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Short Survey



## 人工湿地去除抗生素抗性基因

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抗生素多用和滥用给水生态环境健康造成威胁. 水环境中抗生素的残留会导致微生物耐药性产生和进一步扩散, 从而成为人类健康的潜在威胁 (He *et al.*, 2019; Hu *et al.*, 2020). 作为使微生物产生耐药性的重要驱动因素, 抗生素抗性基因 (Antibiotics Resistance Genes, 简称 ARGs) 在几乎所有种类的环境介质中都已检出 (Zheng *et al.*, 2022; Li *et al.*, 2024), 也已被世界卫生组织列为新兴污染物 (Pruden *et al.*, 2006). 被广泛检出的种类有  $\beta$ -内酰胺类、磺胺类、氨基糖苷类、大环内酯类和四环素类等 (Wang *et al.*, 2022), 其来源分为天然来源和人为来源 2 种, 一些 ARGs 在环境中天然存在 (Perron *et al.*, 2015), 而人为来源主要包括水产养殖与畜牧业、污水处理厂、农业土壤、工农业及生活污水排放等 (Li *et al.*, 2020). 2016 年和 2022 年我国先后发布的《遏制细菌耐药国家行动计划》([https://www.gov.cn/xinwen/2016-08/25/content\\_5102348.htm](https://www.gov.cn/xinwen/2016-08/25/content_5102348.htm)) 和第二项国家行动计划 (<http://www.nhc.gov.cn/yzygj/s7659/202210/2875ad7e2b2e46a2a672240ed9ee750f.shtml>), 均表达了对耐药性问题的重点关注. ARGs 在环境中的传播、控制和去除已愈发受到重视. 其治理难点在于分布广, 传播途径多样, 监测和溯源困难, 政策法规尚不完善且去除技术仍有较大局限. 目前已知能去除水环境中 ARGs 的手段有传统污水处理厂、人工湿地和高级氧化技术等 (García *et al.*, 2020). 传统污水处理厂对常规污染物的去除效果良好, 但对 ARGs 的去除

效果欠佳 (Zhou *et al.*, 2017; Makowska *et al.*, 2020). 部分基于微生物处理技术的污水处理厂而在处理环节富集 ARGs, 导致耐药菌产生 (Boopathy, 2017). 高级氧化技术等新兴技术则因成本高或适用情景少而难以大范围推广. 人工湿地因去除能力好、成本低以及运行维护简单等优势被认为是很有应用前景的 ARGs 去除手段.

人工湿地是模拟天然湿地建造的系统, 由植物、水体和基质 (砂石等填料) 组成. 近年来, 人工湿地因在有效消除传统污染物方面的卓越表现, 及其为社会经济带来的诸多益处, 如提供和扩展绿色空间等 (Wendel *et al.*, 2011), 在新污染物去除中逐渐受到关注, 甚至成为处理部分污水处理厂尾水、养殖废水和农业面源污染物的首选手段 (Chen *et al.*, 2015; He *et al.*, 2019). 为满足实际应用的需求, 人工湿地对 ARGs 的去除潜力已得到证实但也有待进一步改善 (García *et al.*, 2020; Zhang *et al.*, 2023). 受室外条件的限制, 人工湿地去除 ARGs 的研究多通过室内试验进行. 实验室条件下, 人工湿地去除 ARGs 的效果差强人意 (Ávila *et al.*, 2021), 有研究总结其对常见 ARGs 去除率的中位数约为 80% (Zhang *et al.*, 2023), 部分能达到 90% 以上 (Huang *et al.*, 2019; Yuan *et al.*, 2022). 大多数实际应用的人工湿地对 ARGs 的去除效果尚且有限 (García *et al.*, 2020; Du *et al.*, 2022), 有的基本不能去除 (Li *et al.*, 2019), 原因是实际场地中的影响因素非常复杂, 影响机制尚不清楚, 因此很

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难通过人工调控的办法使去除效果达到最优。

与抗生素等的去除不同,ARGs由微生物携带(Hu *et al.*, 2020),其去除主要是通过去除宿主微生物实现。人工湿地去除ARGs的内在机制主要是植物吸收、微生物降解和基质吸附等(Shingare *et al.*, 2019)。影响这三类过程的主要因素有植物种类、基质类型、人工湿地类型与运行条件和可移动遗传元件等(Zhang *et al.*, 2023)。作为人工湿地的重要组成部分,植物对各类污染物的去除都有重要影响。植物不仅可以通过直接吸收或蒸腾作用去除ARGs(Ohore *et al.*, 2021),其根系所营造的微环境也可促进微生物降解(Song *et al.*, 2018)。植物去除ARGs的能力因植物种类而异,且受到种植模式的影响(Chen *et al.*, 2016)。前人研究得出,芦苇是降低ARGs丰度的极优选择(Yi *et al.*, 2017),交叉混种模式较单一种植模式更佳(Abou-Kandil *et al.*, 2021)。目前对于植物对ARGs的吸附和组织传输机制的研究较为薄弱(McCorquodale-Bauer *et al.*, 2023)。基质大多具有多孔性,能作为微生物附着的“骨架”有利于微生物降解作用,同时能达到去除ARGs宿主微生物的效果。基质吸附对ARGs去除的影响已有大量研究,大多数数据表明传统基质中沸石的去除效果较好(Nölvak *et al.*, 2013; Du *et al.*, 2022; Cui *et al.*, 2023)。牡蛎壳(Liu *et al.*, 2021)、凝灰岩(Abou-Kandil *et al.*, 2021)、氯化亚铁(袁涛等, 2022)、生物炭(冯立魁, 2020; Ajibade *et al.*, 2023)和矿石(张丹一, 2022)等也被作为基质或被添加到基质中进行研究。作为湿地的主要成本来源,基质的优化改善对于降低成本意义重大,因此未来的研究还会尝试更多的废弃材料或新材料作为基质以进一步提高成本效益。湿地的水流方向、水力停留时间(HRT)和运行时间等运行条件也是影响ARGs去除的重要因素。研究表明潜流湿地比表面流湿地具有更好的去除效果(薛慧等, 2023),垂向潜流人工湿地的去除效率更高(Huang *et al.*, 2017)。HRT越长越有利于吸附和降解(Chen *et al.*, 2016),但也有例外(Zhang *et al.*, 2018),因此HRT对去除效果的影响还有待进一步探究。湿地运行时间越长ARGs去除效率越低,如运行时间超过十年的去除率将小于50%(Zhang *et al.*, 2023),原因是湿地运行时间越长,基质堵塞一般会越严重,导致过滤性能下降,进而影响过滤和吸附效果(Abou-Kandil *et al.*, 2021)。因此,解决基质堵塞问

题也是难点。考虑到ARGs的迅速传播,控制其扩散也是重要策略。可促进微生物进化的质粒、转座子整合子等被统称为可移动遗传元件,是影响ARGs传播扩散的重要因素(Wang *et al.*, 2021)。因此,对湿地中可移动遗传元件的研究也是十分必要的。

传统单一湿地去除污染物的效果有限,融合了多种新技术的复合型湿地和各类新型湿地已愈发受到重视,也是未来的发展趋势。复合型湿地主要是采用湿地结构耦合、创新技术耦合等方式进行复合,通过增强生物降解、基质吸附及植物吸收等过程提高对各类污染物的去除能力。表面流湿地与潜流湿地结合的复合人工湿地能使ARGs降低1~3个数量级(Chen *et al.*, 2019);上行与下行水流方式结合的垂直潜流人工湿地最高能达到99.1%的去除效果(Huang *et al.*, 2019)。各类新技术的引入也进一步强化了人工湿地对污染物的去除。例如,生物电化学技术与人工湿地结合,如微生物燃料电池与微生物电解槽耦合人工湿地成为探究的新方向之一,其原理是原位电子通路的形成可以显著增强细菌活性并提高其丰度(Liu *et al.*, 2022; Yu *et al.*, 2022),优化方向有添加海绵铁(Li *et al.*, 2019; Wen *et al.*, 2022)、改良介质(Li *et al.*, 2023)和微生物驯化(刘瑶等, 2021)等。光催化技术与人工湿地结合也是创新方向之一。光催化反应产生的活性氧可以通过破坏核苷酸使ARGs失活。已有研究表明光催化能改善人工湿地去除ARGs的效果(Chen *et al.*, 2023; 湛萍萍, 2023)。改进技术较易实现的潮汐流人工湿地也被证明能显著改善去除效果(程羽霄等, 2021)。整体来说,复合人工湿地前景明朗,但还需要更多的研究对工艺参数及技术进行优化,以达到高效节能去除的目的。

综上,人工湿地是未来控制ARGs污染风险的重要手段,未来的研究可集中在这几方面:(1)实际人工湿地的工艺、基质和运行方式等对ARGs去除效果的影响;(2)人工湿地中ARGs的行为与去除机制;(3)人工湿地基质中ARGs的富集和扩散,尤其是扩散引起的生态环境风险;(4)人工湿地与其他技术联合使用改善ARGs去除效果。

笔者近几年以北京的安南人工湿地为案例开展了深入的研究工作,揭示了ARGs在长期运行湿地中的时空分布规律、在基质中的富集情况和去除效果,识别了影响ARGs去除的因素。研究得出该湿地中主要的ARGs种类为喹诺酮类、

$\beta$ -内酰胺类和四环素类,亚型为 *tufA* (聚酮类)和 *fusA* (夫西地酸类),分布呈现明显的季节分布特征,在水体、基质和植物中也呈现显著的生态位分布差异. 人工湿地对 ARGs 有良好的去除作用,但针对不同的 ARGs 类型和亚型的去除存在差异,影响因素有光照、温度等. 成果可为人工湿地的设计和优化提供参考,以更好地防控 ARGs 扩散引起的生态环境和人体健康风险.

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