{-1} (> 100 000 molecular weight)	细菌、真菌 Bacteria, fungi	丰富度 Richness	+	/	[78]
LDPE	薄膜 Films	L: 2 mm W: 2 mm T: 0.01 mm	0.076 g·kg^{-1}	细菌 Bacteria	群落α多样性 Community alpha diversity	=	中国北京大学 Peking University, China	[76]
	薄膜 Films	L: 2 mm W: 2 mm T: 0.01 mm	0.076 g·kg^{-1}	细菌 Bacteria	相似性 Similarity	−	中国北京大学 Peking University, China	[81]
	薄膜 Films	L: 2 mm W: 2 mm T: 0.01 mm	0.076 g·kg^{-1}	细菌 Bacteria	群落周转率(群落演替) Turnover rate of bacterial community (community succession)	+	中国北京大学 Peking University, China	[81]
	颗粒 Pellets	200~630 μm	1% (*w*/*w*)	微生物 Microbial	活性、群落组成、微生物量氮 Activity, community composition, microbial biomass nitrogen	=	德国克莱夫 Kleve, Germany	[80]
	颗粒 Pellets	200~630 μm	1% (*w*/*w*)	微生物 Microbial	微生物量碳 Microbial biomass carbon	−	德国克莱夫 Kleve, Germany	[80]
	颗粒 Pellets	678 μm	1%, 5% ((*w*/*w*)	细菌 Bacteria	固氮 Nitrogen fixation	+	中国浙江省临安市 Lin'an, Zhejiang, China	[74]
HDPE	颗粒 Pellets	<2 mm	0.1%, 0.25%, 0.5%, 1% (*w*/*w*)	微生物 Microbial	群落多样性 Community diversity	=	澳大利亚新南威尔士州 New South Wales, Australia	[50]
PVC	颗粒 Pellets	18 μm	5% (*w*/*w*)	细菌 Bacteria	丰富度、多样性 Richness, diversity	−	中国浙江省临安市 Lin'an, Zhejiang, China	[74]
	颗粒 Pellets	18 μm	1% (*w*/*w*)	细菌 Bacteria	丰富度、多样性 Richness, diversity	=	中国浙江省临安市 Lin'an, Zhejiang, China	[74]
	颗粒 Pellets	<2 mm	0.01%, 0.1%, 0.25%, 0.5%, 1% (*w*/*w*)	微生物 Microbial	群落多样性 Community diversity	=	澳大利亚新南威尔士州 New South Wales, Australia	[50]
	/	125 μm	1%, 5%, 10%, 20% (*w*/*w*)	微生物 Microbial	生物量、碳利用效率 Biomass, carbon utilization efficiency	+	英国威尔士格温内思郡 Gwynedd, Wales, England	[65]
	颗粒 Pellets	18 μm	1%, 5% (*w*/*w*)	细菌 Bacteria	固氮 Nitrogen fixation	+	中国浙江省临安市 Lin'an, Zhejiang, China	[74]
PP	颗粒 Pellets	200~630 μm	1% (*w*/*w*)	微生物 Microbial	活性、群落组成 Activity, community composition	=	德国克莱夫 Kleve, Germany	[80]
	颗粒 Pellets	200~630 μm	1% (*w*/*w*)	微生物 Microbial	生物量、微生物量碳、微生物量氮 Biomass, microbial biomass carbon, microbial biomass nitrogen	−	德国克莱夫 Kleve, Germany	[80]
	颗粒 Pellets	<250 μm	28% (*w*/*w*)	微生物 Microbial	呼吸 Respiration	+	中国陕西省安塞县 Ansai, Shaanxi, China	[82]
PLA	颗粒 Pellets	20~50 μm	2% (*w*/*w*)	细菌 Bacteria	群落多样性和组成以及相关生态系统功能和过程 Community diversity and composition, and related ecosystem functions and processes	=	中国江苏省南京市 Nanjing, Jiangsu, China	[79]
	颗粒 Pellets	20~50 μm	2% (*w*/*w*)	厚壁菌 Firmicutes	生物量 Biomass	−	中国江苏省南京市 Nanjing, Jiangsu, China	[79]
PET	颗粒 Pellets	<2 mm	0.1%, 0.25%, 0.5%, 1% (*w*/*w*)	微生物 Microbial	群落多样性 Community diversity	=	澳大利亚新南威尔士州 New South Wales, Australia	[50]

"+"表示添加微塑料具有正效应; "−"表示添加微塑料具有负效应; "="表示添加微塑料无效应; "/"表示文献中无该栏信息。"L"表示长度; "W"表示宽度; "T"表示厚度; 未标字母为粒径。PE: 聚乙烯; LDPE: 低密度聚乙烯; HDPE: 高密度聚乙烯; PVC: 聚氯乙烯; PP: 聚丙烯; PLA: 聚乳酸; PET: 聚对苯二甲酸乙二醇酯。"+" "−" and "=" means microplastics addition has a positive, negative, and no effect, respectively. "/" means there is no information in the literature. "L": length; "W": width; "T": thickness; unmarked letters mean particle size. PE: polyethylene; LDPE: low-density polyethylene; HDPE: high-density polyethylene; PVC: polyvinyl chloride; PP: polypropylene; PLA: polylactic acid; PET: polyethylene terephthalate.

的 PP 微塑料均能增加土壤磷酸酶 (AP) 和 FDAse 活性, 降低酚氧化酶 (PO) 的活性[82,86]。以上研究结果表明, 微塑料可以促进含氮有机质水解和有机磷矿化, 降低可溶性有机物 (DOM) 的生物降解性, 同时, CAT 活性提高, 表明微塑料的存在增加了需氧微生物的生物量。综上所述, 微塑料对土壤中微生物和酶活性的影响可能随着微塑料自身特性 (粒径、剂量、种类) 的变化而变化 (表 3)。

4　微塑料污染对农田土壤养分循环的影响

微塑料属于高碳聚合物, 碳含量超过 90%, 微塑料污染可以显著改变土壤碳储量[13]。可溶性有机碳 (DOC) 是土壤有机质的重要组成部分, 是土壤质量变化 (如结构、养分有效性、水分) 的敏感指标, 在生物地球化学循环中发挥着重要作用[86-87]。Liu 等[86] 发现添加高浓度 PP 微塑料 (28%, *w*/*w*) 能够促进水解酶活性, 进而增加可溶性碳氮含量, 提高土壤养分。但也有研究表明, 添加 PE (5%, *w*/*w*) 和 PLA(1%, *w*/*w*) 微塑料对 DOC 含量没有显著影响[73,79]。综合来看, 低浓度微塑料对 DOC 形成影响不大, 而高浓度微塑料则促进 DOC 形成。此外, Zhou 等[88] 发现可生物降解微塑料分解产生的生物可利用碳, 增强了微生物和酶的活性, 加速了土壤有机质 (SOM) 矿化, 从而增加了植物和微生物之间的养分竞争。

氮和磷作为作物的主要营养物质, 对于维持农田生态系统结构与功能具有重要作用。在生物降解地膜覆盖研究中, 使用玉米淀粉和共聚酯地膜对硝化过程和亚硝酸盐的产生无显著影响[89]。相反, Chen 等[79] 研究表明添加生物降解塑料 PLA 可以降低土壤中铵态氮浓度, 增加硝态氮浓度, 影响土壤氮素循环过程。另外, 微塑料的衍生物, 如邻苯二甲酸酯类, 也会造成土壤污染[54,90-92], 限制关键土壤酶活性, 影响农田养分循环[91-94]。添加 PS 和 PE 微塑料会抑制土壤氮循环关键酶活性[95-96]。也有研究报道, PP 微塑料可以通过其表面的羰基 (−C=O) 和羟基 (−OH) 来螯合铵态氮, 直接抑制氮的有效性[97]。Liu 等[86] 发现添加 PP 微塑料增加了土壤总可溶性磷和有机磷含量, 但磷酸根离子的含量受污染时间的影

表 3　微塑料污染对土壤酶活性的影响

Table 3　The impact of microplastics pollution on soil enzyme activities

微塑料 Microplastics				土壤 Soil	指标 Index	效应 Effect	地点 Location	参考文献 Reference
种类 Type	形状 Shape	大小 Size	浓度 Concentration					
PE	颗粒 Pellets	678 μm	1%, 5% (*w*/*w*)	壤土 Loamy soil	URE, ACP	+	中国浙江省临安市 Lin'an, Zhejiang, China	[74]
	颗粒 Pellets	678 μm	1%, 5% (*w*/*w*)	壤土 Loamy soil	FDAse	−	中国浙江省临安市 Lin'an, Zhejiang, China	[74]
LDPE	薄膜 Films	L: 2 mm W: 2 mm T: 0.01 mm	0.076 g·kg^{-1}	褐土 Cinnamon soil	URE, CAT	+	中国北京大学 Peking University, China	[76]
	薄膜 Films	L: 2 mm W: 2 mm T: 0.01 mm	0.076 g·kg^{-1}	褐土 Cinnamon soil	Invertase	=	中国北京大学 Peking University, China	[76]
PVC	颗粒 Pellets	678 μm	1%, 5% (*w*/*w*)	壤土 Loamy soil	URE, ACP	+	中国浙江省临安市 Lin'an, Zhejiang, China	[74]
	颗粒 Pellets	678 μm	1%, 5% (*w*/*w*)	壤土 Loamy soil	FDAse	−	中国浙江省临安市 Lin'an, Zhejiang, China	[74]
PP	颗粒 Pellets	<250 μm	28% (*w*/*w*)	黄土 Loess	URE	=	中国陕西省安塞县 Ansai, Shaanxi, China	[82]
	颗粒 Pellets	<250 μm	7%, 28% (*w*/*w*)	黄土 Loess	AP	+	中国陕西省安塞县 Ansai, Shaanxi, China	[82]
	颗粒 Pellets	<250 μm	28% (*w*/*w*)	黄土 Loess	GLU	+	中国陕西省安塞县 Ansai, Shaanxi, China	[82]
	颗粒 Pellets	<180 μm	7%, 28% (*w*/*w*)	黄土 Loess	PO	−	中国陕西省安塞县 Ansai, Shaanxi, China	[86]
	颗粒 Pellets	<180 μm	7%, 28% (*w*/*w*)	黄土 Loess	FDAse	+	中国陕西省安塞县 Ansai, Shaanxi, China	[86]
PLA	颗粒 Pellets	20~50 μm	2% (*w*/*w*)	/	URE, CAT, GLU	=	中国江苏省南京市 Nanjing, Jiangsu, China	[79]

"+"表示添加微塑料具有正效应; "−"表示添加微塑料具有负效应; "="表示添加微塑料无效应; "/"表示文献中无该栏信息。"L"表示长度; "W"表示宽度; "T"表示厚度; 未标字母为粒径。PE: 聚乙烯; LDPE: 低密度聚乙烯; PVC: 聚氯乙烯; PP: 聚丙烯; PLA: 聚乳酸。URE: 脲酶; ACP: 酸性磷酸酶; FDAse: 荧光素二乙酸酯水解酶; CAT: 过氧化氢酶; Invertase: 转化酶(蔗糖酶); AP: 磷酸酶; GLU: β-葡萄糖苷酶; PO: 酚氧化酶。"+" "−" and "=" mean microplastics addition has a positive, negative, and no effect, respectively. "/" means there is no information in the literature. "L": length; "W": width; "T": thickness; unmarked letters mean particle size. PE: polyethylene; LDPE: low-density polyethylene; PVC: polyvinyl chloride; PP: polypropylene; PLA: polylactic acid. URE: urease; ACP: acid phosphatase; FDAse: fluorescein diacetate hydrolase; CAT: catalase; Invertase: invertase (sucrase); AP: phosphatase; GLU: β-glucosidase; PO: phenol oxidase.

响, 表现为初期较高, 后期迅速下降。Chen 等[79] 的研究则发现添加可降解微塑料 PLA 并未对土壤无机磷含量产生影响。总之, 微塑料对农田氮和磷循环的影响在不同研究中结果差异很大, 后续仍需更多研究来阐明其调控机制。

先前的研究表明, 添加生物炭等含碳聚合物会极大地影响温室气体 (GHGs) 排放[98]。因此, 探究微塑料这种高碳聚合物对温室气体排放的影响也非常重要。添加高浓度 LDPE 微塑料使土壤 CO_2 通量增加 7~8 倍[99]。Ren 等[73] 发现在施肥土壤中, 添加 PE 微塑料减少了 N_2O 排放, 进而降低了全球增温潜势 (GWP)。这可能是因为微塑料抑制了绿弯菌门 (Chloroflexi) 和红游动菌属 (*Rhodoplanes* Hiraishi and Ueda) 微生物的活性, 但是增加了嗜热菌 (Thermoleophilia) 的丰度, 降低了氮的有效性。微塑料也可能通过增加含水量或降低孔隙率[61,66], 进而增加或减少 O_2 的利用率, 导致反硝化过程不完全, 改变 N_2O 排放[100]。也有研究表明, PVC 微塑料可以通过抑制水解、酸化和甲烷化来减少 CH_4 排放[101], 较大粒径的微塑料也有可能减少 CH_4 的累积吸收[90](表 4)。因此, 不同微塑料对温室气体排放的潜在影响机理尚需进一步研究。

5 研究展望

由于微塑料的种类多样、形态各异, 其对农田生态系统影响的研究仍非常缺乏, 亟需深入探究微塑料污染对作物-土壤系统的影响。研究表明, 微塑料会改变土壤酶活性和微生物活性, 影响农田养分循环过程, 直接和间接影响作物生长及养分吸收, 最终威胁农田生态系统健康。未来研究需重点关注以下内容:

1) 农田土壤中微塑料的分离提取和分析鉴定。因塑料与土壤有机质密度较为接近, 从有机质含量较高的土壤中分离微塑料非常困难。同时, 农田中微塑料来源和成分复杂, 需建立统一规范的分析鉴定方法。

2) 明确农田微塑料含量安全指标范围。农田土壤中的微塑料不可能在短期内完全去除, 应通过大量试验, 建立数据库, 探究不同区域影响农田生态系统正常运行的微塑料含量阈值, 从而能够有效监测并控制农田微塑料污染。

3) 微塑料对作物-土壤影响的系统评估。应对不同种类的微塑料、作物、土壤等进行多层次深入研究, 进一步明确不同环境条件下微塑料与作物、土壤微生物和酶活性的互作关系。同时, 目前绝大多数微塑料研究都在实验室条件下进行, 且部分研究中微塑料添加量远高于普通农田污染量, 造成了微塑料的试验浓度和自然环境浓度之间的不可比性。应在原位土壤中建立作物和微生物的微塑料剂量-效应关系, 评估土壤理化性质、微生物和作物对不同剂量微塑料胁迫的响应。

4) 微塑料本身、其释放的化学物质 (如增塑剂、阻燃剂、抗氧化剂和稳定剂等) 以及通过吸附解吸释放的污染物对生态系统和人类健康均存在潜在威胁, 应进一步分析微塑料和其负荷物能否被田间作物吸收转运并最终进入食物链。

5) 虽然可降解农膜被大规模使用, 但是可降解微塑料是否也会影响土壤质量进而影响作物健康亟须探明。

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表 4　微塑料污染对土壤养分循环的影响

Table 4　The impact of microplastics pollution on soil nutrient cycling

微塑料 Microplastics				土壤 Soil	指标 Index	效应 Effect	地点 Location	参考文献 Reference
种类 Type	形状 Shape	大小 Size	浓度 Concentration					
PE	地膜 Mulching film	<13 μm, <150 μm	5% (w/w)	黏土 Clay	DOC	=	中国天津市北辰区 Beichen District, Tianjin, China	[73]
	地膜 Mulching film	<13 μm, <150 μm	5% (*w*/*w*)	黏土 Clay	有机化合物 Organic compound	+	中国天津市北辰区 Beichen District, Tianjin, China	[73]
	地膜 Mulching film	<150 μm	5% (*w*/*w*)	黏土 Clay	CO_2日通量 Daily flux of CO_2	+	中国天津市北辰区 Beichen District, Tianjin, China	[73]
	地膜 Mulching film	<150 μm	5% (*w*/*w*)	黏土 Clay	CH_4累积吸收 Cumulative uptake of CH_4	−	中国天津市北辰区 Beichen District, Tianjin, China	[73]
	地膜 Mulching film	<13 μm, <150 μm	5% (*w*/*w*)	黏土 Clay	GHGs, N_2O	−	中国天津市北辰区 Beichen District, Tianjin, China	[73]
LDPE	颗粒 Pellets	200~630 μm	1% (*w*/*w*)	砂质黏壤土 Sandy clay loam	DOC, DON, N_{min}	=	德国克莱夫 Kleve, Germany	[80]
	颗粒 Pellets	25.3±8.4 μm	3% (*w*/*w*)	人工土壤(石英砂75%、高岭石黏土20%、泥炭藓5%) Artificial soil (quartz sand 75%, kaolinite clay 20%, sphagnum peat 5%)	CO_2日通量 Daily flux of CO_2	+	/	[99]
	颗粒 Pellets	25.3±8.4 μm	0.2%, 3% (*w*/*w*)	人工土壤(石英砂75%、高岭石黏土20%、泥炭藓5%) Artificial soil (quartz sand 75%, kaolinite clay 20%, sphagnum peat 5%)	CH_4,N_2O	=	/	[99]
HDPE	颗粒 Pellets	102.6 μm	0.1% (*w*/*w*)	砂质黏壤土 Sandy clay loam	SOM	=	北爱尔兰韦斯特兰 Westland, Northern Ireland	[66]
PVC	薄膜 Films	L: 0.5 mm; W: 0.5 mm; T: 0.008 mm	/	红壤土 Laterite soil	SOC, TOC, SOM	−	中国海南省海口市 Haikou, Hainan, China	[67]

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续表 4

微塑料 Microplastics				土壤 Soil	指标 Index	效应 Effect	地点 Location	参考文献 Reference
种类 Type	形状 Shape	大小 Size	浓度 Concentration					
PP	颗粒 Pellets	<180 μm	7%, 28% (*w*/*w*)	黄土 Loess	DOM, TDN, DON, TDP, DOP	+	中国陕西省安塞县 Ansai, Shaanxi, China	[95]
	颗粒 Pellets	200~630 μm	1% (*w*/*w*)	砂质黏壤土 Sandy clay loam	DOC, DON, N_{min}	=	德国克莱夫 Kleve, Germany	[80]
	颗粒 Pellets	<180 μm	28% (*w*/*w*)	黄土 Loess	DOC	+	中国陕西省安塞县 Ansai, Shaanxi, China	[95]
	颗粒 Pellets	<180 μm	7% (*w*/*w*)	黄土 Loess	DOC	=	中国陕西省安塞县 Ansai, Shaanxi, China	[95]
	颗粒 Pellets	<180 μm	7%, 28% (*w*/*w*)	黄土 Loess	NH_4^+, NO_3^-, PO_4^{3-}	=	中国陕西省安塞县 Ansai, Shaanxi, China	[95]
PLA	颗粒 Pellets	65.6 μm	0.1% (*w*/*w*)	砂质黏壤土 Sandy clay loam	SOM	=	北爱尔兰韦斯特兰 Westland, Northern Ireland	[66]
	颗粒 Pellets	20~50 μm	2% (*w*/*w*)	/	DOC, TDN, NH_4^+, NO_3^-, NO_2^-, IP	=	中国江苏省南京市 Nanjing, Jiangsu, China	[79]
	颗粒 Pellets	20~50 μm	2% (*w*/*w*)+水稻秸秆 Rice straw (2%)	/	DOC	−	中国江苏省南京市 Nanjing, Jiangsu, China	[79]
	颗粒 Pellets	2~50 μm	2% (*w*/*w*)+水稻秸秆 Rice straw (2%)	/	TDN, NH_4^+, NO_3^-, NO_2^-, IP	=	中国江苏省南京市 Nanjing, Jiangsu, China	[79]
PET	颗粒 Pellets	56.3±12.8 μm	0.2%, 0.4% (*w*/*w*)	人工土壤(石英砂75%、高岭石黏土20%、泥炭藓5%) Artificial soil (quartz sand 75%, kaolinite clay 20%, sphagnum peat 5%)	CH_4, N_2O	=	/	[99]

“+”表示添加微塑料具有正效应; “−”表示添加微塑料具有负效应; “=”表示添加微塑料无效应; “/”表示文献中无该栏信息。“L”表示长度; “W”表示宽度; “T”表示厚度; 未标字母为粒径。PE: 聚乙烯; LDPE: 低密度聚乙烯; HDPE: 高密度聚乙烯; PVC: 聚氯乙烯; PP: 聚丙烯; PLA: 聚乳酸; PET: 聚对苯二甲酸乙二醇酯。DOC: 可溶性有机碳; GHGs: 温室气体; DON: 可溶性有机氮; N_{min}: 无机氮; SOM: 土壤有机质; SOC: 土壤有机碳; TOC: 总有机碳; DOM: 可溶性有机质; TDN: 总可溶性氮; TDP: 总可溶性磷; DOP: 可溶性有机磷; IP: 无机磷。“+” “−” and “=” mean microplastics addition has a positive, negative, and no effect, respectively. “/” means no information in the literature. “L”: length; “W”: width; “T”: thickness; unmarked letters mean particle size. PE: polyethylene; LDPE: low-density polyethylene; HDPE: high-density polyethylene; PVC: polyvinyl chloride; PP: polypropylene; PLA: polylactic acid; PET: polyethylene terephthalate. DOC: dissolved organic carbon; GHGs: greenhouse gases; DON: dissolved organic nitrogen; N_{min}: inorganic nitrogen; SOM: soil organic matter; SOC: soil organic carbon; TOC: total organic carbon; DOM: dissolved organic matter; TDN: total dissolved nitrogen; TDP: total dissolved phosphorus; DOP: dissolved organic phosphorus; IP: inorganic phosphorus.

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