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人工湿地在污水净化与碳减排中的作用机制与应用进展

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摘要 【目的】 文章综述了人工湿地在污水净化与碳减排方面的研究进展, 系统分析人工湿地的组成与特征、应用领域及碳排放特征, 明确其在实现减污降碳协同增效中的作用, 为人工湿地的技术推广与优化提供科学依据。【方法】 总结近年来国内外关于人工湿地基质填料、植物配置、微生物群落等组成要素的研究进展, 梳理其在污水处理厂尾水、农村生活污水、水产养殖尾水等多类型水体净化中的工程应用成效, 重点分析人工湿地碳排放与减排机理, 探讨引入机器学习等新兴技术以实现人工湿地过程建模与智能调控的可行性。【结果】 人工湿地在污染物去除方面表现出显著的稳定性和适应性, 对有机物、氮、磷及部分重金属均有较高去除率, 同时具备一定碳汇功能, 可有效吸收二氧化碳(CO₂)并抑制一氧化二氮(N₂O)、甲烷(CH₄)等温室气体排放。多项研究表明, 通过优化基质、植物和运行条件可显著提升人工湿地净水及碳减排性能。【结论】 人工湿地是一种兼具水质净化、生态修复和碳减排的可持续技术, 未来应进一步拓展应用场景, 结合机器学习、大数据等先进技术实现精准设计与智能运行, 为生态环境保护和减污降碳协同增效目标提供有力支撑。

关键词 人工湿地 污水处理 碳减排 机器学习 可持续技术

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Mechanism and Application Progress of Constructed Wetlands in Wastewater Purification and Carbon Reduction

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Abstract [Objective] This paper summarizes the research progress of constructed wetlands in water purification and carbon emission reduction. It systematically analyzes the components, characteristics, application fields, and carbon emission characteristics, aiming to clarify their role in achieving the synergistic effect of pollution reduction and carbon mitigation, and to provide a scientific basis for the technology promotion and optimization of constructed wetland technologies. [Methods] Recent studies on substrates, vegetation, and microbial communities in constructed wetlands are reviewed. The effectiveness of their engineering applications in purifying various types of water bodies, such as effluents from wastewater treatment plants, rural domestic wastewater and aquaculture tailwater, has been synthesized. A key focus is placed on analyzing the mechanisms of carbon missions and reduction in constructed wetlands. The potential of integrating machine learning for process modeling and intelligent control is also explored. [Results] Constructed wetlands demonstrate stable and adaptable pollutant removal performance, with high removal efficiencies for organics, nitrogen, phosphorus, and certain heavy metals. They also exhibit carbon sink functions by absorbing carbon dioxide (CO₂)

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and suppressing the emissions of nitrous oxide (N_2O) and methane (CH_4). Studies indicate that optimizing substrates, plant species, and operational parameters can significantly enhance both pollutant removal and carbon mitigation performance. [**Conclusion**] Constructed wetlands are a sustainable technology that integrates water purification, ecological restoration, and carbon reduction. Future research should further expand application scenarios and incorporate advanced technologies such as machine learning and big data to achieve precision design and intelligent operation, thereby providing robust support for ecological environmental protection and the coordinated goal of pollution reduction and carbon mitigation synergy.

Keywords constructed wetland wastewater treatment carbon emission reduction machine learning sustainable technology

人工湿地组成主要包括基质(填料)、植物、微生物等,作为一种模拟自然湿地的污水处理技术兼具水质净化、生态和碳汇功能,在“双碳”目标背景下受到越来越多的重视和应用,如在污水处理厂尾水、农村污水、水产养殖尾水处理等方面的应用。具体而言,经人工湿地处理后的市政尾水可以资源化回用于城市河道生态补水;人工湿地处理农村污水具有经济低碳、运维管理方便的优点;水产养殖尾水经人工湿地深度处理后则可以达标排放或回用^[1]。

近年来,人工湿地污水处理技术发展迅速,新型基质填料具有更高的污染物去除率,适应环境、性能优异的植物被筛选搭配,微生物的污染物去除机制被深入探讨,碳汇效果被更加关注,机器学习技术被广泛用于人工湿地的优化研究^[2]。因此,本文总结了人工湿地污水处理技术的类型、基质、植物、微生物等方面的研究进展,进一步论述了碳排放、机器学习等前沿热点在人工湿地领域的研究状况,以期为人工湿地技术的进一步应用提供理论技术支撑。

1 人工湿地的组成与特征

1.1 类型

根据进出水方式的不同,人工湿地主要分为表面流人工湿地、水平潜流人工湿地和垂直潜流人工湿地 3 种基本类型;按照基质填料的不同,有天然类填料人工湿地、人造类填料人工湿地和组合类填料人工湿地等;根据湿地植物类型不同,可分为浮游植物系统人工湿地、挺水植物系统人工湿地和沉水植物系统人工湿地等。

1.2 基质

人工湿地常见基质填料如表 1 所示,包括天然类填料、人造类填料(工农业废弃物和生物炭等)。基质填料的前沿研究主要聚焦在废物再利用和开发新型高性能材料等方向。Gu 等^[3]利用厨余垃圾牡蛎壳、工业废弃物钢渣及天然矿石火山岩等制备复

合填料,在大大提高磷去除率的同时降低了填料成本,实现了废物资源化。Munir 等^[4]利用农业废弃物制作生物炭,加强了人工湿地对无机污染物的吸附降解。此外,玉米秸秆制成的生物炭具有较发达的孔隙结构和较大的比表面积,作为改性材料被用于人工湿地中,显著提高了磺酰胺类抗生素的去除效果^[5]。

表 1 人工湿地基质填料

Tab. 1 Substrate Packings of Constructed Wetland

填料分类	填料名称	
天然类填料	砾石	
	沙子	
	石灰石	
	沸石	
	火山岩	
	其他矿石	
	人造类填料	工农业废弃物
		钢渣
		矿渣
		粉煤灰
炉渣		
核桃壳		
花生壳		
其他多孔材料		
生物炭(热解)		
秸秆		
稻壳		
玉米芯		
果壳		
污泥		
粪便		
其他有机废弃物		

1.3 植物

除了常见的人工湿地植物芦苇、香蒲、美人蕉、鸢尾和马蹄莲等,驯化本土植物以及耐盐、耐低温植物成为研究热点。对 21 个国家的 87 个人工湿地调

查研究^[6]表明,常见的挺水植物源于当地,本土植物在去除污染物方面性能优异。盐角草、碱蓬、滨藜及印度地肤等人工湿地耐盐植物被驯化用于处理含盐废水^[7-8]。芦苇、蔗草、香蒲等植物被驯化用于寒冷地区(15℃)的人工湿地处理污水,其中蔗草的污染物去除效果最佳^[9]。

1.4 微生物

相较于基质填料和植物,人工湿地中的微生物对污染物去除作用更大。在有机物、氮、磷、新污染物等方面承担主导功能。变形菌门、拟杆菌门、放线菌门和厚壁菌门是人工湿地中最常见的微生物门类^[10]。在属水平上,研究^[11-12]表明,氨氧化主要通过氨氧化细菌(AOB)完成,但氨氧化古菌(AOA)和全程氨氧化菌(Comammox)也广泛存在,起到不可忽视的作用,尤其在低氨氮浓度的环境中,大多数AOB隶属于β-变形菌门(Betaproteobacteria),具体

菌属如表2所示,其中亚硝化球菌属(*Nitrosococcus*)也存在于γ-变形菌门(Gamma-proteobacteria)中。反硝化菌种类非常多,已知超过50个属,表2列举了常见的反硝化菌属如陶厄氏菌属(*Thauera*)、竞争者菌属(*Candidatus_Cometibacter*)等^[13-14],除磷主要通过聚磷菌属(*Candidatus_Accumulibacter*)、脱氯单胞菌属(*Dechloromonas*)和四球菌属(*Tetrasphaera*)等微生物完成^[15]。研究^[16]表明,沙雷氏菌属(*Serratia*)、假单胞菌属(*Pseudomonas*)等菌属具有去除Cd²⁺和Zn²⁺等重金属离子的功能。人工湿地中的弧菌属(*Vibrio*)、葡糖杆菌属(*Gluconobacter*)、链球菌属(*Streptococcus*)、梭杆菌属(*Fusobacterium*)、盐单胞菌属(*Halomonas*)等具有去除抗生素抗性基因的作用^[17]。人工湿地中微生物的作用机制和影响因素复杂,还需进一步深入研究。

表2 人工湿地去除污染物的代表性功能微生物

Tab. 2 Representative Functional Microorganisms for Pollutants Removal in Constructed Wetlands

功能	分类	属水平
氨氧化	AOB	亚硝化螺菌属(<i>Nitrospira</i>)
		亚硝化单胞菌属(<i>Nitrosomonas</i>)
		<i>Nitrosococcus</i>
		亚硝化叶菌属(<i>Nitrosolobus</i>)
		亚硝化弧菌属(<i>Nitrovibrio</i>)
	AOA	海洋亚硝化侏儒古菌(<i>Nitrosopumilus maritimus</i>)
		海洋亚硝化侏儒古菌 SCM1(<i>Nitrosopumilus maritimus</i> SCM1)
		加尔加斯亚硝化球菌(<i>Nitrososphaera gargensis</i>)
		共生古菌属(<i>Cenarchaeum symbiosum</i>)
		黄石亚硝化热古菌(<i>Nitrosocaldus yellowstonii</i>)
反硝化	全程硝化菌	硝化螺旋菌属(<i>Candidatus Nitrospira nitrosa</i> 、 <i>Candidatus Nitrospira nitrificans</i>)
	反硝化菌	<i>Thauera</i> <i>Candidatus_Cometibacter</i> 其他(50多个属)
	除磷	代表性菌属为 <i>Candidatus Accumulibacter</i> 代表性菌属为 <i>Dechloromonas</i> 代表性菌属为 <i>Tetrasphaera</i> ,其他菌属为不动杆菌属(<i>Acinetobacter</i>)、 <i>Pseudomonas</i> 等
去除重金属	重金属去除菌	<i>Serratia</i> 和 <i>Pseudomonas</i>
去除新污染物	新污染物去除菌	<i>Vibrio</i> 、 <i>Gluconobacter</i> 、 <i>Streptococcus</i> 、 <i>Fusobacterium</i> 和 <i>Halomonas</i>

2 人工湿地的应用

人工湿地目前主要用于污水处理厂尾水、农村

污水、水产养殖尾水处理等,兼具水质净化、生态和碳汇功能,此外也可用于河湖生态修复、初期雨水净

化、农业面源污染防治等多种水环境治理。

2.1 污水处理厂尾水深度处理

由于黑臭水体整治和再生水回用的要求,污水处理厂尾水亟需深度处理,人工湿地技术因净化效果好、运维成本低被广泛应用。张丽等^[18]采用人工湿地处理实际污水处理厂尾水(5 000 m³/d),尾水满足景观用水标准并用作景观湖的日常用水,实现了污水处理厂尾水资源化回用。邬亚君等^[19]采用“复合潜流湿地+表流湿地”将污水处理厂尾水由《城镇污水处理厂水污染物排放标准》(DB11/890—2012)的B标准提高至地表水Ⅲ类水质标准。许兵等^[20]利用农业废弃物强化的人工湿地处理污水处理厂尾水,将总氮(TN)去除率提高了30.8%~41.2%,反硝化菌 *Pseudomonas* 和 *Thauera* 得到了富集(16.38%~22.02%)。邵婷婷等^[21]采用陶粒、沸石和矿渣复合基质的人工湿地系统实现了污水处理厂尾水中97.36%的四环素的去除。研究^[22]表明,潜流人工湿地和表流人工湿地对微塑料的去除率分别是89%和37.5%。综上所述,人工湿地净化污水处理厂尾水效果显著,在有机物、氮磷、新污染物、微塑料深度去除方面起到重要作用,有力保护了水生态环境。

2.2 农村污水处理

农村污水处理亟需运维成本低且管理方便的工艺技术,人工湿地凭借其优异的出水水质和低成本维护等优势,近年来在农村污水处理领域得到了广泛应用。吴树彪等^[23]采用人工湿地处理北方农村生活污水,化学需氧量(COD)、五日生化需氧量(BOD₅)、氨氮、总磷(TP)和总悬浮物(TSS)的平均去除率分别为93.0%、96.0%、88.4%、87.7%和97.0%,证明了在北方低温(7℃)条件下人工湿地应用的可行性。高菊红等^[24]采用人工湿地组合工艺处理太湖三山岛的生活污水,TP出水达到地表水Ⅲ类标准。研究^[25]表明,芦苇水平潜流人工湿地可以通过植物吸收磷实现高效除磷,在水力停留时间大于5.3 d时,能够去除88%的磷。小型的农户庭院型人工湿地同样具有较高的污染物去除率,龙翠芬等^[26]研究了户用水平潜流人工湿地系统和垂直流人工湿地系统,出水均满足《城镇污水处理厂污染物排放标准》(GB 18918—2002)一级A标准。范旭红^[27]估算了扬州市南水北调东线治污人工湿地系统的吨水运行成本为0.184元,远低于其他工艺

的运行成本,有力证明了人工湿地作为一种低成本技术的潜力,对于预算有限的农村污水处理具有重要的参考意义。

2.3 水产养殖尾水处理

水产养殖尾水中含有大量的饵残、药残和鱼虾排泄物等,直接排入水体会造成严重污染,各省近年来陆续出台了水产养殖尾水地方排放标准,加强了监管和监督,人工湿地被广泛用于水产养殖尾水的深度处理单元进一步去除污染物。阙祥尧等^[28]利用潜流人工湿地处理草鱼养殖池塘尾水,实现TP、氨氮和COD去除率分别为24.7%、25.1%和25%。孙琳琳等^[29]研究发现,添加了植物性碳源玉米芯和玉米芯浸出液的湿地反硝化脱氮效果显著提升,硝态氮去除率分别提高至90.63%和88.56%。钱伦等^[30]研究发现,潜流人工湿地对氨氮和TP的去除率分别为72.57%~90.54%和83.18%~93.97%。

3 人工湿地的碳排放与减排

人工湿地在处理污水的过程中,微生物分解有机物会释放甲烷(CH₄)、二氧化碳(CO₂)等直接温室气体,硝化和反硝化过程中会产生一氧化二氮(N₂O),提升泵电耗等产生间接碳排放,同时植物的呼吸作用和光合作用会释放和利用CO₂,所以人工湿地既是碳源又是碳汇,碳排放受到多种因素影响。

3.1 碳排放

CH₄是一种重要的温室气体,其温室效应约为CO₂的25倍。人工湿地的床体厌氧环境会发生有机物通过产甲烷菌产生CH₄的反应。床体的水位、有机物负荷、基质和植物类型等与厌氧产CH₄密切相关。CH₄在湿地床体中的积累可能导致其向大气中的排放^[31]。N₂O是另一种强效温室气体,其温室效应约为CO₂的300倍^[32]。在人工湿地中,AOB和AOA的好氧氨氧化过程存在产生N₂O的生化途径或者非生化途径,此外,反硝化过程中也存在N₂O的释放。在人工湿地中,溶解氧水平、温度、有机物、氮浓度等与N₂O产生释放密切相关。

人工湿地的温室气体排放涉及复杂的机理和过程,不同研究中温室气体排放通量的差异较大。与活性污泥法相比,人工湿地的直接温室气体排放强度显著较低^[33]。Chen等^[34]通过实测发现,人工湿地释放的CO₂、CH₄和N₂O的最大通量分别是(582.01 ± 89.25) mg/(m²·h)、(21.88 ± 2.51)

$\mu\text{g}/(\text{m}^2 \cdot \text{h})$ 和 $(37.27 \pm 15.82) \mu\text{g}/(\text{m}^2 \cdot \text{h})$ 。Wang 等^[35]研究发现,种植有水生狐尾藻表流人工湿地中 N_2O 排放量(以 N 计)为 $(211.03 \pm 44.38) \text{mg}/(\text{m}^2 \cdot \text{h})$ 。上海崇明区水菱和芦苇为主的人工湿地 CH_4 排放量最高为 $178.1 \text{mg}/(\text{m}^2 \cdot \text{min})$ ^[36]。此外,曝气、泵等设备的使用强化了人工湿地的处理性能,但也增加了间接碳排放^[37]。

湿地类型、基质、植物、有机物、氮磷、水位、温度、光照等是影响人工湿地碳排放的主要因素^[38-40]。垂直潜流湿地比其他类型湿地水流路径更长、氧气传统传输效率更高从而减少厌氧产 CH_4 。吸附能力更强的基质如沸石等能够减少碳排放。具有强大根系和快速生长能力的植物,其光合作用产生的氧气能够有效传输到根部减少 CH_4 的产生。高进水有机物浓度更容易使人工湿地形成厌氧环境,促进 CH_4 的产生。高氮浓度带来高 N_2O 排放。高温会加速生化反应速率,增大温室气体的排放量。光照强度通过影响植物的光合作用速率进而影响 CO_2 的吸收。

3.2 碳减排

可以采取多种调控措施实现人工湿地碳减排,通过优化植物、基质填料和运维管理可以显著减少碳排放。

定期收割植物可以减少植物残体在湿地中的分解,减少 CH_4 和 N_2O 排放^[41]。优化植物的种类,选择具有高效光合作用和强大根系结构的植物,可以促进氧气的传输,增强光合作用,增加碳汇等^[42]。定期更换基质可以去除积累的有机物和微生物群落,并减少碳排放,例如锰矿石与活性炭添加到人工湿地中可以吸附固碳,减少 CH_4 等的排放^[43]。合理的水位管理可以优化湿地床体的氧化还原状态,减少厌氧区的形成,从而减少 CH_4 的产生。例如采用间歇淹水或潮汐流运行模式,并控制合理的水力停留时间,能有效打破稳定的厌氧环境,从源头抑制 CH_4 的产生。通过加强水质管理,如控制进水负荷、调节污水 pH 和氧化还原电位,可以优化湿地中的生物化学反应过程,减少温室气体的排放。例如,通过预处理降低污水中的有机物含量,可以减少厌氧条件下 CH_4 的产生;将进水碳氮比(C/N)调节至适宜范围,并将 pH 维持在中性至微碱性,可以平衡微生物代谢,可同步减少 CH_4 和 N_2O 的排放;调节污

水 pH 至适宜范围,可以抑制产甲烷菌的活性,减少 CH_4 的排放。Zhang 等^[44]通过优化进水水质将 N_2O 排放量降低至 $0.027 \text{mg}/(\text{m}^2 \cdot \text{h})$ 。

此外,机器学习在人工湿地碳排放和减排方面得到越来越多的应用。机器学习可以通过历史数据建模预测,大大提高了研究效率和智能化水平。Chinta 等^[45]通过机器学习建模研究了人工湿地 CH_4 产生、释放过程的各种物理、生物和化学参数,发现 CH_4 扩散相关参数表现出最高的敏感性。Jiang 等^[46]通过机器学习研究了生物炭型人工湿地中 N_2O 排放的影响因素,发现 C/N 对 N_2O 通量的贡献高达 18%。Yang 等^[47]开发了一种基于深度神经网络(DNN)的创新框架,可显著提高人工湿地的碳中和潜力和污染物通量评估。Hu 等^[48]利用机器学习识别了人工湿地中微生物功能群与生态风险的因果关系,发现黄铁矿作为基质可在高效去除污染物的同时,将 N_2O 排放降低 78%,为低碳低风险的湿地设计提供了新思路。

4 结论

工农业废弃物和生物炭等被用来改良人工湿地的基质,在提高处理效率的同时实现了废弃物资源化再利用;更适应当地环境的本土植物以及耐盐、耐低温的植物被驯化,提高了人工湿地运行的稳定性和处理性能;微生物去除污染物的复杂过程机制和群落结构得到了不断的深入研究。人工湿地以低维护、低成本和深度净化的优势在污水处理厂尾水、农村污水、水产养殖尾水处理等领域获得越来越广泛的应用。

在全球应对气候变化的大背景和我国“碳达峰碳中和”目标形势下,人工湿地作为一种兼具水质净化、生态和碳汇功能的污水处理技术,成为碳排放和减排研究的热点,人工湿地的温室气体排放涉及复杂的机理和过程,不同研究中温室气体排放通量的差异较大。湿地类型、基质、植物、有机物、氮磷、水位、温度、光照等是影响人工湿地碳排放的主要因素,可以采取多种调控措施实现人工湿地碳减排,通过优化植物、基质填料和运维管理可以显著减少碳排放。借助机器学习等先进方法促进人工湿地的进一步研究应用,助力生态环境保护和减污降碳。

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