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不同环境塑料际病原菌的赋存与传播研究进展

丁贺宁,惠 彩*,龙於洋,沈东升 (浙江工商大学环境科学与工程学院,浙江省固体废物处理与资源化重点实验室,有色金属废弃物资源化浙江省工程研究中心,浙江 杭州 310012)

摘要：塑料际是致病菌和抗生素耐药基因等有害微生物和基因的移动储存库,但目前对塑料际病原菌赋存和传播风险的了解和认识不足,对其在不同环境介质中的分布和传播特性尚不明晰.本文系统介绍了塑料际的定义和组成,总结了水环境、土壤环境、人为环境和大气环境中微塑料及塑料际病原菌的赋存状况,发现弧菌属、假单胞菌属和不动杆菌属等是塑料际常见的病原菌;概述了塑料际病原菌的传播途径和可能的健康风险,指出了携带病原菌的微塑料可在水体、土壤和大气环境中传播,促进病原菌与抗生素耐药性的传播和蔓延,最后对未来的研究提出了展望.本文可为全面评估微塑料污染风险提供科学依据.

关键词：微塑料；塑料际；病原菌；传播风险
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Research progress on the occurrence and dissemination of plastisphere pathogens in different environment. DING He-ning, HUI Cai*, LONG Yu-yang, SHEN Dong-sheng (Zhejiang Engineering Research Center of Non-ferrous Metal Waste Recycling, Zhejiang Provincial Key Laboratory of Solid Waste Treatment and Recycling, School of Environmental Science and Engineering, Zhejiang Gongshang University, Hangzhou 310012, China). *China Environmental Science*, 2025,45(7)：3978~3993

Abstract：The plastisphere is a mobile reservoir of harmful microorganisms and genes such as pathogenic bacteria and antibiotic resistance genes, but the current understanding of the occurrence and dissemination risks of pathogenic bacteria in the plastisphere is still insufficient. The distribution and transmission characteristics of plastisphere pathogens in different environmental media are not yet clear. This article systematically introduces the definition and composition of the plastisphere, summarizes the occurrence status of microplastics and pathogenic bacteria in the plastisphere in water environment, soil environment, anthropogenic environment, and atmospheric environment. Results showed that *Vibrio*, *Pseudomonas*, and *Acinetobacter* are common pathogenic bacteria in the plastisphere. The transmission routes and potential health risks of pathogenic bacteria in plastics were summarized. It was found that microplastics carrying pathogenic bacteria could spread among water body, soil, and atmospheric environments, promoting the spread and proliferation of pathogenic bacteria and antibiotic resistance. Finally, prospects for future research are proposed. This article could provide a basis for a comprehensive assessment of the risk of microplastics pollution.

Key words：microplastics；plastisphere；pathogen；dissemination risk

塑料制品在多种自然和人为作用下破碎成微塑料(MPs,直径≤5mm)[1]进而引发微塑料污染. 微塑料因其结构稳定、疏水性强、密度低和易被吸附等特点,不仅可通过食物链和食物网传播,也可通过大气和洋流进行长距离迁移,最后广泛分布于岩石圈、水圈、大气圈和生物圈.垃圾填埋和大气沉降是微塑料进入陆地生态系统的主要途径[2];河流中的微塑料主要来自污水处理厂、城市污水和工业废水、大气沉降和农业排水[3],而海洋中的微塑料则主要来源于陆地[4]及河流微塑料的汇入[5].作为一种重要的新污染物,微塑料不仅本身具有毒性,还可能携带其他污染物并将其传播到不同环境系统中.已发现微塑料可影响海洋生物的摄入率和摄食能力[6],也可携带污染物进入生物体内造成复合毒性[7],还可阻碍和抑制植物根和叶的生长[8].

微塑料可为微生物附着和生物膜形成提供稳定基质,因此,自然环境中的微塑料会吸引多种微生物定殖,形成独特的生态位,称为塑料际[9].塑料际中的微生物群落与周围环境显著不同[10],意味着塑料际中的微生物生态功能可能与周围环境存在差异.此外,塑料际微生物中抗生素抗性基因(ARGs)和相

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* 责任作者, 副研究员, huicai@zjgsu.edu.cn

关移动遗传元件(MGEs)的丰度高于周围环境和天然基质生物膜中的丰度[11].塑料际微生物群落中的质粒转移更为频繁[12],已成为 ARGs 水平基因转移的热点区域[13].此外,微塑料也会富集多种人类致病菌,成为病原菌传播的潜在载体,而病原菌中毒力因子(Virulence factor)基因的水平转移更增加了塑料际的致病性风险,从而对人类健康构成更大威胁.

微塑料引起的健康风险已被大量报道,但不同环境中塑料际病原菌的富集与传播特性尚不明晰.本文综述了不同环境中微塑料的分布及塑料际病原菌的研究现状,介绍了塑料际病原菌的赋存特征及其传播风险,并对今后的研究提出了展望.

1　塑料际的定义与组成

塑料际的定义最早由 Zettler 等[14]提出,即微塑料表面作为一种外源性的疏水基质,可以为多种微生物的生长和增殖提供生态位,形成一个独特的生态栖息地,称为塑料际.

塑料际是由微生物(细菌、古菌、真菌、藻类、原生动物等)、胞外聚合物(EPS)和无机、有机沉淀物等形成的复杂微型生态系统.EPS 主要由蛋白质、多糖及少量的核酸和脂类组成,含有羟基、羧基、O−C−O、C=O、胺基和磷酸基等多种功能基团[15].由于 EPS 的吸附作用,塑料际还可富集多种重金属和有机污染物.塑料际的微生物群落是近几年研究的重要领域,其中细菌群落是目前研究关注的重点.大量研究报道,淡水、海水和土壤环境中塑料际的细菌群落组成差异显著:淡水塑料际富集的典型种群为变形菌纲(Alpha−proteobacteria、Beta−proteobacteria 和 Gamma−proteobacteria)[16],海水塑料际的细菌群落主要由变形菌门(Proteobacteria)和拟杆菌门(Bacteroidetes)组成[17],而在陆地塑料际定殖的细菌主要为变形菌门(Proteobacteria)和放线菌门(Actinobacteria)[18].此外,塑料际微生物群落组成与周围环境也存在显著差异.Li 等[19]研究来自不同季节和地理位置的微塑料,发现塑料际样本和环境样本趋向于形成两个独立的微生物集群,表明塑料际和自然环境微生物菌群之间可能存在本质差异.

2　不同环境中塑料际病原菌的富集特性

对塑料际病原菌开展研究的前提是要获取塑料际样品,目前,塑料际样品主要通过实地采样、原位培养和实验室模拟 3 种途径来收集.在实地采样过程中,需在采样后立即通过肉眼或显微镜对微塑料进行筛分以防止生物膜发生变化,这不可避免的会受到非微塑料颗粒的影响[20],然后分离生物膜进行培养实验,或储存于−80 ℃下用于后续分子研究[21-22].对于原位培养研究,通常选择特定聚合物类型、形状和大小的微塑料,置于自然条件下培养一段时间,收集微塑料,并分析其表面微生物群落[23-24],但该方法无法精确量化环境条件对塑料际特性的影响[25].与原位培养实验相比,实验室模拟方法可研究受控条件下[26]环境变量对塑料际特性的影响,但无法完全模拟真实环境[27].本文列出的数据多基于实地采样和原位培养方法获得.

2.1　水环境

2.1.1　淡水环境　淡水环境包括湖泊、湿地、冰川、冰山、溪流、池塘、沼泽地、冰盖和地下水等水体.这些淡水环境中存在的微塑料通常属于合成纤维(聚酯和聚酰胺)等大塑料分解产生的次生微塑料.由于废物管理不当,微塑料可通过农田径流[28]、家庭污水排放[29]和工业废水排放[30]等多种途径进入淡水生态系统.微塑料在淡水中的丰度及分布受到水文特征及人类活动的影响,并呈现季节性变化趋势.淡水环境中微塑料形态各异、颜色多样,且多为小粒径微塑料(50μm~0.5mm),使得微塑料更容易被生物摄取进入食物网,进而对生物体及人类健康造成潜在威胁.大量研究证实,水环境微塑料表面会富集致病菌及耐药菌,促进疾病的传播及“超级细菌”的出现[31-32],增大了微塑料对生态环境和人类健康的威胁.

Xu 等[33]对太湖湖水和水中微塑料进行采样,通过宏基因测序分析发现,塑料际存在大量的拟杆菌(Bacteroidetes)和变形菌门(Proteobacteria),111 种病原菌在微塑料和水样中检出且微塑料上病原菌总丰度更高(P<0.05).微塑料样品中丰度前 5 位的病原菌为铜绿假单胞菌(*Pseudomonas aeruginosa*)、肠沙门氏菌(*Salmonella enterica*)、米黄原单胞菌(*Xantho-monas oryzae*)、丁香假单胞菌(*Pseudomonas syringae*)和新绿伯克氏菌(*Burkholderia cenocepacia*).此外,塑料际中家鼠、单子鼠和啮齿动物相关致病菌的富集程度也显著高于水样.上述研究表明,湖水塑料际对生物安全乃至人类健康已构

成了潜在威胁.表 1 列出了全球范围内现有淡水塑料际检出病原菌的相对丰度,总结来看,国内淡水塑料际中检出的主要病原菌为假单胞菌属(*Pseudomonas*),其相对丰度在乌鲁木齐河最高,为43.06%,其次是海河(34.37%).在国外,美国芝加哥溪流(14.6%)、伊利诺斯州北岸海峡(14%)、弗吉尼亚伊丽莎白河(10%)和德国斯特克林湖(4.81%)塑料际中假单胞菌相对丰度较高,此外也检出大量的弧菌属(*Vibrio* spp.)、气单胞菌属(*Aeromonas*,1.15%~4.09%)、水细菌(*Aquabacterium*,0.73%~0.99%)和不动杆菌属(*Acinetobacter*,0.01%~12.09%).不同地区淡水塑料际病原菌的种类和丰度受到当地自然环境的影响.例如,弧菌属通常易于在温暖的咸淡水环境中生长繁殖[34],美国弗吉尼亚伊丽莎白河和中国长江口地区受沿岸海水入侵影响,适宜的水温和盐度条件更有利于弧菌属的生存[35].此外,中国乌鲁木齐河假单胞菌属丰度较高,可能是由于较大的塑料垃圾(>5mm)吸附了大量的病原菌[36].

表 1 国内外淡水塑料际病原菌相对丰度

Table 1 Relative abundance of pathogens in freshwater plastisphere at home and abroad

地点	微塑料特点	采样方法	检测技术	病原菌科/属/种	相对丰度(%)	参考文献
美国弗吉尼亚伊丽莎白河	PE,PP,PS 碎片、纤维、泡沫、薄膜(0.14~8.62mm)	1.实地采样:通过浮游生物网收集样品,筛选疑似微塑料 2.原位培养:将不同类型的塑料和玻璃样品悬挂在码头处的河水中并定期采样	1.定量 PCR 鉴定弧菌属 2.提取 DNA 进行 16S rRNA 高通量测序	假单胞菌属(*Pseudomonas*) 弧菌属(*Vibrio* spp) 霍乱弧菌,副溶血性弧菌(*Vibrio cholerae,Vibrio parahaemolyticus*) 嗜盐弧菌(*Vibrio vulnificus*)	10 30 	[35]
美国伊利诺斯州北岸海峡	聚苯乙烯泡沫、塑料颗粒、纤维、碎片(<2mm)	实地采样:将网孔为 333 μm 的网固定在船后采集微塑料,采集 20min 后用现场水冲洗收集物到容器中	提取 DNA 进行 16S rRNA 高通量测序	假单胞菌属(*Pseudomonas*) 气单胞菌属(*Aeromonas*) 弓形虫(*Arcobacter*) 丛毛单胞菌(*Comamonadaceae*) 水细菌(*Aquabacterium*) 希瓦氏菌属(*Shewanella*) 衣原体目(*Chlamydiales*) 伯克霍尔德氏菌目(*Burkholderiales*) 分支杆菌属(*Mycobacterium*)	14 4.09 4.64 1.80 0.99 0.56 0.43 0.36 0.24	[37]
美国芝加哥溪流	PP,PE,PS 碎片、颗粒、纤维(<5mm)	实地采样:选取区域内 10 条河流,使用网目为 333 μm 的浮游生物网采集河水中的微塑料	提取 DNA 进行 16S rRNA 高通量测序	假单胞菌属(*Pseudomonas*) 弓形虫(*Arcobacter*) 弯曲杆菌(*Campylobacteraceae*) 不动杆菌属(*Acinetobacter*) 水细菌(*Aquabacterium*)	1.2~14.6 0.2~3.5 1.70 0.3~4.3 18.30	[38]
德国斯特克林湖	PS 薄膜(4mm)	1.实验室模拟:在 250mL 烧瓶中装入 100mL 湖水,添加微塑料构建微宇宙实验 2.原位培养:将微塑料颗粒放入不锈钢圆柱笼中置于斯特克林湖中培养 4 周	提取 DNA 进行 16S rRNA 高通量测序	假单胞菌属(*Pseudomonas*) 鞘氨醇单胞菌(*Sphingomonas*) 水细菌(*Aquabacterium*) 不动杆菌属(*Acinetobacter*) 气单胞菌属(*Aeromonas*) 考克斯氏体属(*Coxiella*) 埃舍里奇-志贺氏菌(*Escherichia-Shigella*) 盐单胞菌属(*Halomonas*) 寡养单胞菌(*Stenotrophomonas*) 链球菌属(*Streptococcus*) 枝原体属(*Mycoplasma*)	4.81 1.03 0.73 0.28 1.51 0.06 1.09 0.06 2.66 0.08 0.73	[12]
中国乌鲁木齐河	大型塑料垃圾(> 5mm)	实地采样:沿乌鲁木齐河设置 7 个采样点,在各采样点收集塑料碎片	提取 DNA 进行 16S rRNA 高通量测序	假单胞菌属(*Pseudomonas*) 不动杆菌属(*Acinetobacter*)	0.09~43.06 0.01~12.09	[36]

续表 1

地点	微塑料特点	采样方法	检测技术	病原菌科/属/种	相对丰度(%)	参考文献
中国长江口	PE, PP, PS (<5mm)	实地采样:在中国长江口的象山湾、崇明岛和吕四港 3 个站点采集微塑料样品,在退潮时用无菌镊子收集搁浅在潮间带表面的微塑料	提取 DNA 进行 16S rRNA 高通量测序	假单胞菌属(*Pseudomonas*) 弧菌属(*Vibrio*) 瘦鞘丝藻属(*Leptolyngbya*)	<0.01 0.40 1.60	[39]
中国海河河口	PE、PP、PS、PET、PUR 聚丙烯共聚物 泡沫、薄膜、纤维、碎片 (2~10mm)	实地采样:在中国渤海湾海河河口水线区域 1m^2 的表层沉积物中,用无菌镊子采集塑料样品	提取 DNA 进行 16S rRNA 高通量测序	假单胞菌科(*Pseudomonadaceae*) 莫拉氏菌科(*Moraxellaceae*) 芽胞杆菌科(*Bacillaceae*) 盐单胞菌科(*Halomonadaceae*)	8.03×10^{-3} 2.38×10^{-2} 1.97×10^{-2} 1.35×10^{-2}	[40]
中国海河	PVC 颗粒 (3mm)	实验室模拟:选取聚氯乙烯微塑料颗粒、岩石、树叶 3 种基质,经预处理后包裹消毒纱布放入 5L 的生物反应器中,设置 5 个重复,加入河水培养 2 周	1.流式细胞仪测定生物膜生物量 3.提取 DNA 进行 16S rRNA 高通量测序	假单胞菌属(*Pseudomonas*) 维多细菌属(*Pluralibacter*) 勒克菌属(*Leclercia*) 泛菌属(*Pantoea*)	34.73 21.70 7.53 0.23	[42]

注:PE为聚乙烯,PP为聚丙烯,PS为聚苯乙烯,PET为聚对苯二甲酸乙二醇酯,PUR为聚氨酯,PVC为聚氯乙烯.病原菌相对丰度代表不同种类病原菌在细菌总数中的占比.

表 2　国内外海水塑料际病原菌相对丰度

Table 2　Relative abundance of pathogens in marine plastisphere at home and abroad

地点	微塑料特点	采样方法	检测技术	病原菌科/属/种	相对丰度(%)	参考文献
北波罗的海	PE、PP、PS (0.5~5mm)	实地采样:在北波罗的海 62 个采样站用携带特定捞网的船只采集漂浮的塑料颗粒	定量 PCR	弧菌属 (*Vibrio* spp.) 副溶血性弧菌 (*Vibrio parahaemolyticus*) 嗜盐弧菌 (*Vibrio vulnificus*)	54 59 27	[47]
法国布雷斯特湾	PE(2~5mm)、PP(1~2mm)、PS (0.3~1mm)碎片	实地采样:在法国布雷斯特湾的 2 个站点(人类活动频繁和位于海湾中心)采集样品	提取 DNA 进行 16S rRNA 高通量测序	弧菌科 (*Vibrionaceae*) 黄杆菌科 (*Flavobacteriaceae*) 河口弧菌 (*Vibrio aestuarianus*) 脾弧菌 (*Vibrio splendidus*)	9.9 16.06	[48]
挪威韦斯特兰县海滩	PE、PP、PE~VA (1~15cm)	实地采样:从挪威韦斯特兰郡海滩潮间带收集大塑料样品	提取 DNA 进行 16S rRNA 高通量测序	假单胞菌 (*Pseudomonas*) 气单胞菌属 (*Aeromonas*) 摩根菌 (*Morganella morganii*) 贝氏不动杆菌 (*Acinetobacter beijerinckii*)	16.20	[49]
北欧波罗的海	未分类的微塑料 (>300μm) HDPE、PS 颗粒 (3mm)	原位培养:在德国瓦尔诺河以及波罗的海沿海站点,将微塑料进行原位培养 实地采样:用特定尺寸的拖网在波罗的海采集微塑料	提取 DNA 进行 16S rRNA 高通量测序	弧菌属(*Vibrio* spp.)	0.5~3	[50]

续表 2

地点	微塑料特点	采样方法	检测技术	病原菌科/属/种	相对丰度(%)	参考文献
新加坡海岸线	碎片、纤维、泡沫薄膜颗(1~5mm)	实地采样:在新加坡海滩采集微塑料样品,先采集一定体积的沙,经海水筛滤收集微塑料,然后通过肉眼将微塑料按形状分类	提取 DNA 进行 16S rRNA 高通量测序	假单胞菌(*Pseudomonas*) 弧菌属(*Vibrio* spp.) 弓形虫(*Arcobacter*) 鞘形成层(*Sphingobium*) 产气荚膜杆(*Clostridium*)	5 <0.2 6 4 1	[51]
中国烟台市水产养殖场	PET 纤维	实地采样:在烟台市某海水养殖场中进行塑料采样	提取 DNA 进行 16S rRNA 高通量测序	弧菌属(*Vibrio*) 弓形虫(*Arcobacter*) 嗜盐单胞菌(*Halomonas*) 溶藻弧菌(*Vibrio alginolyticus*)	14.7 1.41 0.26	[52]
长江口	PVC、PS、PP、PET、PE	实地采样:在长江河口选取 8 个采样点采集微塑料样品	提取 DNA 进行 16S rRNA 高通量测序	假单胞菌属(*Pseudomonas*) 杆菌属(*Bacillus*) 分支杆菌属(*Mycobacterium*)		[53]
中国福建省水产养殖场	PET 纤维(0.2~2mm)	实地采样:在中国福建沿海循环水养殖系统中用特定网目尺寸的网从一定量水中采集微塑料	提取 DNA 进行 16S rRNA 高通量测序	弧菌属(*Vibrio*) 杆茵属(*Bacillus*) 弓形虫(*Arcobacter*) 考克斯氏体属(*Coxiella*) 黏着杆菌(*Tenacibaculum*)	<0.10 <0.10 <0.01 <0.10 <0.10	[54]

注:PE~VA为聚乙烯—醋酸乙烯酯,HDPE为高密度聚乙烯.病原菌相对丰度代表不同种类病原菌在细菌总数中的占比.

2.1.2 海洋环境 微塑料可通过生活污水、工业废水及地表径流等途径进入海洋环境[42],其中河流水系是微塑料向海洋传输的主要途径之一.不同密度的微塑料在海洋环境中分布模式存在差异,其中低密度聚合物(如 PE,密度为 0.89~0.98g/cm^3)在表层海水中占主导地位,而密度较高的聚合物(聚酯和丙烯酸,密度为 1.1~1.4g/cm^3)在深海区域占主导地位[43].

Silva 等[44]通过对瓜纳巴拉湾塑料废物及其周边水体中的微生物进行测定,发现海洋塑料碎片上的微生物群落与周围海水明显不同,且塑料表面生物膜中存在大量病原菌.实验从海水和塑料样品中共分离出 120 株细菌,通过生化实验测定,59 株被鉴定为大肠杆菌,61 株鉴定为弧菌.表 2 列出了国内外部分海域塑料际病原菌的分布情况.弧菌属、假单胞菌属、不动杆菌属、弧杆菌属、芽孢杆菌属、水杆菌属、气单胞菌属、大肠杆菌属、克雷伯氏菌属和军团菌属等 10 种常见潜在致病菌被检出.弧菌属在塑料际的检出丰度较高,其次是假单胞菌,其在北波罗的海丰度最高,为 54%,其次是中国烟台沿海水产养殖场(14.7%)和法国布雷斯特湾(9.88%).此外,16.2%的假单胞菌在挪威韦斯特兰县海滩被检测到.有研究报道,与淡水塑料际相比,海洋塑料际中的肠杆菌科丰度较低[45],可能是由于海洋环境中盐度和紫外线辐射度较高导致大肠杆菌和肠球菌的死亡[46].

2.2 土壤环境

微塑料可通过垃圾填埋场渗滤液渗漏[55]、废弃塑料制品的丢弃[56]和活性污泥[57]等多种途径进入土壤环境.虽然微塑料在土壤中广泛存在,但其空间分布极不均匀,浓度相差可多达 6 个数量级[58].在水平方向上,微塑料在土壤中分布存在明显的区域差异.一般来说,农业土壤、工业用地、河口、海岸线及城市附近的土壤中微塑料浓度更高[59].沿土壤的垂直剖面,微塑料的分布和丰度沿土壤深度差异显著.由于覆盖物、堆肥、污水污泥、大气沉降等原因,微塑料更容易积聚在土壤表层[60].

微塑料可通过改变土壤理化环境(例如土壤 pH 值和土壤团聚体)影响土壤微生物群落的多样性[61],一般来说,土壤塑料际的微生物多样性要低于周围土壤[26].Sun 等[62]通过对中国 99 个地点聚乙烯微塑料和周边土壤的细菌群落比较,发现与土壤细菌群落相比,塑料际微生物群落之间的空间分散和差异性变化较小,表明微塑料上的细菌群落高度同质化.此外,大量研究发现塑料际和周围土壤中微生物群落组成和功能存在差异.在中国黄土高原进行的田间试验结果表明,与块状土壤和根际土壤相比,聚乙烯塑料际中的酸杆菌、α-变形菌、不动杆菌、大肠

杆菌、假单胞菌和厚壁菌门更为丰富[19,63].此外,塑料际可选择性富集特定真核生物和细菌(包括多种潜在病原菌),土壤塑料际中潜在病原菌/细菌的比例高于周边土壤[25].许多已知的病原菌,如葡萄球菌和铜绿假单胞菌,可通过分泌胞外多糖和其他粘附素(如蛋白质)等在微塑料上定殖[64].Lin 等[65]通过田间培养实验测定了塑料际的人类致病菌,发现丰度最高的 5 种病原菌为绿色单孢菌(*Saccharomonospora viridis*,16.1%)、褐囊杆菌(*Cystobacter fuscus*,3.6 %)、肺炎链球菌(*Streptococcus pneumoniae*,3.1 %)、类鼻疽伯克霍尔德菌(*Burkholderia pseudomallei*,2.6 %)和蜡样芽孢杆菌(*Bacillus cereus*,2.5 %).Gkoutselis 等[66]从肯尼亚城市 5 个不同垃圾倾倒场的表层土中采集样本并从中分离出微塑料样品.经测定发现微塑料上存在丝状的植物致病性疣孢漆斑菌(*Myrothecium verrucaria*),镰刀菌(*Sordariomycetes*)、互花镰刀菌(*Alternaria crassa*)以及动物致病性霉菌镰刀菌(*delphinoides*)和酵母(*Naganishia albida*),为陆地生态系统中微塑料可积累植物、动物和人类真菌病原菌提供了证据.总体来说,弧菌通常存在于温带和热带海洋塑料际中[67],而假单胞菌(如假单胞菌蒙特利氏菌(*Pseudomonas monteilii*)、门多萨假单胞菌(*P. mendocina*)则主要存在于淡水和土壤塑料际中[68].

2.3　人为环境

污水和固体废弃物是人类活动的重要产物,构成了重要的人为环境.

2.3.1　污水

污水是环境水体中微塑料的主要来源之一.中国海南某市污水处理厂原水中微塑料浓度为(219.50±77.75) MPs/L[69],泰国和越南常规污水处理厂原水中微塑料浓度分别为(77±7.21) MPs/L[70]和 1.86~125.0MPs/L[71].污水中常见的微塑料类型包括聚酯(PES)、聚酰胺(PA)、聚乙烯(PE)、聚丙烯(PP)、醇酸树脂、丙烯酸和聚苯乙烯(PS),超过 80%的微塑料属于热塑性塑料 PE 和 PP 以及不同形状(碎片和纤维)的聚酯[72],主要来源于日常生活和工业生产等多种人类活动[73].由于微塑料微小的颗粒尺寸和较低的密度,污水中的微塑料经常从污水处理厂渗入到出水[74]并被排入周边水体,进而危害水生生物并威胁人类健康[75-76].塑料际病原微生物的存在更增加了微塑料的污染程度,其对生态系统和人类健康的威胁应引起高度重视[77].

Wang 等[77]研究发现,污水样品和塑料际中的微生物群落在门水平上存在显著差异,污水样品中变形菌(Proteobacteria)的相对丰度高于微塑料样品,而放线菌门在塑料际显著富集.此外,塑料际中的军团菌、分枝杆菌、奈瑟菌和弧杆菌的浓度均高于污水样品,证实了微塑料对致病菌的富集作用.表 3 总结了国内外已报道的污水处理厂(WWTP)塑料际病原菌的分布情况,其中弧菌属、不动杆菌属、肠杆菌和水杆菌等病原菌被大量检出,一种准肺炎克雷伯菌(*Klebsiella quasipneumoniae*) 在美国新泽西州 WWTPs 中被检出.

表 3　国内外部分 WWTP 中塑料际病原菌的相对丰度

Table 3　Relative abundance of some WWTP plasticsphere pathogens at home and abroad

地点	微塑料特点	采样方法	检测技术	病原菌科/属/种	相对丰度(%)	参考文献
中国厦门污水陆地景观河	PE、PP (71~120μm)	原位培养:在湿地进水和出水处放置微塑料进行培养	提取 DNA 进行 16S rRNA 高通量测序	水杆菌(*Aquabacterium*)	10~60	[78]
中国北京下水道	PVC	实验室模拟:将微塑料加入到含有污水的 SBR 反应器进行培养	1.提取 DNA 进行 16S rRNA 高通量测序 2.定量 PCR	假单胞菌属(*Pseudomonas*)	2.74~7.15	[79]
坎托布兰科 WWTPs	PLA、PHB、PCL、PET、POM	原位培养:选择西班牙两个活性污泥污水处理厂,将微塑料样品放入笼中置于 WWTP 二沉池出口 20cm 深处培养 48h	提取 DNA 进行 16S rRNA 高通量测序	假单胞菌属(*Pseudomonas*)	0.61	[80]
西班牙瓜达拉哈拉 WWTPs	PS、LDPE (3~5mm)			弓形虫(*Arcobacter*)	1.78	
				不动杆菌属(*Acinetobacter*)	1.30	
				丛毛单胞菌属(*Comamonas*)	0.49	

续表 3

地点	微塑料特点	采样方法	检测技术	病原菌科/属/种	相对丰度(%)	参考文献
				气单胞菌属(*Aeromonas*)	0.26	
				弧菌属(*Vibrio*)	0.08	
德国 WWTPs	HDPE、PS 颗粒(3mm)	原位培养:在德国某 WWTP 的 2 个站点培养微塑料	1.提取 DNA 进行 16S rRNA 高通量测序 2.定量 PCR	弧菌属(*Vibrio*) 肠杆菌科(*Enterobacteriaceae*) 粘着杆菌(*Tenacibaculum*) 杂杆菌(*Acrobacter*) 不动杆菌属(*Acinetobacter*)	6.95×10^4copies/ng 0.13	[45]
美国新泽西州 WWTPs	PE、PS (85~106μm)	实验室模拟:收集 3 个 WWTP 污泥与合成废水混合培养,在 25mL 玻璃瓶中制备 3 种处理方法,其中含有 6mg 3 种微粒中的一种(即 PE、PS 或沙子)和 5mL 污泥,培养 30d	提取 DNA 进行 16S rRNA 高通量测序	解鸟氨酸拉乌尔菌(*Raoultella ornithinolytica*) 嗜麦芽狭窄营养单胞菌(*Stenotrophomonas maltophilia*) 准肺炎克雷伯菌(*Klebsiella quasipneumoniae*)		[81]

注:PLA为聚乳酸,PHB为聚羟基丁酸酯,PCL为聚己内酯,POM为聚甲醛树脂,LDPE为低密度聚乙烯.病原菌相对丰度代表不同种类病原菌在细菌总数中的占比.

2.3.2 固体废物 污水处理厂产生的活性污泥和城市生活垃圾等有机固体废物中也含有大量微塑料和病原菌.城市污水处理厂可从工业生产、垃圾填埋场、生活污水等人类活动产物中接收大量微塑料[82],而污水中超过 90%的微塑料都被污泥拦截[83]. Wang 等[84]研究了活性污泥塑料际的病原菌分布情况,发现不动杆菌(*Acinetobacter*)和分枝杆菌(*Mycobacterium*)均在塑料际富集.Rasool 等[85]从给巴尔的 4 个农村和城郊地区收集了塑料样品,从样品中分离培养出了肺炎克雷伯菌(*Klebsiella pneumoniae*)、阴沟肠杆菌复合体(*Enterobacter cloacae complex*)、弗氏柠檬酸杆菌(*Citrobacter freundii*)、弗氏梭菌复合体(*C. freundii complex*)和霍乱弧菌(*Vibrio cholerae*),证实了塑料垃圾表面病原菌的广泛定殖.

堆肥是减少和净化污泥最环保、最节能的方式[86],但堆肥产品中仍存在大量微塑料,且塑料际病原菌未被彻底去除.微塑料的多孔性和较大的表面积[87]使其更容易吸附抗生素[88]、有机污染物[89]和致病微生物[90],这可能会对污泥的堆肥过程产生负面影响.Li 等[91]采用高通量测序技术探究堆肥成熟期塑料际微生物的群落分布,发现厚壁菌门的相对丰度显著降低,拟杆菌门、变形菌门和嗜热菌门的相对丰度显著升高.Chen 等[92]比较了堆肥过程中 PLA/PBAT 塑料际和厨余垃圾的差异,与堆肥垃圾的细菌群落相比, PLA/PBAT 塑料际观察到厚壁菌门的丰度更高,芽孢杆菌属是堆肥过程中的优势属.

垃圾填埋是废物处理的重要手段之一,大约 21%~42%的城市塑料垃圾会被运送到垃圾填埋场[93],因此,生活垃圾填埋场是微塑料的重要储存库.同时,塑料垃圾还可吸附有机物和生物分子,吸引微生物定殖[94],塑料垃圾表面还会富集抗生素抗性基因和病原菌,并通过水平基因转移增强病原菌的生存和致病性[95].一项研究报道,塑料垃圾表面弧菌的丰度在城市附近的样品中更高[50],这可能是由于人类活动导致周围环境中营养物质增加,从而丰富了塑料垃圾上的病原体.填埋场内部塑料际病原菌的赋存及变化趋势还有待进一步研究.

2.4 大气环境

近年来,大气颗粒物中微塑料和纳米塑料(Nanoplastics)的出现引起了人们的广泛关注,目前已在城市地区、海洋等上空的大气中观察到微塑料的存在[96].作为生物气溶胶的重要组成部分,微生物在大气环境中无处不在[97],虽然大多数微生物对人类没有致病性[98],但也会有流感病毒或冠状病毒等病原体流行.最近的研究表明,微塑料可能通过呼吸系统进入人体[99],若病原菌搭载微塑料便车被人体吸入,势必会对人体健康构成严重威胁.

Peng 等[100]采集了天津市某建筑室内的粉尘样品探究室内环境微塑料对病原菌的富集情况及其健康风险.结果显示微塑料是室内粉尘的重要组成部分,其中 PET、PA、PP 和 PE 最为丰富.对室内气溶胶中的病原菌测定发现,与天然聚合物相比,PA 和 PET 纤维表面的病原菌指数更高,拉尔斯顿菌(Ralstonia)在塑料际显著富集.Jing 等[101]探究了哈尔滨市雾霾期间空气中微塑料和可培养微生物的污染特征及其潜在健康影响,结果表明,芽孢杆菌属、肠杆菌属、赖氏杆菌属、帕尼巴菌属、节杆菌属和假单胞菌属的丰度较高,溶血杆菌和节杆菌可在早晚采集的样本中检出.Xu 等[102]在北京市三个不同城市功能区收集大气沉积物并从中分离微塑料,探究微塑料与空气传播致病菌的相关性及相互作用机制.研究结果表明,微塑料特征与空气中致病菌丰度存在显著正相关,鞘氨醇单胞菌可能是大气微塑料增强气溶胶微生物致病性的重要媒介类群.

目前对塑料际病原菌丰度的研究主要集中于水生环境和陆地环境,大气塑料际的研究尚处于起步阶段.由于现有研究采用的取样方法存在差异,检测技术主要以 16S rRNA 高通量测序为主,因此只能获得塑料际病原菌的相对丰度并对其优势病原菌进行分析,后续还需统一取样和检测方法来提高不同环境中塑料际病原菌的可比性.总体来说,不同环境中塑料际病原菌的种类和丰度主要受环境因素影响[34].环境因素包括生物因素和非生物因素.生物因素以微生物为主,环境中的优势菌属往往决定了塑料际的微生物组成[103].非生物因素则包括 pH 值、温度和盐度等,有研究表明盐度对河口和海洋塑料际有显著影响,且与弧菌属的丰度呈正相关[104].目前的研究结果发现,陆地生态系统中不动杆菌、大肠杆菌、假单胞菌富集于塑料际中[19],而弧菌属、假单胞菌属、不动杆菌属、弓杆菌属、芽孢杆菌属、水杆菌属、分枝杆菌属、气单胞菌属最常与水生塑料际中发现的潜在有害细菌相关.其中,弧菌属是海洋水生环境的特有物种[104].

3　塑料际病原菌的传播特性

3.1　塑料际病原菌存在频繁的抗性基因水平转移

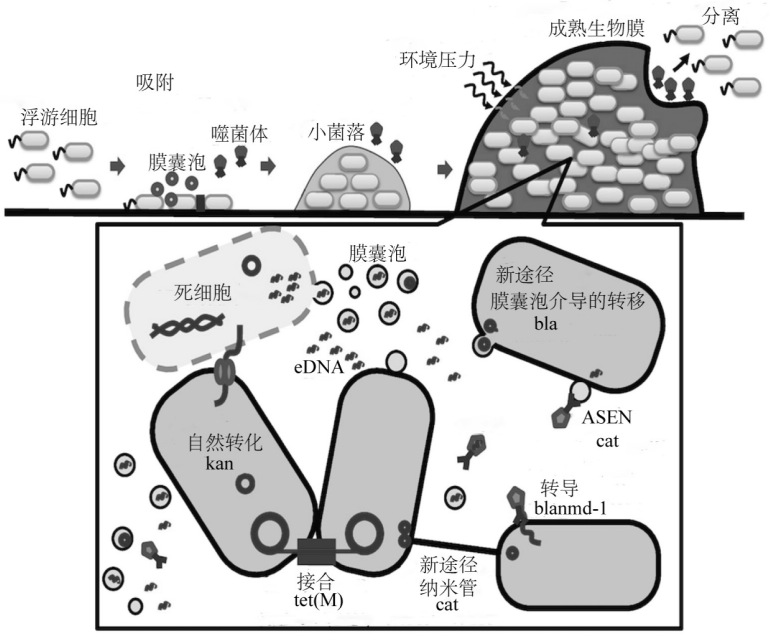


图 1　生物膜的形成过程及其中的抗性基因水平转移(HGT)机制[107]

Fig.1　The formation process of biofilm and the mechanism of horizontal gene transfer (HGT) in it

微塑料因具有高比表面积、高孔隙率和强疏水性,成为微生物理想的栖息地,同时也是抗生素、重金属和农药等多种污染物的有效吸附剂[89].Wang 等[78]发现,淡水、河口和海水中的微塑料可吸附抗生素,而抗生素可以进一步影响聚乙烯塑料际及其周围水域的微生物群落结构,进而影响 ARGs 的分布.

Yang 等[105]分析了微塑料上 ARGs 的多样性和丰度,发现塑料际中 ARGs 和 MGEs 的丰度显著高于周围海水[105].Wu 等[41]对河流中天然介质表面生物膜和塑料际上的 ARGs 进行检测,发现一些特殊的 ARGs 只能在塑料际检出.塑料际已成为 ARGs 和抗生素耐药细菌(ARBs)的重要储存库[105-106].塑料际的 ARGs 可通过接合、转化、转导、囊泡运输和形成纳米管等多种方式在不同细胞间传播,其方式和频率会受外部环境、细菌群落和移动遗传元件的影响[107].此外,塑料际会通过共选择(共耐药性和交叉耐药性)和其他潜在机制导致细菌产生抗生素耐药性[108],一些有机污染物如多氯联苯(PCBs)和多环芳烃等也可能在病原菌的富集过程中起附加或协同作用[109].在海洋和淡水生态系统中,塑料际也已成为 ARGs、毒力因子基因(VFGs)和 MGEs 水平基因转移的热点[78],塑料际频繁的水平基因转移使塑料际富集的致病菌获得多种 VFGs 和 ARGs,增强致病性,产生耐药性,进而更难被杀死[67].而这些耐药性病原菌又可随微塑料的迁移在不同环境介质中传播扩散,进而对生态安全和人类健康产生严重威胁.

3.2 病原菌以微塑料为载体的传播潜力

塑料际病原菌通常跟随微塑料在陆地、水环境和大气环境中的迁移而传播:雨水可将陆地、河岸的微塑料冲刷进河流,潮汐可将海水中的微塑料迁移到海岸,风、气流等可将水体和土壤中的微塑料散播到大气.不同传播途径之间相互关联,共同驱动微塑料在自然生态系统中的迁移,而塑料际病原菌也随之参与多种重要生态过程[110].图 2 为微塑料在环境中的传播途径及相关作用.

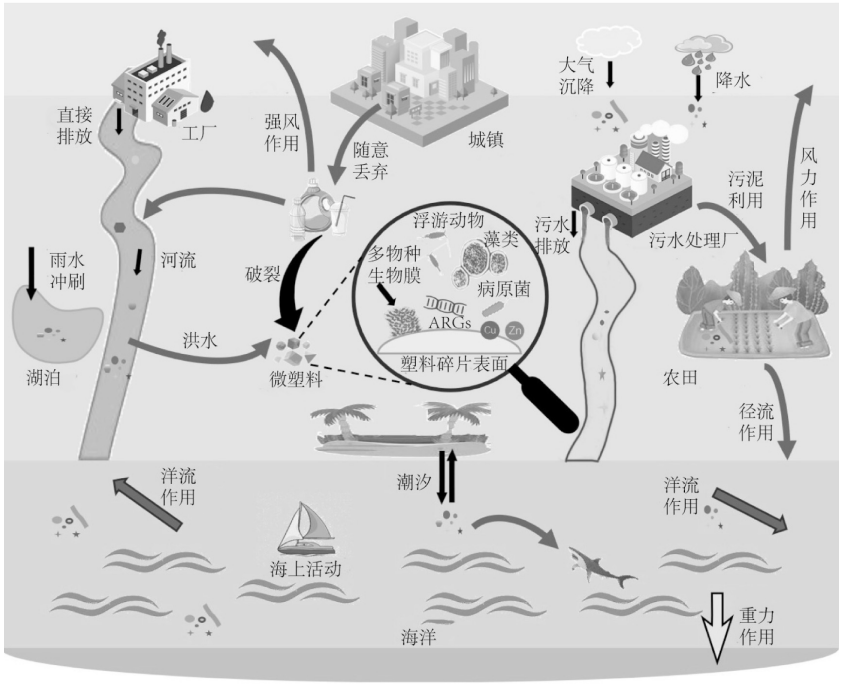


图 2 微塑料在环境中的传播途径

Fig.2 Propagation pathways of microplastics in the environment

3.2.1 水环境中的传播 人类活动释放的大量微塑料会随污水处理厂和垃圾处理厂的排水进入淡水系统[30],也可通过大气沉降和地表径流进入河流和湖泊[111],这些水生及陆生来源的微塑料最终都会随河流汇入海洋[88].大量研究表明,微塑料对水生生物有害,易被水生无脊椎动物、鱼类和哺乳动物摄入[112],进而引起肠道损伤[113]、诱发炎症[114],从而干扰食物链.有研究表明,微塑料可通过海洋食物链转移,导致其在高等捕食者体内富集[115].微塑料表面吸附的重金属和有机污染物等进一步加剧了其对水生生物的毒性作用[116-117].此外,塑料际富集的 ARGs 和致病菌可通过自来水传播,使人类通过摄入和皮肤接触暴露于塑料际病原菌[118-120],进而对人类健康构成健康威胁.Unuofin 等[121]研究发现微塑

料会积聚在海洋动物的组织和器官中,使人类在食用海鲜时暴露于微塑料. 若富集病原菌的微塑料进入人体,必将对人体健康带来双重威胁[122].

3.2.2　土壤系统中的传播　与水环境不同,微塑料在土壤中的流动性较低,因此,土壤塑料际中的微生物群落会受到局部土壤环境的限制[9].土壤中的微塑料类型包括聚丙烯(PP)、聚乙烯(PE)和聚苯乙烯(PS),主要来源于垃圾填埋场、农业地膜、污水灌溉和大气沉降等途径[58].研究表明,微塑料在农田和其他土地类型中的分布特征不同,其含量会随土壤深度的增加而降低[60].

微塑料在土壤中的迁移包括垂直和水平迁移,主要受土壤性质、土壤内生物活动、微塑料形态、孔隙水流[123]和农业活动[55]等因素影响.细粒土壤具有较小的孔隙尺度,大多数大粒径微塑料颗粒会保留在土壤上层[55];粗粒土壤中,细小的微塑料会通过水流或胶体迁移至土壤深处,其中沙质土壤中微塑料呈现明显的垂直迁移行为[60].微塑料的形态也会影响迁移,粒径较小的微塑料更容易在土壤中运输[55],而密度较大的微塑料更有可能迁移到更深的土壤中[123].不同聚合物类型的微塑料迁移能力也不同,PE 疏水性较高,不易随水流迁移[124];PET 由于其化学惰性较强因此迁移能力较弱[124].微塑料老化会导致其表面形态和粒径分布发生改变,进而影响其在土壤中的迁移过程.

土壤是微塑料的储存库,也是其重要来源地之一,土壤中的微塑料可通过地表径流、扬尘等方式进入河流、地下水和空气中.Nizzetto 等[125]发现粒径小于 0.2mm 的微塑料会随地表水流迁移,Rezaei 等[126]通过风洞模拟,证实了土壤中的微塑料会进入空气并随风传播.此外,土壤中的微塑料还会进入根际环境甚至进入植物体内[127],对植物发芽、光合作用和生长产生不利影响.携带致病菌的微塑料在土壤、地下水、植物间迁移,势必会增加土传病害风险,污染地下水,并危害植物和人体健康.

3.2.3　污水处理过程中的传播　污水中含有大量微塑料,但经初级、二级和三级处理后,其中的微塑料去除效率可达 97%[128].初级处理阶段主要用于去除污水中的漂浮物和可沉降的无机固体等.据报道,污水中大部分微塑料可通过初级处理去除[129].二级处理通常是利用微生物的分解作用在好氧或厌氧条件下去除有机物,但曝气过程会导致废水中的微塑料颗粒散播到大气环境.三级处理则是运用膜生物反应器、臭氧技术、砂过滤器等多种技术进一步去除污水中的污染物.有研究表明,初级处理可去除废水中 70%~98%的微塑料,二级处理能将微塑料含量再减少 20%,而三级处理可进一步去除 2%的微塑料[130].但污水处理厂出水中仍会有微塑料残留. Koyuncuoğlu 等[131]调查了土耳其城市污水处理厂中微塑料的去除效率,发现尽管处理效率超过 95%,但每天排出的微塑料浓度仍达到 1.28×10^{10}MP/d.在对污水进行处理时,微生物也会在微塑料表面定殖形成生物膜,Ahamed 等[132]研究表明,水处理过程中微塑料生物膜可通过增强沉淀和吸附过程来强化微塑料、重金属和有机污染物的去除.此外,微塑料生物膜的形成会为微生物提供保护层,降低消毒有效性,导致灭菌效率的下降[133],进而导致出水中仍有塑料际病原菌的存在.Kelly 等[134]对两个 WWTPs 中微塑料生物膜上的细菌群落进行了研究,发现微塑料颗粒上有不同的微生物菌群定殖.处理后微塑料上肠杆菌科、假单胞菌属、鞘单胞菌属和鞘单胞菌科等细菌的丰度显著高于原污水.总之,污水处理不能彻底去除微塑料及塑料际微生物,其中包括一些病原微生物.当 WWTPs 出水排放后,微塑料生物膜上的致病菌、ARB 和 ARGs 会随之进入接收水体并在水体生态系统中存活较长时间[135].塑料际微生物可侵入本地微生物群落,对接收栖息地生态系统产生负面影响[136],塑料际的病原菌也可通过食物链对接收水体的动植物带来一定健康威胁.

在污水处理过程中,处理系统截留的大部分微塑料会进入污泥中.Wei 等[137]对成都市两个污水处理厂污泥中微塑料的丰度和特征进行了测定,发现每个处理阶段的污泥中都存在大量微塑料.网格渣污泥中微塑料的总丰度为 233.33~750.01N/kg,沉淀池中微塑料的丰度为 55.55~61.11N/kg,而干污泥中为 44.44~111.11N/kg.污泥作为农业肥料施加到土壤中又会将其中的微塑料输入土壤环境,塑料际病原菌也会随污泥进入土壤,进而增加土壤的微塑料污染及土传病害风险.

3.2.4　大气传播　大气中的微塑料是一种普遍且持续存在的新污染物,已成为全球关注的环境问题[96].大气中的微塑料主要来源于合成纺织品、轮胎

的磨损和城市灰尘等[138].由于其体积和密度较小,微塑料很容易被风、气流或波浪带入大气中[138],并在大气层中长距离传播.

Jiang 等[139]利用天然放射性核素 ^{7}Be、^{210}Pb 和 ^{210}Po 探讨了天津市大气微塑料的传输规律,发现冬季微塑料比例显著高于其他季节,且秋冬季微塑料大于春夏两季.全年大气颗粒物停留时间为 9.47~22.85d,平均 14.41d.Allen 等[140]报道了对偏远、原始山区的集水区(法国比利牛斯山脉)中大气微塑料沉降的观测结果,气团轨迹分析显示,微塑料在大气中传输的距离可达 95km.Welsh 等[141]在加拿大安大略省中南部的四个化学监测站收集的所有沉积样品中都检测到微塑料颗粒,表明微塑料可从大于 200km 外的地方运输到检测站被收集.上述结果表明大气是微塑料运输的重要载体,微塑料可随大气扩散输送到远离典型点源的偏远区域.

大气中的微塑料经过远距离迁移并沉积到水生和陆生生境后,可通过生物吸收、生物富集、生物蓄积、生态毒性和相关的化学污染等方式,对生态环境造成危害[142].Wang 等[143]研究了大气微塑料进入湿地后带来的生态影响,发现湿地细菌群落的结构和功能受微塑料丰度和大小的影响.大气中小粒径的微塑料很容易被吸入人体诱发氧化应激和炎症反应[144],或影响新陈代谢和繁殖性能.室内实验研究表明,与无机和天然有机颗粒相比,大气微塑料可吸附气溶胶微生物,选择性富集有害细菌和耐药基因[100].因此,携带病原菌与 ARGs 的微塑料在大气中的传播特性及对人体健康的风险应引起高度关注.

目前对塑料际病原菌的风险评估研究大多基于病原菌丰度、毒力因子种类和表达水平及塑料际病原菌的抗生素抗性情况[145].病原菌含量越高,带来的风险越高;毒力因子表达水平越高,病原菌的致病能力越强;塑料际病原菌对抗生素的抗性越强,治疗难度越大,风险也相应增加.Zhu 等[146]改进了塑料际健康风险评估(HRA)的方法,除抗性基因丰度外,还考虑了人类可接触性(HA)、移动性(MO)、人类致病性(HP)以及临床可用性(CA).风险评估结果表明,作为全球最常用的塑料类型之一,PE 微塑料的 HRA 最高.

此外,微塑料会负载重金属、有害污染物和病原菌造成复合污染效应,更增加了塑料际的环境和健康风险.Wu 等[147]研究发现塑料中释放的增塑剂(邻苯二甲酸酯)会促进微生物细胞间抗性基因的传播,增加废塑料的污染风险.Bang 等[148]将微塑料暴露于含 Cu 和消毒剂的土壤中,发现复合污染物激发了塑料际中 ARGs 和 VFGs 的富集作用,同时增加了一些潜在病原菌的相对丰度.Deng 等[149]将小鼠暴露于有机磷阻燃剂和微塑料中,发现小鼠的代谢物发生了显著变化,表明微塑料加剧了有机磷阻燃剂的生物毒性.Cheng 等[150]研究了微塑料和增塑剂双酚 A 对人体肝脏的联合毒性,发现微塑料和双酚 A 具有协同肝毒作用.上述结果表明暴露于塑料际的复合污染中势必会对人体健康带来更大威胁.

4 结论与展望

微塑料为微生物的富集提供了独特的生态位,形成生物膜,而生物膜中 ARGs 和 VFGs 频繁多样的 HGT 使塑料际成为病原菌和 ARGs 的热点区域.弧菌属(*Vibrio*)、假单胞菌属(*Pseudomonas*)和不动杆菌属(*Acinetobacter*)等是塑料际常见的病原菌.携带病原菌的微塑料可在水体、土壤和大气环境中传播,促进病原菌与抗生素耐药性的传播和蔓延,从而对生态系统稳态和人类健康构成威胁.但目前塑料际微生物污染风险的相关研究尚处于起步阶段,后续应在下述几个方面加强研究:

微塑料特性与其表面富集病原菌之间的关系有待进一步研究.后续可从微塑料形状、尺寸、密度、类型、老化程度等方面探究这些变量对其表面病原菌附着、丰度和组成的影响.通过实地采样及实验室模拟等方法,收集不同来源的塑料际样品,运用多光谱学和测序技术深度解析微塑料特性及病原菌丰度及物种组成,并利用机器学习预测微塑料特性与其表面病原菌富集之间的量化关系.

塑料际吸附的抗生素、重金属和有机污染物及塑料释放的有害添加剂对病原菌和抗生素耐药性的影响有待进一步研究.到目前为止,塑料际抗生素和重金属对 ARGs 的共选择作用已被大量报道,而多氯联苯、PPCPs 和多环芳烃等对病原菌富集的附加或协同作用还有待证实.后续可将微塑料、有机污染物和病原菌进行共暴露培养,评估不同浓度有机污染物单独或联合作用下塑料际病原菌的富集程度、群落组成变化与耐药性发展趋势.

塑料际带来的微生物污染风险需纳入风险评估体系,综合考虑病原菌、ARGs 和 VFGs 的丰度及危险性,建立完善的微塑料污染评估框架.微塑料污染相关风险评估已经被大量报道,但塑料际微生物污染风险及微塑料的复合污染风险评估方法与框架急需重塑,相关研究可为全面评估微塑料污染的环境和人体健康风险提供有力支撑.

参考文献：

[1] Ali I, Tan X, Li J, et al. Innovations in the development of promising adsorbents for the remediation of microplastics and nanoplastics – a critical review [J]. Water Research, 2023,230:119526.

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

[3] Tan Y, Dai J, Xiao S, et al. Occurrence of microplastic pollution in rivers globally: driving factors of distribution and ecological risk assessment [J]. Science of The Total Environment, 2023,904:165979.

[4] Lebreton L, Royer S J, Peytavin A, et al. Industrialised fishing nations largely contribute to floating plastic pollution in the north pacific subtropical gyre [J]. Scientific Reports, 2022,12(1):12666.

[5] Bai M, Lin Y, Hurley R R, et al. Controlling factors of microplastic riverine flux and implications for reliable monitoring strategy [J]. Environmental Science & Technology, 2022,56(1):48−61.

[6] Cole M, Lindeque P, Fileman E, et al. The impact of polystyrene microplastics on feeding, function and fecundity in the marine copepod calanus helgolandicus [J]. Environmental Science & Technology, 2015,49(2):1130−1137.

[7] Stollberg N, Kröger S D, Reininghaus M, et al. Uptake and absorption of fluoranthene from spiked microplastics into the digestive gland tissues of blue mussels, *mytilus edulis* L. [J]. Chemosphere, 2021,279:130480.

[8] Lian J, Liu W, Meng L, et al. Foliar−applied polystyrene nanoplastics (psnps) reduce the growth and nutritional quality of lettuce (*lactuca sativa* l.) [J]. Environmental Pollution, 2021,280:116978.

[9] Rillig M C, Kim S W, Zhu Y G. The soil plastisphere [J]. Nature Reviews Microbiology, 2024,22(2):64−74.

[10] Harrison J P, Schratzberger M, Sapp M, et al. Rapid bacterial colonization of low−density polyethylene microplastics in coastal sediment microcosms [J]. BMC Microbiology, 2014,14(1):232.

[11] Chen Y, Yan Z, Zhou Y, et al. Dynamic evolution of antibiotic resistance genes in plastisphere in the vertical profile of urban rivers [J]. Water Research, 2024,249:120946.

[12] Arias−Andres M, Klümper U, Rojas−Jimenez K, et al. Microplastic pollution increases gene exchange in aquatic ecosystems [J]. Environmental Pollution, 2018,237:253−261.

[13] Flemming H C, Wingender J, Szewzyk U, et al. Biofilms: an emergent form of bacterial life [J]. Nature Reviews Microbiology, 2016,14(9):563−575.

[14] Zettler E R, Mincer T J, Amaral−Zettler L A. Life in the “plastisphere”: microbial communities on plastic marine debris [J]. Environmental Science & Technology, 2013,47(13):7137−7146.

[15] Guo W, Ngo H H, Li J. A mini−review on membrane fouling [J]. Bioresource Technology, 2012,122:27−34.

[16] González−Pleiter M, Velázquez D, Casero M C, et al. Microbial colonizers of microplastics in an Arctic freshwater lake [J]. Science of The Total Environment, 2021,795:148640.

[17] Vaksmaa A, Knittel K, Abdala Asbun A, et al. Microbial communities on plastic polymers in the mediterranean sea [J]. Frontiers in Microbiology, 2021,12:673553.

[18] Li K, Jia W, Xu L, et al. The plastisphere of biodegradable and conventional microplastics from residues exhibit distinct microbial structure, network and function in plastic−mulching farmland [J]. Journal of Hazardous Materials, 2023,442:130011.

[19] Li C, Gillings M R, Zhang C, et al. Ecology and risks of the global plastisphere as a newly expanding microbial habitat [J]. The Innovation, 2024,5(1):100543.

[20] Hidalgo−Ruz V, Gutow L, Thompson R C, et al. Microplastics in the marine environment: a review of the methods used for identification and quantification [J]. Environmental Science & Technology, 2012,46(6):3060−3075.

[21] Li Y, Gao W, Wang C, et al. Distinct distribution patterns and functional potentials of rare and abundant microorganisms between plastisphere and soils [J]. Science of The Total Environment, 2023,873:162413.

[22] Di Pippo F, Venezia C, Sighicelli M, et al. Microplastic−associated biofilms in lentic Italian ecosystems [J]. Water Research, 2020,187:116429.

[23] Zadjelovic V, Wright R J, Borsetto C, et al. Microbial hitchhikers harbouring antimicrobial−resistance genes in the riverine plastisphere [J]. Microbiome, 2023,11(1):225.

[24] Ni B, Lin D, Cai T, et al. Soil plastisphere reinforces the adverse effect of combined pollutant exposure on the microfood web [J]. Environmental Science & Technology, 2024,58(49):21641−21652.

[25] Zhu D, Ma J, Li G, et al. Soil plastispheres as hotspots of antibiotic resistance genes and potential pathogens [J]. The ISME Journal, 2022,16(2):521−532.

[26] Sun Y, Shi J, Wang X, et al. Deciphering the mechanisms shaping the plastisphere microbiota in soil [J]. mSystems, 2022,7(4):e0035222.

[27] Barboza L G A, Dick Vethaak A, Lavorante B R B O, et al. Marine microplastic debris: An emerging issue for food security, food safety and human health [J]. Marine Pollution Bulletin, 2018,133:336−348.

[28] Wong J K H, Lee K K, Tang K H D, et al. Microplastics in the freshwater and terrestrial environments: prevalence, fates, impacts and sustainable solutions [J]. Science of The Total Environment, 2020,719:137512.

[29] Zeri C, Adamopoulou A, Koi A, et al. Rivers and wastewater−treatment plants as microplastic pathways to eastern mediterranean waters: first records for the aegean sea, Greece [J]. Sustainability, 2021,13(10):5328.

[30] Qiu R, Song Y, Zhang X, et al. Microplastics in urban environments: sources, pathways, and distribution [C]//He D, Luo Y. Microplastics in Terrestrial Environments: Vol. 95. Cham: Springer International Publishing, 2020:41−61.

[31] Li J, Huang W, Jiang R, et al. Are bacterial communities associated with microplastics influenced by marine habitats? [J]. Science of The Total Environment, 2020,733:139400.

[32] 彭子淇,李佳岭,邱丽婷,等.我国三大水系环境微塑料污染现状及其表面微生物群落特征的研究进展 [J]. 微生物学报, 2023,63(6): 2261−2275.
Peng Z Q, Li J L, Qiu L T, et al. Research progress on the status quo of microplastic pollution and the characteristics of microbial communities on the surface of the three major river systems in China [J]. Acta Microbiologica Sinica, 2023,63(6):2261−2275.

[33] Xu C, Hu C, Lu J, et al. Lake plastisphere as a new biotope in the anthropocene: potential pathogen colonization and distinct microbial functionality [J]. Journal of Hazardous Materials, 2024,461:132693.

[34] Tang K H D. Terrestrial and aquatic plastisphere: formation, characteristics, and influencing factors [J]. Sustainability, 2024,16(5): 2163.

[35] Laverty A L, Primpke S, Lorenz C, et al. Bacterial biofilms colonizing plastics in estuarine waters, with an emphasis on *Vibrio* spp. and their antibacterial resistance [J]. Plos One, 2020,15(8):e0237704.

[36] Xue N, Wang L, Li W, et al. Increased inheritance of structure and function of bacterial communities and pathogen propagation in plastisphere along a river with increasing antibiotics pollution gradient [J]. Environmental Pollution, 2020,265:114641.

[37] McCormick A, Hoellein T J, Mason S A, et al. Microplastic is an abundant and distinct microbial habitat in an urban river [J]. Environmental Science & Technology, 2014,48(20):11863−11871.

[38] McCormick A R, Hoellein T J, London M G, et al. Microplastic in surface waters of urban rivers: concentration, sources, and associated bacterial assemblages [J]. Ecosphere, 2016,7(11):e01556.

[39] 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.

[40] Wu N, Zhang Y, Zhao Z, et al. Colonization characteristics of bacterial communities on microplastics compared with ambient environments (water and sediment) in haihe estuary [J]. Science of The Total Environment, 2020,708:134876.

[41] Wu X, Pan J, Li M, et al. Selective enrichment of bacterial pathogens by microplastic biofilm [J]. Water Research, 2019,165:114979.

[42] Auta H S, Emenike C U, Fauziah S H. Distribution and importance of microplastics in the marine environment: a review of the sources, fate, effects, and potential solutions [J]. Environment International, 2017, 102:165−176.

[43] Erni−Cassola G, Zadjelovic V, Gibson M I, et al. Distribution of plastic polymer types in the marine environment; a meta−analysis [J]. Journal of Hazardous Materials, 2019,369:691−698.

[44] Silva M M, Maldonado G C, Castro R O, et al. Dispersal of potentially pathogenic bacteria by plastic debris in Guanabara Bay, RJ, Brazil [J]. Marine Pollution Bulletin, 2019,141:561−568.

[45] Oberbeckmann S, Kreikemeyer B, Labrenz M. Environmental factors support the formation of specific bacterial assemblages on microplastics [J]. Frontiers in Microbiology, 2018,8:2709.

[46] DeVilbiss S E, Steele M K, Krometis L A H, et al. Freshwater salinization increases survival of *escherichia coli* and risk of bacterial impairment [J]. Water Research, 2021,191:116812.

[47] Kirstein I V, Kirmizi S, Wichels A, et al. Dangerous hitchhikers? evidence for potentially pathogenic *vibrio* spp. on microplastic particles [J]. Marine Environmental Research, 2016,120:1−8.

[48] Frère 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.

[49] Radisic V, Nimje P S, Bienfait A M, et al. Marine plastics from norwegian west coast carry potentially virulent fish pathogens and opportunistic human pathogens harboring new variants of antibiotic resistance genes [J]. Microorganisms, 2020,8(8):1200.

[50] Kesy K, Labrenz M, Scales B S, et al. *Vibrio* colonization is highly dynamic in early microplastic−associated biofilms as well as on field−collected microplastics [J]. Microorganisms, 2020,9(1):76.

[51] Curren E, Leong S C Y. Profiles of bacterial assemblages from microplastics of tropical coastal environments [J]. Science of The Total Environment, 2019,655:313−320.

[52] Zhang Y, Lu J, Wu J, et al. Potential risks of microplastics combined with superbugs: enrichment of antibiotic resistant bacteria on the surface of microplastics in mariculture system [J]. Ecotoxicology and Environmental Safety, 2020,187:109852.

[53] Guo X P, Sun X L, Chen Y R, et al. Antibiotic resistance genes in biofilms on plastic wastes in an estuarine environment [J]. Science of The Total Environment, 2020,745:140916.

[54] Lu J, Zhang Y, Wu J, et al. Effects of microplastics on distribution of antibiotic resistance genes in recirculating aquaculture system [J]. Ecotoxicology and Environmental Safety, 2019,184:109631.

[55] Ren Z, Gui X, Xu X, et al. Microplastics in the soil−groundwater environment: aging, migration, and co−transport of contaminants – a critical review [J]. Journal of Hazardous Materials, 2021,419:126455.

[56] Yang L, Zhang Y, Kang S, et al. Microplastics in soil: a review on methods, occurrence, sources, and potential risk [J]. Science of The Total Environment, 2021,780:146546.

[57] Gao D, Li X Y, Liu H T. Source, occurrence, migration and potential environmental risk of microplastics in sewage sludge and during sludge amendment to soil [J]. Science of The Total Environment, 2020, 742:140355.

[58] Zhang Z, Cui Q, Chen L, et al. A critical review of microplastics in the soil−plant system: distribution, uptake, phytotoxicity and prevention [J]. Journal of Hazardous Materials, 2022,424:127750.

[59] Gao J, Pan S, Li P, et al. Vertical migration of microplastics in porous media: multiple controlling factors under wet−dry cycling [J]. Journal of Hazardous Materials, 2021,419:126413.

[60] 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.

[61] Sarkar B, Dissanayake P D, Bolan N S, et al. Challenges and opportunities in sustainable management of microplastics and nanoplastics in the environment [J]. Environmental Research, 2022, 207:112179.

[62] Sun Y, Wu M, Xie S, et al. Homogenization of bacterial plastisphere community in soil: a continental−scale microcosm study [J]. ISME Communications, 2024,4(1):ycad012.

[63] Shi Z, Xiong L, Liu T, et al. Alteration of bacterial communities and co-occurrence networks as a legacy effect upon exposure to polyethylene residues under field environment [J]. Journal of Hazardous Materials, 2022,426:128126.

[64] Wang L, Wang H, Zhang H, et al. Formation of a biofilm matrix network shapes polymicrobial interactions [J]. The ISME journal, 2023,17(3):467-477.

[65] Lin D, Xu J Y, Wang L, et al. Long-term application of organic fertilizer prompting the dispersal of antibiotic resistance genes and their health risks in the soil plastisphere [J]. Environment International, 2024,183:108431.

[66] Gkoutselis G, Rohrbach S, Harjes J, et al. Microplastics accumulate fungal pathogens in terrestrial ecosystems [J]. Scientific Reports, 2021,11(1):13214.

[67] Junaid M, Siddiqui J A, Sadaf M, et al. Enrichment and dissemination of bacterial pathogens by microplastics in the aquatic environment [J]. Science of The Total Environment, 2022,830:154720.

[68] MacLean J, Mayanna S, Benning L G, et al. The terrestrial plastisphere: diversity and polymer-colonizing potential of plastic-associated microbial communities in soil [J]. Microorganisms, 2021,9(9):1876.

[69] Bao R, Wang Z, Qi H, et al. Occurrence and distribution of microplastics in wastewater treatment plant in a tropical region of china [J]. Journal of Cleaner Production, 2022,349:131454.

[70] Tadsuwan K, Babel S. Microplastic abundance and removal via an ultrafiltration system coupled to a conventional municipal wastewater treatment plant in thailand [J]. Journal of Environmental Chemical Engineering, 2022,10(2):107142.

[71] Le T M T, Truong T N S, Nguyen P D, et al. Evaluation of microplastic removal efficiency of wastewater-treatment plants in a developing country, vietnam [J]. Environmental Technology & Innovation, 2023,29:102994.

[72] Ragoobur D, Huerta-Lwanga E, Somaroo G D. Microplastics in agricultural soils, wastewater effluents and sewage sludge in mauritius [J]. Science of The Total Environment, 2021,798:149326.

[73] Talvitie J, Mikola A, Koistinen A, et al. Solutions to microplastic pollution – Removal of microplastics from wastewater effluent with advanced wastewater treatment technologies [J]. Water Research, 2017,123:401-407.

[74] Ngo P L, Pramanik B K, Shah K, et al. Pathway, classification and removal efficiency of microplastics in wastewater treatment plants [J]. Environmental Pollution, 2019,255:113326.

[75] Mak C W, Tsang Y Y, Leung M M L, et al. Microplastics from effluents of sewage treatment works and stormwater discharging into the victoria harbor, hong kong [J]. Marine Pollution Bulletin, 2020, 157:111181.

[76] Mak C W, Ching-Fong Yeung K, Chan K M. Acute toxic effects of polyethylene microplastic on adult zebrafish [J]. Ecotoxicology and Environmental Safety, 2019,182:109442.

[77] Wang Z, Gao J, Zhao Y, et al. Plastisphere enrich antibiotic resistance genes and potential pathogenic bacteria in sewage with pharmaceuticals [J]. Science of The Total Environment, 2021,768: 144663.

[78] Wang S, Xue N, Li W, et al. Selectively enrichment of antibiotics and ARGs by microplastics in river, estuary and marine waters [J]. Science of The Total Environment, 2020,708:134594.

[79] Dai H H, Gao J F, Wang Z Q, et al. Behavior of nitrogen, phosphorus and antibiotic resistance genes under polyvinyl chloride microplastics pressures in an aerobic granular sludge system [J]. Journal of Cleaner Production, 2020,256:120402.

[80] Martínez-Campos S, González-Pleiter M, Fernández-Piñas F, et al. Early and differential bacterial colonization on microplastics deployed into the effluents of wastewater treatment plants [J]. Science of The Total Environment, 2021,757:143832.

[81] Pham D N, Clark L, Li M. Microplastics as hubs enriching antibiotic-resistant bacteria and pathogens in municipal activated sludge [J]. Journal of Hazardous Materials Letters, 2021,2:100014.

[82] Lin J Y, Liu H T, Li X Y, et al. Influence of sludge treatment methods on behaviors of microplastics adsorbed cadmium and its driving factors [J]. Journal of Environmental Management, 2022,322:116113.

[83] Carr S A, Liu J, Tesoro A G. Transport and fate of microplastic particles in wastewater treatment plants [J]. Water Research, 2016,91: 174-182.

[84] Wang Z, Gao J, Zhao Y, et al. Fates of extracellular and intracellular antibiotic resistance genes in activated sludge and plastisphere under sulfadiazine pressure [J]. Water Research, 2023,247:120752.

[85] Rasool F N, Saavedra M A, Pamba S, et al. Isolation and characterization of human pathogenic multidrug resistant bacteria associated with plastic litter collected in zanzibar [J]. Journal of Hazardous Materials, 2021,405:124591.

[86] Chen L, Li W, Zhao Y, et al. Effects of compound bacterial agent on gaseous emissions and compost maturity during sewage sludge composting [J]. Journal of Cleaner Production, 2022,366:133015.

[87] Law K L, Thompson R C. Microplastics in the seas [J]. Science, 2014,345(6193):144-145.

[88] Amaral-Zettler L A, Zettler E R, Mincer T J. Ecology of the plastisphere [J]. Nature Reviews Microbiology, 2020,18(3):139-151.

[89] Fu L, Li J, Wang G, et al. Adsorption behavior of organic pollutants on microplastics [J]. Ecotoxicology and Environmental Safety, 2021,217: 112207.

[90] Galafassi S, Sabatino R, Sathicq M B, et al. Contribution of microplastic particles to the spread of resistances and pathogenic bacteria in treated wastewaters [J]. Water Research, 2021,201:117368.

[91] Li X, Qi X, Liu X, et al. PET addition delays the composting mature process and promotes microbiota associated with plastic degradation in plastisphere [J]. Journal of Cleaner Production, 2023,389:136066.

[92] Chen W, Feng Z, Chang Y, et al. Comparing the bacterial composition, succession and assembly patterns in plastisphere and kitchen waste composting with PLA/PBAT blends [J]. Journal of Hazardous Materials, 2023,454:131405.

[93] Nizzetto L, Futter M, Langaas S. Are agricultural soils dumps for microplastics of urban origin? [J]. Environmental Science & Technology, 2016,50(20):10777-10779.

[94] Meng J, Zhang Q, Zheng Y, et al. Plastic waste as the potential carriers of pathogens [J]. Current Opinion in Food Science, 2021,41:224-230.

[95] Bowley J, Baker-Austin C, Porter A, et al. Oceanic hitchhikers – assessing pathogen risks from marine microplastic [J]. Trends in

Microbiology, 2021,29(2):107−116.

[96] Hsiao T C, Cheng P C, Chi K H, et al. Interactions of chemical components in ambient $PM_{2.5}$ with influenza viruses [J]. Journal of Hazardous Materials, 2022,423:127243.

[97] Zhai Y, Li X, Wang T, et al. A review on airborne microorganisms in particulate matters: composition, characteristics and influence factors [J]. Environment International, 2018,113:74−90.

[98] Liu H, Zhang X, Zhang H, et al. Effect of air pollution on the total bacteria and pathogenic bacteria in different sizes of particulate matter [J]. Environmental Pollution, 2018,233:483−493.

[99] Wang M, Li Q, Shi C, et al. Oligomer nanoparticle release from polylactic acid plastics catalysed by gut enzymes triggers acute inflammation [J]. Nature Nanotechnology, 2023,18(4):403−411.

[100] Peng C, Zhang X, Zhang X, et al. Bacterial community under the influence of microplastics in indoor environment and the health hazards associated with antibiotic resistance genes [J]. Environmental Science & Technology, 2022,56(1):422−432.

[101] Jiang J, Ren H, Wang X, et al. Pollution characteristics and potential health effects of airborne microplastics and culturable microorganisms during urban haze in harbin, China [J]. Bioresource Technology, 2024, 393:130132.

[102] Xu L, Bai X, Li K, et al. Human exposure to ambient atmospheric microplastics in a megacity: spatiotemporal variation and associated microorganism−related health risk [J]. Environmental Science & Technology, 2024,58(8):3702−3713.

[103] Li Y, Liu C, Yang H, et al. Leaching of chemicals from microplastics: a review of chemical types, leaching mechanisms and influencing factors [J]. Science of The Total Environment, 2024,906:167666.

[104] Kesy K, Oberbeckmann S, Kreikemeyer B, et al. Spatial environmental heterogeneity determines young biofilm assemblages on microplastics in baltic sea mesocosms [J]. Frontiers in Microbiology, 2019,10.

[105] Yang Y, Liu G, Song W, et al. Plastics in the marine environment are reservoirs for antibiotic and metal resistance genes [J]. Environment International, 2019,123:79−86.

[106] 吴效俭,施国静,王莹莹.微塑料影响抗性基因的传播与水平基因转移 [J]. 中国环境科学, 2022,42(8):3957−3968.
Wu X J, Shi G J, Wang Y Y. Effects of microplastics on the spread and horizontal gene transfer of antibiotic resistance genes [J]. Chinese Environmental Science, 2022,42(8):3957−3968.

[107] Abe K, Nomura N, Suzuki S. Biofilms: hot spots of horizontal gene transfer (HGT) in aquatic environments, with a focus on a new HGT mechanism [J]. FEMS Microbiology Ecology, 2020,96(5):fiaa031.

[108] Li Z, Junaid M, Chen G, et al. Interactions and associated resistance development mechanisms between microplastics, antibiotics and heavy metals in the aquaculture environment [J]. Reviews in Aquaculture, 2022,14(2):1028−1045.

[109] Imran Md, Das K R, Naik M M. Co−selection of multi−antibiotic resistance in bacterial pathogens in metal and microplastic contaminated environments: an emerging health threat [J]. Chemosphere, 2019,215:846−857.

[110] Sun Y, Wu M, Zang J, et al. Plastisphere microbiome: methodology, diversity, and functionality [J]. iMeta, 2023,2(2):e101.

[111] Dris R, Gasperi J, Tassin B. Sources and fate of microplastics in urban areas: a focus on paris megacity [M]//Wagner M, Lambert S. Freshwater Microplastics: Vol. 58. Cham: Springer International Publishing, 2018:69−83.

[112] Junaid M, Wang J. Interaction of micro(nano)plastics with extracellular and intracellular biomolecules in the freshwater environment [J]. Critical Reviews in Environmental Science and Technology, 2022,52(23):4241−4265.

[113] Bakaraki Turan N, Sari Erkan H, Onkal Engin G. Microplastics in wastewater treatment plants: occurrence, fate and identification [J]. Process Safety and Environmental Protection, 2021,146:77−84.

[114] Jin Y, Xia J, Pan Z, et al. Polystyrene microplastics induce microbiota dysbiosis and inflammation in the gut of adult zebrafish [J]. Environmental Pollution, 2018,235:322−329.

[115] Saley A M, Smart A C, Bezerra M F, et al. Microplastic accumulation and biomagnification in a coastal marine reserve situated in a sparsely populated area [J]. Marine Pollution Bulletin, 2019,146:54−59.

[116] Ma H, Pu S, Liu S, et al. Microplastics in aquatic environments: toxicity to trigger ecological consequences [J]. Environmental Pollution, 2020,261:114089.

[117] 李 雪,罗玉华,李 华,等.水环境中微塑料与微生物的相互作用研究进展 [J]. 中国环境科学, 2024,44(12):6962−6971.
Li X, Luo Y H, LI H, et al. Advances in the study of microplastic−microbial interactions in the aquatic environment [J]. Chinese Environmental Science, 2024,44(12):6962−6971.

[118] Li Y, Tao L, Wang Q, et al. Potential health impact of microplastics: a review of environmental distribution, human exposure, and toxic effects [J]. Environment & Health, 2023,1(4):249−257.

[119] Smith M, Love D C, Rochman C M, et al. Microplastics in seafood and the implications for human health [J]. Current Environmental Health Reports, 2018,5(3):375−386.

[120] Dong H, Chen Y, Wang J, et al. Interactions of microplastics and antibiotic resistance genes and their effects on the aquaculture environments [J]. Journal of Hazardous Materials, 2021,403:123961.

[121] Unuofin J O, Igwaran A. Microplastics in seafood: implications for food security, safety, and human health [J]. Journal of Sea Research, 2023,194:102410.

[122] Jin Y, Lu L, Tu W, et al. Impacts of polystyrene microplastic on the gut barrier, microbiota and metabolism of mice [J]. Science of The Total Environment, 2019,649:308−317.

[123] Yu Y, Flury M. Current understanding of subsurface transport of micro- and nanoplastics in soil [J]. Vadose Zone Journal, 2021,20(2): e20108.

[124] Chiellini E, Corti A, Swift G. Biodegradation of thermally−oxidized, fragmented low−density polyethylenes [J]. Polymer Degradation and Stability, 2003,81(2):341−351.

[125] Nizzetto L, Bussi G, Futter M N, et al. A theoretical assessment of microplastic transport in river catchments and their retention by soils and river sediments [J]. Environmental Science: Processes & Impacts, 2016,18(8):1050−1059.

[126] Rezaei M, Riksen M J P M, Sirjani E, et al. Wind erosion as a driver for transport of light density microplastics [J]. Science of The Total Environment, 2019,669:273−281.

[127]Ran T, Liao H, Zhao Y, et al. Soil plastisphere interferes with soil bacterial community and their functions in the rhizosphere of pepper (*capsicum annuum* l.) [J]. Ecotoxicology and Environmental Safety, 2024,270:115946.

[128]Michielssen M R, Michielssen E R, Ni J, et al. Fate of microplastics and other small anthropogenic litter (SAL) in wastewater treatment plants depends on unit processes employed [J]. Environmental Science: Water Research & Technology, 2016,2(6):1064−1073.

[129]Chaisar M, Garg S K. Selection of sewage treatment technology using analytic hierarchy process [J]. Materials Today: Proceedings, 2022,56: 3433−3440.

[130]Okoffo E D, O'Brien S, O'Brien J W, et al. Wastewater treatment plants as a source of plastics in the environment: a review of occurrence, methods for identification, quantification and fate [J]. Environmental Science: Water Research & Technology, 2019,5(11): 1908−1931.

[131]Koyuncuoğlu P, Erden G. Microplastics in municipal wastewater treatment plants: a case study of denizli/turkey [J]. Frontiers of Environmental Science & Engineering, 2023,17(8):99.

[132]Ahamed T, Brown S P, Salehi M. Investigate the role of biofilm and water chemistry on lead deposition onto and release from polyethylene: an implication for potable water pipes [J]. Journal of Hazardous Materials, 2020,400:123253.

[133]Shen M, Zeng Z, Li L, et al. Microplastics act as an important protective umbrella for bacteria during water/wastewater disinfection [J]. Journal of Cleaner Production, 2021,315:128188.

[134]Kelly J J, London M G, McCormick A R, et al. Wastewater treatment alters microbial colonization of microplastics [J]. PLOS ONE, 2021, 16(1):e0244443.

[135]Metcalf R, White H L, Ormsby M J, et al. From wastewater discharge to the beach: survival of human pathogens bound to microplastics during transfer through the freshwater−marine continuum [J]. Environmental Pollution, 2023,319:120955.

[136]Li C, Wang L, Ji S, et al. The ecology of the plastisphere: microbial composition, function, assembly, and network in the freshwater and seawater ecosystems [J]. Water Research, 2021,202:117428.

[137]Wei F, Xu C, Chen C, et al. Distribution of microplastics in the sludge of wastewater treatment plants in chengdu, china [J]. Chemosphere, 2022,287:132357.

[138]郭梓萌,崔小梅,陈均玉,等.大气中微塑料的研究进展 [J]. 环境化学, 2023,42(12):4079−4092.
Guo X M, Cu X M, Chen J Y, et al. Research progress on atmospheric microplastics [J]. Environmental Chemistry, 2023,42(12):4079−4092.

[139]Jiang K, Zhu J, Su K, et al. Tracing the transport and residence times of atmospheric microplastics using natural radionuclides [J]. Environmental Science & Technology, 2024,58(35):15702−15710.

[140]Allen S, Allen D, Phoenix V R, et al. Atmospheric transport and deposition of microplastics in a remote mountain catchment [J]. Nature Geoscience, 2019,12(5):339−344.

[141]Welsh B, Aherne J, Paterson A M, et al. Atmospheric deposition of anthropogenic particles and microplastics in south−central ontario, Canada [J]. Science of The Total Environment, 2022,835:155426.

[142]Qian J, Tang S, Wang P, et al. From source to sink: review and prospects of microplastics in wetland ecosystems [J]. Science of The Total Environment, 2021,758:143633.

[143]Wang X, Li C, Liu K, et al. Atmospheric microplastic over the south china sea and east indian ocean: abundance, distribution and source [J]. Journal of Hazardous Materials, 2020,389:121846.

[144]Zhang Y, Pu S, Lv X, et al. Global trends and prospects in microplastics research: a bibliometric analysis [J]. Journal of Hazardous Materials, 2020,400:123110.

[145]Li C, Liu J, Rillig M C, et al. What harmful microbes are lurking in the world's 7billion tonnes of plastic waste? [J]. Nature, 2024,634(8032): 30−32.

[146]Zhu L, Li R, Yang K, et al. Quantifying health risks of plastisphere antibiotic resistome and deciphering driving mechanisms in an urbanizing watershed [J]. Water Research, 2023,245:120574.

[147]Wu J, Zhou J H, Liu D F, et al. Phthalates promote dissemination of antibiotic resistance genes: an overlooked environmental risk [J]. Environmental Science & Technology, 2023,57(17):6876−6887.

[148]Ni B, Zhang T L, Cai T G, et al. Effects of heavy metal and disinfectant on antibiotic resistance genes and virulence factor genes in the plastisphere from diverse soil ecosystems [J]. Journal of Hazardous Materials, 2024,465:133335.

[149]Deng Y, Zhang Y, Qiao R, et al. Evidence that microplastics aggravate the toxicity of organophosphorus flame retardants in mice (*Mus musculus*) [J]. Journal of Hazardous Materials, 2018,357:348−354.

[150]Cheng W, Zhou Y, Xie Y C, et al. Combined effect of polystyrene microplastics and bisphenol A on the human embryonic stem cells−derived liver organoids: The hepatotoxicity and lipid accumulation [J]. Science of The Total Environment, 2023,854:158585.

作者简介：丁贺宁(2001−),男,山东济宁人,浙江工商大学硕士研究生,主要从事固废资源化利用与处理处置.发表论文 1 篇. 23020160040@pop.zjgsu.edu.cn.