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长江经济带PM_{2.5}空间异质性和驱动因素的地理探测

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鄱阳湖白鹤保护区微塑料表面微生物群落结构特征

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摘要: 微塑料作为一种新型污染物所带来的环境问题越来越受到关注. 以鄱阳湖五星垦殖场白鹤保护区为研究区, 采集沉积物 (SL) 及不同类型微塑料样品, 微塑料的主要类型是薄膜类 (PE)、碎片类 (PP1)、纤维类 (PP2) 和发泡类 (PS), 聚合物被确定为聚乙烯、聚丙烯和聚苯乙烯. 采用 16S 高通量测序鉴定微生物 (细菌和真菌) 群落结构. 结果表明, PE 和 PP1 表面细菌物种丰富度指数 Ace 和 Chao 与周围沉积物中的无显著性差异 ($P > 0.05$), 而 PP2 和 PS 显著低于周围沉积物 ($P < 0.05$). 真菌物种丰富度指数 Ace 和 Chao 则表现为 PE 和 PS 与沉积物无显著性差异 ($P > 0.05$), 而 PP1 和 PP2 显著低于周围沉积物 ($P < 0.05$). 不同类型微塑料表面细菌和真菌物种多样性指数 Shannon 和 Simpson 均低于沉积物. 沉积物和微塑料表面细菌优势菌门以变形菌门 (Proteobacteria) 和拟杆菌门 (Bacteroidetes) 为主. 而真菌群落以担子菌门 (Basidiomycota)、子囊菌门 (Ascomycota) 和壶菌门 (Chytridiomycota) 为优势菌群. 通过 KEGG 功能预测发现: 微塑料表面细菌与沉积物之间具有显著差异且丰度比例高于 1% 的代谢通路中, 大部分通路与代谢有关. 研究表明微塑料可以改变微生物群落结构, 其表面微生物群落可以催化代谢反应, 促进微塑料的分解.

关键词: 鄱阳湖; 微塑料; 沉积物; 微生物群落; 丰富度; 多样性

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Microbial Community Structure on Microplastic Surface in the *Grus leucogeranus* Reserve of Poyang Lake

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Abstract: As a new type of pollutant, microplastics have attracted increasing attention. Microplastics in aquatic ecosystems are accumulating at an unprecedented scale, causing significant environmental and economic impacts. In this study, sediments and different types of microplastic samples were collected from the *Grus leucogeranus* Reserve of Wuxing Reclamation Farm of Poyang Lake, which is the largest freshwater lake in China. The main types of microplastics were film (PE), debris (PP1), fiber (PP2), and foam (PS), and the polymers were identified as polyethylene, polypropylene, and polystyrene in the study area. The structures of microbial communities (fungi and bacteria) were identified using 16S high-throughput sequencing. The results showed that there was no significant difference in the Ace and Chao of bacteria between the surface of PE and PP1 and that of the surrounding sediments ($P > 0.05$), whereas PP2 and PS were significantly lower than those in surrounding sediments ($P < 0.05$). Ace and Chao of fungi showed that PE and PS had no significant differences with the sediment ($P > 0.05$), and PP1 and PP2 were significantly lower than those in surrounding sediments ($P < 0.05$). The species diversity Shannon and Simpson index of bacteria and fungi on different types of microplastic surfaces were lower than that of sediment. The bacterial communities on the sediment and microplastic surface mainly included Proteobacteria and Bacteroidetes. In the fungal community, Basidiomycota, Ascomycota, and Chytridiomycota were the dominant bacteria. Through KEGG functional prediction, it was found that most of the metabolic pathways with a significant difference between bacteria and sediments on the surface of microplastics and with an abundance ratio higher than 1% were related to metabolism. Compared with that of sediment, the metabolic pathways of PE and PP2 on microplastic surfaces were down-regulated mainly in cell motility, signal transduction, and carbohydrate metabolism, whereas the energy metabolism, general and global metabolism pathways, and cofactor metabolism were up-regulated. Compared with that of sediment, the bacterial metabolic pathways of PS and PP1 on microplastic surfaces were down-regulated, mainly including general and global metabolic pathways, translation, and exogenous biodegradation, and cell motility and signal transduction were up-regulated. However, the abundance of other functional genes in sediments and microplastic samples showed little difference. The results indicated that microplastics can change the structure of microbial communities, and the microbial community on the surface of microplastics could catalyze metabolic reactions and promote the decomposition of microplastics. The study of microplastic surface microbial structure in Poyang Lake can support management decisions to protect the ecological integrity of the lake.

Key words: Poyang Lake; microplastics; sediment; microbial community; richness; diversity

塑料制品被广泛应用于工业、农业和日常生活^[1], 自 1960 年以来, 全球塑料产量呈指数级增长, 于 2018 年达到 3.59 亿 t^[2]. 然而由于自然环境中缺乏降解塑料的细菌和酶, 废旧塑料不易降解而在环境中堆积^[3]. 积累在环境中的塑料垃圾可以降解为更小的颗粒. 其中粒径小于 5 mm 的塑料被称为微

塑料^[4]. 同时, 大多数消费者每天使用的个人护理

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品和化妆品中也含有微塑料,其可随排水系统进入污水处理厂但不易被截获从而进入河流、湖泊和海洋等各大水系中^[5,6].微塑料已经成为水生环境中不可忽视的新型污染物^[7,8].由于微塑料体积小,许多水生生物可以摄入微塑料从而使其进入食物链,并对水生生态系统造成严重威胁^[9].此外,微塑料可能成为微生物、特别是有害微生物和致病微生物的新基质^[10,11].

微塑料具有低密度、疏水表面和高表面/体积比等固有特征,这些特征可促进水生生态系统中微生物的定植^[12].同时,微塑料的浮力和持久性可能显著加剧各种微生物的长距离运输^[13].有研究发现了微生物在各种环境中塑料碎片和微塑料的定植现象——从淡水到海水、海洋沉积物和海滩^[14~16].所有这些研究都证明了微塑料中微生物的高度多样性和丰富度,构成了一种独特的群落结构^[17].此外,微塑料上经常检测到含有众所周知的人类、鱼类和贝类致病菌株的细菌家族^[10,18].因此,需要进行更多的研究,以了解塑料定植微生物的时空格局以及海洋生态系统、食品安全和公共卫生的生态风险^[19].鄱阳湖是中国最大的淡水湖,“洪水一片、枯水一线”的自然地理特征使鄱阳湖在维护长江中下游水生生物多样性方面起着十分重要的作用^[20].近年来,受气候变化与大型水利工程的影响,鄱阳湖水位变化较大,其沉积物出露时间提前并延长,增加了微塑料污染的风险^[21].近几年来,鄱阳湖微塑料污染问题受到了越来越多的关注,前期研究表明鄱阳湖水体和沉积物中存在大量的微塑料^[22,23],但是关于微塑料表面微生物的研究还很缺乏.

本文选取鄱阳湖白鹤保护区五星垦殖场为研究区,采集沉积物和不同类型微塑料样品,采用16S高通量测序鉴定微生物群落(真菌和细菌)结构.研究微塑料表面微生物(细菌和真菌)丰富度和多样性,分析微塑料表面与沉积物中微生物群落结构差异,进一步探讨微塑料如何决定表面微生物菌群结构以及微生物如何适应微塑料表面生态环境.本研究有助于进一步阐述鄱阳湖微塑料的污染机制,分析鄱阳湖微塑料表面微生物结构可以支持旨在安全保护湖泊生态完整性的管理决策.

1 材料与方法

1.1 研究区设置

鄱阳湖位于北纬28°22'~29°45',东经115°47'~116°45',地处江西省的北部,长江中下游南岸^[24].鄱阳湖是一个过水性吞吐型湖泊,“高水是湖、低水似河”的自然地理特征使鄱阳湖湿地成为

生物多样性十分丰富的国际重要湿地.鄱阳湖湿地随季节性洪枯水位变化,洪、枯季节的水面面积、蓄水容积悬殊,丰水季节出现在7~8月,枯水季节出现于11~12月,年水位变幅8~14 m^[25].本研究拟将研究区域设置在鄱阳湖白鹤保护区五星垦殖场,选择枯水期(11~12月)进行沉积物和其中微塑料样品的采集.

1.2 样品采集

收集1 L表层沉积物混匀,在消毒过的托盘上将微塑料和沉积物分开,取1 mL沉积物放入2 mL离心管中,将微塑料(1~5 mm)分成碎片、发泡、薄膜和纤维这4种类型分别收集在不同的2 mL离心管中,设置3个重复,每个重复相隔50 m,但不是每个点都包括这4种类型的微塑料.置于冷藏箱带回实验室分别作为沉积物和沉积物中微塑料表面微生物分析样品.

1.3 样品处理

收集到的样品尽量在最短时间内处理完毕,所有过程均在无菌条件下进行以避免DNA变性、损失或污染.在无菌条件下利用镊子和显微镜进行微粒子的识别,所有材料均用酒精消毒,在操作每个粒子前利用10%氯水清洗镊子.视觉识别疑似微塑料并储存在无菌玻璃皿中,利用红外光谱对微塑料进行组成成分分类.分类的颗粒保存在封闭无菌的培养皿中,并储存在-20℃冰箱中.不同类型微塑料按照微塑料表观类型和组成成分分类,本研究中分为发泡类聚苯乙烯(PS)、碎片类聚丙烯(PP1)、纤维类聚丙烯(PP2)和薄膜类聚丙烯(PE).每个类型的样本,均保存在2 mL离心管中做后续DNA分离.

1.4 样品DNA提取

使用MoBio Powersoil DNA(Qiagen,美国)试剂盒从沉积物以及微塑料样品中提取DNA^[13].依据试剂盒操作步骤提取DNA.

1.5 PCR扩增

以稀释后的DNA为模板,细菌采用带有Barcode的引物338F(5'-ACTCCTACGGGAGGCAGCA-3')和806R(5'-GGACTACHVGGGT-WTCTAAT-3')进行扩增,真菌采用引物ITS1F(5'-CTTGGTCATTTAGAGGAAGTAA-3')和ITS2(5'-GCTGCGTTCTTCATCGATGC-3')进行扩增.PCR产物用1%琼脂糖凝胶电泳检测提取质量,然后使用DNA凝胶回收试剂盒(Axygen Biosciences,美国)进行纯化回收.将PCR产物用Qubit3.0荧光剂进行检测定量,进行相应比例的混合.最后送上海美吉生物医药科技有限公司进行建库测序.

1.6 序列处理

利用 Illumina MiSeq PE300 测序平台进行高通量测序,通过对原始测序数据处理得到优化序列. 16S rRNA 的序列分析基于软件 QIIME 完成^[26],将分类操作单元(operational taxonomic units, OTU)划分,序列相似性设为 97%,得到 OTU 代表序列.对 OTU 结果进行物种注释,通过 α 多样性来分析样品的细菌和真菌物种多样性,根据物种注释结果,选取每个样品在门(phylum)分类水平上最大丰度排名前 10 的物种以及相对丰度 > 1% 的属,生成物种相对丰度柱形累加图,以便直观查看各样品在不同分类水平上,相对丰度较高的物种及其比例.通过 KEGG 功能基因预测分析不同类型微塑料表面和沉积物细菌代谢通路上的差异和变化.

2 结果与分析

2.1 微塑料表面及沉积物中微生物群落丰富度和多样性

对细菌原始数据进行拼接、过滤等优化处理后,

表 1 微塑料表面和沉积物中细菌和真菌的序列信息和多样性指数¹⁾

Table 1 Sequence information and alpha index of bacteria and fungi in the microplastics and sediment						
项目	样品	OTU	Ace 指数	Chao 指数	Shannon 指数	Simpson 指数
细菌	PE	1 383 ± 4.58	1 405.14 ± 8.31b	1 422.01 ± 13.1b	8.89 ± 0.13c	0.99 ± 0.01c
	PP1	1 380 ± 11.55	1 411.09 ± 8.03b	1 428.12 ± 11.9b	8.35 ± 0.41c	0.98 ± 0.01bc
	PP2	859.5 ± 21.07	1 139.81 ± 46.19a	1 110.44 ± 44.2a	5.32 ± 0.38b	0.92 ± 0.04b
	PS	833 ± 24.05	1 136.96 ± 32.82a	1 073.13 ± 30.98a	4.05 ± 0.12a	0.74 ± 0.02a
	SL	1 344 ± 38.8	1 375.74 ± 39.71ab	1 395.43 ± 40.28b	8.93 ± 0.26c	0.99 ± 0.03c
真菌	PE	426 ± 24.58	486.6 ± 21.19a	499.7 ± 21.31b	2.9 ± 0.57a	0.52 ± 0.1a
	PP1	336 ± 35.8	406.2 ± 42.8a	398.5 ± 33.77a	5.55 ± 0.02c	0.93 ± 0.01c
	PP2	293 ± 14.72	413.9 ± 68.75a	377.1 ± 22.05a	5.19 ± 0.28c	0.91 ± 0.02c
	PS	355 ± 10.25	453.2 ± 13.08a	442.2 ± 12.77ab	3.66 ± 0.11b	0.75 ± 0.02b
	SL	423 ± 12.21	482.3 ± 13.92a	490 ± 14.15b	6.12 ± 0.18c	0.96 ± 0.03c

1) 同列小写字母相同表示不同类型微塑料及沉积物多样性指数差异不显著 ($P > 0.05$)

如图 1 所示,微塑料表面细菌与其周围沉积物共享 OTU 数目为 472 个.此外,各样品也存在独有的细菌 OTU:沉积物中 8 个,PE 表面 6 个,PP1 表面 3 个,PP2 表面 19 个和 PS 表面 4 个[图 1(a)].微塑料表面真菌与其周围沉积物共享 OTU 数目为 132 个,各样品独有的真菌 OTU 为沉积物中 38 个,PE 表面 23 个,PP1 表面 31 个,PP2 表面 19 个 PS 表面 8 个[图 1(b)].

2.2 微生物群落结构分析

本研究中细菌共检测到 28 个门、67 个纲、157 个目、254 个科、432 个属和 472 个种.在门水平上,21 个细菌物种群门均存在于微塑料和沉积物样品上,但不同样品间各物种的丰度明显不同.其中 PE、PP1 表面和 SL 中细菌优势菌门为变形菌门

PE、PP1、PP2、PS 和 SL 得到的有效序列数分别为 248 100、132 092、248 050、166 142 和 78 784 条.以 97% 以上的相似性划分共得到 1 503 条 OTU(表 1).同样对真菌原始数据进行处理后,PE、PP1、PP2、PS 和 SL 得到的有效序列数分别为 180 261、58 151、63 033、82 947 和 171 615 条.以 97% 以上的相似性划分共获得 421 个 OTU.所有处理的测序覆盖率均高于 99%,且稀释曲线已趋于平缓,表明测序数据量大,样品测序完整.

α 多样性中的 Ace 和 Chao 指数衡量微生物物种丰富度;Shannon 和 Simpson 指数用于衡量物种多样性;本研究结果表明 PP1 和 PE 表面细菌的物种丰富度与周围沉积物中无显著性差异 ($P > 0.05$),而 PP2 和 PS 表面细菌的物种丰富度显著低于周围沉积物 ($P < 0.05$).与沉积物相比,4 种微塑料表面细菌的物种多样性均低于沉积物.真菌的物种丰富度指数 Ace 和 Chao 则表现为 PE 和 PS 表面真菌的物种丰富度与周围沉积物中无显著性差异 ($P > 0.05$),而 PP1 和 PP2 表面真菌的物种丰富度显著低于周围沉积物 ($P < 0.05$).

(Proteobacteria)、蓝藻门(Cyanobacteria)、拟杆菌门(Bacteroidetes)、酸杆菌门(Acidobacteria)、硝化螺旋菌门(Nitrospirae)和绿弯菌门(Chloroflexi),总计占比达 90%.而 PP2 和 PS 表面细菌以变形菌门(Proteobacteria)和拟杆菌门(Bacteroidetes)占绝对优势,相对丰度高达 90% 以上[图 2(a)].

本研究中真菌共检测到 7 个门、20 个纲、43 个目、79 个科、112 个属和 116 个种.在门水平上,各样品间各物种的丰度明显不同. PE 微塑料样品表面真菌以担子菌门(Basidiomycota)占绝对优势,PP1、PP2 和 SL 上优势真菌门为子囊菌门(Ascomycota)、担子菌门(Basidiomycota)和壶菌门(Chytridiomycota),占比 80% 以上.而 PS 表面真菌以子囊菌门(Ascomycota)占绝对优势,占比达到

85%左右[图2(b)].

图3是不同微塑料类型和沉积物微生物属水平分类,只显示相对丰度>1%的物种,并将其他物种

合并为 others. 细菌相对丰度>1%的属共有14个,其中7个属于未分类的,以 uncultured 作为标记. 这14个丰度较大的属有13个属在PE、PP1和SL上

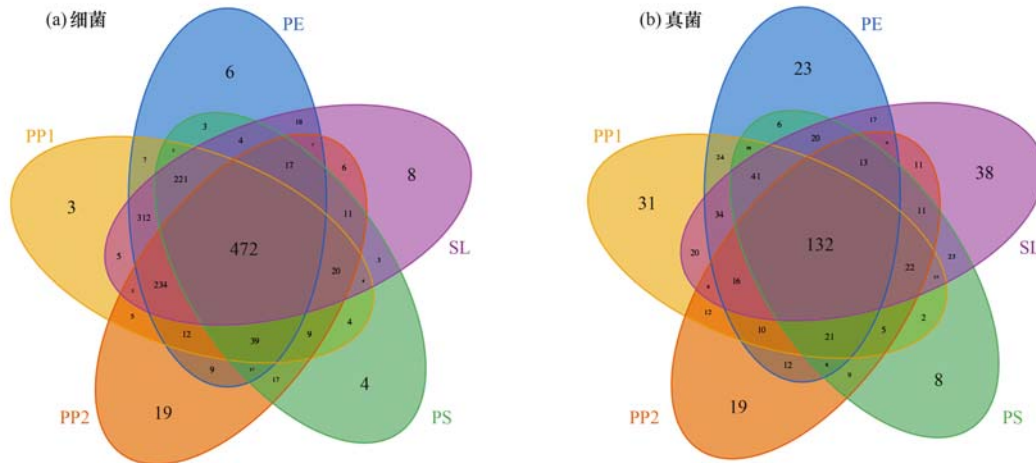


图1 微塑料表面和沉积物中的 Venn 图

Fig. 1 Venn diagrams of microplastic surfaces and sediments

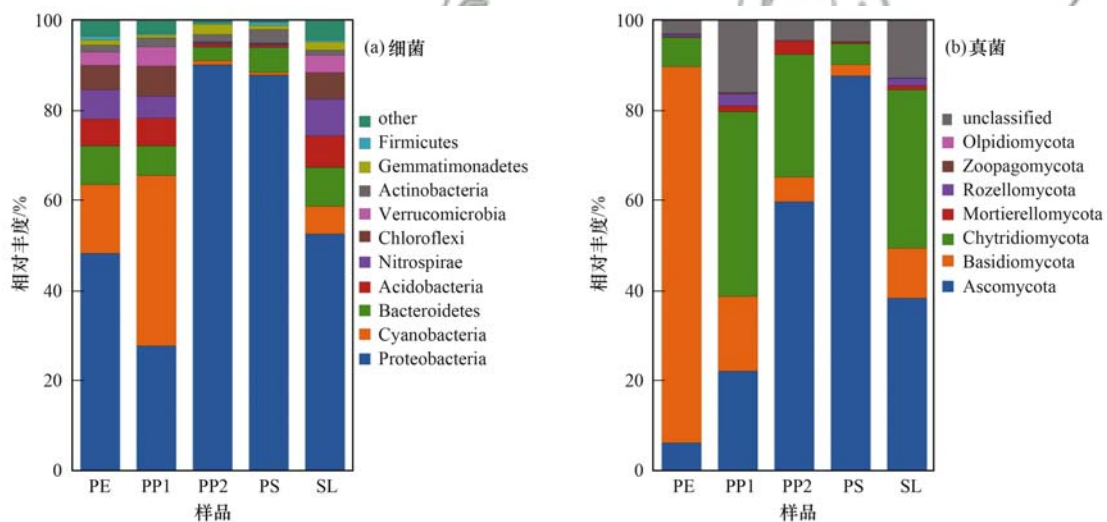


图2 微塑料和沉积物微生物门水平分类

Fig. 2 Histogram of species distribution of microbial in microplastics and sediment at the phylum level

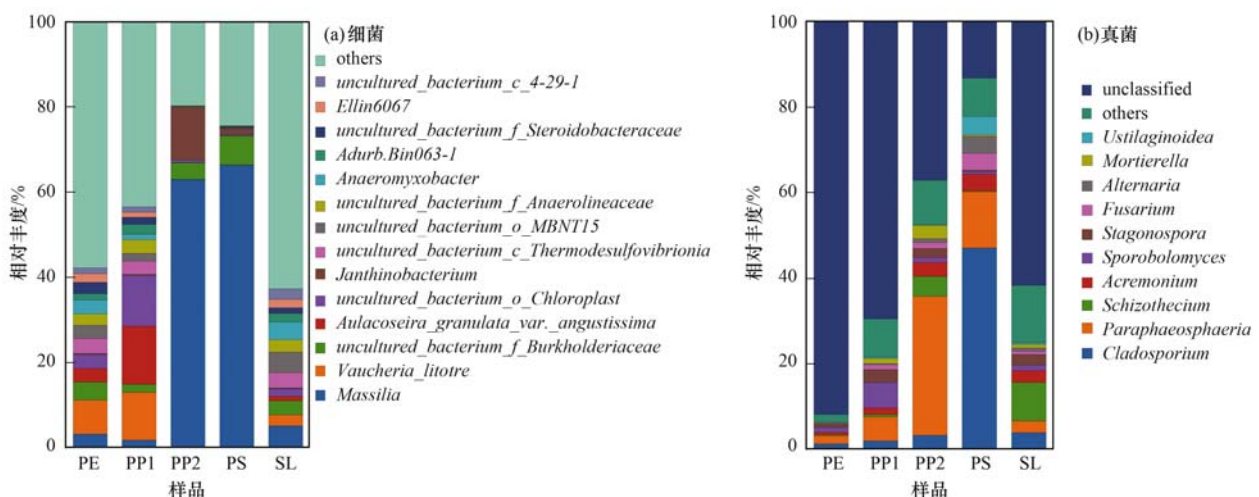


图3 微塑料和沉积物微生物属水平分布柱状图

Fig. 3 Histogram of species distribution of microbial in microplastics and sediment at the genus level

分布均匀,总占比在 38%~57%。而 PP2 和 PS 表面细菌则主要由马赛菌属 (*Massilia*, 63%~66%)、未分类伯克氏菌 (*uncultured_bacterium_f_Burkholderiaceae*, 3.9%~6.8%) 和紫色杆菌属 (*Janthinobacterium*, 1.3%~12%) 组成,紫色杆菌属为 PP2 和 PS 表面特有优势细菌[图 3(a)]。

真菌相对丰度 > 1% 的属共有 10 个。真菌据置信度阈值的筛选,1 种细菌在属分类级别分值较低时,在统计时以 Unclassified 标记。在 PE、PP1 和 SL 上 Unclassified 占比很大,SL 中相对丰度最高的是裂壳菌属 (*Schizothecium*)。微塑料表面真菌丰度较大的包括枝孢属 (*Cladosporium*) 和 *Paraphaeosphaeria* [图 3(b)]。

2.3 微塑料对微生物功能基因影响预测

KEGG 数据库的核心为生物代谢通路分析数据库 (KEGG pathway database, [http://www.genome](http://www.genome.jp/kegg/pathway.html)。

[jp/kegg/pathway.html](http://www.genome.jp/kegg/pathway.html)), 它将代谢通路分为 6 大类,包括细胞进程、环境信息处理、遗传信息处理、人类疾病、代谢和生物体系统。图 4 是微塑料表面细菌与沉积物之间具有显著差异且丰度比例高于 1% 的代谢通路 ($P < 0.05$)。在所有有显著差异的代谢通路中,不同代谢通路丰度具有差异性,其中一般和全局通路占比最高,且大部分通路于代谢有关。预测结果显示,PE 和 PP2 与沉积物相比,微塑料表面细菌代谢通路下调的途径主要有细胞运动性、信号转导和碳水化合物代谢,而能量代谢、一般和全局代谢通路及辅助因子代谢为上调途径。PS 和 PP1 与沉积物相比,微塑料表面细菌代谢通路下调的途径主要包括一般和全局代谢通路及翻译,外源性物质生物降解、细胞运动性和信号转导为上调途径。而其他功能基因在沉积物和微塑料样品中丰度差异较小。

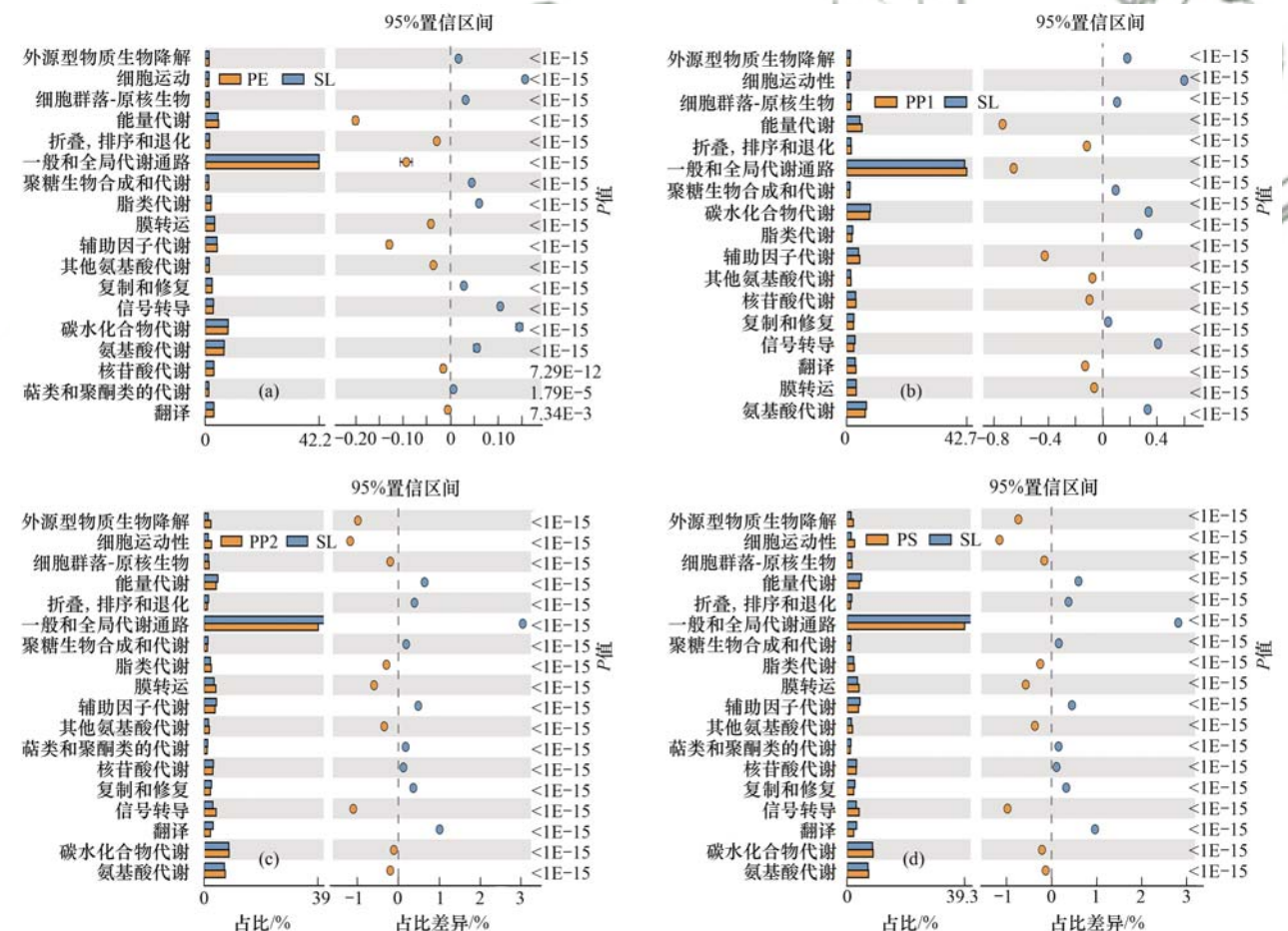


图 4 KEGG 代谢通路功能预测
Fig. 4 KEGG functional gene prediction

3 讨论

3.1 微塑料对微生物群落结构的影响

本研究表明微塑料表面细菌和真菌多样性与周围沉积物不同,其中 PP1 和 PE 表面细菌的物种丰

度与多样性高于周围沉积物但差异不显著 ($P > 0.05$),而 PP2 和 PS 表面细菌的物种丰富度和多样性显著低于周围沉积物 ($P < 0.05$)。McCormick 等^[27]的研究发现微塑菌群的分类单元丰富度、多样性和均匀性均低于其他底物,与本研究结果中

PP2 和 PS 的结果一致. 也有研究表明微塑料的物种丰富度和多样性高于周围的环境样品^[17,28], 与本研究结果中 PP1 和 PE 的结果一致. 同时微塑料表面细菌和真菌不同于周围沉积物, 微塑料表面存在相对于周围沉积物独有的细菌和真菌. 这些结果表明, 微塑料表面选择了一套独特的细菌组合. 这些微生物/组合可能受益于给定的塑料特性, 或至少在有限的碳资源下生长^[29]. 但是目前还不清楚微塑料细菌组合是简单地通过微塑料的坚硬表面选择的, 还是通过微塑料的化学组成^[13]. PS 与 PP1 和 PE 的细菌群落结构表现出了明显的差异. Frère 等^[28]的研究表明, PS 的细菌群落具有明显不同于 PE 和 PP 的细菌结构特征. 早期在大西洋和太平洋进行的研究也表明 PS 的细菌群落与 PE 和 PP 不同^[30], 与本研究结果相似. 不同微塑料类型之间的差异可能是由于形态/表面结构而不是聚合物组成^[31]. 有研究发现了细菌对塑料的相似黏附行为, 不同类型塑料的固有表面性质对细菌的粘附有影响, 同时塑料表面硬度是也决定细菌附着在塑料表面的关键因素^[32]. 本研究中碎片类聚丙烯微塑料 (PP1) 和纤维类聚丙烯微塑料 (PP2) 属于相同聚合物类型, 但是表面微生物群落结构相差很大, 可能也是由于塑料表面硬度不同造成的. 也可能是由于不同微塑料表明粗糙度不同从而影响了细菌的定植. 也可能是由于野外采样无法控制微塑料在环境中的存在时间, 不同类型微塑料在环境中的实际降解率和保留时间也难以确定^[14,33]. 真菌表现出与细菌不同的丰度趋势. 但总体上沉积物中和微塑料表面都是细菌丰度远大于真菌丰度, 说明细菌是微塑料上定植的主要微生物, 但是真菌的定植也很明显^[15]. 一些真菌类群也被报道能够进行塑料降解^[34].

本研究表明微塑料样品表面细菌优势菌门为变形菌门 (Proteobacteria) 和拟杆菌门 (Bacteroidetes). 结果与之前长江口潮间带上微塑料表面生物膜的群落结构研究一致^[28,35]. 变形杆菌是海洋环境中非自然亚层生物膜的早期定植菌, 其次是次级定植菌, 如拟杆菌门 (Bacteroidetes). 拟杆菌门, 常在有机物颗粒上被发现, 可以适应降解聚合物碳源^[36]. 蓝藻菌门也是本研究中的重要细菌. 在聚合物的氧化过程中, 像蓝藻细菌这样的产氧细菌在塑料表面的出现尤其重要^[17,19]. 在属水平上, 本研究中微塑料表面细菌主要由马赛菌属 (*Massilia*) 和未分类的伯克氏菌 (*uncultured_bacterium_f_Burkholderia*) 组成. 以往研究发现微塑料上常见的生物标志物 *Litoribacter* 和弧菌属 (*Vibrio*) 在本研究中未发现^[18,37]. 近年来, 人们越来越关注微塑料作为微生物, 尤其是有害和

致病微生物载体的作用^[38,39]. 弧菌属作为潜在致病菌属也受到研究者的关注. 在以往的研究里, 弧菌属经常被发现与塑料碎片有关^[18,40], 从塑料组分中检测到了弧菌属, 但是弧菌属是否存在潜在致病性弧菌菌株还需要进一步了解微塑料对病原菌株群迁移和最终病害发生的作用^[28]. 甚至在北大西洋收集到的聚丙烯颗粒中所占比例高达 24%^[17]. 然而, 并不是所有研究的结果都一致, Oberbeckmann 等^[14] 和 Bryant 等^[16] 的研究没有观察到弧菌属在微塑料上的富集, 本研究也没有得出这一结果.

3.2 微生物对微塑料的适应探讨

有研究表明塑料颗粒上的微生物群落与周围环境微生物不同的生活方式、代谢途径和生物地球化学活性^[12], 微塑料表面细菌群落似乎很好地适应了与塑料表面相关的生活方式^[41]. 总的来说, 塑料碎片形成了一个独特的微生物群落的栖息地, 这些微生物群落具有其独特的生活方式和代谢途径^[16]. 本研究的 KEGG 功能基因预测结果显示, 在所有与沉积物有显著差异的代谢通路中, 大部分通路代谢有关, 但是不同微塑料又表现出不同的结果. PE 和 PP2 表面细菌表现为细胞运动性、信号转导和碳水化合物代谢降低, 而能量代谢及辅助因子代谢升高. PS 和 PP1 表面细菌促进了外源性物质生物降解、细胞运动性和信号转导. Jiang 等^[35] 的研究通过代谢途径分析得出, 微塑料相关细菌组合对塑料表面定植生活方式的适应包括降低细胞活力和增加的异种生物降解和代谢. 微塑料表面的微生物群落可以催化代谢反应, 促进微塑料相关化合物的吸收、解吸和分解, 甚至碎片本身的分解^[9,42]. 而且与环境中自由生活的微生物的生活方式相比, 微塑料表面微生物群落的聚集会导致更高的代谢周转率^[43]. 外源性物质生物降解和细胞运动性和信号转导的上调可能是细菌在加速降解微塑料时信号调节途径的基因表达水平的提高^[40]. 微生物对微塑料的生物降解产生影响. 在水生环境中, 微生物作为先驱的表面定植体, 驱动着重要的生态系统过程, 包括初级生产、生物地球化学循环和人为污染物的生物降解^[9]. Zettler 等^[17] 的研究发现塑料微粒上的微生物群落的分类组成与周围的海水截然不同, 这些塑料相关微生物能够降解塑料聚合物, 改变聚合物的浮力, 对塑料的毒性产生影响^[43]. 细菌附着在塑料上在自然环境中很常见, 也会影响塑料在水环境中的命运和运输. 而且还具有多种降解微塑料的功能^[44]. 有研究通过调查发现了几种降解烃类的细菌, 支持了微生物在降解微塑料中发挥作用的可能性^[45].

微塑料作为一种特殊的微生物栖息地, 不仅可

以改变微生物群落结构,还可以影响微生物功能,从而潜在地影响水生生态系统中微生物群落的生态功能^[31]。因此,需要对微塑料表面微生物和它们的周围环境之间的相互作用有更多的认识,以便更好地预测微塑料的生态后果,因为这些持久的微粒是通过全球海洋运输的^[46]。本研究将有助于减少微塑料积累、生物影响的减缓和预防策略的制定。

4 结论

(1) 微塑料表面细菌和真菌群落丰富度和多样性与周围沉积物中不同,不同类型微塑料差异也不相同,微塑料表面存在相对于周围沉积物独有的细菌和真菌。

(2) 本研究表明微塑料样品表面细菌群落主要包括:变形菌门(Proteobacteria)、蓝藻门(Cyanobacteria)、拟杆菌门(Bacteroidetes)、酸杆菌门(Acidobacteria)、硝化螺旋菌门(Nitrospirae)和绿弯菌门(Chloroflexi),属水平上微塑料表面细菌主要由马赛菌属(*Massilia*)和未分类的伯克氏菌(*uncultured_bacterium_f_Burkholderia*)组成。真菌优势菌门为:子囊菌门(Ascomycota)、担子菌门(Basidiomycota)和壶菌门(Chytridiomycota),属水平上沉积物中相对丰度最高的是裂壳菌属(*Schizothecium*)。微塑料表面真菌丰度较大的属包括枝孢属(*Cladosporium*)和*Paraphaeosphaeria*。

(3) KEGG 功能基因预测结果显示,在所有与沉积物有显著差异的代谢通路中,大部分通路代谢有关,但是不同微塑料又表现出不同的结果。表明微塑料表面的微生物群落可以催化代谢反应,促进微塑料的分解。

参考文献:

- [1] Akhbarizadeh R, Moore F, Keshavarzi B, *et al.* Microplastics and potentially toxic elements in coastal sediments of Iran's main oil terminal (Khark Island) [J]. *Environmental Pollution*, 2017, **220**: 720-731.
- [2] Amelia T S M, Khalik W M A W M, Ong M C, *et al.* Marine microplastics as vectors of major ocean pollutants and its hazards to the marine ecosystem and humans [J]. *Progress in Earth and Planetary Science*, 2021, **8**, doi: 10.1186/s40645-020-00405-4.
- [3] Yoshida S, Hiraga K, Takehana T, *et al.* A bacterium that degrades and assimilates poly (ethylene terephthalate) [J]. *Science*, 2016, **351**(6278): 1196-1199.
- [4] Thompson R C, Olsen Y, Mitchell R P, *et al.* Lost at sea: Where is all the plastic? [J]. *Science*, 2004, **304**(5672): 838.
- [5] Lyons B P, Cowie W J, Maes T, *et al.* Marine plastic litter in the ROPME Sea Area: Current knowledge and recommendations [J]. *Ecotoxicology and Environmental Safety*, 2020, **187**, doi: 10.1016/j.ecoenv.2019.109839.
- [6] 林旭萌, 宿程远, 吴淑敏, 等. 微塑料 PES 与 2,4-DCP 复合污染对厌氧污泥胞外聚合物与微生物群落的影响 [J]. *环境科学*, 2021, **42**(4): 1946-1955.
- [7] Lin X Y, Su C Y, Wu S M, *et al.* Effects of PES and 2,4-DCP on the extracellular polymeric substances and microbial community of anaerobic granular sludge [J]. *Environmental Science*, 2021, **42**(4): 1946-1955.
- [8] 周倩, 章海波, 周阳, 等. 滨海滩涂土壤中微塑料的分离及其表面微观特征 [J]. *科学通报*, 2016, **61**(14): 1604-1611.
- [9] Zhou Q, Zhang H B, Zhou Y, *et al.* Separation of microplastics from a coastal soil and their surface microscopic features [J]. *Chinese Science Bulletin*, 2016, **61**(14): 1604-1611.
- [10] Heindler F M, Alajmi F, Huerlimann R, *et al.* Toxic effects of polyethylene terephthalate microparticles and Di (2-ethylhexyl) phthalate on the calanoid copepod, *Parvocalanus crassirostris* [J]. *Ecotoxicology and Environmental Safety*, 2017, **141**: 298-305.
- [11] Harrison J P, Sapp M, Schratzberger M, *et al.* Interactions between microorganisms and marine microplastics: A call for research [J]. *Marine Technology Society Journal*, 2011, **45**(2): 12-20.
- [12] Viršek M K, Lovšin M N, Koren Š, *et al.* Microplastics as a vector for the transport of the bacterial fish pathogen species *Aeromonas salmonicida* [J]. *Marine Pollution Bulletin*, 2017, **125**(1-2): 301-309.
- [13] 黄福义, 杨凯, 张子兴, 等. 微塑料对河口沉积物抗生素抗性基因的影响 [J]. *环境科学*, 2019, **40**(5): 2234-2239.
- [14] Huang F Y, Yang K, Zhang Z X, *et al.* Effects of microplastics on antibiotic resistance genes in estuarine sediments [J]. *Environmental Science*, 2019, **40**(5): 2234-2239.
- [15] 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**, doi: 10.1186/s12866-014-0232-4.
- [16] 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.
- [17] Oberbeckmann S, Löder M G J, Labrenz M. Marine microplastic-associated biofilms-a review [J]. *Environmental Chemistry*, 2015, **12**(5): 551-562.
- [18] Baptista Neto J A, Gaylarde C, Beech I, *et al.* Microplastics and attached microorganisms in sediments of the Vitória bay estuarine system in SE Brazil [J]. *Ocean & Coastal Management*, 2019, **169**: 247-253.
- [19] Bryant J A, Clemente T M, Viviani D A, *et al.* Diversity and activity of communities inhabiting plastic debris in the North Pacific Gyre [J]. *Msystems*, 2016, **1**(3), doi: 10.1128/mSystems.00024-16.
- [20] 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.
- [21] 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.
- [22] Keswani A, Oliver D M, Gutierrez T, *et al.* Microbial hitchhikers on marine plastic debris: Human exposure risks at bathing waters and beach environments [J]. *Marine Environmental Research*, 2016, **118**: 10-19.
- [23] 胡振鹏, 葛刚, 刘成林, 等. 鄱阳湖湿地植物生态系统结构

- 及湖水位对其影响研究[J]. 长江流域资源与环境, 2010, **19**(6): 597-605.
- Hu Z P, Ge G, Liu C L, *et al.* Structure of Poyang Lake wetland plants ecosystem and influence of lake water level for the structure [J]. Resources and Environment in the Yangtze Basin, 2010, **19**(6): 597-605.
- [21] 弓晓峰, 陈春丽, 周文斌, 等. 鄱阳湖底泥中重金属污染现状评价[J]. 环境科学, 2006, **27**(4): 732-736.
- Gong X F, Chen C L, Zhou W B, *et al.* Assessment on heavy metal pollution in the sediment of Poyang Lake [J]. Environmental Science, 2006, **27**(4): 732-736.
- [22] 刘淑丽, 简敏菲, 周隆胤, 等. 鄱阳湖湿地候鸟栖息地微塑料污染特征[J]. 环境科学, 2019, **40**(6): 2639-2646.
- Liu S L, Jian M F, Zhou L Y, *et al.* Pollution characteristics of microplastics in migratory bird habitats located within Poyang Lake Wetlands [J]. Environmental Science, 2019, **40**(6): 2639-2646.
- [23] Yuan W K, Liu X N, Wang W F, *et al.* Microplastic abundance, distribution and composition in water, sediments, and wild fish from Poyang Lake, China [J]. Ecotoxicology and Environmental Safety, 2019, **170**: 180-187.
- [24] 赵其国, 黄国勤, 钱海燕. 鄱阳湖生态环境与可持续发展[J]. 土壤学报, 2007, **44**(2): 318-326.
- Zhao Q G, Huang G Q, Qian H Y. Ecological environment and sustainable development of Poyang Lake [J]. Acta Pedologica Sinica, 2007, **44**(2): 318-326.
- [25] 简敏菲, 李玲玉, 余厚平, 等. 鄱阳湖湿地水体与底泥重金属污染及其对沉水植物群落的影响[J]. 生态环境学报, 2015, **24**(1): 96-105.
- Jian M F, Li L Y, Yu H P, *et al.* Heavy Metals pollution on the water and sediments and its influence on the submerged macrophyte community in the wetland of Poyang Lake [J]. Ecology and Environmental Sciences, 2015, **24**(1): 96-105.
- [26] DeSantis T Z, Hugenholtz P, Larsen N, *et al.* Greengenes, a chimera-checked 16S rRNA gene database and workbench compatible with ARB [J]. Applied and Environmental Microbiology, 2006, **72**(7): 5069-5072.
- [27] 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), doi: 10.1002/ecs2.1556.
- [28] 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.
- [29] Kirstein I V, Wichels A, Gullans E, *et al.* The Plastisphere: Uncovering tightly attached plastic “specific” microorganisms [J]. Plos One, 2019, **14**(4), doi: 10.1371/journal.pone.0215859.
- [30] Amaral-Zettler L A, Zettler E R, Slikas B, *et al.* The biogeography of the Plastisphere: implications for policy [J]. Frontiers in Ecology and the Environment, 2015, **13**(10): 541-546.
- [31] Miao L Z, Yu Y, Adyel T M, *et al.* Distinct microbial metabolic activities of biofilms colonizing microplastics in three freshwater ecosystems [J]. Journal of Hazardous Materials, 2021, **403**, doi: 10.1016/j.jhazmat.2020.123577.
- [32] Cai L, Wu D, Xia J H, *et al.* Influence of physicochemical surface properties on the adhesion of bacteria onto four types of plastics [J]. Science of the Total Environment, 2019, **671**: 1101-1107.
- [33] 李婉逸, 刘智临, 苗令占, 等. 淡水系统中4种塑料颗粒的老化过程及DOC产物分析[J]. 环境科学, 2021, **42**(8): 3829-3836.
- Li W Y, Liu Z L, Miao L Z, *et al.* Aging process and DOC analysis of four different types of plastic particles in freshwater systems [J]. Environmental Science, 2021, **42**(8): 3829-3836.
- [34] Ali Shah A, Hasan F, Hameed A, *et al.* Biological degradation of plastics: a comprehensive review [J]. Biotechnology Advances, 2008, **26**(3): 246-265.
- [35] Jiang P L, Zhao S Y, Zhu L X, *et al.* Microplastic-associated bacterial assemblages in the intertidal zone of the Yangtze Estuary [J]. Science of the Total Environment, 2018, **624**: 48-54.
- [36] Lee J W, Nam J H, Kim Y H, *et al.* Bacterial communities in the initial stage of marine biofilm formation on artificial surfaces [J]. The Journal of Microbiology, 2008, **46**(2): 174-182.
- [37] Kesey K, Oberbeckmann S, Müeller F, *et al.* Polystyrene influences bacterial assemblages in *Arenicola marina*-populated aquatic environments *in vitro* [J]. Environmental Pollution, 2016, **219**: 219-227.
- [38] Naik R K, Naik M M, D’Costa P M, *et al.* Microplastics in ballast water as an emerging source and vector for harmful chemicals, antibiotics, metals, bacterial pathogens and HAB species: A potential risk to the marine environment and human health [J]. Marine Pollution Bulletin, 2019, **149**, doi: 10.1016/j.marpolbul.2019.110525.
- [39] Li W J, Zhang Y, Wu N, *et al.* Colonization characteristics of bacterial communities on plastic debris influenced by environmental factors and polymer types in the Haihe Estuary of Bohai Bay, China [J]. Environmental Science & Technology, 2019, **53**(18): 10763-10773.
- [40] 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.
- [41] Carson H S, Nerheim M S, Carroll K A, *et al.* The plastic-associated microorganisms of the North Pacific Gyre [J]. Marine Pollution Bulletin, 2013, **75**(1-2): 126-132.
- [42] Zhu L X, Zhao S Y, Bittar T B, *et al.* Photochemical dissolution of buoyant microplastics to dissolved organic carbon: Rates and microbial impacts [J]. Journal of Hazardous Materials, 2020, **383**, doi: 10.1016/j.jhazmat.2019.121065.
- [43] Miao L Z, Wang P F, Hou J, *et al.* Distinct community structure and microbial functions of biofilms colonizing microplastics [J]. Science of the Total Environment, 2019, **650**: 2395-2402.
- [44] Raddadi N, Fava F. Biodegradation of oil-based plastics in the environment: Existing knowledge and needs of research and innovation [J]. Science of the Total Environment, 2019, **679**: 148-158.
- [45] Syranidou E, Karkanorachaki K, Amorotti F, *et al.* Biodegradation of weathered polystyrene films in seawater microcosms [J]. Scientific Reports, 2017, **7**, doi: 10.1038/s41598-017-18366-y.
- [46] Tarafdar A, Lee J U, Jeong J E, *et al.* Biofilm development of *Bacillus siamensis* ATKU1 on pristine short chain low-density polyethylene: A case study on microbe-microplastics interaction [J]. Journal of Hazardous Materials, 2021, **409**, doi: 10.1016/j.jhazmat.2020.124516.

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