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# 农田土壤微塑料分布、来源和行为特征

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**摘要:** 微塑料(MPs)作为一种新型污染物广泛存在于农田土壤中. 针对农田土壤中微塑料可能发生的污染问题, 对全球农田土壤中微塑料的分布、丰度、来源、形状、聚合物组成、尺寸和迁移等方面特征的研究进展进行了综述, 提出了研究展望. 全球各地所调查农田土壤均有微塑料检出, 其来源主要包括农用塑料薄膜、有机肥、污泥、地表径流与农业灌溉、大气沉降和轮胎磨损颗粒. 土壤中微塑料形状以碎片、纤维和薄膜为主, 微塑料聚合物组成以聚乙烯(PE)、聚丙烯(PP)和聚苯乙烯(PS)为主. 农田土地利用方式显著影响土壤中微塑料的丰度, 农田土壤中微塑料丰度随颗粒变小而增加. 土壤中微塑料可在耕作、淋溶、生物扰动和重力作用下发生迁移. 今后应加强土壤微塑料检测方法、数据库建立、安全阈值、迁移转化规律、潜在生态健康风险评价和防控技术体系构建等方面的研究, 为农田土壤微塑料污染的风险管控与治理提供参考.

**关键词:** 农田土壤; 微塑料(MPs); 聚合物; 迁移; 特征

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## Distribution, Sources, and Behavioral Characteristics of Microplastics in Farmland Soil

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**Abstract:** Microplastics (MPs) are widely present in farmland soil as an emerging contaminant. This paper serves as a comprehensive and systematic review of research progress on the characteristics of distribution, abundance, sources, shape, polymer composition, size, and migration of MPs in farmland soils around the world. Moreover, research prospects were also proposed. MPs have been detected in farmland soils around the world, mainly coming from agricultural plastic films, organic fertilizers, sludge, surface runoff, agricultural irrigation, atmospheric deposition, and tire wear particles. The morphology of MPs in soil mainly includes debris, fibers, and films. MPs polymer forms mainly include polyethylene, polypropylene, and polystyrene. Farmland land use significantly affects soil MPs abundance. Additionally, the abundance of MPs increase with the reduction in size. MPs in soil can migrate to deep soil through tillage, leaching, bioturbation, and gravity. Research on soil MPs detection methods, database establishment, safety thresholds, migration and transformation laws, potential ecological health risk assessment, and the construction of prevention and control technology systems should be strengthened in the future. The paper can provide a reference for the risk control and governance of farmland soil MPs pollution.

**Key words:** farmland soil; microplastics(MPs); polymer; migration; characteristic

微塑料(microplastics, MPs)指粒径小于5 mm的塑料,最初在海洋中被发现. 据调查,每年排入海洋的微塑料达9.3~23.6 t<sup>[1]</sup>. 与海洋相比,土壤中存在的微塑料是海洋的4~23倍<sup>[2]</sup>,土壤成为微塑料重要的“汇”. 微塑料污染在第二届联合国环境大会上被列入环境与生态科学研究领域的第二大科学问题,成为重大全球环境问题之一<sup>[3]</sup>. 微塑料可通过有机肥和农膜使用进入农田土壤,其中,我国经有机肥使用进入农田土壤的微塑料含量高达52.4~26 400 t<sup>[1]</sup>. 农业灌溉和大气沉降也是微塑料进入农田土壤的重要途径<sup>[4]</sup>. 全球各地不同土地利用方式下的农田土壤中均有微塑料检出<sup>[5,6]</sup>. 微塑料不仅会影响土壤容重、微生物群落、土壤动植物等物理化学和生物学性质<sup>[7,8]</sup>,还可与其他污染物结合形

成复合污染<sup>[9~16]</sup>,最终对环境产生潜在生态风险和对人体产生潜在健康风险.

基于Web of Science和中国知网(CNKI)数据库,查询了2012~2022年间发表的关于土壤微塑料的学术论文,有关土壤微塑料的研究增长较快,已成为研究的热点和焦点. 基于此,本文总结了国内外有关农田土壤微塑料行为特征的最新研究进展,包括土壤微塑料的分布、丰度、来源和形貌等方面的特征,同时对土壤中微塑料的迁移规律进行了总结,最后对土壤微塑料的研究重点进行了

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展望,以期为土壤微塑料的污染风险管控与治理提供科学依据.

## 1 全球农田土壤中微塑料分布和丰度

全球农田土壤中微塑料的分布和丰度调查研究比较匮乏,加之微塑料检测和计数尚未有统一标准,导致全球各地农田土壤中微塑料丰度差异较大.从现有研究结果来看,全球内所调查农田土壤均有微塑料检出(表1).德国南部传统耕作方

式下的农田土壤受微塑料影响较小,其丰度范围为 $0 \sim 1.25$ 个 $\cdot\text{kg}^{-1}$ ,平均值仅为 $0.34$ 个 $\cdot\text{kg}^{-1}$ ;相比德国,加拿大、伊朗、瑞士农田土壤微塑料丰度较高,最高丰度值接近 $600$ 个 $\cdot\text{kg}^{-1}$ ;墨西哥菜田土壤微塑料丰度平均值达到 $870$ 个 $\cdot\text{kg}^{-1}$ ;西班牙和巴基斯坦农田土壤微塑料丰度范围接近;智利和韩国农田土壤微塑料丰度变异较大,丹麦农田土壤微塑料丰度异常高,最高丰度值达 $236\,000$ 个 $\cdot\text{kg}^{-1}$ .

表1 全球不同国家和地区农田土壤微塑料基本特征<sup>1)</sup>

Table 1 Characteristics of MPs in farmland soil in different countries and regions around the world

国家或地区	土地利用类型	取样深度/cm	粒径/mm	聚合物类型	外貌形态	丰度/个 $\cdot\text{kg}^{-1}$	文献
德国	农田	0~5	1~5	PE、PP和PS	碎片、纤维和薄膜	0~1.25	[17]
墨西哥	菜田	0~20	0~5	—	—	$870 \pm 1\,900$	[18]
智利	农田	0~25	0~2	PES和PVC	纤维和薄膜	600~10\,400	[19]
西班牙	农田	0~30	0.15~0.25	PP和PVC	碎片、纤维和薄膜、	2\,030~5\,190	[20]
韩国	农田	0~5	0.1~2	PE、PP、PS和PET	碎片、纤维、薄膜和颗粒	10~7\,630	[21]
丹麦	农田	0~10	0.02~0.5	PE、PP和PA	—	82\,000~236\,000	[22]
加拿大	农田	0~15	0.1~1	PE、PP和PET	纤维和碎片	18~298	[23]
瑞士	农田	0~5	0.5~1	PE、PS和PP	—	0~593	[24]
巴基斯坦	农田	0~10	0.5~5	—	碎片、纤维、薄膜、颗粒和泡沫	2\,200~6\,875	[25]
伊朗	农田	0~10	0.04~0.74	—	碎片和纤维	67~400	[26]
北京	菜田	0~20	0~5	PE和PP	碎片、纤维、薄膜、颗粒和泡沫	160~5\,220	[27]
山东	菜田	0~25	0~5	PE、PP、PS、PU、EPC和ABS	碎片、纤维、薄膜、颗粒和泡沫	310~5\,698	[28,29]
湖南	菜田	0~15	0~5	PE、PP、PS和PVC	碎片和纤维	826~1\,198	[30]
河南	菜田	0~15	0~5	PE、PP、PS和PVC	碎片和纤维	250~1\,220	[30]
安徽	菜田	0~15	0~5	PE、PP、PS和PVC	碎片和纤维	218~445	[30]
上海	菜田	0~6	0.02~5	PE和PP	碎片、纤维和薄膜	62.5~78.0	[31]
贵州	菜田	0~15	0~5	PE、PP、PS和PVC	碎片和纤维	44~50	[30]
重庆	菜田	0~40	0~5	PE和PVC	碎片、纤维和薄膜	$1.2 \sim 54.3 \text{ mg} \cdot \text{kg}^{-1}$	[32,33]
福建	菜田	0~15	0~5	PE、PP、PS和PVC	碎片和纤维	79~112	[30]
四川	菜田	0~15	0~5	PE、PP、PS和PVC	碎片和纤维	17.6~79.4	[30]
河北	菜田	0~15	0~5	PE、PP、PA和PES	碎片和纤维	1\,180~2\,730	[30]
河北	粮田	0~30	0~5	PE、PP、PA、PET和PES	碎片、纤维、薄膜和颗粒	173~2\,253	[34]
甘肃	粮田	0~30	0~5	—	碎片、纤维和薄膜	580~11\,900	[35]
江西	粮田	0~20	0~1	PE、PP和PES	碎片、纤维、薄膜和颗粒	16.4~43.8	[36]
黑龙江	粮田	0~30	0.1~5	PE	薄膜	0~800	[37]
广东	果园	0~15	0~5	PE、PP、PS和PVC	碎片和纤维	188~279	[30]
广西	果园	0~15	0~5	PE、PP、PS和PVC	碎片和纤维	3~53	[30]
新疆	棉田	0~40	0~5	PE	碎片和薄膜	$80.3 \sim 1\,076.5$	[33]
吉林	菜田/粮田	0~15	0~5	PE、PP、PS和PVC	碎片、纤维、薄膜和颗粒	$5\,215 \pm 839$	[38]
辽宁	菜田/粮田	0~30	0~5	PE、PP和PS	碎片、纤维、薄膜和颗粒	$217 \sim 2\,512 \text{ mg} \cdot \text{kg}^{-1}$	[39]
云南	菜田/粮田	0~10	0.05~1	PE	碎片、纤维、薄膜和细绳	7\,100~42\,960	[40]
西藏	菜田/粮田	0~6	0~2	PE、PP、PS和PA	碎片、纤维、薄膜、颗粒和泡沫	0~270	[41]
青海	菜田/粮田	0~10	0~5	PP和PVC	碎片、纤维、薄膜和颗粒	$93.8 \sim 4\,782$	[42,43]
江苏	菜田/茶园	0~20	1~5	PE和PP	纤维	420~1\,290	[44]
浙江	菜田/果园	0~10	0~5	PE和PP	碎片和纤维	0~2\,760	[45]
湖北	菜田/烟田	0~20	0~5	PA、PP和PS	碎片、纤维、薄膜、颗粒和泡沫	320~12\,560	[46,47]
内蒙古	粮油田	0~30	0~3	—	碎片、纤维、薄膜和颗粒	756~2\,197	[48]
陕西	农田	0~10	0~0.49	PE、PP、PS、PVC、PET和HDPE	碎片、纤维、薄膜和颗粒	1\,430~3\,410	[49]
山西	农田	0~20	0.02~5	PE、PP和PS	碎片、纤维和薄膜	20~1\,840	[50]
宁夏	农田	0~40	0~5	—	碎片和薄膜	$0 \sim 48.6 \text{ mg} \cdot \text{kg}^{-1}$	[33]
天津	农田	0~40	0~5	—	碎片和薄膜	$10.0 \sim 13.1 \text{ mg} \cdot \text{kg}^{-1}$	[33]

1) PE:聚乙烯,PP:聚丙烯,PS:聚苯乙烯,PVC:聚氯乙烯,PET:聚对苯二甲酸乙二醇酯,PA:聚酰胺,PES:聚酯纤维,PU:聚氨酯,PES:聚酯纤维,ABS:丙烯腈-丁二烯-苯乙烯共聚物,EPC:乙烯-丙烯共聚物,HDPE:高密度聚乙烯;“—”表示所引参考文献没有相关数据或描述

相比国外,我国农田土壤微塑料调查研究虽然起步较晚,仍取得了一定的进展.有研究发现,除中国香港、中国澳门和中国台湾未见相关报道外,我国大部分农田土壤均有微塑料检出(表1),从时空分布上看,各省市农田土壤微塑料丰度在空间上呈现较大差异,具体表现为:同一利用方式下不同地区和不同利用类型农田土壤微塑料丰度均呈现较大差异.就菜田而言,河北土壤微塑料丰度平均值最高,均值为 $2\ 110\ \text{个}\cdot\text{kg}^{-1}$ ,其次是北京、山东、河南和安徽,均值分别为 $1\ 246$ 、 $1\ 444$ 、 $632$ 和 $360\ \text{个}\cdot\text{kg}^{-1}$ ,上海、贵州、重庆、福建和四川土壤微塑料丰度平均值低于 $100\ \text{个}\cdot\text{kg}^{-1}$ .对于粮田来说,甘肃土壤微塑料丰度平均值高达 $5\ 090\ \text{个}\cdot\text{kg}^{-1}$ ,其次是黑龙江和江西.果园土壤微塑料丰度虽然较低,但依然呈现一定分布差异.由于多数研究未将农田进一步细分利用类型,吉林、辽宁、云南、西藏、江苏、浙江、湖北、内蒙古、陕西、山西和宁夏等地只列出农田土壤中微塑料的丰度,难以准确对比分析不同地区间特定土地利用类型下的土壤微塑料丰度差异.因此,下一步有必要从建立土壤微塑料数据库,以便有效监测农田土壤可能发生的微塑料污染.

## 2 农田土壤微塑料来源

农田土壤中微塑料的来源主要包括农用塑料薄膜及农田投入品塑料包装、有机肥、污泥、地表径流与农业灌溉、大气沉降和轮胎磨损颗粒等.

### 2.1 农用塑料薄膜及农田投入品塑料包装

塑料薄膜因其显著的经济效益被广泛用于农业生产,其主要成分为PVC和PE.我国是农膜消费大国.国家统计局数据显示,2018年全国农用薄膜使用量 $246.5\ \text{万}\ \text{t}$ ,地膜使用量 $140.4\ \text{万}\ \text{t}$ ,覆盖面积 $1.77\times 10^7\ \text{hm}^2$ (约2.66亿亩),在新疆、山东、内蒙古和甘肃等9省区覆盖面积均超过 $6.67\times 10^5\ \text{hm}^2$ (约1000万亩).Zhang等<sup>[51]</sup>研究发现,我国每年有18.6%的农膜留在农田土壤中,西北和黄土高原地区土壤塑料残膜量达 $71.9\sim 259.1\ \text{kg}\cdot\text{hm}^{-2}$ ,当残膜量超过 $240\ \text{kg}\cdot\text{hm}^{-2}$ 时,作物产量会显著下降<sup>[52]</sup>.土壤中残留的薄膜会在光照和微生物等外力作用下逐渐破碎分解成微塑料<sup>[53]</sup>,并且微塑料残留量会随着地膜使用年限增加而增加<sup>[33]</sup>.此外,中国作为农业大国,化肥和农药使用量大,塑料包装废弃物产生量大.据统计,2018年化肥包装废弃物每年达15万t,2019年农药废弃包装多达 $10^{10}$ 个<sup>[54]</sup>,大部分为塑料材质,多数残留在田间地头或附近水体,回收难度大,最终会分解成微塑料并通过灌溉等形式进入农

田.因此,需要加强残膜和农田投入品塑料包装的回收和监管.

### 2.2 有机肥的使用

有机肥是农业生产过程中重要的投入品,在菜田中使用较为广泛.我国在推进果菜茶有机肥替代化肥行动以来,有机肥应用更加广泛.然而,有机肥也是土壤微塑料的重要来源.德国学者调查发现有机肥中含粒径大于 $1\ \text{mm}$ 的塑料碎片丰度达到 $14\sim 895\ \text{个}\cdot\text{kg}^{-1}$ <sup>[55]</sup>,进一步发现粒径 $>0.5\ \text{mm}$ 的微塑料含量达到 $2.38\sim 180\ \text{mg}\cdot\text{kg}^{-1}$ <sup>[56]</sup>,更有学者发现有机肥中塑料高达 $1\ 200\ \text{mg}\cdot\text{kg}^{-1}$ <sup>[57]</sup>.尽管如此,上述有机肥中统计的数据仍未将 $0.5\ \text{mm}$ 以下的微塑料计算在内.澳大利亚和德国分别制定了相关标准,澳大利亚允许有机肥中存在0.5%的硬质塑料和0.05%的轻质塑料,德国则允许有机肥中含有0.1%的塑料(未考虑粒径小于 $2\ \text{mm}$ 的微塑料)<sup>[55]</sup>.我国是有机肥生产和使用大国,据估算,每年由有机肥施用带入的农田土壤微塑料量最高可达 $26\ 400\ \text{t}$ <sup>[1]</sup>.加强有机肥制作原料的监管是限制微塑料进入农田土壤的重要措施.

### 2.3 污泥的使用

污泥含有大量的有机质、大量和中微量元素,在国外通常被当作肥料施用到农田中<sup>[56]</sup>.北美和欧洲约有50%的城市污泥农用,芬兰等国的污泥农用比例高达80%<sup>[2]</sup>.然而,国内外大量研究表明,污泥中含有大量的微塑料,其含量范围为 $1\ 500\sim 56\ 000\ \text{个}\cdot\text{kg}^{-1}$ <sup>[58-60]</sup>.常规污泥预处理方法难以有效去除微塑料<sup>[59]</sup>,污泥进入土壤后比如导致土壤微塑料丰度增加.据估算,欧洲和北美每年进入农田土壤的微塑料分别达 $6.3\times 10^4\sim 4.3\times 10^5\ \text{t}$ 和 $4.3\times 10^4\sim 3.0\times 10^5\ \text{t}$ <sup>[2]</sup>.我国每年通过污泥进入环境中的微塑料约有 $1.56\times 10^{14}$ 个.限制含高丰度微塑料的污泥农用是防控农田土壤微塑料增加的另一重要举措.

### 2.4 地表径流和农业灌溉

地表径流、渗透和农业灌溉是微塑料进入农田土壤中的一个重要途径.Pion-Colin等<sup>[61]</sup>研究发现墨西哥Tijuana地区雨水径流中微塑料丰度为 $66\sim 191\ \text{个}\cdot\text{L}^{-1}$ ,据此估算得出雨水径流中微塑料的年排放量为 $8\times 10^5\sim 3\times 10^6\ \text{个}\cdot\text{hm}^{-2}$ ,该部分径流可直接或通过渗透进入农田土壤.全球范围内,农业灌溉水源包括地表水、地下水和净化污水.我国在长江和翻阳湖等大型地表水体均有微塑料的发现<sup>[62-64]</sup>,例如,重庆至宜昌江段长江水体中微塑料丰度为 $46.7\sim 204\ \text{个}\cdot\text{L}^{-1}$ ,鄱阳湖中表面水体微塑料丰度为 $5\sim 34\ \text{个}\cdot\text{L}^{-1}$ ,青藏高原地区河流表层水

同样发现微塑料的存在,丰度为  $0.48 \sim 0.97$  个 $\cdot$ L $^{-1}$ [65]. 美国的伊利诺伊州地下水中微塑料污染的最高丰度可达  $15.2$  个 $\cdot$ L $^{-1}$ [66]. 据统计,全球目前有  $2 \times 10^7$  hm $^2$  的农田使用污水(含未处理和部分处理)进行灌溉,而经污水处理厂处理后的污水也不能完全拦截去除微塑料,微塑料丰度仍可达到  $1$  个 $\cdot$ L $^{-1}$ . 所以,需要从源头上切断微塑料进入水体的途径.

### 2.5 大气沉降

大气沉降也是微塑料进入农田土壤的途径之一. Allen 等[67]研究发现微塑料通过大气传输的距离可高达  $95$  km,并且数量惊人. 巴黎地区大气环境中每天沉降的微塑料为  $29 \sim 280$  个 $\cdot$ m $^{-2}$ ,每年沉降的微塑料可达到  $3 \sim 10$  t,其中纤维状占比达  $90\%$ . 我国烟台大气中微塑料的年沉降量高达  $1.46 \times 10^5$  个 $\cdot$ m $^{-2}$ [68],东莞和上海等城市也发现大气中存在纤维状的微塑料[69]. 然而,目前有关微塑料在大气和土壤之间传输的相关性研究相对较少,未来需加强探索.

### 2.6 轮胎磨损颗粒

随着经济社会的发展和农业机械的普及,人均汽车和各类农业机械保有量持续增加,轮胎磨损颗粒在土壤中也逐渐被发现[70~72]. 有研究表明,轮胎颗粒可从道路扩散至  $100$  m 远的土壤[73],约有  $74\%$  的轮胎磨损颗粒直接沉淀进入路边  $5$  m 以内的土壤[74]. 据估算,全球道路车辆轮胎磨损产生的微塑料量人均达  $0.81$  kg $\cdot$ a $^{-1}$ [75],欧盟和美国每年产生的轮胎磨损颗粒分别约为  $1.33 \times 10^6$  t 和  $1.12 \times 10^6$  t[76]. Kole 等[77]估算了 2021 年全球的轮胎磨损颗粒年释放量为  $7.22 \times 10^9$  t,如此数量惊人的轮胎磨损颗粒在土壤中的迁移、转化和危害等方面却鲜有报道,未来亟待加强该方面的研究和探索.

## 3 农田土壤微塑料行为特征

### 3.1 不同利用方式下的农田土壤微塑料含量特征

农田利用类型对土壤微塑料丰度有显著影响. 从不同农田土地利用方式看,覆膜菜田最高(图 1),为  $(707 \pm 721)$  个 $\cdot$ kg $^{-1}$ ,棉田、未覆膜粮田和果园土壤微塑料分别为  $(488 \pm 521)$ 、 $(167 \pm 174)$  和  $(131 \pm 140)$  个 $\cdot$ kg $^{-1}$ . 在青藏高原地区也呈现类似趋势,不同类型土壤的微塑料丰度从高到低分别为:地膜覆盖土壤 > 大棚土壤 > 裸露土壤[78]. 即使在同一土地利用类型下,种植方式也影响土壤中微塑料丰度. 例如,废弃设施大棚土壤中微塑料丰度为  $(2216 \pm 1550)$  个 $\cdot$ kg $^{-1}$ ,高于常规设施大棚  $(891 \pm 317)$  个 $\cdot$ kg $^{-1}$ 和简易拱棚  $(632 \pm 567)$  个 $\cdot$ kg $^{-1}$ [22],大棚内

部土壤微塑料丰度高于外部[21]. 此外,值得注意的是,无论种植樟子松还是杨树,土壤中微塑料丰度均随着种植年限的增加显著下降[79],这给土壤微塑料污染治理提供了有益的启示,可以通过改变农田利用方式防治土壤微塑料污染.

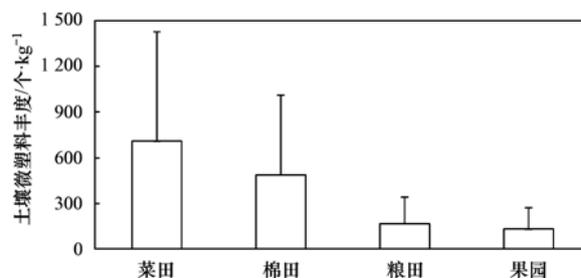


图 1 不同利用方式下农田土壤中微塑料丰度

Fig. 1 Abundance of MPs in farmland soils under different utilization types

### 3.2 形状特征

微塑料主要存在形态有碎片、纤维、薄膜、颗粒和泡沫(表 1),在我国 30 省市检出比例分别为  $93.3\%$ 、 $86.7\%$ 、 $60.0\%$ 、 $33.3\%$  和  $13.3\%$ . 寿光菜田土壤中的碎片、薄膜、纤维、颗粒和泡沫形态微塑料分别占比  $46.3\%$ 、 $25.4\%$ 、 $15.1\%$ 、 $12.8\%$  和  $0.4\%$ [28];北京城郊废弃大棚、普通温室大棚和拱棚土壤中微塑料以碎片形态为主,分别占比  $74.3\%$ 、 $47.1\%$  和  $68.2\%$ [27]. 陕西农田土壤中微塑料以纤维、碎片和薄膜为主,平均占比达  $43.8\%$ 、 $27.4\%$  和  $20.2\%$ ,颗粒形态微塑料仅占  $8.1\%$ [49,79]. 在青藏高原地区,设施菜田土壤、覆膜土壤和未覆膜土壤中薄膜形态微塑料占比最高,分别占比  $33\%$ 、 $36\%$  和  $29\%$ ,其次是纤维和碎片形态微塑料,泡沫和颗粒形态微塑料形态占比最低[41]. Van Den Berg 等[20]研究发现西班牙农田土壤微塑料以碎片形态为主,占比超过  $80\%$ ,且使用污泥后土壤微塑料会显著下降. 德国农田土壤微塑料薄膜和碎片均占比  $43.75\%$ 、纤维占比  $12.50\%$ [17]. 巴基斯坦农田土壤微塑料以纤维为主,占比达  $64\%$ ,其次是薄膜 ( $28\%$ )、碎片 ( $7\%$ )、泡沫 ( $0.75\%$ ) 和颗粒 ( $0.25\%$ )[25]. 农田土壤中微塑料形态差异较大的原因可能与其来源不同有关,可进一步加强微塑料来源与农田土壤中微塑料形态相关性的研究.

### 3.3 聚合物组成特征

农田土壤中微塑料聚合物形态主要包括 PE、PP、PS 和 PVC 等(表 1),在 30 省市检出比例分别为  $80.0\%$ 、 $73.3\%$ 、 $50.0\%$  和  $40.0\%$ . Ren 等[32]对我国 19 省市农田土壤微塑料聚合物形态进行分析发现,微塑料以 PE 和 PVC 为主,两者占比超过  $95\%$ . 北京城郊设施菜田土壤微塑料中聚合物以 PP

和 PE 为主,分别占比 37.1% 和 15.0%<sup>[27]</sup>; 寿光设施菜田土壤微塑料聚合物略有不同, PE 占比 39.7%, PP 和 EPC 两者占比 45.0%<sup>[28]</sup>. 陕西农田土壤微塑料中 PP、PE、PS、PVC 和 PET 分别占比 53.1%、24.8%、15.9%、5.5% 和 0.67%<sup>[79]</sup>; 青藏高原地区农田土壤微塑料聚合物以 PP 和 PE 为主, 分别占比 50.5% 和 22.0%, PET 和 PS 均占比 8%<sup>[78]</sup>. 瑞士农田土壤微塑料聚合物以 PE 为主, 占比高达 88%<sup>[24]</sup>; Kim 等<sup>[21]</sup> 研究了韩国温室大棚内外土壤、稻田和覆膜农田的微塑料聚合物形态, 其中, 温室大棚内土壤微塑料聚合物形态为 PE (68%)、PET (15%) 和 PP (11%), 棚外 3 种聚合物形态为 PP (40%)、PE (27%) 和 PET (20%), 稻田土壤微塑料聚合物形态为 PE (61%)、PP (18%) 和 PET (9%), 覆膜农田土壤微塑料聚合物形态为 PP (31%)、PE (21%)、PET (10%); 除此以外, 不同形态微塑料中聚合物类型有显著差异, 如陕西农田土壤碎片和薄膜形态微塑料中 PE 和 HDPE 占比 79.1% 和 21.9%, 纤维形态微塑料中 PP、PET 和 PE 分别占比 65.2%、20.9% 和 13.9%, 颗粒形态微塑料中 PS 占比 100%<sup>[49]</sup>. 韩国不同类型农田土壤微塑料形态中聚合物也呈现显著差异<sup>[21]</sup>. 造成农田土壤中微塑料组成差异大的原因可能也与其来源有关.

### 3.4 尺寸特征

农田土壤中微塑料丰度随颗粒变小而增加. 北京城郊菜田土壤中 0~1 mm 和 1~2 mm 微塑料平均占比为 43.0% 和 35.1%, 2~5 mm 微塑料累计占比 21.9%<sup>[27]</sup>. 寿光菜田土壤在 0~0.5 mm 占比达到 65.2%, 0.5~1.0 mm 占比 19.2%, 1.0~2.0 mm 和 2.0~5.0 mm 分别占比 9.7% 和 5.9%<sup>[28]</sup>. 陕西农田土壤微塑料 0~0.5 mm 占比达到 79.7%~84.2%, 0.5~1 mm 微塑料占比 8.16%~11.6%, 2~5 mm 微塑料累计占比仅为 3.42%~8.70%<sup>[49,79]</sup>. 青海省农田土壤 0~0.5、0.5~1 和 1~2 mm 微塑料分别占比 50%、33% 和 17%<sup>[42]</sup>. 青藏高原区温室土壤、覆膜土壤和粮田土壤中 0~0.5 mm 微塑料分别占比 71%、62% 和 61%, 0.5~1 mm 微塑料分别占比 17%、27% 和 24%<sup>[41]</sup>. 西班牙学者 Berg 等<sup>[20]</sup> 研究发现与未使用污泥相比, 污泥农用能增加 0~0.5 mm 低密度微塑料的比例, 提高约 5.4%, 但会降低高密度微塑料的比例, 降低比例达 13.3%.

### 3.5 迁移特征

微塑料进入土壤后, 会在耕作、淋溶、生物扰动和重力作用下发生迁移. 农业频繁耕作会导致微

塑料在土壤表层向深层迁移<sup>[80]</sup>. 通常耕作条件下, 土壤微塑料丰度随着深度的增加而降低<sup>[28,41]</sup>; 然而, 也存在深层土壤微塑料丰度高于表层土壤的现象. 以设施农田为例, 废弃设施大棚和常规设施大棚 0~10 cm 土壤中微塑料丰度分别为  $(827 \pm 261)$  个 $\cdot$ kg<sup>-1</sup> 和  $(560 \pm 52.9)$  个 $\cdot$ kg<sup>-1</sup>, 10~20 cm 土壤微塑料丰度为  $(1073 \pm 306)$  个 $\cdot$ kg<sup>-1</sup> 和  $(720 \pm 111)$  个 $\cdot$ kg<sup>-1</sup><sup>[27]</sup>; 不同覆膜年限棉田土壤中微塑料丰度随着土壤深度(0~5、5~20 和 20~40 cm) 的增加均呈现先增加后下降的趋势<sup>[33]</sup>; 此外, 还发现土壤微塑料丰度随着深度(0~5、5~10 和 10~25 cm) 的增加无显著变化<sup>[28]</sup> 和微塑料随着深度(0~5、5~10 和 10~15 cm) 的增加而增加<sup>[23]</sup> 的现象, 这可能是不同耕作方式所致, 翻耕更有利于微塑料向深层土壤迁移, 而浅耕、旋耕或耙地可导致微塑料颗粒分布在整个耕作层中<sup>[80]</sup>.

微塑料在雨水淋溶和重力作用下可通过土壤孔隙发生自然的纵向迁移<sup>[17,81]</sup>, 并且干湿交替可加速微塑料向下运移<sup>[82]</sup>. 有研究发现, 直径为 0.53  $\mu$ m 和 3.7  $\mu$ m 的微塑料颗粒可通过淋溶移动至 70 cm 以上的深层土壤, 粒径范围为 0.1~6 mm 的微塑料颗粒同样可通过淋溶作用发生垂直移动<sup>[83]</sup>. O'Connor 等<sup>[82]</sup> 利用我国 347 个城市的气象信息进一步估算了 100 a 后土壤中微塑料的迁移深度, 平均渗透深度达 5.24 m, Nizzetto 等<sup>[84]</sup> 采用 INCA-污染物理论模型发现残留在土壤中的微塑料比例为 16%~38%, 其余大部分微塑料最终会从土壤中迁移进入水体, 成为水环境中微塑料污染的来源, 从而提高水体中微塑料生态风险<sup>[85]</sup>. 因此, 微塑料在土壤和水体之间的迁移仍是未来研究的重点.

生物(动物、植物和微生物)扰动可驱动土壤中微塑料发生迁移. 微塑料在蚯蚓体表的外部附着和被蚯蚓摄入和排泄可以驱动微塑料发生迁移, 14 d 内其迁移距离可达约 18 cm<sup>[86]</sup>. 螨虫及跳虫等土壤动物的活动也有利于微塑料在土壤中的迁移, 并且当跳虫的捕食-被捕食关系存在时, 微塑料在土壤的迁移能力显著增加, 而相比跳虫, 甲螨对微塑料迁移的促进效果更强<sup>[87]</sup>. 植物则主要通过根系运动、根系扩张和根系吸水等影响土壤中微塑料的运移, 当根系分解时, 可产生近似于根系的大孔隙, 有利于土壤中微塑料的迁移. 除动物和植物外, 微生物也影响微塑料在土壤中的迁移, 铜绿假单胞菌、乳酸菌等细菌可附着在微塑料表面降低其迁移能力<sup>[88]</sup>, 但另一方面细菌的生长基质又能掩蔽微塑料的沉积位点, 提高其迁移能力<sup>[89]</sup>. 而微塑料的迁移会进一步影响土壤中微生物的生物量<sup>[90]</sup>.

## 4 展望

(1) 土壤中微塑料的分离、提取和检测方法的标准化研究 土壤中微塑料在分离提取和检测手段上缺乏统一标准,难以科学客观地比较不同地区土壤中的微塑料含量水平,应针对不同性质土壤开展不同类型微塑料的分离提取与检测的方法学研究,并建立标准化技术规范。

(2) 农田土壤中微塑料数据库的建立和安全阈值研究 基于土壤污染难治理性的特点,农田土壤中的微塑料难以在短期内完全去除,应建立土壤微塑料数据库,研究影响农业生产和保障生态安全和人体健康的微塑料安全阈值,以便有效监测和控制农田土壤微塑料污染。

(3) 农田土壤中微塑料的溯源、迁移和转化规律研究 明确农田土壤中微塑料的来源和贡献,揭示微塑料在土壤中的迁移和转化规律,建立微塑料在土壤中的迁移转化模型,预测微塑料在土壤的污染行为特征,为防控微塑料污染和技术研发提供依据。

(4) 土壤中微塑料的潜在生态风险和潜在人体健康风险研究 研究不同种类微塑料对土壤理化性质、微生物、植物和动物的影响,明确微塑料在土壤中的潜在生态风险;研究微塑料在食物链中的富集和传递效应,明确其潜在的人体健康风险。

(5) 土壤微塑料污染修复技术研究 研发土壤微塑料污染源控制技术和降解修复技术,构建农田土壤微塑料污染风险管控和治理的技术体系。

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