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农村黑臭水体沉积物细菌群落结构特征

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摘要: 沉积物微生物是农村黑臭水体物质循环和有机物降解等过程的主要驱动者, 其群落结构组成常因外界环境的微小变化而变化。以菏泽市东明县 29 个农村黑臭水体为研究对象, 测定农村黑臭水体上覆水和沉积物氮、磷及重金属等污染物指标, 结合 Illumina 测序结果, 分析农村黑臭水体沉积物细菌群落组成和多样性特征及其与环境因子的相关性。结果表明, 该区域农村黑臭水体上覆水和沉积物中污染物分布范围均较广。与农业面源相比, 以农村生活污水为主要污染来源的农村黑臭水体上覆水中氮、磷污染物浓度更高, 分别是农业面源的 3.1 倍和 1.5 倍。此外, 该区域农村黑臭水体沉积物中重金属含量处于较低水平, 普遍低于菏泽市土壤元素背景值。该区域农村黑臭水体沉积物细菌群落的优势菌门为变形菌门、放线菌门、绿弯菌门、厚壁菌门和酸杆菌门, 这 5 种优势菌门的序列总和占全部序列的 70.3%~83.6%。γ-变形菌纲、α-变形菌纲、厌氧绳菌纲和放线菌纲是沉积物细菌群落的优势菌纲; 硫杆菌属和假节杆菌属是其优势菌属。Spearman 相关性分析结果表明, 环境因子中 DO、COD、TN、TP 和有机质对农村黑臭水体沉积物细菌菌属有显著影响 ($P < 0.05$), 沉积物细菌群落丰富度受 TN 的影响显著 ($P < 0.05$)。研究结果可为农村黑臭水体治理提供微生物学方面的理论依据。

关键词: 农村黑臭水体; 细菌群落; 微生物多样性; 相关性分析; 表层沉积物

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Characteristics of Bacterial Community Structure in the Sediment of Rural Black and Odorous Water Bodies

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Abstract: Sediment microorganisms are the main drivers of the material circulation and organic matter degradation processes in rural black and odorous water bodies (RBOWB), and the community structure of sediment microorganisms follows the changes in the external environment. Here, the pollutant indicators, including nitrogen, phosphorus, and heavy metals in the overlying water and sediment of 29 RBOWB in Dongming County of Heze City were measured, respectively. Combined with Illumina sequencing results, the composition and diversity characteristics of sediment bacterial communities in RBOWB and their correlation with environmental factors were further analyzed. The experimental results showed a wide distribution of pollutants in both of the overlying water and sediment in the RBOWB of this region. Compared with agricultural non-point source pollution, the concentrations of nitrogen and phosphorus pollutants in the overlying water with domestic sewage as the main source of pollution were 3.1 and 1.5 times higher than those of agricultural non-point source pollution, respectively. In addition, the contents of heavy metals in the sediments of RBOWB were generally lower than the soil element background value in Heze City. The dominant bacteria phyla in the sediments of the RBOWB were Proteobacteria, Actinobacteria, Chloroflexi, Firmicutes, and Acidobacteria, and the total abundance of these five dominant phyla accounted for 70.3%-83.6% of all sequences. The dominant classes were γ-Proteobacteria, α-Proteobacteria, Anaerolineae, and Actinobacteria. The dominant genera were *Thiobacillus* and *Pseudarthrobacter*. Moreover, Spearman correlation analysis showed that the environmental factors of DO, COD, TN, TP, and organic matter exerted significant effects ($P < 0.05$) on sediment bacterial genera in RBOWB, and sediment bacterial community richness was significantly influenced by TN ($P < 0.05$). The above results provided the microbiological knowledge for treating RBOWB.

Key words: rural black and odorous water bodies; bacterial communities; microbial diversity; correlation analysis; surface sediments

农村黑臭水体治理是农业农村污染治理攻坚战的重要内容^[1,2]。“十四五”规划纲要提出,要稳步解决农村黑臭水体等突出环境问题,推进农村水系综合整治^[3,4]。中共中央办公厅、国务院办公厅 2021 年印发的《农村人居环境整治提升五年行动方案(2021-2025 年)》,明确指出要突破瓶颈,系统整治农村黑臭水体^[5]。到 2025 年,基本消除较大面积农村黑臭水体,推动农村黑臭水体“长治久清”,显著提升农村环境整治水平^[3~5]。农村黑臭水体治理可推动农村生态环境的显著改善,事关居民的日常生活,对增强广大农村群众的获得感、幸福感具有极其重要的意义^[2,5]。

农村水体黑臭作为我国目前突出的水环境恶化现象,微生物驱动的生物化学过程扮演着至关重要的作用^[2,6]。当水体纳入超出自净能力的有机污染物时,微生物在降解污染物过程中大量消耗水体中的溶解氧,加速水体呈现缺氧或厌氧状态,促使污染物进一步分解转化为致黑致臭物质^[2,3,6]。沉积物作为污染物的源和汇,是微生物群落集聚的栖息地^[6~8]。同时,沉积物微生物群落在水体物质和能量

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的交换过程中,发挥着桥梁和纽带作用,对水质的改善至关重要^[8-12]. 沉积物微生物群落对水体环境因子的细微变化可敏感反映^[13-16],其群落组成和多样性对水体生态系统污染程度、完整性和稳定性有重要的生物学指示作用^[6,13,17]. 有研究发现,沉积物细菌群落受黑臭水体上覆水和沉积物全氮(TN)和总磷(TP)等因素显著影响^[17-19];水体污染越严重,沉积物微生物功能基因的丰度越低^[20,21]. 在黑臭形成过程中,沉积物微生物群落中 γ -变形菌纲和厌氧绳菌纲常作为优势菌纲,在污染物质的降解及黑臭物质的产生中发挥着重要的作用^[14]. 有研究发现,城市黑臭水体修复后,沉积物微生物群落中对氮、有机污染物和硫化氢的去除有重要作用的假单胞菌属和盐单胞菌属的相对丰度将增加^[19]. 相较于城市黑臭水体,目前针对农村黑臭水体的研究多集中在上覆水或沉积物理化指标的分析^[3],对农村黑臭水体沉积物中微生物群落组成及其多样性研究鲜见报道. 因此,系统掌握农村黑臭水体沉积物微生物群落结构及优势菌群,了解沉积物中微生物群落与环境因子的关系,对于深入理解农村黑臭水体成因及治理农村黑臭水体具有重要的参考意义.

本文研究区域为菏泽市东明县,在该县域范围内采集农村黑臭水体上覆水和沉积物样品,并对样品进行常规污染物测定,分析上覆水和沉积物中污染物的分布特征,并比较不同污染来源的水体上覆水和沉积物中各因子差异;结合高通量测序技术,分析各农村黑臭水体沉积物中细菌群落结构组成和多样性,探讨农村黑臭水体污染物与沉积物中细菌群落多样性及组成的关系,以期为农村黑臭水体治理提供微生物学方面的科学依据.

1 材料与方法

1.1 样品来源

本文选取山东省东明县为研究区域. 样品采集于该区域的29个农村黑臭水体. 样品采集区域及农村黑臭水体分布见图1所示. 29个农村黑臭水体分别用S1~S29命名. 采样点布设依据农村黑臭水体类型而确定. 沟渠型沿沟渠等距离(间隔100 m)布置采样点,不足100 m,则布设点位1个. 坑塘型采用3点取样法均匀布点. 每个采样点随机取样3次并均匀混合,随后每个农村黑臭水体的所有采样点再均匀混合. 因29个农村黑臭水体面积较小,每个均匀混合后的样品可代表此农村黑臭水体.

2021年8月现场采集农村黑臭水体上覆水和沉积物样品. 上覆水采集后装入密封的聚乙烯瓶中;沉积物样品采集于0~20 cm表层,采集约1 kg置

于无菌聚乙烯自封袋. 现场采集的所有样品置于4℃冷藏箱临时保存,24 h内运回实验室. 其中上覆水经0.45 μm 滤膜抽滤后直接分析测定;沉积物样品过2 mm 尼龙筛后,细致挑拣出石块和根系等杂质,分成两份,一份置于-80℃冰箱中存储用于细菌群落结构分析,另一份室内自然风干研磨后用于理化性质测定.



图1 东明县农村黑臭水体分布示意
Fig. 1 Distribution of rural black and odorous water bodies in Dongming County

1.2 水样和沉积物样品指标测定

农村黑臭水体上覆水测定指标包括pH、电导率(EC)、透明度、溶解氧(DO)、化学需氧量(COD)、氨氮($\text{NH}_4^+\text{-N}$)和 TP_1 等. 其中,pH和EC使用便携式pH/EC仪现场测定;透明度采用透明度计法;便携式溶解氧仪现场测定DO;重铬酸盐法测定COD; $\text{NH}_4^+\text{-N}$ 和 TP_1 均采用紫外可见分光光度法测定.

沉积物样品测定指标包括有机质(OM)、TN、 TP_2 和铅(Pb)、镉(Cd)、铜(Cu)、镍(Ni)、锌(Zn)、铬(Cr)、汞(Hg)、砷(As)等重金属. pH值采用电极电位法;有机质采用重铬酸钾法;TN采用酸式滴定管凯氏法; TP_2 采用碱熔-钼锑抗分光光度法. Pb和Cd采用石墨炉原子吸收分光光度法;Cu、Ni、Zn和Cr采用火焰原子吸收分光光度法;Hg采用流动注射测汞仪法;As采用电感耦合等离子体质谱法.

1.3 DNA提取和Illumina测序

沉积物样品送至上海美吉生物医药科技有限公司进行细菌总DNA提取和高通量测序. DNA采用FastDNA Spin Kit for Soil试剂盒(美国Mpbio公司)提取. PCR采用16S rRNA基因通用引物338F(5'-

ACTCCTACGGGAGGCAGCAG-3') 和 806R (5'-GGACTACHVGGGTWTCTAAT-3') 在 V3 ~ V4 高变区进行扩增. 采用 TruSeqTM DNA Sample Prep Kit 进行 MiSeq 文库构建, 高通量测序在 Illumina MiSeq 测序平台进行.

1.4 数据分析

MiSeq 测序的结果分析在美吉生物-生信云工具 (<https://cloud.majorbio.com/>) 上进行. 通过 Uparse (version 7.0.1090 <http://drive5.com/uparse/>) 软件平台将相似性大于 97% 的优化序列划分为一个操作分类单元 (operational taxonomic units, OTU), 并进行 OTU 聚类分析, 计算 Sobs、Chao1、Shannon、ACE、Simpson 和 Coverage 指数.

方差和显著性分析采用 SPSS 27.0 软件. 水样和沉积物中理化指标与微生物 α 多样性指数的 Spearman 相关性 Heatmap 分析采用 OriginPro 2022 (学习版) 绘制; 相关性热图和 Venn 图分别采用 RStudio 4.20 中的 pheatmap、plotrix 和 ggplot2 包绘制.

2 结果与讨论

2.1 农村黑臭水体理化指标分布特征

本研究 29 个农村黑臭水体上覆水和沉积物的物理化学特征如表 1 所示. 结果表明, 农村黑臭水体上覆水和沉积物中的理化性质分布范围皆较广. 例

如, 上覆水中 $\rho(\text{NH}_4^+-\text{N})$ 范围在 0.10 ~ 14.25 $\text{mg}\cdot\text{L}^{-1}$, 沉积物中 $\omega(\text{OM})$ 范围在 4.40 ~ 45.60 $\text{g}\cdot\text{kg}^{-1}$. 此外, 重金属 Pb、Cd、Cu、Ni、Cr、As、Zn 和 Hg 在该区域农村黑臭水体沉积物中的含量都较低^[21], 普遍低于菏泽市土壤元素背景值^[22]. 尤其是重金属 Hg, 在各点位中的检测值均低于检出限. 这可能是因为农业面源和农村生活污水等农村黑臭水体外源污染物中, N 和 P 等污染物组分各异, 重金属含量却都较低^[3].

污染来源是影响农村黑臭水体上覆水和沉积物理化性质的重要因素^[2]. 本研究区域中, 农村生活污水和农业面源是主要的污染来源, 居民生活垃圾和畜禽养殖均合理规划、有效管控. Mann-Whitney 非参数检验结果显示, 上覆水中 NH_4^+-N 和 DO 在不同污染来源间差异显著 ($P < 0.05$). 与农业面源相比, 主要污染来源为生活污水的农村黑臭水体上覆水中 N 和 P 污染物浓度更高, 分别是农业面源的 3.1 倍和 1.5 倍. 这可能是因为直排的农村生活污水主要由厨余灰水和部分化粪池黑水组成^[1,3,5].

2.2 农村黑臭水体沉积物微生物群落多样性分析

农村黑臭水体沉积物细菌群落 α 多样性如图 2 所示 (覆盖率大于 95%). Sobs 指数用来表征实际 OTUs 数量, Chao1 和 ACE 指数用来表征物种的丰富度, Shannon 和 Simpson 指数用来表征物种的多样性. 沉积物样品 Sobs、Chao1、ACE、Shannon 和

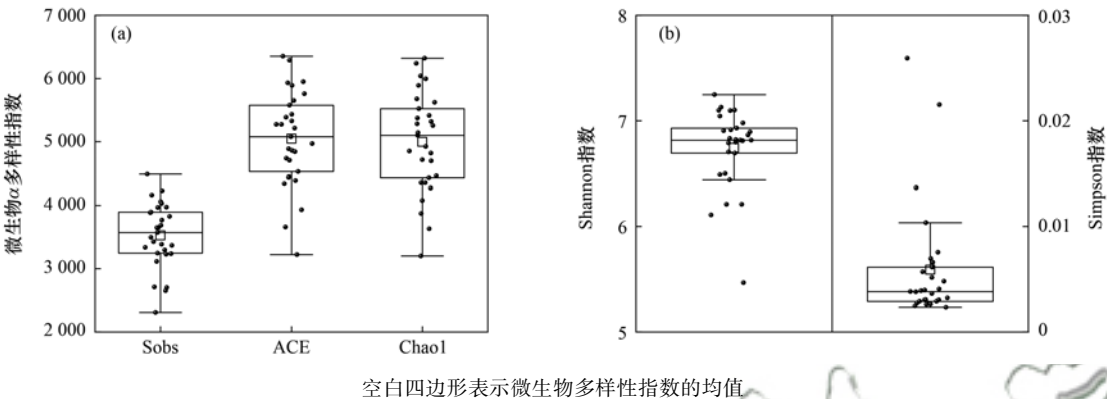
表 1 农村黑臭水体上覆水和沉积物的理化特征分析¹⁾
Table 1 Analysis of physicochemical characteristics of overlying water and sediments in rural black and odorous water bodies

类型	项目	范围	均值	标准差	变异系数	农村生活污水 (<i>N</i> = 15)	农业面源 (<i>N</i> = 14)
上覆水	pH	7.10 ~ 9.20	7.86	0.48	6.11	7.84	7.92
	NH_4^+-N	0.10 ~ 14.25	4.49	4.04	89.98	6.54	2.09
	DO	1.00 ~ 8.37	3.34	1.72	51.50	2.75	4.13
	TP_1	0.08 ~ 2.57	0.83	0.58	69.88	0.97	0.65
	COD	17.0 ~ 110.0	51.4	24.2	47.08	53.7	48.7
	EC	245.00 ~ 1 210.00	630.03	213.77	33.93	794.06	561.43
	透明度	6 ~ 30	27	6	22.22	26	27
沉积物	TN	0.32 ~ 2.36	0.90	0.44	48.89	0.86	0.95
	TP_2	0.49 ~ 1.10	0.71	0.17	23.94	0.75	0.67
	OM	4.40 ~ 45.60	15.48	10.63	68.67	14.48	16.54
	Pb	13.90 ~ 31.30	21.03	4.47	21.26	20.71	21.38
	Hg	—	—	—	—	—	—
	Cd	0.05 ~ 0.20	0.11	0.04	33.36	0.10	0.12
	Cu	9.00 ~ 32.00	17.80	5.98	33.60	17.72	17.89
	Ni	16.00 ~ 32.00	20.94	3.66	17.48	20.27	21.65
	Cr	30.50 ~ 66.00	43.41	8.41	19.37	44.90	41.81
	Zn	37.00 ~ 176.00	66.90	30.92	46.22	66.48	67.35
	As	4.07 ~ 13.50	8.33	2.22	26.65	8.65	7.98

1) 单位说明: pH 无量纲, 变异系数为%, 上覆水涉及浓度为 $\text{mg}\cdot\text{L}^{-1}$, EC 为 $\mu\text{S}\cdot\text{cm}^{-1}$, 透明度为 cm, 沉积物 (TN、 TP_2 和 OM) 为 $\text{g}\cdot\text{kg}^{-1}$, 沉积物 (其他元素) 为 $\text{mg}\cdot\text{kg}^{-1}$; “—”表示检测值低于检出限; *N* 表示污染源为农村生活污水和农业面源的农村黑臭水体个数, 其中 S5、S6、S8、S10、S12、S13、S14、S16、S18、S19、S20、S23、S24、S25 和 S29 主要受农村生活污水影响; S1、S2、S3、S4、S7、S9、S11、S15、S17、S21、S22、S26、S27 和 S28 主要受农业面源影响

Simpson 指数的平均值分别为3 530、4 995、5 046、6.74 和0.006. 其中,主要污染源为农村生活污水的沉积物中 Sobs、Chao1 和 ACE 指数均高于对应指数平均值;而主要污染源为农业面源时,各指数均低于对应指数平均值. 这说明以农村生活污水为主要污染源的农村黑臭水体沉积物细菌群落可呈更高的

物种丰富度(表2). 这主要是沉积物作为黑臭水体污染物的源和汇,当农村生活污水排入水体后,为沉积物中的微生物生长繁殖提供更为丰富的可利用 C 源和 N 源^[14,23,24];而微生物的大量繁殖也有利于有机污染物的分解,进而提高上覆水中 N 和 P 等污染物的浓度^[3,24].



空白四边形表示微生物多样性指数的均值
图2 农村黑臭水体沉积物细菌群落 α 多样性
Fig. 2 The α diversity of bacterial communities in the sediments of rural black and odorous water bodies

表2 不同污染来源的农村黑臭水体沉积物细菌群落 α 多样性指数状况

Table 2 The α diversity index of bacterial communities in the sediments of rural black and odorous water bodies from different pollution sources

污染来源	Sobs 指数	ACE 指数	Chao1 指数	Shannon 指数	Simpson 指数
生活污水	3603	5194	5109	6.74	0.007
农业面源	3451	4887	4872	6.74	0.005

农村黑臭水体沉积物细菌群落 Venn 图结果显示,在 29 个水体沉积物中共有的 OTUs 有 230 个,独有的 OTUs 范围为2 079 ~4 258个,平均值为3 230 个(图3). 这表明细菌群落不同沉积物样品中都具有较高的物种多样性和物种丰富度,但是细菌群落的多样性也存在差异.

2.3 农村黑臭水体沉积物细菌群落组成分析

该地区农村黑臭水体沉积物中平均丰度大于3%的菌门有 11 种(图4),主要的优势菌门为变形菌门(Proteobacteria,7.08% ~42.22%)、放线菌门(Actinobacteria,5.73% ~36.52%)、绿弯菌门(Chloroflexi,7.87% ~20.50%)、厚壁菌门(Firmicutes,2.57% ~49.42%)和酸杆菌门(Acidobacteria,2.40% ~20.74%),这5种优势菌门的序列总和占全部序列的70.3%~83.6%.

变形菌门在该区域农村黑臭水体沉积物细菌群落中的丰度优势与城市黑臭水体沉积物存在相似性. 例如,金川河南京段、东莞市黑臭排沟和广州黑臭河流等点位均发现变形菌门是其沉积物中的优势菌门^[21,25,26],该菌门主要参与沉积物中腐殖质、氨基酸等有机物的降解以及生物脱氮除磷过程^[27]. 此外,放线菌门、厚壁菌门和绿弯菌门也是该区域农村黑臭水体沉积物中 C 和 N 循环的主要参与者,在

降解各种生物或非生物来源的有机物中发挥着重要作用^[16,28,29]. 与多数城市黑臭水体沉积物不同,该地区农村黑臭水体沉积物中酸杆菌门作为优势菌门而非拟杆菌门,对多聚物和植物残体起降解作用^[30]. 此外,放线菌门作为该地区农村黑臭水体沉积物中特殊的优势菌门亦参与复杂有机化合物降解^[16]. 有研究发现,农村黑臭水体沉积物中的优势菌门与水质良好水体沉积物存在明显差异. 例如,长江口和三峡水库等沉积物菌群中优势菌门为变形菌门、酸杆菌门和绿弯菌门等^[31,32].

该区域农村黑臭水体沉积物中相对丰度大于1%的优势菌纲有 4 种,分别是 γ -变形菌纲(γ -Proteobacteria,3.56% ~28.04%)、 α -变形菌纲(α -Proteobacteria,3.52% ~20.50%)、厌氧绳菌纲(Anaerolineae,1.62% ~15.32%)和放线菌纲(Actinobacteria,2.06% ~15.72%),如图5所示.

上述结果表明, γ -变形菌纲和 α -变形菌纲是该区域农村黑臭水体中主要的微生物菌群. 本研究结果与城市黑臭水体沉积物中细菌群落组成类似^[25,33,34]. γ -变形菌纲和 α -变形菌纲均属于变形菌门,是评估受污染水体沉积物细菌群落的重要生态指标^[35,36]. 根据 γ -变形菌纲和 α -变形菌纲的高丰度研究结果,可推测 C 和 N 循环在农村黑臭水体沉

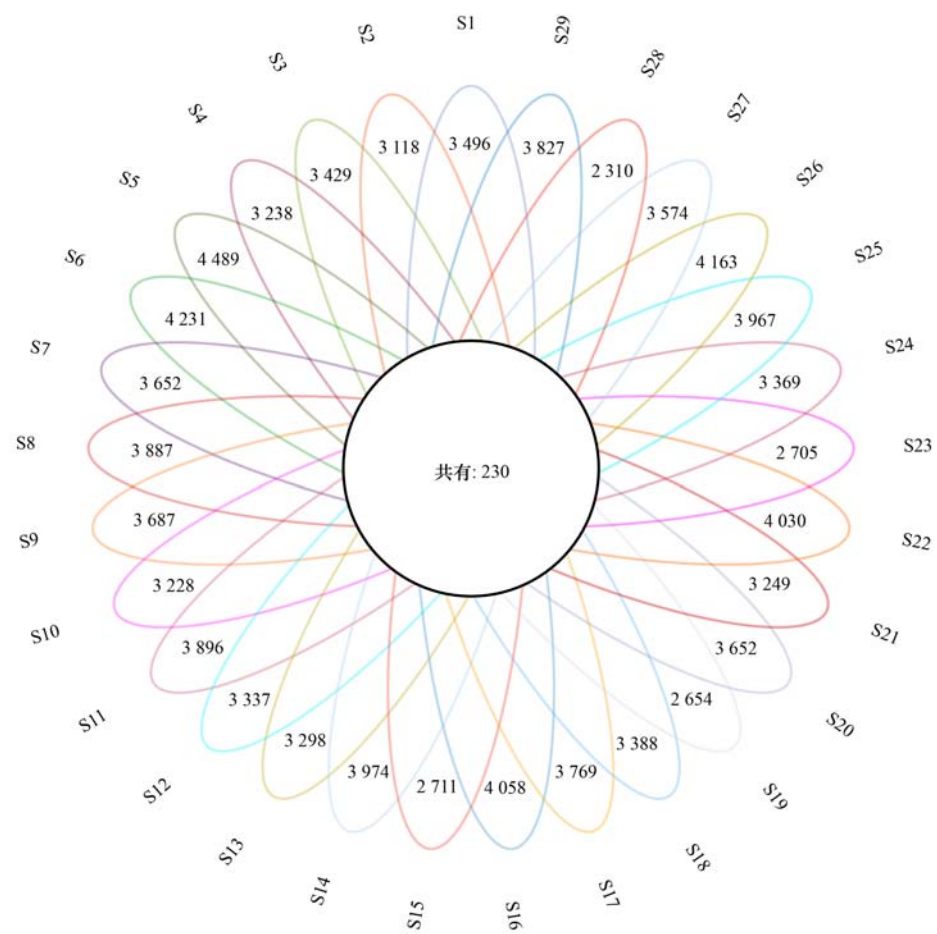


图3 农村黑臭水体沉积物细菌群落 Venn 图(97%相似度)

Fig. 3 Venn diagram of bacterial communities in the sediments of rural black and odorous water bodies(97% similarity)

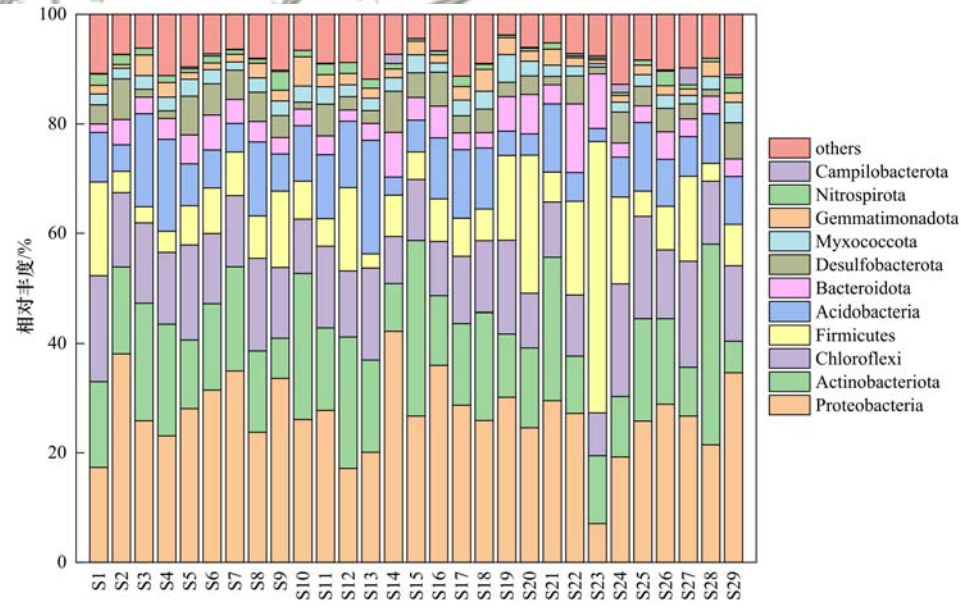


图4 农村黑臭水体沉积物细菌群落门水平的相对丰度

Fig. 4 Relative abundance of bacterial communities in the sediments of rural black and odorous water bodies at phylum level

积物中可能频繁进行. γ -变形菌纲主要参与沉积物中有机物降解和厌氧氨氧化过程^[26], 由于此纲涉及大量致病菌, 累积过多可对居民健康产生潜在的危害^[21]. α -变形菌纲主要在硝化和反硝化、硫代硫酸

盐和有机质生物合成与降解中发挥作用^[37]. 厌氧菌纲属于绿弯菌门, 参与降解生活污水和农业面源污染中各种氨基酸和脂类等有机化合物^[38]; 它作为优势菌纲的出现, 表明 N 污染在该区域农村黑臭

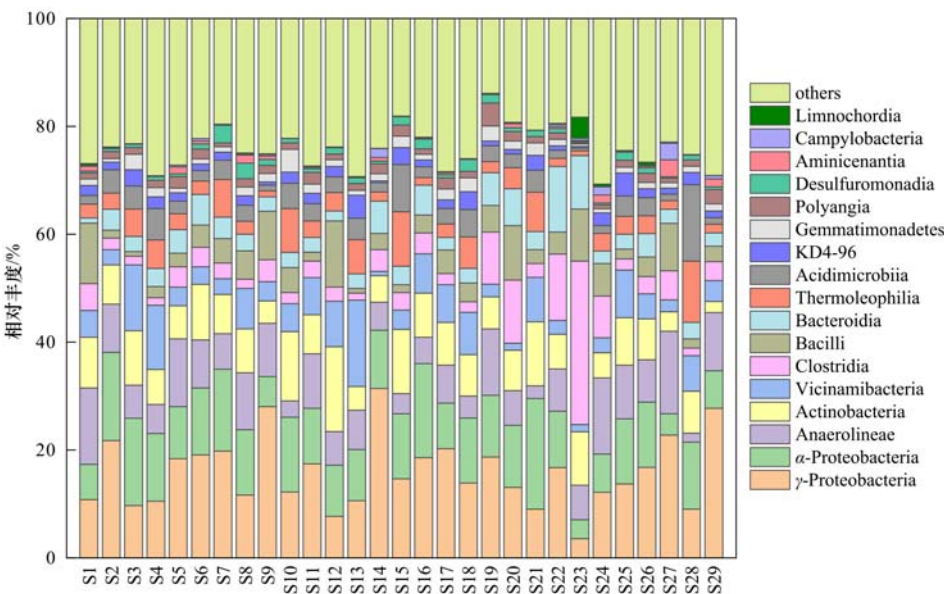


图5 农村黑臭水体沉积物细菌群落纲水平的相对丰度

Fig. 5 Relative abundance of bacterial communities in the sediments of rural black and odorous water bodies at class level

水体沉积物具有普遍性。

不同农村黑臭水体沉积物中细菌群落在属水平上的组成(相对丰度前30的菌属)如图6所示。硫杆菌属(*Thiobacillus*, 0.01%~8.98%)、*norank_f_norank_o_Vicinamibacterales* (0.35%~6.71%)、未命名厌氧绳菌科(*norank_f_Anaerolineaceae*, 0.19%~5.47%)、假节杆菌属(*Pseudarthrobacter*, 0.16%~11.86%) 和 *norank_f_norank_o_norank_c_KD4_96* (0.32%~4.27%) 为该地区农村黑臭水体沉积物中的优势菌属。

优势菌属的组成在不同农村黑臭水体沉积物中具有差异性。如硫杆菌属在S5、S9、S14、S27和S29的相对丰度较高,假节杆菌属在S1和S12的

相对丰度较高。硫杆菌属在脱硫反硝化和除臭中发挥着重要作用,主要以硫和硫代硫酸盐等物质为能源,在城市黑臭水体沉积物中常作为优势菌属出现^[39~43]。假节杆菌属主要参与沉积物碳氮循环过程,以及复杂有机化合物和蛋白质等物质代谢过程^[42,44,45]。不同农村黑臭水体沉积物优势菌属组成的差异性可能与黑臭水体污染物来源等因素密切相关^[34,46]。

2.4 农村黑臭水体沉积物微生物群落组成与环境因子的相关性

农村黑臭水体沉积物中细菌群落的丰富度和多样性与环境因子的Spearman相关性分析结果见图7所示。从图可见,沉积物中TN与Sobs和ACE指数

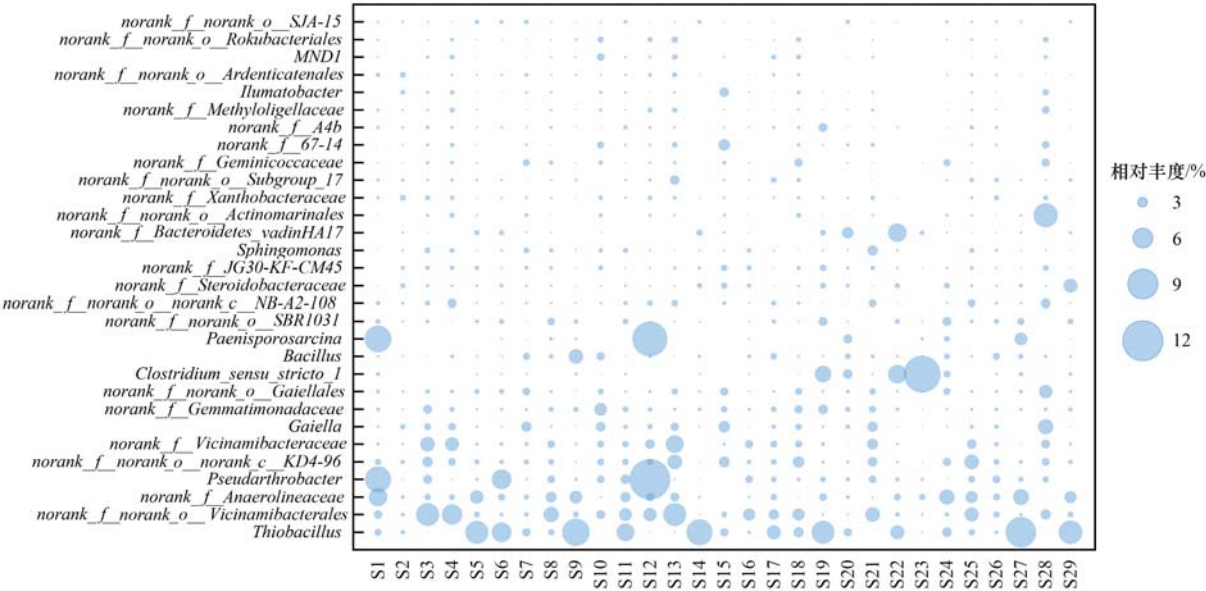
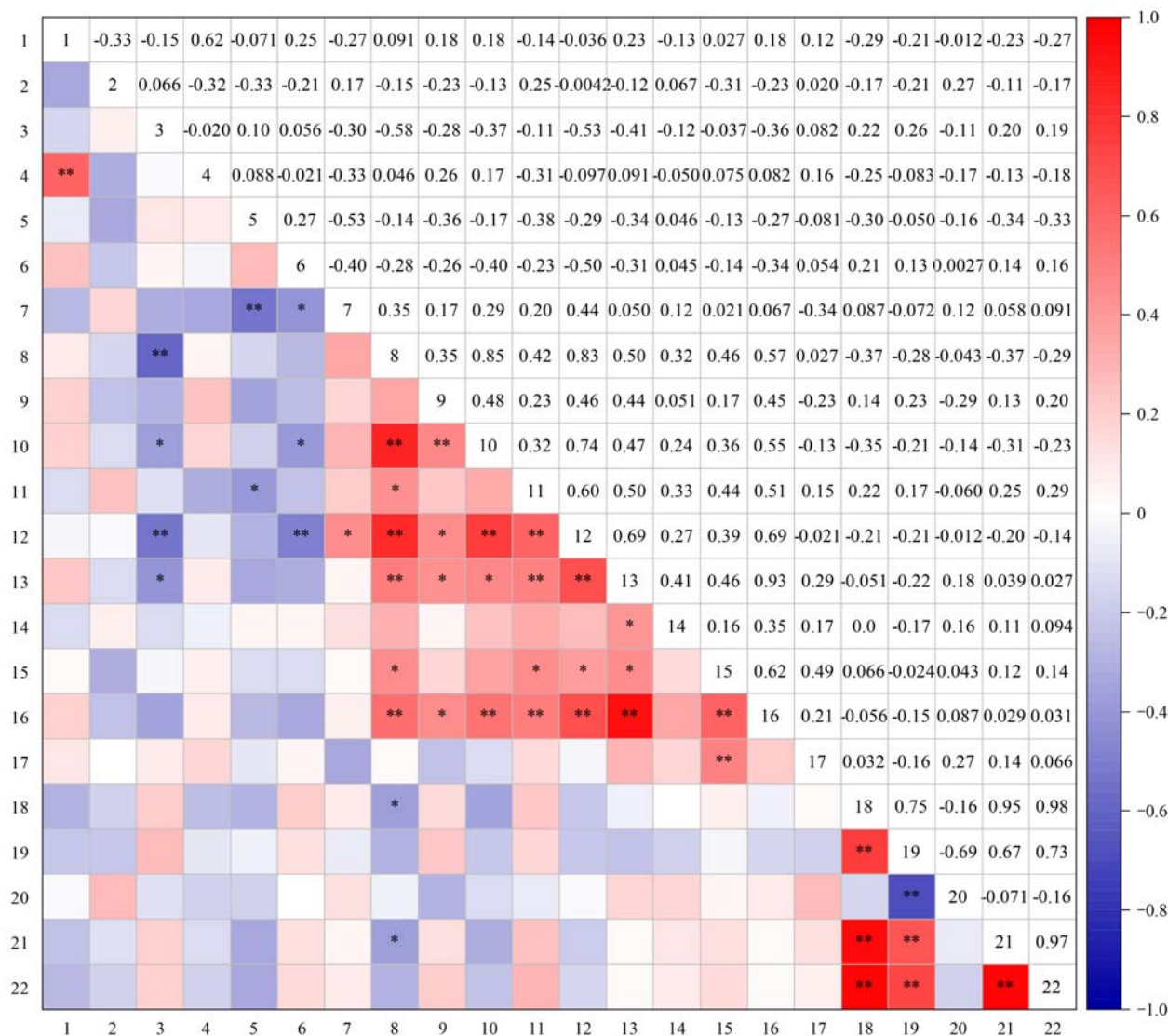


图6 农村黑臭水体沉积物优势菌属相对丰度

Fig. 6 Relative abundance of dominant bacterial genera in the sediments of rural black and odorous water bodies



1. $\text{NH}_4^+\text{-N}$, 2. DO, 3. pH, 4. TP_1 , 5. COD, 6. EC, 7. 透明度, 8. TN, 9. TP_2 , 10. OM, 11. Pb, 12. Cd, 13. Cu, 14. Ni, 15. Cr, 16. Zn, 17. As, 18. Sobs 指数, 19. Shannon 指数, 20. Simpson 指数, 21. ACE 指数, 22. Chao1 指数; 色柱表示相关性, 红色表示正相关, 蓝色表示负相关; * 表示 $P < 0.05$, ** 表示 $P < 0.01$

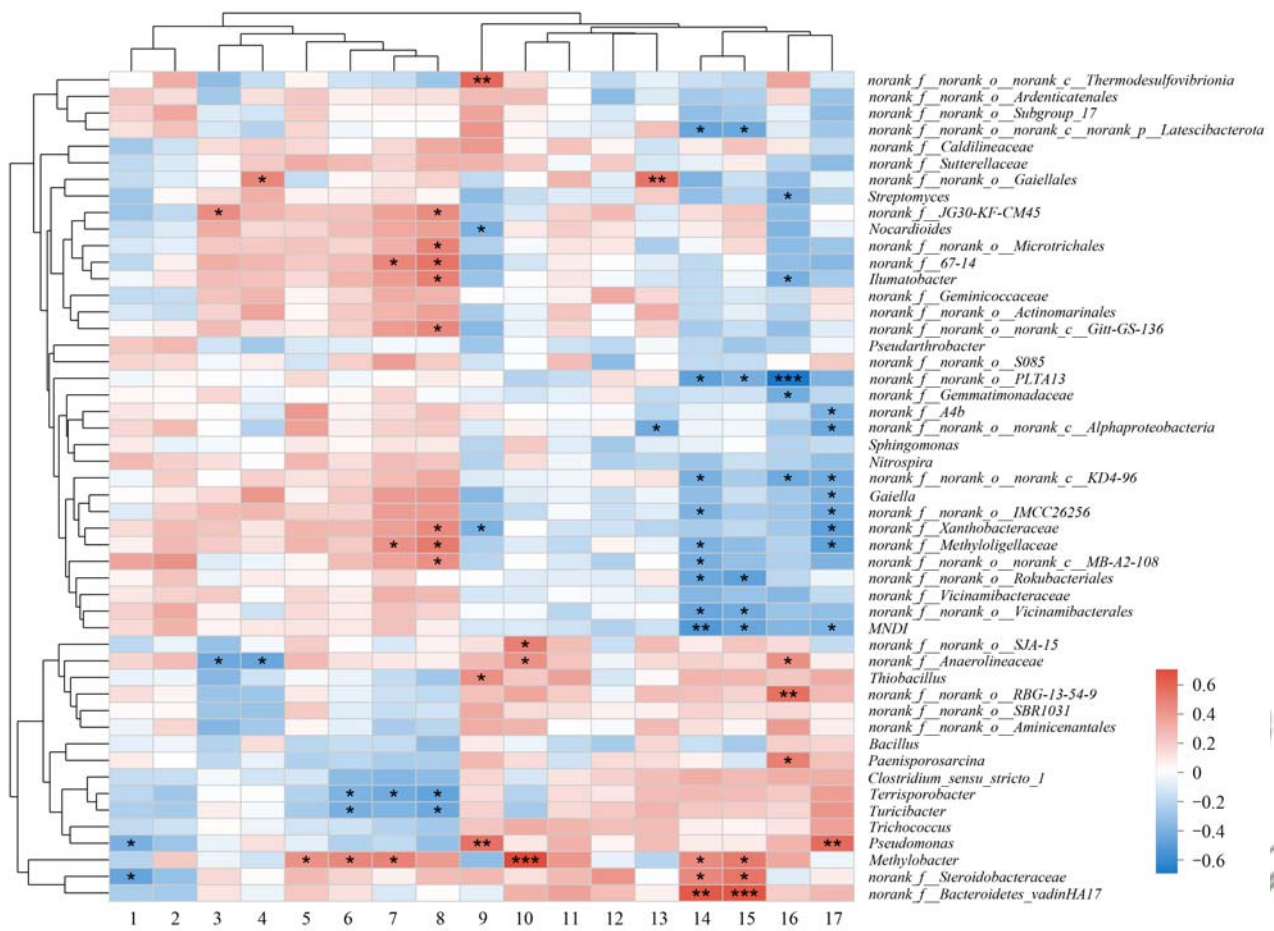
图7 农村黑臭水体沉积物微生物多样性与理化因子的相关性

Fig. 7 Relationship between microbial diversity and environmental factors in the sediments of rural black and odorous water bodies

呈显著负相关($P < 0.05$),即高含量的TN可降低沉积物中细菌群落的丰富度.然而,沉积物中细菌群落的多样性未受到环境因子的显著影响,该结果与别人研究结果存在差异.多个城市黑臭水体研究发现,沉积物中pH、TN和TP是影响细菌群落多样性的主要因素^[16,20,47].这可能是N和P等元素在农村黑臭水体中长期富集且样本间差异性特征不显著引起的.

沉积物中OM与TN和 TP_2 之间具有显著相关性,说明沉积物中N和P释放来源于有机质分解^[3].沉积物中TN和 TP_2 与上覆水中 $\text{NH}_4^+\text{-N}$ 和 TP_1 不具有显著相关性,说明沉积物对上覆水水质的影响较小,内源污染非该地区农村黑臭水体的主要污染源.

为进一步探究农村黑臭水体沉积物细菌群落组成与环境因子的关系,将属水平上的优势菌属(相对丰度前50的菌属)与环境因子进行Spearman相关性分析,结果如图8所示.从图可见,沉积物中 γ -变形菌纲不同菌属的丰度与上覆水DO和EC以及沉积物TN和 TP_2 存在显著相关性.例如,I型甲烷氧化菌属(*Methylobacter*)与沉积物TN和 TP_2 呈显著正相关($r = 0.42$, $P < 0.05$; $r = 0.37$, $P < 0.05$);假单胞菌属(*Pseudomonas*)与上覆水DO和EC分别呈显著负相关和正相关($r = -0.38$, $P < 0.05$; $r = 0.48$, $P < 0.01$);硫杆菌属与上覆水EC呈显著正相关($r = 0.38$, $P < 0.05$).这是因为 PO_4^{3-} 对参与N循环的I型甲烷氧化菌的生长繁殖有正向的促进作用^[48],EC与水体溶解性营养盐关



1. DO, 2. 透明度, 3. TP₁, 4. COD, 5. TP₂, 6. Cd, 7. TN, 8. OM, 9. EC, 10. Pb, 11. Cr, 12. NH₄⁺-N, 13. pH, 14. Cu, 15. Zn, 16. Ni, 17. As; 红色表示正相关, 蓝色表示负相关; * 表示 $P < 0.05$, ** 表示 $P < 0.01$, *** 表示 $P \leq 0.001$

图 8 农村黑臭水体沉积物细菌物种(属水平)与环境因子的相关性

Fig. 8 Correlations between bacterial genus and environmental factors in the sediments of rural black and odorous water bodies

系密切^[49],有利于沉积物细菌的生长^[16].此外,一些属于放线菌纲和 α -变形菌纲的菌属(如*Ilumatobacter*和未命名的黄杆菌科等)还与上覆水COD和沉积物OM呈显著正相关($P < 0.05$).这说明农村黑臭水体沉积物细菌群落除参与TN和TP的生物代谢,还有较多的细菌在降解OM和COD等有机物中发挥重要作用,共同驱动环境中C、N和P等元素循环.综上所述,沉积物细菌群落与环境因子的相关性可作为评价农村黑臭水体生态系统的参考依据.

3 结论

- (1)该区域农村黑臭水体上覆水和沉积物的理化性质分布范围广.以农村生活污水为主要污染来源的水体中,上覆水污染物浓度较高;然而,农村黑臭水体沉积物中的重金属含量处于较低水平,普遍低于菏泽市土壤元素背景值.
- (2)该区域农村黑臭水体沉积物中细菌群落优势菌门为变形菌门、放线菌门、绿弯菌门、厚壁菌

门和酸杆菌门等5种,它们的序列总和占全部序列的70.3%~83.6%; γ -变形菌纲、 α -变形菌纲、厌氧绳菌纲和放线菌纲是其优势菌纲;硫杆菌属和假节杆菌属等是其优势菌属.

(3)Spearman相关性分析结果表明,环境因子中DO、COD、TN、TP和有机质对农村黑臭水体沉积物细菌菌属有显著影响($P < 0.05$),沉积物细菌群落丰富度受TN的影响显著($P < 0.05$),说明沉积物中多个菌属共同参与驱动环境中C、N和P等元素循环.

参考文献:

[1] 崔艳智,贾小梅,黄亚捷,等.农村黑臭水体治理现状、问题及对策建议[J].中国环境管理,2022,14(3):54-59.
Cui Y Z, Jia X M, Huang Y J, et al. Current situation, problems and countermeasures of black and odorous water treatment in rural areas[J]. Chinese Journal of Environmental Management, 2022, 14(3): 54-59.

[2] 张飞剑,彭云清,章茹.潮汐流人工湿地处理南方农村黑臭水体实验研究[J].水处理技术,2022,48(4):114-118, 123.
Zhang F J, Peng Y Q, Zhang R. Experimental study on the black and odorous water body in southern rural areas by tidal flow

- constructed wetland[J]. *Technology of Water Treatment*, 2022, **48**(4): 114-118, 123.
- [3] 马杰, 蒋月, 张秀, 等. 重庆农村黑臭水体水质及底泥氮磷污染分析[J]. *中国农学通报*, 2022, **38**(10): 92-96.
Ma J, Jiang Y, Zhang X, *et al.* Analysis of nitrogen and phosphorus pollution in water and sediment of black and odorous water bodies in rural area of Chongqing[J]. *Chinese Agricultural Science Bulletin*, 2022, **38**(10): 92-96.
- [4] 陈颖, 吴娜伟, 董旭辉, 等. 农业农村污染治理攻坚战的重点与难点解析——《农业农村污染治理攻坚战行动计划》解读[J]. *环境保护*, 2019, **47**(1): 8-11.
Chen Y, Wu N W, Dong X H, *et al.* Key points analysis of tough battle for rural and agricultural pollution control: interpretation of action plan for tough battle against rural and agricultural pollution[J]. *Environmental Protection*, 2019, **47**(1): 8-11.
- [5] 中华人民共和国生态环境部. 中共中央办公厅 国务院办公厅印发《农村人居环境整治提升五年行动方案(2021-2025年)》[EB/OL]. https://www.mee.gov.cn/zcwj/zyygwj/202112/t20211205_963040.shtml, 2021-12-05.
- [6] Shao Y T, He Q, Fu Y S, *et al.* Construction of the comprehensive evaluation system of waterbody pollution degree and the response of sedimentary microbial community[J]. *Environmental Pollution*, 2023, **317**, doi: 10.1016/j.envpol.2022.120837.
- [7] 刘嘉元, 丰玥, 杨雪纯, 等. 天津独流减河流域不同等级河流沉积物细菌区系及功能辨识[J]. *环境科学*, 2022, **43**(7): 3635-3644.
Liu J Y, Feng Y, Yang X C, *et al.* Identification of bacterial flora and metabolic function of sediments in different channels of Duliujian River basin, Tianjin[J]. *Environmental Science*, 2022, **43**(7): 3635-3644.
- [8] Zhang L, Huang S Z, Peng X, *et al.* Potential ecological implication of *Cladophora oligoclora* decomposition: characteristics of nutrient migration, transformation, and response of bacterial community structure[J]. *Water Research*, 2021, **190**, doi: 10.1016/j.watres.2020.116741.
- [9] Zhang W L, Li Y, Wang C, *et al.* Modeling the biodegradation of bacterial community assembly linked antibiotics in river sediment using a deterministic-stochastic combined model[J]. *Environmental Science & Technology*, 2016, **50**(16): 8788-8798.
- [10] Liu Q, Wu H W, Huang C, *et al.* Microbial compositions, ecological networks, and metabolomics in sediments of black-odour water in Dongguan, China[J]. *Environmental Research*, 2022, **210**, doi: 10.1016/j.envres.2022.112918.
- [11] Pascasio S, Crecchio C, Scagliola M, *et al.* Microbial-based soil quality indicators in irrigated and rainfed soil portions of Mediterranean olive and peach orchards under sustainable management[J]. *Agricultural Water Management*, 2018, **195**: 172-179.
- [12] 李鹏洋, 安启睿, 王新皓, 等. 辽河四平段流域河流沉积物微生物群落多样性和结构分析[J]. *环境科学*, 2022, **43**(5): 2586-2594.
Li P Y, An Q R, Wang X H, *et al.* Analysis on diversity and structure of microbial community in river sediment of Siping section of Liaohe River[J]. *Environmental Science*, 2022, **43**(5): 2586-2594.
- [13] Huang H Q, Liu J H, Zhang F H, *et al.* Characteristics of planktonic and sediment bacterial communities in a heavily polluted urban river[J]. *PeerJ*, 2021, **9**, doi: 10.7717/peerj.10866.
- [14] Zhang D, Yang H L, Lan S H, *et al.* Evolution of urban black and odorous water: the characteristics of microbial community and driving-factors[J]. *Journal of Environmental Sciences*, 2022, **112**: 94-105.
- [15] Wanek A S, Hargiss C L M, Norland J, *et al.* Assessment of water quality in ponds across the rural, peri-urban, and urban gradient[J]. *Environmental Monitoring and Assessment*, 2021, **193**(11), doi: 10.1007/s10661-021-09471-7.
- [16] Zhu J Y, Zhang J X, Li Q, *et al.* Phylogenetic analysis of bacterial community composition in sediment contaminated with multiple heavy metals from the Xiangjiang River in China[J]. *Marine Pollution Bulletin*, 2013, **70**(1-2): 134-139.
- [17] Zhang W L, Lei M T, Li Y, *et al.* Determination of vertical and horizontal assemblage drivers of bacterial community in a heavily polluted urban river[J]. *Water Research*, 2019, **161**: 98-107.
- [18] Liu C Y, Yang Y T, Zhou J Q, *et al.* Migration and transformation of nitrogen in sediment-water system within storm sewers[J]. *Journal of Environmental Management*, 2021, **287**, doi: 10.1016/j.jenvman.2021.112355.
- [19] Zang J, Tang Y, Kou Z G, *et al.* Shift of sediments bacterial community in the black-odor urban river during in situ remediation by comprehensive measures[J]. *Water*, 2019, **11**(10), doi: 10.3390/w11102129.
- [20] Yao Y, Zhao J Q, Miao L Z, *et al.* Effects of sediment physicochemical factors and heavy metals on the diversity, structure, and functions of bacterial and fungal communities from a eutrophic river[J]. *Environmental Pollution*, 2022, **303**, doi: 10.1016/j.envpol.2022.119129.
- [21] Wu H N, Li Y, Zhang W L, *et al.* Bacterial community composition and function shift with the aggravation of water quality in a heavily polluted river[J]. *Journal of Environmental Management*, 2019, **237**: 433-441.
- [22] 庞绪贵, 代杰瑞, 陈磊, 等. 山东省 17 市土壤地球化学背景值[J]. *山东国土资源*, 2019, **35**(1): 46-56.
Pang X G, Dai J R, Chen L, *et al.* Soil geochemical background value of 17 cities in Shandong Province[J]. *Shandong Land and Resources*, 2019, **35**(1): 46-56.
- [23] Sun Y M, Wang S W, Niu J F. Microbial community evolution of black and stinking rivers during *in situ* remediation through micro-nano bubble and submerged resin floating bed technology[J]. *Bioresource Technology*, 2018, **258**: 187-194.
- [24] Liu L L, Sun F F, Zhao H B, *et al.* Compositional changes of sedimentary microbes in the Yangtze River Estuary and their roles in the biochemical cycle[J]. *Science of the Total Environment*, 2020, **760**, doi: 10.1016/j.scitotenv.2020.143383.
- [25] Shi F, Liu Z L, Li J L, *et al.* Alterations in microbial community during the remediation of a black-odorous stream by acclimated composite microorganisms[J]. *Journal of Environmental Sciences*, 2022, **118**: 181-193.
- [26] Liang Z W, Fang W W, Luo Y K, *et al.* Mechanistic insights into organic carbon-driven water blackening and odorization of urban rivers[J]. *Journal of Hazardous Materials*, 2021, **405**, doi: 10.1016/j.jhazmat.2020.124663.
- [27] Cao J X, Sun Q, Zhao D H, *et al.* A critical review of the appearance of black-odorous waterbodies in China and treatment methods[J]. *Journal of Hazardous Materials*, 2020, **385**, doi: 10.1016/j.jhazmat.2019.121511.
- [28] 鲜文东, 张潇潼, 李文均. 绿弯菌的研究现状及展望[J]. *微生物学报*, 2020, **60**(9): 1801-1820.
Xian W D, Zhang X T, Li W J. Research status and prospect on

- bacterial phylum Chloroflexi [J]. *Acta Microbiologica Sinica*, 2020, **60**(9): 1801-1820.
- [29] Su Z G, Dai T J, Tang Y S, *et al.* Sediment bacterial community structures and their predicted functions implied the impacts from natural processes and anthropogenic activities in coastal area [J]. *Marine Pollution Bulletin*, 2018, **131**: 481-495.
- [30] 王光华, 刘俊杰, 于镇华, 等. 土壤酸杆菌门细菌生态学研究进展 [J]. *生物技术通报*, 2016, **32**(2): 14-20.
Wang G H, Liu J J, Yu Z H, *et al.* Research progress of *Acidobacteria* ecology in soils [J]. *Biotechnology Bulletin*, 2016, **32**(2): 14-20.
- [31] Yi J, Lo L S H, Cheng J P. Dynamics of microbial community structure and ecological functions in estuarine intertidal sediments [J]. *Frontiers in Marine Science*, 2020, **7**, doi: 10.3389/fmars.2020.585970.
- [32] Li Y, Gao Y, Zhang W L, *et al.* Homogeneous selection dominates the microbial community assembly in the sediment of the Three Gorges Reservoir [J]. *Science of the Total Environment*, 2019, **690**: 50-60.
- [33] El Najjar P, Pfaffl M, Ouaini N, *et al.* Water and sediment microbiota diversity in response to temporal variation at the outlet of the Ibrahim River (Lebanon) [J]. *Environmental Monitoring and Assessment*, 2020, **192**(3), doi: 10.1007/s10661-020-8139-z.
- [34] Yang C, Zeng Z, Zhang H, *et al.* Distribution of sediment microbial communities and their relationship with surrounding environmental factors in a typical rural river, Southwest China [J]. *Environmental Science and Pollution Research*, 2022, **29**(56): 84206-84225.
- [35] Li H B, Xing P, Wu Q L. Characterization of the bacterial community composition in a hypoxic zone induced by *Microcystis* blooms in Lake Taihu, China [J]. *FEMS Microbiology Ecology*, 2012, **79**(3): 773-784.
- [36] Kirchman D L, Dittel A I, Findlay S E G, *et al.* Changes in bacterial activity and community structure in response to dissolved organic matter in the Hudson River, New York [J]. *Aquatic Microbial Ecology*, 2004, **35**(3): 243-257.
- [37] Zhong H H, Sun H, Liu R H, *et al.* Comparative genomic analysis of *Labrenzia aggregata* (*Alphaproteobacteria*) strains isolated from the Mariana Trench: insights into the metabolic potentials and biogeochemical functions [J]. *Frontiers in Microbiology*, 2021, **12**, doi: 10.3389/fmicb.2021.770370.
- [38] Zhu P, Wang Y P, Shi T T, *et al.* Intertidal zonation affects diversity and functional potentials of bacteria in surface sediments: a case study of the Golden Bay mangrove, China [J]. *Applied Soil Ecology*, 2018, **130**, doi: 10.1016/j.apsoil.2018.06.003.
- [39] Lu Q H, Liang Y Y, Fang W W, *et al.* Spatial distribution, bioconversion and ecological risk of PCBs and PBDEs in the surface sediment of contaminated urban rivers: a nationwide study in China [J]. *Environmental Science & Technology*, 2021, **55**(14): 9579-9590.
- [40] 孙雅君, 王铁宇, 彭霞薇, 等. 全氟化合物对表层沉积物中细菌群落结构的影响 [J]. *环境科学*, 2015, **36**(7): 2496-2503.
- Sun Y J, Wang T Y, Peng X W, *et al.* Effects of perfluoroalkyl substances on the microbial community structure in surface sediments of typical river, China [J]. *Environmental Science*, 2015, **36**(7): 2496-2503.
- [41] 程森, 路平, 冯启言. 渔业复垦塌陷地抗生素抗性基因与微生物群落 [J]. *环境科学*, 2021, **42**(5): 2541-2549.
Cheng S, Lu P, Feng Q Y. Distribution of antibiotic resistance genes and microbial communities in a fishery reclamation mining subsidence area [J]. *Environmental Science*, 2021, **42**(5): 2541-2549.
- [42] Wang B B, Wang Y F, Cui X Y, *et al.* Bioconversion of coal to methane by microbial communities from soil and from an opencast mine in the Xilingol grassland of northeast China [J]. *Biotechnology for Biofuels*, 2019, **12**(1), doi: 10.1186/s13068-019-1572-y.
- [43] Lee E Y, Lee N Y, Cho K S, *et al.* Removal of hydrogen sulfide by sulfate-resistant *Acidithiobacillus thiooxidans* AZ11 [J]. *Journal of Bioscience and Bioengineering*, 2006, **101**(4): 309-314.
- [44] Zhang R C, Xu X J, Chen C, *et al.* Interactions of functional bacteria and their contributions to the performance in integrated autotrophic and heterotrophic denitrification [J]. *Water Research*, 2018, **143**: 355-366.
- [45] Ouyang E M, Liu Y, Ouyang J T, *et al.* Effects of different wastewater characteristics and treatment techniques on the bacterial community structure in three pharmaceutical wastewater treatment systems [J]. *Environmental technology*, 2019, **40**(3): 329-341.
- [46] Lourenço K S, Suleiman A K A, Pijl A, *et al.* Resilience of the resident soil microbiome to organic and inorganic amendment disturbances and to temporary bacterial invasion [J]. *Microbiome*, 2018, **6**(1), doi: 10.1186/s40168-018-0525-1.
- [47] 陈倩茹, 夏雪, 王川, 等. 沙颍河下游城市黑臭内河沉积物微生物群落季节变化特征 [J]. *水生生物学报*, 2021, **45**(1): 182-189.
Chen Q R, Xia X, Wang C, *et al.* Seasonal variation characteristics of microbial communities in the sediments of urban black-odorous river in lower reaches of Shaying River [J]. *Acta Hydrobiologica Sinica*, 2021, **45**(1): 182-189.
- [48] 秦宇, 黄璜, 李哲, 等. 内陆水体好氧甲烷氧化过程研究进展 [J]. *湖泊科学*, 2021, **33**(4): 1004-1017.
Qin Y, Huang H, Li Z, *et al.* Research progress of aerobic methane oxidation process in inland waters [J]. *Journal of Lake Sciences*, 2021, **33**(4): 1004-1017.
- [49] 璩伟卿, 张博美, 黄雪, 等. 基于 16S rRNA 测序技术的青藏高原河流细菌群落多样性 [J]. *环境科学*, 2023, **44**(1): 262-271.
Qu W Q, Zhang B M, Huang X, *et al.* Bacterial community and diversity of river ecosystems on the Qinghai-Tibet Plateau based on 16S rRNA gene sequencing [J]. *Environmental Science*, 2023, **44**(1): 262-271.

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