

肆秩芳华担使命 踔厉扬帆向未来
——庆祝厦门大学环境学科创立40周年



■ 主办 中国科学院生态环境研究中心

■ 出版 科学出版社



2022年11月

第43卷 第11期
Vol.43 No.11

目次

厦门大学环境学科创立 40 周年专栏

新污染物共排放对生态环境监测和管理的挑战	王佩, 黄欣怡, 曹致纬, 吴朝阳, 吕永龙 (4801)
河口-近海环境新污染物的环境过程、效应与风险	王新红, 于晓璇, 王思权, 殷笑晗, 钱韦旭, 林晓萍, 吴越, 刘畅 (4810)
海水痕量营养盐和金属的分子光谱分析方法研究进展	袁东星, 黄勇明, 王婷 (4822)
环境水体中硫化物的分析方法: 从实验室分析到原位监测	李鹏, 林坤德, 袁东星 (4835)
环境水体中无机砷现场分析方法研究进展	薄光永, 陈钊英, 弓振斌, 马剑 (4845)
海洋痕量元素采样技术和分析方法的发展及展望: 厦门大学痕量元素平台建设进展	黄勇明, 周宽波, 陈耀瑾, 张楠, 杨俊波, 戴民汉, 曹知勉, 蔡毅华 (4858)

聚乙烯微塑料的微生物降解研究进展	骆苑蓉, 钱义谦, 齐雅楠 (4869)
水稻土中氮素对微生物固氮的扰动及效应机制	王锋, 张静, 周少余, 王鸿辉, 李建, 赵聪媛, 黄鹏, 陈铮 (4876)
中国海洋生态毒理学研究中的毒性测试生物	史天一, 洪海征, 王明华, 谭巧国, 史大林 (4888)
中国油气系统甲烷逸散排放估算	陈春赐, 吕永龙, 贺桂珍 (4905)
2015 ~ 2020 年厦漳泉地区大气氨排放清单及分布特征	李香, 吴水平, 姜炳祺, 刘怡靖 (4914)
九龙江口微塑料与抗生素抗性基因污染分布特征	程宏, 陈荣 (4924)
厦门湾沙滩沉积物微塑料污染特征	姚蕊, 刘花台, 李永玉, 刘潇雅, 吴海波, 王新红 (4931)
九龙江口-厦门湾海域中溶解态痕量金属的时空分布特征与影响机制	戚柳倩, 岳新利, 钟灏文, 王棋, 王德利, 陈能汪 (4939)
福建省流域-近海溶解氧时空格局与低氧调控机制	杨艾琳, 杨芳, 李少斌, 余其彪, 陈能汪 (4950)
厦门西溪河口沉积物活性磷的分布特征及迁移转化机制	潘峰, 蔡宇, 郭占荣, 王新红 (4961)
改性生物炭固定床对模拟湖水体中 Mn^{2+} 的吸附	赵洁, 叶志隆, 王佳妮, 蔡冠竟 (4971)
基于表面增强拉曼光谱技术的饮用水中痕量恩诺沙星和环丙沙星快速检测	徐婧, 郑红, 卢江龙, 刘国坤 (4982)
紫外驱动高级氧化法降解水体中的磷酸三苯酯	徐子文, 印红玲, 熊远明, 宋娇娇, 谯杨 (4992)

研究报告

2019 年秋季海南省 4 次臭氧污染过程特征及潜在源区分析	符传博, 陈红, 丹利, 徐文帅 (5000)
伊犁河谷夏季 $PM_{2.5}$ 和 PM_{10} 中水溶性无机离子浓度特征和形成机制	陈巧, 谷超, 徐涛, 周春华, 张国涛, 赵雪艳, 吴丽萍, 李新琪, 杨文 (5009)
城区与郊区 $PM_{2.5}$ 污染及传输特征差异性	齐鹏, 周颖, 程水源, 白伟超 (5018)
南京北郊 BTESX 特征及健康风险评估	冯悦政, 安俊琳, 张玉欣, 王俊秀 (5030)
我国陆域水体系统表层水中微塑料生态风险评估	孙晓楠, 陈浩, 贾其隆, 朱奔, 马长文, 叶建峰 (5040)
东江流域不同空间尺度景观格局对水质影响分析	陈优良, 邹文敏, 刘星根, 曾金凤, 李丹, 郑汉奕 (5053)
长江与黄河源丰水期地表水中汞的分布特征、赋存形态及来源解析	刘楠涛, 吴飞, 袁巍, 王训, 王定勇 (5064)
青藏高原湖泊水环境特征及水质评价	刘智琦, 潘保柱, 韩谔, 李刚, 王韬轶 (5073)
基于水化学与硫同位素的卡林型金矿区岩溶水文地球化学特征及控制因素	查学芳, 吴攀, 李学先, 陈世万, 黄家琰, 李清光, 陈思睿 (5084)
丹江口水库真核浮游植物群落分布特征及其与环境因子的关系	贺玉晓, 买思婕, 任玉芬, 李卫国, 赵同谦, 马寅男 (5096)
铜沸石对磷和重金属的吸附与底泥钝化性能	王哲, 朱俊, 李雯, 闫德馨, 董雯, 刘玉玲, 李家科 (5106)
基于宏基因组与宏转录组分析石化废水生物处理系统脱氮功能菌群	章旭, 周佳佳, 周珉, 罗西子, 严新杰, 刘勇弟, 厉巍 (5115)
寒冷地区 IFAS + 磁混凝污水厂菌群结构和抗生素抗性基因分析	杜文琰, 姚俊芹, 马辉英, 胡渊鑫, 张春雷, 陈银广 (5123)
中国旱作农田一氧化氮排放及减排: Meta 分析	田政云, 吴雄伟, 吴媛媛, 魏佳楠, 白鹤, 顾立新 (5131)
硝化抑制剂对我国蔬菜生产产量、氮肥利用率和氧化亚氮减排效应的影响: Meta 分析	刘发波, 马笑, 张芬, 梁涛, 黎亮武, 王军杰, 陈新平, 王孝忠 (5140)
不同施肥措施对热带地区稻菜轮作体系土壤 CH_4 和 N_2O 排放的影响	邵晓辉, 汤水荣, 孟磊, 伍延正, 李金秋, 张广林 (5149)
不同水分条件下土地利用方式对我国热带地区土壤硝化过程及 NO 和 N_2O 排放的影响	唐瑞杰, 胡煜杰, 赵彩悦, 赵炎, 袁新生, 汤水荣, 伍延正, 孟磊 (5159)
基于文献计量分析的长江经济带农田土壤重金属污染特征	刘孝严, 樊亚男, 刘鹏, 吴秋梅, 胡文友, 田康, 黄标 (5169)
基于 EBK 插值预测和 GDM 模型的襄州区耕地土壤重金属时空分布及来源变化分析	高浩然, 周勇, 刘甲康, 程晓明, 郭嵩, 江衍, 谭恒鑫 (5180)
基于 GIS 对宁夏某铜银矿区周边土壤重金属来源解析	张扣扣, 贺婧, 钟艳霞, 魏琪琪, 陈锋 (5192)
老化作用对生物炭钝化白云鄂博矿区碱性土壤中 Cd^{2+} 的影响	王哲, 程俊丽, 卞园, 郑春丽, 王维大, 姜庆宏 (5205)
磁性氧化铁/桑树杆生物炭的制备及其对砷污染土壤溶解性有机碳和砷形态的影响	芦琳, 颜利玲, 梁美娜, 成官文, 朱宗强, 朱义年, 王敦球 (5214)
牡蛎壳粉和石灰改良酸性水稻土对磷有效性、形态和酶活性的影响	赵丽芳, 黄鹏武, 杨彩迪, 卢升高 (5224)
磷、锌和镉交互作用对小白菜生长和锌镉累积的影响	帅祖华, 刘汉燧, 崔浩, 魏世强 (5234)
重庆开州区农地土壤抗生素污染特征及潜在生态环境风险评估	方林发, 叶萃萃, 方标, 范晓霞, 高坤鹏, 李士洋, 陈新平, 肖然 (5244)
基于 InVEST 和 GeoSoS-FLUS 模型的黄河源区碳储量时空变化特征及其对未来不同情景模式的响应	侯建坤, 陈建军, 张凯琪, 周国清, 尤号田, 韩小文 (5253)
黄土丘陵区不同恢复植被类型的固碳特征	许小明, 张晓萍, 何亮, 郭晋伟, 薛帆, 邹亚东, 易海杰, 贺洁, 王浩嘉 (5263)
土壤多功能性对微生物多样性降低的响应	陈桂鲜, 吴传发, 葛体达, 陈剑平, 邓扬悟 (5274)
氮添加对不同坡度退化高寒草甸土壤真菌多样性的影响	苏晓雪, 李希来, 李成一, 孙华方 (5286)
碳减排背景下我国与世界主要能源消费国能源消费结构与模式对比	李辉, 庞博, 朱法华, 孙雪丽, 徐静馨, 王圣 (5294)
中国能源消费碳排放的空间化与时空动态	郝瑞军, 魏伟, 刘春芳, 颜斌斌, 杜海波 (5305)
京津冀及周边地区“2+26”城市结构性调整政策的 CO_2 协同减排效益评估	杨添祺, 王洪昌, 张辰, 朱金伟, 崔宇韬, 谭玉玲, 束轲 (5315)
我国塑料污染防治政策分析与建议	李欢, 朱龙, 沈茜, 贺亚楠, 邓义祥, 安立会 (5326)

聚乙烯微塑料的微生物降解研究进展

骆苑蓉^{1,2}, 钱义谦¹, 齐雅楠¹

(1. 厦门大学环境与生态学院, 滨海湿地生态系统教育部重点实验室, 厦门 361102; 2. 厦门大学环境与生态学院, 福建省海陆界面生态环境重点实验室, 厦门 361102)

摘要: 现代工业的发展使得塑料制品的使用量急剧增加, 由此产生的大量废旧塑料垃圾在环境中裂解形成粒径更小的微塑料 (< 5 mm). 由于微塑料结构稳定, 分布广泛且生物可利用性低, 在环境中长期存在, 已经逐渐成为对海洋生态和环境造成巨大影响的重要污染物. 近年的研究表明, 自然环境中存在一些能降解这些难降解微塑料的微生物, 微生物降解无二次污染且对环境扰动少, 在微塑料的去除中具有很好地应用潜力, 但亦有一些局限性. 综述了环境中数量最多的聚乙烯微塑料的微生物降解研究现状, 着重探讨了降解效果和量化方法. 基于微塑料生物分解效率普遍较低现状, 开展进一步的研究还非常有必要.

关键词: 塑料垃圾; 微塑料; 聚乙烯 (PE); 生物降解; 表征方法

中图分类号: X172 文献标识码: A 文章编号: 0250-3301(2022)11-4869-07 DOI: 10.13227/j.hjxx.202206017

Biodegradation of Polyethylene Microplastic: A Review

LUO Yuan-rong^{1,2}, QIAN Yi-qian¹, QI Ya-nan¹

(1. Key Laboratory of Ministry of Education for Coast and Wetland Ecosystems, College of the Environment and Ecology, Xiamen University, Xiamen 361102, China; 2. Fujian Provincial Key Laboratory for Coastal Ecology and Environmental Studies, College of the Environment and Ecology, Xiamen University, Xiamen 361102, China)

Abstract: Over the recent decades, global plastic production has grown dramatically due to the huge demands of consumption. As a consequence, large amounts of plastic waste have accumulated in the environment and will be cleaved into microplastics. Due to the low bioavailability, the microplastics will exist in the environment persistently and cause massive environmental stress. Plastic pollution is currently one of the biggest environmental concerns. Recent studies have shown the possibility to obtain degrading microorganisms of microplastics from the natural environment. Some microorganisms can break down microplastics into water and carbon dioxide. This paper reviewed the current research on biodegradation of polyethylene (PE), which is the most abundant microplastic type in the environment, and discussed the quantification methods of the degradation effect. Given that current biodegradation efficiency is relatively limited, further research is required.

Key words: plastic waste; microplastics; polyethylene (PE); biodegradation; quantification method

现代工业的发展使得塑料制品的使用急剧增加, 全球塑料的产量从 1950 年的 150 t 剧增到 2020 年的 3.67 亿 t^[1], 由此也造成了大量废旧塑料垃圾的产生. 这些合成多聚物由于其化学结构稳定而难以被降解, 在环境中经过风吹日晒而裂解, 形成稳定的小颗粒, 一般把直径 5 mm 以下的塑料碎片、颗粒和纺织纤维统称为微塑料 (microplastics). 微塑料污染已经成为一个全球性的环境问题.

聚乙烯 (polyethylene, PE) 是全球生产量最高的塑料^[2], 主要用途包括制作薄膜、包装材料和电线电缆等, 它是一种以乙烯为原料聚合加工得到的热塑性树脂材料, 其结构式为: $-\text{[CH}_2\text{—CH}_2\text{]}_n\text{—}$. 根据聚合方法、相对分子质量和碳链结构的不同, 聚乙烯可分为低密度聚乙烯 (low density polyethylene, LDPE)、高密度聚乙烯 (high density polyethylene, HDPE)、线性低密度聚乙烯 (linear low density polyethylene, LLDPE) 和低分子量聚乙烯 (low molecular weight polyethylene, LMWPE) 等.

合成塑料的产生, 仅有不到 80 年的历史, 原来普遍认为尚不足以进化出能降解塑料的微生物或

酶, 近年来有报道则显示自然环境中存在着对塑料具有降解能力的微生物. 尽管分解速率缓慢, 但已有研究预示从自然环境中获得原本认为难以降解的塑料的降解微生物是可能的. 由于反应条件温和且产物无污染, 微生物降解逐渐被认为是可行的处理微塑料的方法^[3]. 本文综述了当前生物降解 PE 的研究现状, 总结和分析 PE 降解菌株的种类、来源和降解机制并讨论了降解效果的量化方法, 以期科学评估微塑料降解效果及微塑料污染去除提供参考.

1 PE 生物降解效果的表征

由于 PE 的结构特性, 生物可利用率较低, 现有降解菌普遍分解缓慢, 降解现象不够明显. 为了确定微生物对 PE 的生物降解程度, 一方面可通过监测微生物在以 PE 作为唯一碳源生长时的生长动力学变化, 来判断对 PE 的降解能力; 另一方面通过分析 PE 材料的性质变化, 如表面官能团变化、机械性

收稿日期: 2022-06-01; 修订日期: 2022-07-04

基金项目: 国家自然科学基金国际合作与交流项目 (41961144011); 中央高校基本科研业务费专项 (20720190093)

作者简介: 骆苑蓉 (1979 ~), 女, 博士, 副教授, 主要研究方向为有机污染物微生物降解与修复, E-mail: lyr@xmu.edu.cn

能、表面形貌、疏水性/亲水性、相对分子质量分布和降解产物等,评价生物降解的效果^[4]. 目前常用的方法包括观察法、失重法、CO₂生成量法、傅里叶变换红外光谱仪(fourier transform infrared spectrometer, FTIR)法、凝胶渗透色谱(gel permeation chromatography, GPC)法和气相色谱-质谱联用(gas chromatograph-mass spectrometer, GC-MS)法等,以上方法也可以从定性和定量两种角度进行区分.

1.1 定性法

1.1.1 显微镜观察法

观察法通常使用原子力显微镜(atomic force microscope, AFM)和扫描电子显微镜(scanning electronic microscope, SEM)两种仪器. AFM可观察微生物降解前后PE本身材质的变化,包括空洞、凹坑的出现和粗糙度的变化等;SEM在此基础上还可观察微生物在PE表面的定殖情况,如生物膜的形成和细胞形态大小等. 因此通过与对照组比较,根据PE的变化和微生物的定殖情况,能够直观地判断接种微生物后PE表面是否发生降解现象.

Zahra等^[5]通过SEM发现培养100 d后 *Aspergillus fumigatus* 和 *A. terreus* 这2株真菌在紫外线照射后的LDPE膜表面形成了明显的生物膜. Esmaeili等^[6]的研究也显示, *A. niger* F1与预先照射紫外线的LDPE膜共培养后,SEM显示其菌丝黏附并穿透紫外线照射的LDPE膜表面. 同一研究中细菌 *Lysinibacillus xylanilyticus* S7-10F也在LDPE膜表面形成了生物膜. Awasthi等^[7]通过SEM图像观察到,菌株 *Klebsiella pneumoniae* CH001培养60 d后HDPE膜表面粗糙,有许多裂缝和凹槽,而对照组则保持光滑,AFM图像也观察到表面拓扑结构的类似变化,证明该菌株能够利用PE并形成凹槽. Auta等^[8]接种 *Bacillus* 属细菌与PE粉末共培养40 d后,PE表面变得粗糙并出现许多孔洞、侵蚀、裂缝和凹槽. Yang等^[9]观察到在经高压灭菌的LDPE膜表面生长的 *Enterobacter asburiae* YT1和 *Bacillus* sp. YP1分别为0.2 μm × 0.8 μm的棒状细胞和0.5 μm × 3 μm的不规则短棒状细胞.

1.1.2 FTIR法

FTIR法是利用傅里叶变换红外光谱仪检测微生物处理前后PE样品差异,通过官能团对应的吸收峰的变化判断PE结构是否因聚合物链断裂或氧化产物形成发生变化.

Skariyachan等^[10]在3 375.46 cm⁻¹处发现了由于C—H键断裂形成的额外的峰,认为可能是由于生物降解导致的长链烃的分解. 经 *Aspergillus flavus*

PEDX3处理后的HDPE微塑料颗粒与对照样品相比,在3 500 ~ 3 100 cm⁻¹范围内出现对应羟基(—OH)的宽吸收峰,还在1 113 cm⁻¹和1 647 ~ 1 716 cm⁻¹处分别出现对应醚基(C—O—C)和羰基(—C=O)的吸收峰,3种官能团的出现为HDPE微塑料颗粒的生物氧化提供了证据^[11]. Skariyachan等^[12]报道了处理后LDPE条由于羰基的形成在光谱的1 700 cm⁻¹和1 600 cm⁻¹处出现新的吸收峰. Chen等^[13]利用衰减全反射红外光谱(ATR-FTIR)和光谱图像对在自然环境中暴露的PE降解程度进行建模分析,结果表明可利用1 720 cm⁻¹处的羰基指数表征降解程度,为预测原位暴露微塑料降解程度提供有效帮助. 而随着生物降解的进行,氧化聚合物被微生物利用,羰基指数也将降低^[14]. 因此使用FTIR检测羰基峰的形成对阐明PE降解机制有着重要的作用^[15].

1.1.3 GPC法

GPC法通过测定数均相对分子质量(M_n)、重均相对分子质量(M_w)和相对分子质量分布(MWD),反映PE相对分子质量的变化,根据相对分子质量的损失判断PE长链结构是否解聚.

Yamada-Onodera等^[16]通过3个月对PE相对分子质量的监测验证了 *Penicillium simplicissimum* YK对PE的降解作用,当用热硝酸处理过的PE作为唯一碳源时,相对分子质量高于100 000的PE会被真菌降解为较低的相对分子质量. Zhang等^[11]利用高温凝胶等效色谱(HT-GPC)对经 *Aspergillus flavus* PEDX3处理过的HDPE微塑料颗粒样品进行检测发现,与对照样品的相对分子质量($M_w = 222\ 003$ 和 $M_n = 55\ 135$)相比,处理后样品的 M_w (89 801)和 M_n (26 064)分别下降了132 202和29 069,差异明显. 同样的,用菌株 *Enterobacter asburiae* YT1和 *Bacillus* sp. YP1培养的PE样品使用HT-GPC测定培养60 d后的相对分子质量(M_w/M_n)和相对分子质量分布(MWD),与对照相比,显示出明显的负趋势. 二者培养的PE样品 M_w/M_n 分别为82 500/24 700和78 200/23 900,降解组与对照相比减少了6% ~ 13%^[9]. 然而值得注意的是,降解现象的发生也可能导致相对分子质量增加,这是由于降解菌株优先降解PE样品中低相对分子质量的部分,致使剩下的PE样品的相对分子质量因生物降解而增加^[17,18].

1.1.4 GC-MS法

GC-MS法是利用气相色谱-质谱联用仪对PE降解过程中的代谢产物进行分析.

Albertsson等^[18]利用 *Arthrobacter paraffineus* 降

解高温处理后的 LDPE 膜, 3.5 a 后对照组(非生物降解样品)中检测出一元和二元羧酸和酮酸的同系物, 而这些产物在生物降解样品中则完全被吸收, 只发现疑似醇类的物质. Abraham 等^[19]用曲霉菌处理 LDPE 膜, 90 d 后 LDPE 膜上鉴定出烷烃、芳香烃、饱和脂肪酸和不饱和脂肪酸等无毒化合物. Ambika 等^[20]利用气相色谱法洗脱大量挥发性和半挥发性化合物, GC-MS 分析鉴定了 *Achromobacter Denitrificans* s1 对 LDPE 的降解产物包括醛、酮、酯和羧酸. 分别对经 *Alternaria alternata* FB1 处理 60 d 和 120 d 的 PE 膜进行检测, 结果表明处理 60 d 的样品产物碳数范围在 12 ~ 30 之间, 主要产物碳数为 27, 占比为 51.24%, 而时间延长到 120 d 后产物碳数在 3 ~ 27 之间, 具有 4 个碳的二甘醇胺是 *Alternaria alternata* FB1 降解 PE 膜的主要产物, 占有产物的 93.28%^[3].

1.2 定量法

1.2.1 失重法

通过测定 PE 材料在微生物降解前后的质量损失, 并与对照进行比较, 可以直观地以百分比判断微生物对 PE 的降解效果, 有利于横向比较不同菌株的降解能力, 失重法是目前使用较多的一种方法.

将 *Bacillus subtilis* 接种在经紫外线照射且加入表面活性剂的 PE 膜上, 30 d 内减重 9.26%^[21]. 菌株 *Pseudomonas* sp. AKS2 可直接降解未经预处理的 LDPE 膜, 45 d 内可降解(5 ± 1)% 的原始材料, 若添加矿物油改变疏水性, 效果增强至(14 ± 1)%^[22]. 在 15 d 的培养过程中, 接种 *Streptomyces albobrisesolus* LBX-2 菌株的 PE 粉末的重量损失显著增加. 此外, LBX-2 对低相对分子质量的 PE 粉末降解效果更好^[23]. 若是在同一实验体系内, 由于降解对象的初始状态且培养条件相同, 失重法是比较不同降解菌株降解效果的最简单直接的方法. 如对于 HDPE 的降解, *Pseudomonas* sp. (15%) 比 *Arthrobacter* sp. (12%) 表现出更好的降解效果^[24]. Devi 等^[25]从沿海塑料垃圾倾倒地区土壤中分离出 248 株细菌并运用失重法进行比较, 最终得到了 10 株有效的 HDPE 降解菌.

1.2.2 CO₂ 生成量法

结合已有研究可知, 微生物不论是好氧还是厌氧降解 PE, CO₂ 的产生都是 PE 被完全降解的标志. 有研究通过测量 CO₂ 产生量来表征降解效果. Shah 等^[26]测定 *Fusarium* sp. AF4 降解 PE 膜, 4 周后 CO₂ 产量为 1.85 g·L⁻¹, 显著高于空白对照的 0.45 g·L⁻¹. Abraham 等^[19]的研究显示, *Aspergillus*

nomius JAPE1 和 *Streptomyces* sp. AJ1 降解 LDPE, 4 周后的 CO₂ 产生量则分别为 2.85 g·L⁻¹ 和 4.27 g·L⁻¹.

定性法可以直观地表现微生物的生长或 PE 的表形变化, 但是判断某一菌株是否为 PE 降解菌, 通常需要多种方法确认. 且由于定性法难以量化, 无法对不同降解菌的降解能力进行横向比较. 定量法虽然可以在同一体系中针对不同降解菌的降解能力进行比较, 但由于降解对象本身质量很轻, 操作过程中易造成较大误差, 且不同体系使用的 PE 材质不同(是否含有添加剂)、反应条件不同(温度、时间), 无法简单地凭借重量的失去判断降解能力地强弱. 因此 PE 降解菌降解能力的量化仍然比较困难. 降解效果的表征虽然可以直观体现降解菌对 PE 的降解能力, 表征 PE 的生物降解尚需要几种方法结合, 如 SEM 结合失重和 FTIR 法, 从微生物的生长状态结合 PE 材料的变化, 较全面地评价降解菌对 PE 的降解能力.

2 PE 的微生物降解

PE 的微生物降解最早可追溯到 20 世纪 70 年代, 通过检测 CO₂ 的生成, 发现由 C₁₄ 标记合成的 PE 能被微生物成功降解, 并最终矿化为 CO₂ 和 H₂O, 但是过程极为缓慢^[27]. 近年来, 相继有不同的研究从土壤、海洋和昆虫肠道等生境中筛选出对 PE 具有降解能力的微生物^[25, 28], 表 1 和表 2 分别归纳了目前为止报道的 PE 降解细菌和降解真菌类群. 如表中所示, 已筛选出的 PE 降解细菌分属 4 个门, 其中变形菌门 γ-变形菌纲和放线菌门放线菌纲所包含的降解菌种类最多. 相较于细菌, 真菌对于 PE 的降解速率似乎更高^[29]. 真菌能以菌丝体结构在不同基质上生长, 延伸到其他微生物难以生长的地方^[2, 30], 成为真菌降解 PE 的优势之一^[4]. 已报道的 PE 降解真菌分属于囊菌门和担子菌门下共 4 个纲, 包括链格孢菌、曲霉菌、镰孢菌和青霉菌等多个属, 其中与曲霉菌相关的研究较多.

Harshvardhan 等^[37]从阿拉伯海沿岸海水中分离出 60 株海洋细菌并从中筛选出 3 株(*Kocuria palustris* M16、*Bacillus pumilus* M27 和 *Bacillus subtilis* H1584)能够在以 PE 为唯一碳源的培养基中生长的菌株, 30 d 共培养后, PE 失重分别为 1%、1.5% 和 1.75%, FTIR 光谱也显示了酯、酮、乙烯基和内部双键的形成. Sangale 等^[46]在印度西海岸红树林根际土壤中得到的 109 株真菌中, 从重量变化和拉伸强度变化两个角度, 在不同 pH 条件下筛选出了 *Aspergillus terreus* MANGF1/WL (pH = 9.5) 和

表 1 PE 降解细菌类群

Table 1 Bacterial taxa capable of PE degradation

类群	降解菌	文献
变形菌门 (Proteobacteria)	β -变形菌纲 (β -Proteobacteria)	无色杆菌 (<i>Achromobacter</i>)、丛毛单胞菌 (<i>Comamonas</i>) 和代尔夫特菌 (<i>Delftia</i>) [31,32]
	γ -变形菌纲 (γ -Proteobacteria)	不动杆菌 (<i>Acinetobacter</i>)、食碱菌 (<i>Alcanivorax</i>)、肠杆菌 (<i>Enterobacter</i>)、微泡菌 (<i>Microbulbifer</i>)、寡养单胞菌 (<i>Stenotrophomonas</i>) 和假单胞菌 (<i>Pseudomonas</i>) [9,22,24,25,32~35]
厚壁菌门 (Firmicutes)	芽孢杆菌纲 (Bacilli)	芽孢杆菌 (<i>Bacillus</i>) 和赖氨酸芽孢杆菌 (<i>Lysinibacillus</i>) [9,21,25,36~39]
放线菌门 (Actinobacteria)	放线菌纲 (Actinomycetia)	节杆菌 (<i>Arthrobacter</i>)、考克氏菌 (<i>Kocuria</i>) 和诺卡氏菌 (<i>Nocardia</i>)、红球菌 (<i>Rhodococcus</i>)、链霉菌 (<i>Streptomyces</i>) 和 <i>Leucobacter</i> [25,25,37,40]
拟杆菌门 (Bacteroidetes)	鞘脂杆菌纲 (Sphingobacteriia)	鞘氨醇杆菌 (<i>Sphingobacterium</i>) [35]

表 2 PE 降解真菌类群

Table 2 Fungal taxa capable of PE degradation

类群	降解菌属	文献
子囊菌门 (Ascomycota)	座囊菌纲 (Dothideomycetes)	链格孢菌 (<i>Alternaria</i>) 和毛色二孢菌 (<i>Lasiodiplodia</i>) [3,41]
	散囊菌纲 (Eurotiomycetes)	曲霉菌 (<i>Aspergillus</i>)、青霉菌 (<i>Penicillium</i>) 和拟青霉菌 (<i>Paecilomyces</i>) [5,6,11,14,19,29,41~47]
	粪壳菌纲 (Sordariomycetes)	镰孢菌 (<i>Fusarium</i>)、 <i>Purpureocillium</i> 、木霉菌 (<i>Trichoderma</i>)、炭角菌 (<i>Xylaria</i>) 和 <i>Zalerion</i> [5,35,37,41,43,48,49]
担子菌门 (Basidiomycota)	伞菌纲 (Agaricomycetes)	<i>Phanerodontia</i> 、 <i>Phlebiopsis</i> 和裂褶菌 (<i>Schizophyllum</i>) [50]

Aspergillus sydowii PNP15/TS (pH = 3.5) 两株 PE 降解真菌. 相较于海洋环境, 更多的 PE 降解菌筛选自土壤环境. Watanabe 等^[38] 从田地土壤中筛选到 3 株能够降解 LDPE 的菌株, 分别属于 *Bacillus circulans*、*B. brevis* 和 *B. sphaericus*. Muhonja 等^[29] 从富含塑料垃圾的土壤中分离具有 LDPE 降解能力的细菌和真菌, 培养 16 周后, 其中曲霉菌 (*Aspergillus oryzae* A5,1) 对 LDPE 膜的降解效率最高, 减重 $(36.4 \pm 5.53)\%$. Soleimani 等^[40] 从含有塑料垃圾的城市垃圾填埋场土壤中筛选可降解 LDPE 膜的放线菌, 获得链霉菌属 (*Streptomyces*)、诺卡氏菌属 (*Nocardia*) 和红球菌属 (*Rhodococcus*) 这 3 个属共 17 株降解菌, 其中以链霉菌降解效果更好, 经 60 d 培养, *Streptomyces* sp. IR-SGS-T10 对 LDPE 膜重量降低速率为 $1.58 \text{ mg} \cdot (\text{g} \cdot \text{d})^{-1}$. Hou 等^[51] 从污水处理厂长期受塑料污染的活性污泥和废水中分离到 54 株能以 PE 农用地膜为唯一碳源进行生长的细菌, 其中两株假单胞菌 (*Pseudomonas knackmussii* N1-2 和 *P. aeruginosa* RD1-3) 能有效降解 PE 地膜, 在 8 周的培养周期中, PE 地膜分别失重 $(5.95 \pm 0.03)\%$ 和 $(3.62 \pm 0.32)\%$. 此外, 昆虫肠道也是一个特殊的筛选来源. Yang 等^[9] 以 PE 作为唯一碳源在食用 PE 膜的印度谷螟幼虫肠道中分离

出 *Bacillus* sp. YP1 和 *Enterobacter asburiae* YT1 两株细菌, 共培养 28 d 后 LDPE 膜的物理性能、化学结构和相对分子质量等均发生改变. Zhang 等^[11] 将从蜡蛾肠道分离出的 *Aspergillus flavus* PEDX3 与 HDPE 微塑料共培养 28 d 后, FTIR 检测到新的官能团出现, 相对分子质量降低, 且两个与降解相关的基因表达上调.

有研究表明, 将 PE 膜进行预处理, 如紫外线照射或添加表面活性剂, 可以增强降解菌对 PE 的降解效果. 这是由于紫外线可以使聚乙烯链发生解聚, 生成烷烃、烯烃、酮、醛等低相对分子质量产物^[9], 而表面活性剂可以提高 PE 的水溶性, 从而提高它的生物可利用性. Montazer 等^[35] 以紫外线处理过的 LDPE 膜为降解对象, 利用 *Sphingobacterium multivourum* IRN11 和 *Acinetobacter pittii* IRN19 对其进行降解, 结果表明二者均可在 LDPE 膜表面产生表面活性剂并定殖, 培养 4 周后 *Acinetobacter pittii* IRN19 降解了 $(26.8 \pm 3.04)\%$ 的 PE 薄膜. Dwicania 等^[52] 发现将铜绿假单胞菌 (*Pseudomonas aeruginosa*) 和短杆菌 (*Brevibacterium* sp.) 混合培养, 在 25℃, pH = 7 的条件下, 30 d 后失重测定, 去除了 2% ~ 7% 的经紫外线预处理的 LLDPE. Sowmya 等^[49] 比较了 PE 膜经高压灭菌、膜表面消毒和紫外

线照射 3 种处理后,木霉菌(*Trichoderma harzianum*) 对其的降解效果,3 个月后该菌株对这 3 种处理的 PE 的降解效率分别是 23%、13% 和 40%,其中漆酶和锰过氧化物酶 2 种降解酶的活性在第 10 周达到最高.将 LDPE 片和 HDPE 片预先用表面活性剂 Tween-80 处理,再经 *Penicillium oxalicum* NS4 和 *Penicillium chrysogenum* NS10 降解,取得较好的降解效果,90 d 后菌株 NS4 对 LDPE 和 HDPE 的降解率分别为 36.60% 和 55.34%,菌株 NS10 的降解率为 34.35% 和 58.60%^[14].

3 PE 生物降解影响因子和降解机制

PE 的生物降解受化合物、微生物和环境因子这 3 方面的影响.从化合物角度,PE 的分子量、表面官能团(羰基、酯、乙烯基和碳碳双键)组成和疏水/亲水性等影响其生物可利用性,一般来说带氧化基团和亲水性较好的 PE 更易被微生物降解^[53].从微生物角度,微生物能否顺利在 PE 表面定殖,形成生物膜,并分泌相应的酶对降解至关重要.而温度、pH 和培养时间等因素则影响 PE 的微生物降解效率.

微塑料 PE 的微生物降解通常包括 4 个阶段^[3,4,29,50,54]: 劣化(deterioration)、解聚(depolymerization)、同化(assimilation)和矿化(mineralization).劣化阶段是指 PE 在外因作用下(如紫外线照射或微生物分泌的胞外酶)物理化学性质发生改变^[55,56],在此过程中引入羰基,随后被氧化形成羧酸^[54,57];解聚阶段 PE 在微生物分泌的特定酶的作用下进一步被分解成低聚物、二聚体和单体,即易于吸收的低相对分子质量的片段^[2,58];这些解聚产物中的一些水溶性短链中间体被受体识别,跨膜转运到微生物体内参与多种代谢活动,并将这些物质代谢为碳或能量来源^[3,56],该过程被称为同化;最终微生物通过有氧或无氧代谢将这些短链低相对分子质量化合物转化为 CO₂、H₂O 和 CH₄ 从细胞中排出,由此产生的能量供给细胞生长^[55,56,59].由此可见,劣化和解聚是 PE 降解的重要步骤,只有特定的微生物才能分泌相应的降解相关酶类,以达到降解的目的.目前已报道的参与劣化与解聚阶段的 PE 降解酶类群包括^[11,60-64]:单加氧酶(如烷烃单加氧酶)、过氧化物酶(锰过氧化物酶、大豆过氧化物酶和谷胱甘肽过氧化物酶等)和漆酶等. Jeon 等^[65]发现烷烃单加氧酶基因直接参与热解制备的低分子量 PE 的生物降解,而红氧还蛋白酶和红氧还蛋白还原酶通过相关电子的转移间接参与. Santo 等^[61]发现从 *Rhodococcus ruber* C208 中分离出的漆

酶具有高热稳定性和铜诱导性,与 PE 共培养两周后,羰基指数增加且 PE 分子量减少,证明漆酶参与了劣化与解聚过程. Zhao 等^[66]使用大豆过氧化物酶对 HDPE 进行改性,在处理过的 HDPE 表面检测到羟基和羰基基团,表明酶的处理显著增加了材料亲水性.

尽管在 PE 的微生物降解机制方面已经有研究,但总体而言,当前的研究还不够深入,对于降解中间产物的产生和微生物利用途径仍然未知.

4 结论与展望

相对分子质量高、疏水性强和化学性质稳定等特点使环境中的微塑料难以自行降解,尽管越来越多的 PE 降解菌被筛选出,但是由于降解现象不明显和分解速率普遍比较缓慢等原因,降解菌的筛选难度还比较大,本文认为,在降解菌筛选方法上可以进行适当的改进,如原位环境的定向驯化、稳定同位素探针技术(stable isotope probe, SIP)结合实验室培养和基于合成微生物组的高效降解菌群构建等方法,可以提高从环境中分离降解菌的效率.此外,对 PE 降解菌的特性研究、降解条件的优化和降解机制的研究,对于提高降解菌的降解效率,并为其成为潜在的修复菌源也具有很重要的意义.综上,进一步开展对 PE 具有高效降解能力的微生物筛选和特异性研究仍然很有必要.

参考文献:

- [1] Europe Plastic. Plastics-the Facts 2021 An analysis of European plastics production, demand and waste data [R]. Brussels: Association of Plastic Manufacturers, 2022.
- [2] Cowan A R, Costanzo C M, Benham R, et al. Fungal bioremediation of polyethylene: challenges and perspectives[J]. Journal of Applied Microbiology, 2022, 132(1): 78-89.
- [3] Gao R R, Liu R, Sun C M. A marine fungus *Alternaria alternata* FBI efficiently degrades polyethylene[J]. Journal of Hazardous Materials, 2022, 431, doi: 10.1016/j.jhazmat.2022.128617.
- [4] Sen S K, Raut S. Microbial degradation of low density polyethylene (LDPE): a review[J]. Journal of Environmental Chemical Engineering, 2015, 3(1): 462-473.
- [5] Zahra S, Abbas S S, Mahsa M T, et al. Biodegradation of low-density polyethylene (LDPE) by isolated fungi in solid waste medium[J]. Waste Management, 2010, 30(3): 396-401.
- [6] Esmacili A, Pourbabae A A, Alikhani H A, et al. Colonization and biodegradation of photo-oxidized low-density polyethylene (LDPE) by new strains of *Aspergillus* sp. and *Lysinibacillus* sp [J]. Bioremediation Journal, 2014, 18(3): 213-226.
- [7] Awasthi S, Srivastava P, Singh P, et al. Biodegradation of thermally treated high-density polyethylene (HDPE) by *Klebsiella pneumoniae* CH001 [J]. 3 Biotech, 2017, 7(5), doi: 10.1007/s13205-017-0959-3.
- [8] Auta H S, Emenike C U, Fauziah S H. Screening of *Bacillus* strains isolated from mangrove ecosystems in Peninsular Malaysia for microplastic degradation[J]. Environmental Pollution, 2017,

- 231**: 1552-1559.
- [9] Yang J, Yang Y, Wu W M, *et al.* Evidence of polyethylene biodegradation by bacterial strains from the guts of plastic-eating waxworms[J]. *Environmental Science & Technology*, 2014, **48** (23): 13776-13784.
 - [10] Skariyachan S, Patil A A, Shankar A, *et al.* Enhanced polymer degradation of polyethylene and polypropylene by novel thermophilic consortia of *Brevibacillus* sps. and *Aneurinibacillus* sp. screened from waste management landfills and sewage treatment plants[J]. *Polymer Degradation and Stability*, 2018, **149**: 52-68.
 - [11] Zhang J Q, Gao D L, Li Q H, *et al.* Biodegradation of polyethylene microplastic particles by the fungus *Aspergillus flavus* from the guts of wax moth *Galleria mellonella*[J]. *Science of the Total Environment*, 2020, **704**, doi: 10.1016/j.scitotenv.2019.135931.
 - [12] Skariyachan S, Setlur A S, Naik S Y, *et al.* Enhanced biodegradation of low and high-density polyethylene by novel bacterial consortia formulated from plastic-contaminated cow dung under thermophilic conditions[J]. *Environmental Science and Pollution Research*, 2017, **24**(9): 8443-8457.
 - [13] Chen X, Xu M, Yuan L M, *et al.* Degradation degree analysis of environmental microplastics by micro FT-IR imaging technology [J]. *Chemosphere*, 2021, **274**, doi: 10.1016/j.chemosphere.2021.129779.
 - [14] Ojha N, Pradhan N, Singh S, *et al.* Evaluation of HDPE and LDPE degradation by fungus, implemented by statistical optimization[J]. *Scientific Reports*, 2017, **7**, doi: 10.1038/srep39515.
 - [15] Selke S, Auras R, Nguyen T A, *et al.* Evaluation of biodegradation-promoting additives for plastics [J]. *Environmental Science & Technology*, 2015, **49** (6): 3769-3777.
 - [16] Yamada-Onodera K, Mukumoto H, Katsuyaya Y, *et al.* Degradation of polyethylene by a fungus, *Penicillium simplicissimum* YK [J]. *Polymer Degradation and Stability*, 2001, **72**(2): 323-327.
 - [17] Jeon H J, Kim M N. Isolation of a thermophilic bacterium capable of low-molecular-weight polyethylene degradation [J]. *Biodegradation*, 2013, **24**(1): 89-98.
 - [18] Albertsson A C, Erlandsson B, Hakkarainen M, *et al.* Molecular weight changes and polymeric matrix changes correlated with the formation of degradation products in biodegraded polyethylene [J]. *Journal of Environmental Polymer Degradation*, 1998, **6** (4): 187-195.
 - [19] Abraham J, Ghosh E, Mukherjee P, *et al.* Microbial degradation of low density polyethylene [J]. *Environmental Progress & Sustainable Energy*, 2017, **36**(1): 147-154.
 - [20] Ambika D K, Lakshmi B K M, Hemalatha K P J. Degradation of low density polythene by *Achromobacter denitrificans* strain S1, a novel marine isolate [J]. *International Journal of Recent Scientific Research*, 2015, **6**(7): 5454-5464.
 - [21] Vimala P P, Mathew L. Biodegradation of polyethylene using *Bacillus subtilis* [J]. *Procedia Technology*, 2016, **24**: 232-239.
 - [22] Tribedi P, Sil A K. Low-density polyethylene degradation by *Pseudomonas* sp. AKS2 biofilm[J]. *Environmental Science and Pollution Research*, 2013, **20**(6): 4146-4153.
 - [23] Shao H H, Chen M J, Fei X T, *et al.* Complete genome sequence and characterization of a polyethylene biodegradation strain, *Streptomyces Albogriseolus* LBX-2 [J]. *Microorganisms*, 2019, **7**(10), doi: 10.3390/microorganisms7100379.
 - [24] Balasubramanian V, Natarajan K, Hemambika B, *et al.* High-density polyethylene (HDPE)-degrading potential bacteria from marine ecosystem of Gulf of Mannar, India [J]. *Letters in Applied Microbiology*, 2010, **51**(2): 205-211.
 - [25] Devi R S, Ramya R, Kannan K, *et al.* Investigation of biodegradation potentials of high density polyethylene degrading marine bacteria isolated from the coastal regions of Tamil Nadu, India[J]. *Marine Pollution Bulletin*, 2019, **138**: 549-560.
 - [26] Shah A A, Hasan F, Hameed A, *et al.* Isolation of *Fusarium* sp. AF4 from sewage sludge, with the ability to adhere the surface of Polyethylene [J]. *African Journal of Microbiology Research*, 2009, **3**(10): 658-663.
 - [27] Albertsson A C. Biodegradation of synthetic polymers. II. A limited microbial conversion of ^{14}C in polyethylene to $^{14}\text{CO}_2$ by some soil fungi[J]. *Journal of Applied Polymer Science*, 1978, **22**(12): 3419-3433.
 - [28] Pathak V M, Navneet. Review on the current status of polymer degradation: a microbial approach [J]. *Bioresources and Bioprocessing*, 2017, **4**(1), doi: 10.1186/s40643-017-0145-9.
 - [29] Muhonja C N, Makonde H, Magoma G, *et al.* Biodegradability of polyethylene by bacteria and fungi from Dandora dumpsite Nairobi-Kenya[J]. *PLoS One*, 2018, **13**(7), doi: 10.1371/journal.pone.0198446.
 - [30] Sánchez C. Fungal potential for the degradation of petroleum-based polymers: an overview of macro-and microplastics biodegradation[J]. *Biotechnology Advances*, 2020, **40**, doi: 10.1016/j.biotechadv.2019.107501.
 - [31] Kowalczyk A, Chyc M, Ryszka P, *et al.* *Achromobacter xylosoxidans* as a new microorganism strain colonizing high-density polyethylene as a key step to its biodegradation [J]. *Environmental Science and Pollution Research*, 2016, **23**(11): 11349-11356.
 - [32] Peixoto J, Silva L P, Krüger R H. Brazilian Cerrado soil reveals an untapped microbial potential for unpretreated polyethylene biodegradation[J]. *Journal of Hazardous Materials*, 2017, **324**: 634-644.
 - [33] Delacuvellerie A, Cyriaque V, Gobert S, *et al.* The plastisphere in marine ecosystem hosts potential specific microbial degraders including *Alcanivorax borkumensis* as a key player for the low-density polyethylene degradation [J]. *Journal of Hazardous Materials*, 2019, **380**, doi: 10.1016/j.jhazmat.2019.120899.
 - [34] Li Z Y, Wei R, Gao M X, *et al.* Biodegradation of low-density polyethylene by *Microbulbifer hydrolyticus* IRE-31 [J]. *Journal of Environmental Management*, 2020, **263**, doi: 10.1016/j.jenvman.2020.110402.
 - [35] Montazer Z, Habibi-Najafi M B, Mohebbi M, *et al.* Microbial degradation of UV-pretreated low-density polyethylene films by novel polyethylene-degrading bacteria isolated from plastic-dump soil[J]. *Journal of Polymers and the Environment*, 2018, **26** (9): 3613-3625.
 - [36] Biki S P, Mahmud S, Akhter S, *et al.* Polyethylene degradation by *Ralstonia* sp. strain SKM2 and *Bacillus* sp. strain SM1 isolated from land fill soil site[J]. *Environmental Technology & Innovation*, 2021, **22**, doi: 10.1016/j.eti.2021.101495.
 - [37] Harshvardhan K, Jha B. Biodegradation of low-density polyethylene by marine bacteria from pelagic waters, Arabian Sea, India [J]. *Marine Pollution Bulletin*, 2013, **77** (1-2): 100-106.
 - [38] Watanabe T, Ohtake Y, Asabe H, *et al.* Biodegradability and

- degrading microbes of low-density polyethylene [J]. Journal of Applied Polymer Science, 2009, **111**(1): 551-559.
- [39] Esmaili A, Pourbabae A A, Alikhani H A, *et al.* Biodegradation of low-density polyethylene (LDPE) by mixed culture of *Lysinibacillus xylanilyticus* and *Aspergillus niger* in soil [J]. PLoS One, 2013, **8**(9), doi: 10.1371/journal.pone.0071720.
- [40] Soleimani Z, Gharavi S, Soudi M, *et al.* A survey of intact low-density polyethylene film biodegradation by terrestrial Actinobacterial species [J]. International Microbiology, 2021, **24**(1): 65-73.
- [41] Sheik S, Chandrashekar K R, Swaroop K, *et al.* Biodegradation of gamma irradiated low density polyethylene and polypropylene by endophytic fungi [J]. International Biodeterioration & Biodegradation, 2015, **105**: 21-29.
- [42] Gajendiran A, Krishnamoorthy S, Abraham J. Microbial degradation of low-density polyethylene (LDPE) by *Aspergillus clavatus* strain JASK1 isolated from landfill soil [J]. 3 Biotech, 2016, **6**(1), doi: 10.1007/s13205-016-0394-x.
- [43] Das M P, Kumar S. Microbial deterioration of low density polyethylene by *Aspergillus* and *Fusarium* sp [J]. International Journal of ChemTech Research, 2014, **6**(1): 299-305.
- [44] Priyanka N, Archana T. Biodegradability of polythene and plastic by the help of microorganism; a way for brighter future [J]. Journal of Environmental & Analytical Toxicology, 2011, **1**(4), doi: 10.4172/2161-0525.1000111.
- [45] Dharshni S J, Kanchana M. Microbial degradation of low-density polyethylene (LDPE) by fungus isolated from landfill soil [J]. Plant Archives, 2021, **21**(1): 809-815.
- [46] Sangale M K, Shahnawaz M, Ade A B. Potential of fungi isolated from the dumping sites mangrove rhizosphere soil to degrade polythene [J]. Scientific Reports, 2019, **9**(1), doi: 10.1038/s41598-019-41448-y.
- [47] Spina F, Tummino M L, Poli A, *et al.* Low density polyethylene degradation by filamentous fungi [J]. Environmental Pollution, 2021, **274**, doi: 10.1016/j.envpol.2021.116548.
- [48] Paço A, Duarte K, da Costa J P, *et al.* Biodegradation of polyethylene microplastics by the marine fungus *Zalerion maritimum* [J]. Science of the Total Environment, 2017, **586**: 10-15.
- [49] Sowmya H V, Ramalingappa, Krishnappa M, *et al.* Degradation of polyethylene by *Trichoderma harzianum*—SEM, FTIR, and NMR analyses [J]. Environmental Monitoring and Assessment, 2014, **186**(10): 6577-6586.
- [50] Perera P, Deraniyagala A S, Mahawaththage M P S, *et al.* Decaying hardwood associated fungi showing signatures of polyethylene degradation [J]. Bioresources, 2021, **16**(4): 7056-7070.
- [51] Hou L J, Xi J, Liu J X, *et al.* Biodegradability of polyethylene mulching film by two *Pseudomonas* bacteria and their potential degradation mechanism [J]. Chemosphere, 2022, **286**, doi: 10.1016/j.chemosphere.2021.131758.
- [52] Dwicania E, Rinanti A, Fachrul M F. Biodegradation of LLDPE plastic by mixed bacteria culture of *Pseudomonas aeruginosa* and *Brevibacterium* sp. [J]. Journal of Physics: Conference Series, 2019, **1402**(2), doi: 10.1088/1742-6596/1402/2/022105.
- [53] Restrepo-Flórez J M, Bassi A, Thompson M R. Microbial degradation and deterioration of polyethylene-A review [J]. International Biodeterioration & Biodegradation, 2014, **88**: 83-90.
- [54] Montazer Z, Najafi M B H, Levin D B. Challenges with verifying microbial degradation of polyethylene [J]. Polymers, 2020, **12**(1), doi: 10.3390/polym12010123.
- [55] Tiwari N, Santhiya D, Sharma J G. Microbial remediation of micro-nano plastics; current knowledge and future trends [J]. Environmental Pollution, 2020, **265**, doi: 10.1016/j.envpol.2020.115044.
- [56] Singh J J, Bansal S, Sonthalia A, *et al.* Biodegradation of plastics for sustainable environment [J]. Bioresource Technology, 2022, **347**, doi: 10.1016/j.biortech.2022.126697.
- [57] Mohanan N, Montazer Z, Sharma P K, *et al.* Microbial and enzymatic degradation of synthetic plastics [J]. Frontiers in Microbiology, 2020, **11**, doi: 10.3389/fmicb.2020.580709.
- [58] Ali S S, Elsamahy T, Al-Tohamy R, *et al.* Plastic wastes biodegradation; mechanisms, challenges and future prospects [J]. Science of the Total Environment, 2021, **780**, doi: 10.1016/j.scitotenv.2021.146590.
- [59] Bardaji D K R, Moretto J A S, Furlan J P R, *et al.* A mini-review: current advances in polyethylene biodegradation [J]. World Journal of Microbiology and Biotechnology, 2020, **36**(2), doi: 10.1007/s11274-020-2808-5.
- [60] Amaral-Zettler L A, Zettler F R, Mincer T J. Ecology of the plastisphere [J]. Nature Reviews Microbiology, 2020, **18**(3): 139-151.
- [61] Santo M, Weitsman R, Sivan A. The role of the copper-binding enzyme-laccase-in the biodegradation of polyethylene by the actinomycete *Rhodococcus ruber* [J]. International Biodeterioration & Biodegradation, 2013, **84**: 204-210.
- [62] Sarmah P, Rout J. Efficient biodegradation of low-density polyethylene by cyanobacteria isolated from submerged polyethylene surface in domestic sewage water [J]. Environmental Science and Pollution Research, 2018, **25**(33): 33508-33520.
- [63] Sowmya H V, Ramalingappa, Krishnappa M. Degradation of polyethylene by *Chaetomium* sp. and *Aspergillus flavus* [J]. International Journal of Research Scientific Research, 2012, **3**(6): 513-517.
- [64] Tang K H D, Lock S S M, Yap P S, *et al.* Immobilized enzyme/microorganism complexes for degradation of microplastics; a review of recent advances, feasibility and future prospects [J]. Science of the Total Environment, 2022, **832**, doi: 10.1016/j.scitotenv.2022.154868.
- [65] Jeon H J, Kim M N. Functional analysis of alkane hydroxylase system derived from *Pseudomonas aeruginosa* E7 for low molecular weight polyethylene biodegradation [J]. International Biodeterioration & Biodegradation, 2015, **103**: 141-146.
- [66] Zhao J C, Guo Z A, Ma X Y, *et al.* Novel surface modification of high-density polyethylene films by using enzymatic catalysis [J]. Journal of Applied Polymer Science, 2004, **91**(6): 3673-3678.

CONTENTS

Challenges Regarding the Co-emission of Emerging Pollutants to Eco-environmental Monitoring and Management	WANG Pei, HUANG Xin-yi, CAO Zhi-wei, <i>et al.</i> (4801)
Environmental Process, Effects and Risks of Emerging Contaminants in the Estuary-Coastal Environment	WANG Xin-hong, YU Xiao-xuan, WANG Si-quan, <i>et al.</i> (4810)
Research Progress of Analytical Methods with Molecular Spectroscopy for Determination of Trace Nutrients and Metals in Seawaters	YUAN Dong-xing, HUANG Yong-ming, WANG Ting (4822)
Research Progress on the Determination of Sulfide in Natural Waters: From Laboratory Analysis to In-Situ Monitoring	LI Peng, LIN Kun-de, YUAN Dong-xing (4835)
Advances in On-site Analytical Methods for Inorganic Arsenic in Environmental Water	BO Guang-yong, CHEN Zhao-ying, GONG Zhen-bin, <i>et al.</i> (4845)
Advances and Prospect of Sampling Techniques and Analytical Methods for Trace Elements in the Ocean; Progress of Trace Element Platform Construction in Xiamen University	 HUANG Yong-ming, ZHOU Kuan-bo, CHEN Yao-jin, <i>et al.</i> (4858)
Biodegradation of Polyethylene Microplastic: A Review	 LUO Yuan-rong, QIAN Yi-qian, QI Ya-nan (4869)
Mechanism and Environmental Effect on Nitrogen Addition to Microbial Process of Arsenic Immobilization in Flooding Paddy Soils	WANG Feng, ZHANG Jing, ZHOU Shao-yu, <i>et al.</i> (4876)
Toxicity Testing Organisms for Marine Ecotoxicological Research in China	SHI Tian-yi, HONG Hai-zheng, WANG Ming-hua, <i>et al.</i> (4888)
Estimating Methane Fugitive Emissions from Oil and Natural Gas Systems in China	CHEN Chun-ci, LÜ Yong-long, HE Gui-zhen (4905)
Atmospheric NH ₃ Emission Inventory and Its Tempo-spatial Changes in Xiamen-Zhangzhou-Quanzhou Region from 2015 to 2020	LI Xiang, WU Shui-ping, JIANG Bing-qi, <i>et al.</i> (4914)
Distribution of Microplastic and Antibiotic Resistance Gene Pollution in Jiulong River Estuary	CHENG Hong, CHEN Rong (4924)
Pollution Characteristics of Microplastics in Sediments of Xiamen Bay Beach	YAO Rui, LIU Hua-tai, LI Yong-yu, <i>et al.</i> (4931)
Spatial and Temporal Distribution and Influencing Factors of Dissolved Trace Metals in Jiulong River Estuary and Xiamen Bay	QI Liu-qian, YUE Xin-li, ZHONG Hao-wen, <i>et al.</i> (4939)
Spatiotemporal Characteristics of Dissolved Oxygen and Control Mechanism of Hypoxia (Low Oxygen) in the Watershed-Coastal System in Fujian Province	 YANG Ai-lin, YANG Fang, LI Shao-bin, <i>et al.</i> (4950)
Distribution, Migration, and Transformation Mechanism of Labile Phosphorus in Sediments of Xixi River Estuary, Xiamen	PAN Feng, CAI Yu, GUO Zhan-rong, <i>et al.</i> (4961)
Adsorption of Mn ²⁺ by Modified Biochar Fixed Bed in Simulated Lakes and Reservoir Waters	ZHAO Jie, YE Zhi-long, WANG Jia-ni, <i>et al.</i> (4971)
Rapid Detection of Trace Enrofloxacin and Ciprofloxacin in Drinking Water by SERS	XU Jing, ZHENG Hong, LU Jiang-long, <i>et al.</i> (4982)
Degradation of Triphenyl Phosphate in Water by UV-driven Advanced Oxidation Processes	XU Zi-wen, YIN Hong-ling, XIONG Yuan-ming, <i>et al.</i> (4992)
Characteristics and Potential Sources of Four Ozone Pollution Processes in Hainan Province in Autumn of 2019	FU Chuan-bo, CHEN Hong, DAN Li, <i>et al.</i> (5000)
Characterization and Formation Mechanism of Water-soluble Inorganic Ions in PM _{2.5} and PM ₁₀ in Summer in the Urban Agglomeration of the Ili River Valley	 CHEN Qiao, GU Chao, XU Tao, <i>et al.</i> (5009)
Difference in PM _{2.5} Pollution and Transport Characteristics Between Urban and Suburban Areas	QI Peng, ZHOU Ying, CHENG Shui-yuan, <i>et al.</i> (5018)
Characteristics and Health Risk Assessment of BTEX in the Northern Suburbs of Nanjing	FENG Yue-zheng, AN Jun-lin, ZHANG Yu-xin, <i>et al.</i> (5030)
Ecological Risk Assessment of Microplastics Occurring in Surface Water of Terrestrial Water Systems across China	SUN Xiao-nan, CHEN Hao, JIA Qi-long, <i>et al.</i> (5040)
Scale Effects of Landscape Pattern on Water Quality in Dongjiang River Source Watershed	CHEN You-liang, ZOU Wen-min, LIU Xing-gen, <i>et al.</i> (5053)
Mercury Speciation, Distribution, and Potential Sources in Surface Waters of the Yangtze and Yellow River Source Basins of Tibetan Plateau During Wet Season	 LIU Nan-tao, WU Fei, YUAN Wei, <i>et al.</i> (5064)
Water Environmental Characteristics and Water Quality Assessment of Lakes in Tibetan Plateau	LIU Zhi-qi, PAN Bao-zhu, HAN Xu, <i>et al.</i> (5073)
Karst Hydrogeochemical Characteristics and Controlling Factors of Carlin-type Gold Mining Area Based on Hydrochemistry and Sulfur Isotope	 ZHA Xue-fang, WU Pan, LI Xue-xian, <i>et al.</i> (5084)
Characteristics of Eukaryotic Phytoplankton Community Structure and Its Relationship with Environmental Factors in Danjiangkou Reservoir	HE Yu-xiao, MAI Si-jie, REN Yu-fen, <i>et al.</i> (5096)
Adsorption of Phosphate and Heavy Metals by Lanthanum Modified Zeolite and Its Performance in Sediment Inactivation	WANG Zhe, ZHU Jun, LI Wen, <i>et al.</i> (5106)
Metagenomic and Metatranscriptomic Analysis of Nitrogen Removal Functional Microbial Community of Petrochemical Wastewater Biological Treatment Systems	 ZHANG Xu, ZHOU Jia-jia, ZHOU Min, <i>et al.</i> (5115)
Bacterial Community Structure and Antibiotic Resistance Gene Changes in IFAS + Magnetic Coagulation Process Wastewater Treatment Plant in Cold Regions	 DU Wen-yan, YAO Jun-qin, MA Hui-ying, <i>et al.</i> (5123)
Nitric Oxide Emissions from Chinese Upland Cropping Systems and Mitigation Strategies: A Meta-analysis	 TIAN Zheng-yun, WU Xiong-wei, WU Yuan-yuan, <i>et al.</i> (5131)
Impact of Nitrification Inhibitors on Vegetable Production Yield, Nitrogen Fertilizer Use Efficiency and Nitrous Oxide Emission Reduction in China: Meta Analysis	 LIU Fa-bo, MA Xiao, ZHANG Fen, <i>et al.</i> (5140)
Effect of Different Fertilization Treatments on Methane and Nitrous Oxide Emissions from Rice-Vegetable Rotation in a Tropical Region, China	 SHAO Xiao-hui, TANG Shui-rong, MENG Lei, <i>et al.</i> (5149)
Effects of Land-use Conversion on Soil Nitrification and NO & N ₂ O Emissions in Tropical China Under Different Moisture Conditions	TANG Rui-jie, HU Yu-jie, ZHAO Cai-yue, <i>et al.</i> (5159)
Characteristics of Heavy Metal Pollution in Farmland Soil of the Yangtze River Economic Belt Based on Bibliometric Analysis	LIU Xiao-yan, FAN Ya-nan, LIU Peng, <i>et al.</i> (5169)
Spatial and Temporal Distribution and Source Variation of Heavy Metals in Cultivated Land Soil of Xiangzhou District Based on EBK Interpolation Prediction and GDM Model	 GAO Hao-ran, ZHOU Yong, LIU Jia-kang, <i>et al.</i> (5180)
Identification of Soil Heavy Metal Sources Around a Copper-silver Mining Area in Ningxia Based on GIS	ZHANG Kou-kou, HE Jing, ZHONG Yan-xia, <i>et al.</i> (5192)
Effect of Aging on Stabilization of Cd ²⁺ Through Biochar Use in Alkaline Soil of Bayan Obo Mining Area	WANG Zhe, CHENG Jun-li, BIAN Yuan, <i>et al.</i> (5205)
Preparation of Magnetic Iron Oxide/Mulberry Stem Biochar and Its Effects on Dissolved Organic Carbon and Arsenic Speciation in Arsenic-Contaminated Soils	 LU Lin, YAN Li-ling, LIANG Mei-na, <i>et al.</i> (5214)
Effects of Oyster Shell Powder and Lime on Availability and Forms of Phosphorus and Enzyme Activity in Acidic Paddy Soil	ZHAO Li-fang, HUANG Peng-wu, YANG Cai-di, <i>et al.</i> (5224)
Effects of Interaction of Zinc and Cadmium on Growth and Cadmium Accumulation of <i>Brassica campestris</i> L.	SHUAI Zu-ping, LIU Han-yi, CUI Hao, <i>et al.</i> (5234)
Pollution Characteristics and Ecological Risk Assessment of Antibiotics in Vegetable Field in Kaizhou, Chongqing	FANG Lin-fa, YE Ping-ping, FANG Biao, <i>et al.</i> (5244)
Temporal and Spatial Variation Characteristics of Carbon Storage in the Source Region of the Yellow River Based on InVEST and GeoSoS-FLUS Models and Its Response to Different Future Scenarios	 HOU Jian-kun, CHEN Jian-jun, ZHANG Kai-qi, <i>et al.</i> (5253)
Carbon Sequestration Characteristics of Different Restored Vegetation Types in Loess Hilly Region	XU Xiao-ming, ZHANG Xiao-ping, HE Liang, <i>et al.</i> (5263)
Response of Soil Multifunctionality to Reduced Microbial Diversity	CHEN Gui-xian, WU Chuan-fa, GE Ti-da, <i>et al.</i> (5274)
Effect of Nitrogen Addition on Soil Fungal Diversity in a Degraded Alpine Meadow at Different Slopes	SU Xiao-xue, LI Xi-lai, LI Cheng-yi, <i>et al.</i> (5286)
Comparative Energy Consumption Structure and Mode between China and Major Energy-Consuming Countries Under the Background of Carbon Emission Reduction	 LI Hui, PANG Bo, ZHU Fa-hua, <i>et al.</i> (5294)
Spatialization and Spatio-temporal Dynamics of Energy Consumption Carbon Emissions in China	HAO Rui-jun, WEI Wei, LIU Chun-fang, <i>et al.</i> (5305)
Carbon Dioxide Mitigation Co-effect Analysis of Structural Adjustment Measures in the "2 + 26" Cities in the Jing-Jin-Ji Region and Its Surroundings	 YANG Tian-qi, WANG Hong-chang, ZHANG Chen, <i>et al.</i> (5315)
Policy Analysis in Plastic Pollution Governance and Recommendations in China	LI Huan, ZHU Long, SHEN Qian, <i>et al.</i> (5326)