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人工湿地净化污染物的应用及机制研究进展

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摘要: 人工湿地是一个复杂的生态处理系统，其污染物净化过程是物理、化学和生物过程的综合作用，但不同来源污水中污染物种类与浓度差异显著，导致人工湿地在污染物去除效果及机制上存在复杂性与差异性，制约了人工湿地技术的推广应用。本文总结了人工湿地处理工业污水、农业污水和生活污水等不同来源污水的研究成果，归纳了可处理的污染物包括营养元素、有机物、重金属、新污染物、氟化物、硫酸盐和氯化物等，其中生活污水相关研究文献占比高达 64.45%，污染物主要集中于氮、磷和有机物。重点阐述了人工湿地各功能单元的净化机制：①微生物通过降解和转化过程去除氮与有机物；②填料基质依靠过滤、吸附、沉淀和离子交换等方式去除磷、重金属和氟化物；③植物则在为微生物提供生存环境的同时，参与污染物吸收与转化；④对于石油类和新污染物，则依赖于驯化微生物的生物降解与植物辅助吸收，硫酸盐的去除亦依赖于硫酸盐还原菌、硫氧化菌等硫代谢微生物的协同作用。实际污水中常存在氮、磷、有机物、重金属等多种污染物共存的复合污染问题，传统人工湿地系统对多污染物的协同去除机制仍缺乏系统认识，未来可构建适用于复合污染情境的人工湿地系统，提升其协同净化能力和抗冲击性能；部分污染物如石油烃和新污染物在湿地中虽能被有效去除，但其在处理过程中的转化路径及最终产物尚不明确，需加强对这类污染物处理后转化产物的定量检测与毒理评估；人工湿地中，微生物、植物与填料在污染物去除过程中发挥着协同作用，但目前对其各自贡献及其在多介质、多过程中的耦合机制缺乏量化与机制性认知，未来研究应致力于多组分作用过程的解析与优化调控，为人工湿地结构设计与功能提升提供理论支撑。

关键词: 人工湿地；污染物；营养元素；重金属；新污染物；净化机制；协同净化

要点:

(1) 由于生成量小和技术要求高等因素的限制，人工湿地在工业污水及其他类型污水处理中的应用仍相对有限。

(2) 人工湿地去除污水中污染物主要依靠微生物、植物和基质单元的协同作用。

(3) 未来可进一步量化人工湿地各单元对污染物去除的贡献度，并重点解析处理复合污染物和新污染物后转化产物的毒理风险。

中图分类号: X505　　**文献标识码:** A

随着全球人口增长、城市化进程加快及工业化程度不断提升，水环境污染问题日益严峻，传统污水处理技术面临运行能耗高、设施投资大及对复杂污染物适应性差等多重挑战[1]。人工湿地作为一种

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融合生态工程理念的绿色低碳技术, 以构建简单、运行经济、维护便捷和生态景观价值高等优势[2], 在污水资源化与可持续治理方面受到国际广泛关注[3]。自 20 世纪 50 年代以来, 人工湿地已应用于污水净化[4], 进入二十一世纪, 中国人工湿地的数量超过了 10 万个[5]。近年来, 人工湿地技术从最初的生活污水处理拓展至农业面源污染、工业废水[6]、雨水径流和矿山排水等多领域[7], 研究重心逐渐由"污染物去除效率"转向"去除机制解析"及"系统协同效应优化"。同时, 新污染物[8]的不断检出对湿地系统提出更高要求, 也推动该领域向多污染物协同净化与新材料引入[9]等方向迈进[10]。因此, 从水资源可持续管理的战略高度出发, 系统梳理人工湿地对多类型污水中不同污染物净化的应用现状与机制研究, 对于推动人工湿地技术发展与提升生态环境治理水平具有重要科学价值和现实意义。

近年来, 国内外围绕人工湿地的结构优化、填料创新、植物筛选及运行模式改良等领域开展了大量研究, 采用人工湿地措施对工业、农业、生活、其他来源等多种污水净化进行了广泛应用, 显著推动了人工湿地技术的多元与高效化发展。工业污水处理方面, 以核桃壳为原料制备颗粒状生物炭, 可显著增强人工湿地对酸性采矿废水的重金属吸附能力[11]; 种植菖蒲并采用砾石、生物陶瓷和沸石组合填料的垂直流人工湿地, 可去除含石油废水中 90% 以上的石油烃[12]; 改进人工湿地的设计和运行工艺也能提升污染物净化效果, 组合式多级湿地在污染物处理深度和系统稳定性方面优势突出, 如美国佛罗里达州一组合湿地系统在矿山废水处理中对重金属具有良好的去除效果[13]。农业污水处理方面, 多种植物的合理搭配不仅有助于提升人工湿地的污染物去除效率, 同时也兼具生态美化功能。在一项研究中, 采用芦苇、风铃草和鸢尾共植的水平潜流人工湿地系统在处理养殖二级废水时, 对有机物及氮、磷去除方面表现出显著效果[14]; 意大利一种植芦苇和香蒲的地表流人工湿地, 可高效净化农业排水中的氮、磷和重金属[15]; 绿沸石、火山岩和活性炭组合填料的人工湿地, 对养猪场外排尾水中的糖皮质激素也具有较高的去除率[16]。生活污水处理方面, 特定功能填料可增强湿地系统对磷、重金属及有机污染物的去除性能: 凹凸棒土基质的人工湿地处理垃圾渗滤液时具有良好的吸附除磷效果[17]; 城市垃圾焚烧炉底灰作为湿地填料可以显著降低校园废水中的生化需氧量[18]; 另一研究表明, 由水葫芦、香蒲、芦苇、浮萍和灯心草构建的复合型人工湿地对垃圾渗滤液中多种重金属污染物具有良好的去除能力[19]; 欧洲部分国家利用浅层地热辅助湿地技术, 实现了冬季低温条件下城市生活污水的稳定处理[20]; 中国某地区采用砾石-微藻共生系统, 显著提升了污水处理厂二级出水中抗生素等新污染物的净化能力[21]; 且大型多级人工湿地可以去除生活污水中 89% ~ 98% 的微塑料[22]。澳大利亚玛丽华莱士湿地在水力停留时间为 36h 时, 对工业化地区雨水径流中的总氮 (TN)、总磷 (TP)、锌、铝、铁、铜等污染物具有良好去除效果[23]。再如, 中国一种植金鱼藻和浮萍的水平潜流式人工湿地, 对景观污水中有机物和悬浮固体的去除率达 70% 以上[24]。

尽管人工湿地研究取得诸多进展, 但在污水中多种污染物共存的条件下, 系统内植物、微生物、填料之间的协同净化机制尚不清晰, 人工湿地对于新污染物的去除效能及其机制仍有待深入研究。国外某菖蒲人工湿地对于含石油废水中的石油类污染物和氮磷都具有良好去除效果, 但湿地系统各单元对于污染物的机制解析不够明确[12]。有研究表明垂直流人工湿地可以去除生活污水中的二乙基甲苯酰胺和邻苯二甲酸二乙酯, 但其去除率只有 50% ~ 60%, 且具体机理仍需深入探究[25]。针对上述人工湿地研究中的关键科学问题, 本文聚焦人工湿地处理不同污水源中的主要污染物净化过程, 主要对以下内容进行总结分析: ①不同来源污水分类及其所含的主要污染物; ②湿地净化污水过程中植物、微生物与填料单元的作用机制; ③人工湿地对新污染物(如微塑料、抗生素、药品和个人护理品等) 的去除潜力与应用。在此基础上, 对人工湿地的应用和发展提出了展望。

1　人工湿地的应用领域与污染物来源

人工湿地作为一种生态友好型污水处理技术, 广泛应用于工业、农业、生活及其他来源污水的处理 (图 1)。总体而言, 人工湿地在去除氮、磷、有机物等常规污染物方面表现出较高的稳定性和适应性, 不同类型污水的处理均可通过植物吸收、基质吸附与微生物降解等综合作用实现高效净化[26]。在共性方面, 各类污水处理均依赖于人工湿地的核心机制: 物理拦截、化学沉淀及生物转化; 湿地系统通常可同时实现多种污染物的协同去除, 并在一定程度上削减病原微生物与部分新兴污染物含量[27]。但在差异性上, 不同来源污水的污染物组成、浓度及可

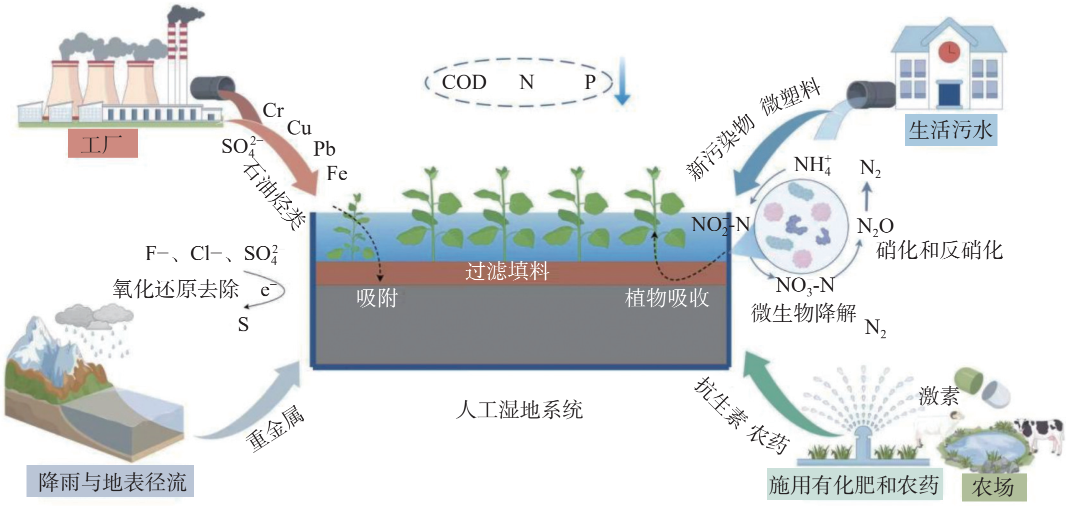

图1 人工湿地净化污染物示意图

Fig. 1 Schematic diagram of pollutant purification by constructed wetlands.

降解性差异明显。工业污水常含有重金属[28]、难降解有机物及有毒化学物,需结合特定耐受性植物及功能微生物强化处理;农业污水则以氮磷营养盐及农药残留为主[29],易受季节和降雨径流影响;生活污水主要为可生化降解的有机物和营养盐[30],处理负荷相对稳定;而其他污水(如景观废水、雨水径流)则常呈现水质波动大、污染类型复杂的特点,需因地制宜设计湿地结构与运行模式。

1.1 工业污水源

矿业、化工、造纸、纺织、食品加工、制药、电子制造等行业的发展产生了多种类型的工业污水,此类污水水质成分复杂、波动大,从文献发表比例可见一斑,其中含石油废水文献占比 2.27%,采矿废水文献占比 4.54%,其他工业废水文献占比 10.22%(图 2a)。除了化学需氧量(COD)、总氮和总磷三类共性污染物,含石油废水还含有石油烃类[21]污染物,其在污水中通常以三种状态存在:浮油、分散油和乳化油。而采矿废水中含有悬浮物、重金属、硒、F^-[31]等有害组分,具有较低的 pH 和高硫酸盐浓度,会导致环境严重恶化[11]。食品、加工、冶金等行业[32-34]的废水含有硝酸盐等污染物[35],部分工业废水中还含有农药阿维菌素(ABM)等成分[36]。人工湿地在工业污水治理中,可通过植物吸收固定、基质吸附沉淀及微生物降解转化等途径协同去除污染物[37]。研究表明,种植香根草的人工湿地处理咖啡加工厂废水,其硝酸盐、氨氮、COD 和磷酸盐的含量显著降低[38]。结合混合沉淀池、垂直流人工湿地和表面流人工湿地的多级人工湿地系统,处理高浓度酸性矿井水(AMD),可改善出水 pH 值(从 2.5 至 8.1)和去除大部分重金属(89.4% 的 Mn,99% 的 Fe、Zn、Cd 和 Cu)[39]。种植美人蕉的垂直潜流人工湿地处理炼油厂污水,对总悬浮物、总氮、硝态氮、铵态氮的去除率分别为 85%、96.38%、96.15% 和 99.15%,重金属 Cr、Cu、Fe、Pb 的含量也有明显降低[40]。垂直流-表面流-水平流组合人工湿地通过基质吸附和生物降解,有效去除了生活-工业混合废水中的多种污染物[41]。

1.2 农业污水源

农业污水来源于畜禽养殖、农田灌溉径流、水产养殖及农产品加工等生产活动,主要包括农田径流、养殖污水、农产品加工污水等(图 2b)。以上几类污水除了总溶解性固体、总氮、总磷和 COD 几种共性污染物,农田径流中还含有重金属、阿维菌素农药[36]等污染物,养殖污水中除含有细菌、病毒等微生物外,还可能含有激素[16]、抗生素等兽药残留物和微量重金属,这些物质对人体健康和环境都具有潜在的危害。人工湿地在农业污水治理中表现出显著优势,其主要依靠植物吸收固定、基质拦截吸附及微生物反硝化等途径去除氮、磷和有机污染物[42]。在中国西北干旱、半干旱地区,土壤和水体的含盐量较高,运用种植特定水生植物的人工湿地处理高盐度农业废水具有良好的效果[43]。伊朗胡泽斯坦省西南部 Naseri 人工湿地处理甘蔗地农业排水,在 ST3 取样站时氮、磷和有机物的去除率达到最大值(65%、94% 和 64%)[44]。采用废杉木和铁杉木屑为基质、沸石与镧改性活性氧化铝作为联合吸附剂的

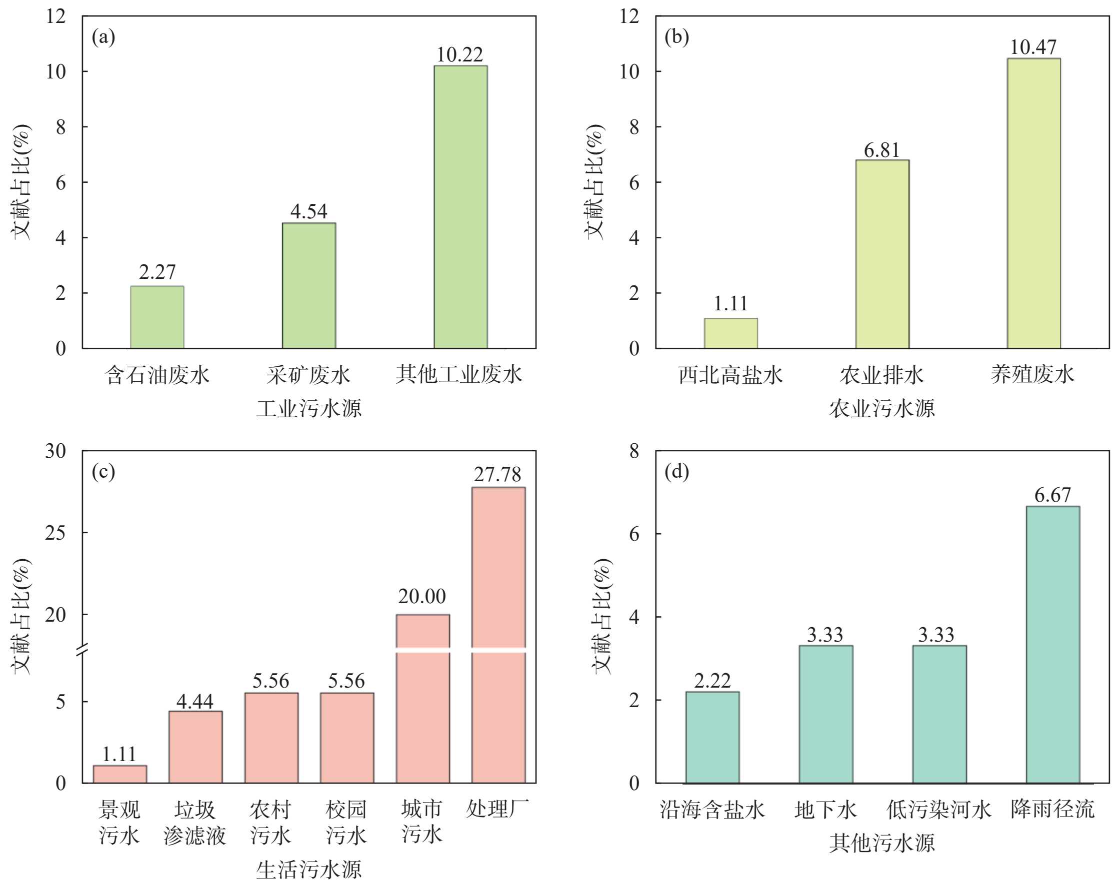

图2　污水源分类及文献占比

Fig. 2　Classification of sewage sources and the proportion of literatures.

垂直流人工湿地, 处理成都平原农田地表径流, 对总氮和总磷的去除率分别为 51.66% 和 60.44% [45] 。种植浮萍和水葫芦两种水生植物的人工浮床湿地用来处理含有肥料和农药的农业污染水时, 高温和增加太阳照射有助于提高净化效能 (氮、磷: 27.4% ~ 83.6%, 农药: 12.4% ~ 42.7%) [46] 。

1.3　生活污水源

生活污水主要来源于居民日常生活排放及城市公共服务活动, 例如: 城市生活污水、农村生活污水、校园生活污水、污水处理厂出水、垃圾渗滤液和景观污水等 (图 2c)。除了 NH_4^+-N、NO_3^--N、NO_2^--N、TN、TP、PO_4^{3-}-P、总悬浮固体 (TSS) 以及五日生化需氧量 (BOD_5) 和 COD 等共同污染物, 由于活动场景和水资源用途的不同, 污水中所含污染物种类也有所差异。城市生活污水中还含有重金属、氟、氯、硫酸盐、个人护理产品、病原微生物、四环素等污染物; 常用作人工湿地处理水源的污水处理厂出水中还含有多环芳烃-菲 [47] 、*β*-内酰胺类抗生素 [21] 、环丙沙星抗生素 [48] 、微塑料 [22] 等新污染物; 垃圾填埋处理产生的渗滤液中还含有重金属和有机微污染物 [49] 等有害组分。近年来, 由于旅游业和服务业的兴起产生了大量的景观污水, 景观污水中除了共性污染物外还含有重金属污染物 [24] 。人工湿地在生活污水处理中的应用已相对成熟。研究表明, 一级垂直流复合人工湿地在水力停留时间 1d 的情况下, 对城市生活污水中 COD、TP、NH_4^+-N 和 NO_3^--N 的去除率分别为 89.90%、88.83%、99.09% 和 96.05% [50] 。印度—垂直流人工湿地系统在热带气候条件下且水力负荷为 2700L/d 时, 对 COD 的去除率高达 72.37% [51] 。14 种热带湿地植物通过实验得出, 墨西哥剑草、蓝水草和空心菜对生活污水中的铁具有较好的稳定作用 [52] 。采用沉淀-厌氧消化-生物过滤-水平潜流人工湿地复合系统处理农村生活污水, 证明高炉钢渣作为湿地基质具有最好的综合去除效果 (NH_4^+-N: 97.1%, TN: 76.6%, TP: 89.7%, COD: 71.0%) [53] 。大型多阶段人工湿地净化污水处理厂出水, 微塑料去除率高达 82.8% ~ 88.9% [22] 。种植美人蕉的垂直潜流人工湿地处理含环丙沙星的

污水处理厂污水,其去除率可达 88.6% [48] 。

1.4 其他污水源

由于尾气排放、施工扬尘、生活排污、农业生产等人类活动和降雨、径流、下渗等自然现象,使得降雨产流 [3] 、地下水、低污染河水 [54] 沿海含盐污水 [55] 等成为人工湿地新的处理对象 (图 2d)。降雨产流污染物类型复杂,包括悬浮颗粒物、氮磷营养盐、石油烃、重金属、有机物及细菌等 [14] ,其特点是突发性强、污染物浓度随雨型和初期冲刷效应显著波动。地下水 [56] 主要受到农业施肥、畜禽养殖渗漏、工业废水渗透等人类活动影响,其典型污染物包括硝酸盐、氨氮、挥发性有机物、重金属及部分有机农药残留。河水中污染物以低浓度的有机物、氮磷营养盐和悬浮物 [57] 为主,同时可能含有部分病原微生物。沿海含盐污水除盐度较高 [58] 外,还含有抗生素等部分新兴污染物。

人工湿地因其多功能净化机制,在上述污水处理中展现出一定优势。填充砾石、粒状活性炭和火山岩的潮汐流人工湿地在厌氧氨氧化的关键作用下,对地下水中氨氮的去除率达到 89.20%±3.09% [59] 。火山岩和陶瓷颗粒由于具有较高的孔隙率和比表面积,充当湿地填料对城市河流污水中磷的去除效果较好,除磷率分别为 92.67% 和 80.82% [60] 。添加零价铁和芦苇的模拟滨海人工湿地在不同盐度条件下,反硝化性能显著提高, NO_3^--N的去除率达到 94% [61] 。微生物脱盐电池 (MDC) 和人工湿地复合系统通过优化设计参数,对沿海含盐水的总氮平均去除率为 87.33%, COD 平均去除率为 92.79%, 平均脱盐率为 55.78%, 在去除污染物的同时也可实现海水淡化和发电功能 [62] 。

尽管人工湿地处理污水源各不相同,但共性污染物如 TN、TP、COD、BOD_5 和重金属出现频率较高,而涉及污水中个人护肤品、抗生素和微塑料等新污染物以及硫酸盐、氟化物、氯化物等有害组分的处理和研究则较少;此前分析人工湿地处理单一或某一类污染物较多,但对于污水中复合污染物的净化研究较少,将来可有针对性地设置人工湿地,考察其对复合污染物的去除效果。

2 不同来源污染物的人工湿地净化机理

从文献统计来看,人工湿地在污水处理研究中主要聚焦于含营养元素与有机物的污水,分别占比 48% 和 36%,显示其在氮磷削减与有机物去除方面具有突出优势。其中氮素 (TN、NH_4^+-N、NO_3^--N和 NO_2^--N) 和磷素 (TP、PO_4^{3-}-P) 的去除率可达 30%～99%,而 BOD_5 与 COD 的去除率则在 26%～98% 之间,表明人工湿地对营养盐与有机物净化均表现出良好的普适性与稳定性。重金属污水相关研究占比为 8%,尽管比例较低,但去除率普遍在 41%～98%,反映其在去除高风险污染物方面也具有实际应用潜力。近年来兴起的新污染物治理研究占比为 6%,去除率为 41%～99%,其主要依赖微生物降解、基质吸附与植物吸收等协同作用。相比之下,针对典型阴离子污水 (如 F^-、SO_4^{2-}、Cl^-) 的研究比例显著偏低,仅为 2% 左右,且去除率差异较大 (15%～80%),显示出处理机制尚不完善。本文在分析人工湿地处理各类污水源的基础上,结合文献研究占比,将其所处理污染物分为营养元素、有机物、重金属、新污染物和典型阴离子五大类 (图 3),并探讨其主要净化机理。

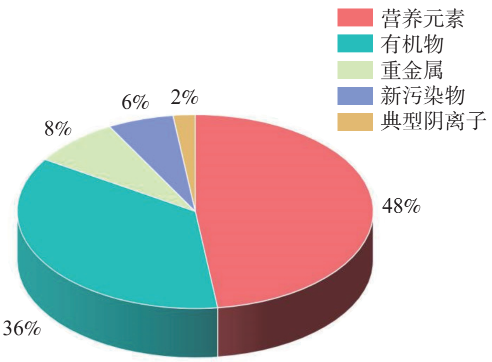

图3　人工湿地处理主要污染物类别

Fig. 3　The main categories of pollutants treated by constructed wetlands.

2.1 含营养元素污水

在人工湿地中,氮和磷是最主要的营养元素污染物,其去除效果直接决定系统的净化效率与稳定性。氮的去除主要依赖于微生物介导的多种生物过程以及部分化学途径;而磷的去除则以基质的物理化学作用为主,并辅以植物吸收和微生物同化。二者均受到基质类型、植物-微生物互作及运行条件等因素的显著影响。对营养元素污染物的去除率和相关去除机理见表 1。

人工湿地氮去除主要依赖微生物介导的多种生物过程,微生物在人工湿地脱氮过程中贡献率超过 80% [71] 。在氮循环中,微生物通过固氮、氨化、硝化和反硝化等关键途径参与氮的转化,这些过程依赖于多种氮转化酶及功能基因 (如 *napA*、*amoA*、*nirS*、

表 1　含营养元素污水人工湿地净化去除机理

Table 1　The purification and removal mechanism of wastewater containing nutrient elements in constructed wetlands.

污水类型	人工湿地类型	营养元素及初始浓度	营养元素污染物去除率	净化去除机理	参考文献
大学生活污水	垂直潜流	TN: 16 ~ 55mg/L TP: 1 ~ 7mg/L	TN: 42% ~ 58% TP: 26% ~ 86%	微生物降解，基质吸附，植物吸收	[6]
小城镇生活污水	综合垂直流	TN: 2 ~ 48mg/L TP: 0.5 ~ 4.1mg/L	TN: 30% TP: 64%	微生物降解，基质吸附，植物吸收	[9]
含石油废水	垂直流	TN: 5 ~ 12mg/L TP: 1 ~ 4mg/L	TN: 67% TP: 54%	微生物降解，基质吸附，植物吸收	[12]
垃圾渗滤液	垂直流	NH_4^+-N: 29 ~ 320mg/L TN: 42 ~ 325mg/L	NH_4^+-N: 96% ~ 99% TN: 62% ~ 70% TP: 84% ~ 88%	微生物降解，基质吸附，植物吸收	[17]
地下水	垂直潜流	NO_3^--N: 12mg/L	NO_3^--N: 95%	微生物降解，植物吸收	[29]
西北干旱和半干旱地区含盐水	模拟	TN: 20 ~ 60mg/L TP: 5mg/L	TN: 60% ~ 90% TP: 91%	微生物降解，基质吸附，植物吸收	[42]
养猪废水	复合	NH_4^+-N: 400 ~ 540mg/L TP: 11mg/L	NH_4^+-N: 99%, TP: 62%	微生物降解，基质吸附，植物吸收	[45]
污水处理厂污水	垂直流	NH_4^+-N: 7mg/L NO_3^--N: 10mg/L	NO_3^--N: 91%	微生物降解，植物吸收	[47]
低磷污染河水	多级	TP: 0.1mg/L	TP: 5% ~ 21%	基质吸附，植物吸收	[57]
生活污水	垂直流	TN: 30 ~ 50mg/L TP: 3 ~ 5mg/L	TN: 61% TP: 31%	微生物降解，基质吸附，植物吸收	[63]
污水处理厂出水	卧式地下流	NH_4^+-N: 4mg/L NO_3^--N: 10mg/L	NH_4^+-N: 95% TN: 85%	微生物降解，植物吸收	[64]
养猪废水	地下流	TN: 80mg/L TP: 8mg/L	TN: 11% ~ 63% TP: 93% ~ 95%	微生物降解，基质吸附，植物吸收	[65]
动物养殖废水	垂直流	TN: 280mg/L TP: 47mg/L	TN: 60% ~ 80% TP: 24%	微生物降解，基质吸附，植物吸收	[66]
农业废水	垂直流	TN: 10mg/L TP: 0.7mg/L	TN: 85%	微生物降解，植物吸收	[67]
污水处理厂尾水	垂直流	NO_3^--N: 15mg/L	NO_3^--N: 95% TN: 79% TP: 98%	微生物降解，基质吸附，植物吸收	[68]
模拟生活污水	垂直潜流	NH_4^+-N: 22mg/L TP: 3mg/L	NH_4^+-N: 51% TP: 69%	微生物降解，基质吸附，植物吸收	[69]
农村生活污水	潜流	TN: 40mg/L TP: 5mg/L	TN: 68% TP: 91%	微生物降解，基质吸附，植物吸收	[70]

nirK 等)[72]。其中，异养反硝化是最主要的脱氮机制，以有机碳为电子供体[73]；而在碳源不足的条件下，自养反硝化 (如硫驱动反硝化) 能够发挥重要作用，硫杆菌利用硫作为电子供体来实现高效脱氮，NO_3^--N 去除率可达 95%[56]。此外，无机填料 (如零价铁和磁铁矿) 可通过化学反硝化与氢驱动反应实现高效脱氮，NO_3^--N 去除率最高可达 92%[35]。人工湿地中微生物群落丰富，主要包括固氮菌、异养氨化菌、氨氧化细菌、氨氧化古菌、亚硝酸盐氧化菌和反硝化菌等[58, 74]。不同基质条件会影响其群落结构与脱氮性能。例如，以生物炭为填料的人工湿地中，硝化菌和反硝化菌的丰度明显高于砾石基质湿地，从而表现出更好的脱氮效果，但同时可能导致 N_2O 排放增加，加剧温室效应[75]。进一步研究表明，椰子壳生物炭能显著提升氮去除率，总氮去除率高达 97.78%±0.91%[76]。进水碳氮浓度比值 (C/N) 亦是影响机制的重要因素，当 C/N 为 6 ~ 7 时，微生物群落多样性与稳定性最佳，氮去除效率也更高。

功能基因、运行条件及植物-微生物互作机制对脱氮过程也具有深远影响。功能基因在氮素去除中具有关键作用，其中 *nirK* 基因在 NH_4^+-N 转化过程中占据重要地位，而 *AOA* 基因在 NO_2^--N 与 TN 去除中发挥主导作用[77]。在氮与抗生素共存的系统中，总氮去除率并未受到显著影响，而放线菌在氮素与

抗生素协同去除过程中表现出关键作用[78]。运行环境条件同样深刻影响脱氮过程。在 10℃ 干湿交替条件下，各类氮素的去除率可保持在 20%～40% 之间[79]；在低 C/N 值的污水处理中，以铁屑和单质硫作为电子供体，可选择性富集嗜铁菌和脱氯单胞菌属，从而提高反硝化效率，NO_3^--N 平均去除率达到 71.66%±12.54%[80]。此外，有研究表明施加外部压力能够强化厌氧氨氧化、异养硝化与好氧反硝化等过程，从而进一步提升脱氮性能[81]。植物-微生物互作机制在人工湿地氮循环中同样至关重要。根系发达的水生植物能够提升氧气与碳源的供应，从而促进硝化与反硝化效率[82]。植物混养可刺激根系分泌物的释放，进一步增强氮素去除能力[83]。农业生物质的添加则能够补充外加碳源并促进相关反硝化菌群的富集，从而提高脱氮性能[84]。植物根际的径向氧损失可促进硝化与反硝化过程的耦合，提高氮素去除效率[85]；同时，微生物通过对活性炭与活性氮的代谢调节，驱动土壤碳氮循环[86]。然而，当湿地长期处于盐胁迫条件下，微生物群落的氮转化功能将受到抑制，此时短程硝化-反硝化途径的重要性增加，并可能伴随共生固氮的增强[87]。

在人工湿地中，磷去除机制主要包括基质的物理化学过程与植物-微生物的协同作用。人工湿地中磷的去除主要依赖基质的物理化学作用，包括吸附、沉淀、截留及离子交换等过程，其贡献率可达 70%～87%[71]。植物在磷循环中同样发挥重要作用，一方面通过同化作用将无机磷转化为细胞成分[88]，另一方面根际分泌物与信号分子能够促进磷的吸收与固定[89]。根系发达的水生植物能够增强对磷的吸收效率[82]，多枝柽柳根际的聚磷菌作用可使 TP 去除率超过 91%[42]。中试水平潜流人工湿地中，芦苇、加州雪芹混种可提高湿地对磷的吸收[90]。农业生物质的添加亦可为聚磷菌群提供额外碳源，促进其富集与磷固定作用。微生物机制以聚磷菌 (PAOs) 为代表，其在交替的好氧-厌氧条件下完成磷的吸收与释放，相关功能基因如 *ppx*、*phoA*/*phoD* 在磷转化过程中具有重要作用[6, 91]。此外，脲酶和磷酸酶等水解酶通过促进有机磷向无机磷转化，进一步提升了磷的去除效率[92]。而在植物-微生物互作方面，引入植物根际促生菌 (PGPR) 优化磷在基质表面的结合形态，增加 Ca/Mg-P 比例，从而促进植物吸收，TP 去除率可提高 36.7%[93]。

基质优化与耦合技术能够进一步提升人工湿地的除磷效率。基质优化是提高磷去除效率的重要途径。具有高比表面积和丰富官能团 (如—COOH、—OH) 的材料能够增强微生物附着与离子吸附能力[48]。例如，玄武岩纤维填料可使 TP 去除率较空白组提高 10%～25%[73]；凹凸棒土通过孔隙填充、表面沉淀和配体交换等机制实现高效除磷[71]；新型陶粒则利用均相与非均相活性位点，除磷率可达 99%[94]。复合填料 (如铜炭、石英砂) 不仅改善吸附效果，还能优化细菌群落结构，从而提高系统稳定性[47]。在高盐度条件下，凹凸棒土表现出独特的除磷机制：NaCl 促进磷矿物溶解，Na^+取代磷酸根上的金属阳离子并中和负电荷，增强静电吸附；同时，Na^+可替代 Ca^{2+}、Mg^{2+}、Al^{3+}和 Fe^{2+}等金属离子，交换产生的新离子与磷酸根结合生成沉淀，从而显著促进磷的去除[71]。不同基质类型的湿地除磷机理有所差异。天然锰矿石人工湿地的 TP 去除率可达 76%，其主要依赖沉淀作用，扫描电镜 (SEM) 与能谱 (EDS) 分析表明磷主要以沉淀形态存在[95]。热改性海泡石基质人工湿地 TP 去除率可达 91.05%，除磷机理主要为基质吸附，结合形态以 Ca/Mg-P 与 Fe/Al-P 为主[96]。镧/铝改性硅藻土与生物质炭复合填料则通过形成钙结合态磷与铝结合态磷，实现进水 TP 平均 95% 的去除率[97]。此外，生物过程与耦合系统能够进一步强化磷的去除。有研究表明，外源电子供体可促进烟酰胺腺嘌呤二核苷酸的生成，从而促进磷化氢 (PH_3) 的形成与迁移，显著增加湿地中有效磷比例，使磷吸附量提高 103.6%[98]。在人工湿地-微生物燃料电池系统中，引入耐盐电活性菌-藻类生物膜可通过细胞膜转运蛋白将 K_2HPO_4 直接吸收入微藻细胞，TP 去除率达到 90.81%±5.67%[99]。在实际应用中，人工湿地作为曝气塘出水的后处理工艺，总磷去除率可达 74%[100]。

2.2 含有机物污水

人工湿地对有机物去除以微生物降解为核心，同时受植物修复、基质吸附及运行条件优化的协同影响，实现高效净化效果。对有机物的去除率和相关去除机理见表 2。

微生物降解在有机物去除方面，贡献率超过 70%[12]，在不同氧环境下，功能菌可将有机物转化为营养物质、CO_2 和 H_2O，并可分泌过氧化氢酶加速 COD 去除[63, 71]。不同微生物类群在去除过程中具有特定功能：拟杆菌门可分解大分子有机物[14]，厚壁菌门参与纤维素降解和反硝化[84]，嗜热假单胞菌门丰度与 COD、NH_4^+-N 和 TP 去除呈正相关[109]。此外，微生物可合成生物表面活性剂，增强有机物吸

表 2　含有机物污水人工湿地净化去除机理

Table 2　The purification and removal mechanism of wastewater containing organic matter in constructed wetlands.

污水类型	人工湿地类型	有机物及初始浓度	有机物去除率	净化去除机理	参考文献
小城镇生活污水	综合垂直流	COD: 28 ~ 33mg/L	COD: 80%	微生物降解, 基质吸附	[9]
含石油废水	垂直流	COD: 413 ~ 708mg/L TPH: 106 ~ 228mg/L	COD: 80% TPH: 97%	微生物降解, 植物吸收	[12]
养殖二级废水、农业径流	水平流	BOD_5: 39mg/L COD: 100mg/L	BOD_5、COD: >40%	微生物降解, 基质吸附	[14]
景观污水	水平潜流式	COD: 50mg/L	COD: 70%	微生物降解, 基质吸附	[24]
洗澡水、洗衣废水	垂直流	COD: 270 ~ 320mg/L	COD: 73%	微生物降解, 基质吸附	[25]
污水处理厂污水	垂直流	COD: 104mg/L	COD: 75%	微生物降解, 基质吸附	[47]
生活污水	垂直流	COD: 33 ~ 300mg/L	COD: 92%	微生物降解, 基质吸附	[63]
养猪废水	垂直流	COD: 400mg/L	COD: 91%	微生物降解, 基质吸附	[65]
动物养殖场废水	垂直流	COD: 4300mg/L BOD_5: 1672mg/L	COD: 91% BOD_5: 95%	微生物降解, 基质吸附	[66]
雨水径流和工业废水	垂直上升流	COD: 500mg/L	COD: 93%	微生物降解, 基质吸附	[101]
养猪废水	复合	COD: 570 ~ 620mg/L	COD: 87%	微生物降解, 基质吸附	[102]
污水处理厂二级出水	折流式垂直流	COD: 200 ~ 300mg/L	COD: 66%	微生物降解, 基质吸附	[103]
二级养猪场污水、雨水径流	自由水面	BOD_5: 32 ~ 55mg/L COD: 200 ~ 304mg/L	BOD_5、COD: 34% ~ 50%	微生物降解, 基质吸附	[104]
牲畜次生废水	垂直流	COD: 374mg/L	COD: 95%	微生物降解, 基质吸附	[105]
厌氧消化黑水	垂直流	COD: 112 ~ 601mg/L	COD: 74%	微生物降解, 基质吸附	[106]
生活污水	自由水面	BOD_5: 350mg/L	BOD_5: 62% ~ 92%	微生物降解, 基质吸附	[107]
污水处理厂处理后的中水	水平潜流	COD: 33.2mg/L	COD: 51%	微生物降解, 基质吸附	[108]

附与降解。植物通过提取、转化、稳定、挥发及根系降解参与有机物去除[73], 根系释放氧气改善局部好氧环境, 促进需氧菌活性[110], 内生菌亦可在体内降解污染物。基质通过吸附和载体作用强化有机物去除, 其中生物炭的多孔结构有利于生物膜形成, 提高 COD 去除效率[82]; 改性生物炭可使 COD 去除率达 89%, 马缨丹草生物炭 (15% 投加) 可达 92.71%[111]。自然老化垃圾焚烧炉底灰作为基质可实现资源化利用, 同时使 BOD_5 去除率达到 51%[18]。植物-微生物-基质协同作用进一步强化有机物去除: 根系为微生物提供氧气与碳源, 微生物可分解根际吸附的有机物, 实现高效循环利用。藻类投加提高微生物多样性和丰富度, 并通过细胞吸附增强 COD 去除 (74%)[112]。新型运行工艺同样有效: 跌水强化潮汐流人工湿地中淹没阶段 COD 主要依靠好氧降解与生物炭吸附, 而实验阶段微生物可降解生物炭吸附的有机物[113]; 垂直流复合磁场人工湿地通过优势菌群分解作用显著提升 COD 去除率, 进一步验证微生物在有机物去除中的主导地位[109]。

总石油烃 (TPH) 作为典型难降解有机污染物, 其来源包括石油开采、加工、运输及城市污水排放。TPH 的去除路径以微生物降解为主, 贡献率超过 60%, 特定微生物可将石油烃作为碳源代谢, 表现出较强耐受性和降解能力[23]。研究显示, 环境中已有 40 多种微生物具备 TPH 降解能力, 其中部分在湿地生态系统中占据优势[12]。人工湿地中基质 (如砂、砾石、生物陶瓷等) 可通过吸附、过滤和沉淀固定 TPH, 其去除性能受基质成分、结构及比表面积影响。植物能够有限吸收并富集特定石油组分, 部分湿地植物表现出较强富集能力。在菖蒲湿地中, 不动杆菌、红杆菌、雷氏菌和鞘菌等微生物与多种填料协同作用, 可实现 TPH 高达 97% 的去除率[12]。浮动处理湿地 (FTW) 中植物根部垂入水体, 既作为生物过滤器去除污染物, 又为碳氢化合物降解细菌提供附着和生长空间, 微生物在根际外形成生物膜, 对水体中有机污染物进行降解[114]。在种植香蒲的水平流人工湿地中, 芽孢杆菌属作为主要烃类降解菌, 与水生植物协同, 可显著降低污水中烃类有机物含量[115]。通过改善湿地运行条件, 也可强化 TPH 去除效果。例如, 在系统中曝气并添加表面活性剂, 可促进恶臭假单胞菌、琼氏不动杆菌等有益菌群活性, 使石油烃去除率达到 97%[116]。当污水氧化还原电位为−100 ~ 300mV 时, 兼性条件占主导, 有利于反硝化过程及 TPH 去除, 去除率大于 84%[117]。此外,

通过改善石油污染物与滤料的接触,如采用间歇加载和底部输入方式,可减少短链烃挥发,提高去除效率[118]。尽管湿地系统对石油类有机污染物去除效果良好,但其降解产物的生态毒性及与其他有机污染物的协同去除机制仍需进一步研究。

2.3 含重金属污水

重金属因其高毒性、生物不可降解及易富集特性,对生态系统和人体健康构成严重威胁[11]。人工湿地因其低运行成本和生态友好性,被广泛用于含重金属污水治理。其重金属去除主要依赖植物吸收与基质吸附,贡献率超过 70%[119],同时还涉及化学沉淀、与有机物结合及植物根系对悬浮颗粒的过滤等途径[15]。这些过程受 pH 和氧化还原电位等环境因子影响。基质通过过滤、吸附、絮凝、沉淀及离子交换等方式去除重金属,其效率与比表面积及物理化学结构密切相关[42]。腐殖质、几丁质等有机成分中的羧基、羟基和胺基官能团可与重金属形成络合物,从而增强吸附性能[19]。植物通过根部富集和转运去除重金属,其吸收能力顺序为根>茎>叶[120],同时可分泌有机酸螯合重金属以降低毒性[17]。植物根际微生物可促进重金属的还原、吸附和沉淀,是植物吸收重金属的重要辅助[73]。接种丛枝菌根真菌 (AMF) 并在芦苇垂直流人工湿地中进行曝气,可显著促进植物生长和抗氧化酶活性,缓解氧化胁迫,同时增加植物根系及基质中重金属的积累,并优化其亚细胞分布,从而提升系统的去除效果[121]。生物炭的添加可优先吸附二价 Cd,并通过积累 Fe/Mn 氧化键,使湿地中 Cd 的去除率高达 99.7%[122]。将核桃壳制成的颗粒生物炭置于砂基湿地处理矿山废水,可增强金属吸附能力和酸性中和作用,同时有机废液促进植物生长并刺激生物源硫酸盐还原,可有效去除多种重金属并减轻金属向地上转移[11]。此外,在湿地基质中添加腐植酸与生物炭,高通量测序显示该处理通过增加拟杆菌丰度,提高了 Cr 和 Ni 的去除效率[123]。

在具体应用中,采用松树皮基质的垂直流湿地处理垃圾渗滤液中 Zn、Ni、Cu 和 Cr,去除率为 41%~56%[17];以核桃壳生物炭为填料处理重金属初始浓度均为 5mg/L 的采矿废水时,Cu、Cd、Cr 和 Zn 的去除率分别超过 98%、95%、91% 和 91%[11]。种植多枝柽柳的人工湿地处理含 Pb 和 Cr 污水时,去除率分别大于 94% 和 97%[42]。铁碳基人工湿地系统对 Cr 和 Pb 的去除率可达 75%~97%[74];添加腐植酸可显著提高湿地基质对 Cr 的截留能力,去除率达 91.82%[124]。此外,人工湿地与微生物燃料电池联用可进一步提高重金属去除效率,Zn、Cd、Cu 和 Pb 的去除率分别达到 92.91%、90.75%、98.83% 和 95.74%[125];三级植物湿地系统中对 Cd 和 W 的去除率分别为 87.01%~89.18% 与 64.62%~73.36%[126]。

2.4 含新污染物污水

近年来,人工湿地在新污染物去除方面表现出显著潜力,对新污染物的去除率及相关去除机理总结于表 3。

微生物降解是其主要去除机制,对抗生素、激素、农药及表面活性剂等新污染物的贡献可达 40%~70%,而基质吸附可进一步去除 20%~40% 的污染物,如磺胺类药物、农药残留及微塑料[36]。植物通过根系吸收和酶促转化,可辅助去除如乙酰氨基酚和咖啡因等污染物[16],光降解、络合、水解及氧化还原等物理化学过程在特定条件下也起到促进作用。在微塑料去除方面,大型多级湿地对聚氯乙烯、聚苯乙烯、聚丙烯和聚乙烯的去除率均超过 89%,微型纤维在水力作用下可相互缠绕形成线圈,有利于截留[22]。生物炭的加入可增强低 C/N 湿地的生物氧化和还原过程,有助于磺胺甲恶唑去除 (36.8%±6.2%),且在碱性介质条件下效果最佳[132]。NaOH 改性玉米秸秆生物炭湿地对 8 种磺胺类抗生素去除率超过 94%,增加 DO 和进水负荷可进一步提高去除效率,且其去除过程与湿地中氮转化密切相关[133]。人工曝气及串联湿地处理生活污水,对甾体激素的去除率为 14.7%±3.04% 至 100%,以微生物降解为主,基质吸附和植物吸收起辅助作用[134]。芦苇人工湿地处理三唑类杀菌剂农药时,通过微生物降解至第 14 天去除率可达 84%[135]。大型复合湿地对污水处理厂出水中 19 种农药的去除率为 49.99%~84.96%,且呈季节变化趋势,这是由于负责生物降解的微生物受温度影响明显,优势菌门包括变形菌门、绿弯菌门、酸菌门、浮游菌门和拟杆菌门[136]。对于表面活性剂,革兰氏阴性菌接种至湿地处理中直链烷基苯磺酸盐 (LAS),当初始浓度低于 100mg/L 时,其去除率可超过 80%[137]。掺入生物炭、颗粒活性炭和天然沸石可增强城市污水中有机物、硝酸盐、磷酸盐及 PFAS 的去除效果,但长链 PFAS (≥8 碳) 在常规湿地和沸石湿地中仍部分残留[138]。人工湿地对含聚乙烯微珠、轮胎磨损颗粒及聚丙烯腈纤维的污水处理结果显示,植被可促进漂浮微塑料沉降,微塑料附着于水生植物表面,植物

表 3　含新污染物污水人工湿地净化去除机理

Table 3　The purification and removal mechanism of wastewater containing emerging pollutants in constructed wetlands.

污水类型	人工湿地类型	新污染物	新污染物初始浓度	新污染物去除率	净化去除机理	参考文献
小城镇生活污水	综合垂直流	四环素	2μg/L	75%	微生物降解	[9]
养猪场外排尾水	垂直流	4 种糖皮质激素	50μg/L	30% ~ 70%	微生物降解	[16]
污水处理厂二级出水	垂直流	β-内酰胺类代表性抗生素 (CED)	35mg/L	98.84%	微生物降解	[21]
污水处理厂出水	大型多阶段	微塑料: PVC、PS、PP 和 PE 等	42mg/L	82% ~ 88%	基质吸附, 根际过滤	[22]
灰水: 洗澡水 90%, 洗衣废水 10%	垂直流	个人护理产品 (PCPs)	500μg/L	50% ~ 90%	微生物降解	[25]
农业废水	垂直流	农药 (阿维菌素 ABM 等)	0.5 ~ 1.5mg/L	99%	微生物降解	[36]
污水处理厂污水	垂直流	多环芳烃: 菲	12mg/L	94%	微生物降解	[47]
污水处理厂污水	垂直潜流	环丙沙星	400μg/L	69% ~ 88%	微生物降解	[48]
垃圾渗滤液	水平潜流	有机微污染物 (DEP 等)	170 ~ 700μg/L	DEP: 63% ~ 89% DBP: 62% ~ 80%	微生物降解	[49]
生活废水	水平-垂直混合	磺胺类药物和氟喹诺酮类药物 (CIP 等)	442ng/L	80% ~ 93.9%	微生物降解	[106]
城市污水	垂直流	32 种全氟和多氟烷基化合物 (PFAS)	153 ~ 405ng/L	＜30%	微生物降解	[127]
入湖口进水	潜流湿地和表流	萘和菲	萘: 67ng/L 菲: 0.04ng/L	萘: 41% 菲: 70%	微生物降解	[128]
农村生活污水	组合	19 种药物及个人护理产品 (PPCPs)	20 ~ 80ng/L	50% ~ 80%	微生物降解	[129]
居民生活污水	组合	阿特拉津、丙嗪、丁酸盐等 19 种农药	51 ~ 146ng/L	49% ~ 84%	微生物降解	[130]
禽畜养殖尾水	垂直流	磺胺甲噁唑 (SMZ)	SMZ: 4.95mg/L	99%	微生物降解	[131]

形态对截留率具有关键影响[139]。引入蚯蚓可显著提高聚乳酸微塑料、COD、总氮及铵态氮去除效率, 蚯蚓摄入微塑料可促进微生物丰度和氮循环相关微生物群落富集[140]。国外一组合湿地对药物及个人护理品类 (PPCPs) 的去除率为 82.7%, 主要依赖微生物降解, 同时植物吸收和生物降解起协同作用[141]。此外, 光催化与人工湿地结合可有效去除细胞内外抗生素耐药基因 (ARGs), 降低其传播风险[142]。

针对典型新污染物[143], 人工湿地的去除效果呈现较大差异。例如, 持久性有机污染物 (POPs) 中的邻苯二甲酸酯类 (如 DEP、DBP) 在不同填料系统中去除率为 54% ~ 89%, 而对 PFAS[144] 等持久性氟化合物去除率普遍较低 (＜30%)[49]。PPCPs 类物质[145] 中, DEET、DEP 去除率为 50% ~ 60%, 而人工合成麝香类如 HHCB 和 AHTN 去除率可达 90% 以上[25]; 组合式人工湿地对初始浓度分别为 67ng/L 和 0.04ng/L 的多环芳烃萘和菲去除率分别为 41% 和 70%[128]。抗生素方面, 四环素在曝气垂直流人工湿地中可去除 75%[9], β-内酰胺类在藻菌共生湿地系统中去除率可达 98%[21]。组合湿地系统对磺胺甲恶唑、环丙沙星、磺胺嘧啶等去除效果良好[106]。种植黄花鸢尾等植物的湿地系统中, 土霉素、磺胺嘧啶、洛美沙星的去除率为 65% ~ 80%[129]。人工湿地对微塑料的主要作用机制为基质过滤与植物截留[22], 去除率普遍维持在 82% ~ 88%, 部分实验室湿地对特定微塑料如聚乙烯微珠等的去除率甚至超过 99%[12]。此外, 有研究表明人工湿地对抗生素抗性基因 (如 TRGs) 也具有一定净化能力, TRGs 的绝对丰度可降低 1.2 ~ 2.9 个数量级[145]。

新污染物种类繁杂, 虽然人工湿地对其具有一定的净化效果, 但处理后的产物是否具有更大的环境危害还不明确, 且不同新污染物在人工湿地中的去除过程是否相互影响, 去除机理是否存在耦合关系还需进一步探究。

2.5　含典型阴离子污水

在污水中, 氟化物 (F^-)、硫酸盐 (SO_4^{2-}) 和氯化物 (Cl^-) 是常见的无机阴离子, 来源包括工业排放、农业活动及日常生活等。人工湿地系统 (CWs) 对这些阴离子的去除主要依赖于植物吸收、基质吸附和微生物转化等过程。

人工湿地 (CWs) 中氟化物的去除主要依赖基质吸附和共沉淀作用, 贡献率约为 50% ~ 60%[83]。其中, F^-可与 Ca^{2+}形成球形沉淀被固定。植物根系具有较强的 F^-富集能力, 吸收顺序为根＞茎＞叶, 而氟离子转运蛋白 (FEX) 在植物体内起关键的排毒作用[146]。微生物方面, 根际低 pH、高溶解氧 (DO) 环境有利于氟化物去除, 耐氟菌可通过生物吸附、生

物沉积及氟离子通道排出 F^-,进一步提升湿地的净化能力。实际应用中,钙基底物在磷酸盐存在下可沉淀 F^-生成羟基磷灰石,配植鸢尾的钙基人工湿地可实现约 33% 的 F^-去除[89];而采用砾石、砂、改性粉煤灰基类水滑石(MAFO)结合芦苇构建的人工湿地,其 F^-去除率可超过 80%[31]。此外,以羟基磷灰石为填料的湿地对污水中的氟和重金属具有较高吸附能力,可降低氟及重金属对硝化与反硝化功能菌的胁迫,从而提高系统中NO_3^--N 的去除效率[147]。

人工湿地中SO_4^{2-}的去除依赖植物、基质与微生物的协同作用。植物可吸收硫酸盐并将其还原为含硫氨基酸[148],其凋落物及根系分泌物还能促进异化硫酸盐的还原。基质中特定官能团可参与硫的沉积,约 50% 的输入硫以固态形式累积[35]。微生物方面,硫酸盐还原菌 (SRB) 是主要作用菌群。在碳源充足时,碳降解菌分解有机碳源 (如葡萄糖、乙酸、乳酸等) 释放小分子有机物、氢气或其他还原性产物,这些产物可作为电子供体被 SRB 利用,在厌氧环境下将硫酸盐还原为硫化氢,后者可与重金属形成不溶性硫化物沉淀[71]。当碳源受限时,可通过引入替代电子供体或调控电子传递维持系统稳定。在具体应用中,砾石、河砂及潮间带沉积物填料构建的垂直流 CWs 可去除约 60% 的SO_4^{2-}。采用石英砂、零价铁 (ZVI) 和磁铁矿混合填料处理初始浓度 35mg/L 的硫酸盐水体,可在 ZVI 辅助作用下实现 66% 的去除率[35]。湿地系统中土壤硫源参与硫酸盐还原及部分硫氧化过程,有机质促进硫的固定,而良好的植物生长状态对土壤硫沉积至关重要[149]。在高 COD 条件下,石英砂和 ZVI 基质人工湿地对硫酸盐的去除率可达 96.9%,ZVI 不仅作为硝酸盐和硫酸盐还原的电子供体,还能在高 COD 条件下促进化学反硝化,但其产生的硫化物会抑制反硝化菌的相对丰度[35]。在香蒲砾石人工湿地中,植物自身对硫酸盐去除贡献有限,但其富含碳的凋落物显著提高了硫酸盐去除率。去除后的硫主要以 S(-Ⅱ) 和 S(0) 形式沉积在富铁砾石表面,硫酸盐还原菌在凋落物中的硫库主要为酸性挥发硫化物,从而实现硫酸盐与硫化物的可持续循环[150]。人工湿地与椰壳生物炭相结合治理酸性矿山废水,由于生物炭的吸附作用和沉积物中硫酸盐还原菌的还原作用,使得体系中硫酸盐和 Cd 的浓度分别降低了 72.03% 和 80.16%[151]。在种植菖蒲、荷叶和香蒲的自由表面流人工湿地中,通过 RT-PCR 和 16S rDNA PCR 分析证实,硫酸盐还原菌对SO_4^{2-}具有显著还原作用[152]。

人工湿地对 Cl^-的去除效果相对有限,主要依赖植物吸收与基质吸附,两者总贡献率超过 68%[153]。部分 Cl^-可在预处理或湿地运行过程中通过气化或微生物转化被去除。特定植物和微生物可富集或转化 Cl^-,例如某些酶促反应 (如氯化物组合酶) 可将 Cl^-转化为无毒形态。观赏植物混养系统对 Cl^-的去除率约为 31%[12],而基库尤草湿地处理埃塞俄比亚麦芽厂废水时,Cl^-去除率可超过 99%[154]。采用人工湿地与微生物燃料电池组合系统处理含盐废水,Cl^-去除率为 29.96%,在盐度为 2% 时发电效果最佳,但盐度升高会抑制 COD 和 TN 去除[155]。京津冀地区人工湿地中盐生植物对 Cl^-的吸收率可达 60.6g/kg,同时使水质电导率下降约 40%[156]。自由表面流人工湿地中种植水浮莲处理生活污水,在水力停留时间为 10 天时,出水氯化物含量可降低 80%[157]。此外,采用粉煤灰与土壤混合物作为湿地基质时,Cl^-去除率可达 89.6%[158]。

2.6 含复合污染物污水

尽管已有大量研究聚焦于人工湿地对单一污染物的去除,但对于复合污染体系的净化机制关注较少。考虑到废水中污染物种类繁多、相互作用复杂,以及水体理化性质的多样性,深入剖析人工湿地对复合污染物的去除过程具有重要意义。目前,人工湿地中填料、植物和微生物在污染物去除中各有作用,但其贡献尚未被系统量化,不同环境条件下各净化单元之间的协同或拮抗机制仍需进一步明确。

研究表明,人工湿地处理含 PPCPs 和微塑料的复合污染体系时,去除率可分别达到 29% ~ 95% 与 10.61% ~ 99.9%[159],但部分去除过程 (如 PPCPs 的生物降解) 可能伴随温室气体的增加[160]。在抗生素与重金属共存的湿地净水过程中,如四环素与铜离子、磺胺甲恶唑 (SMZ) 与 Cr(Ⅵ)/Cu 组合的复合污染,不仅会诱导四环素抗性基因 (TRGs) 丰度升高[160],还会通过形成结构复杂、毒性可变的络合物[161],干扰湿地系统中植物与微生物的正常功能,进一步削弱氮元素等污染物的去除效率[145]。另有研究发现 SMZ 和 Cr(Ⅵ) 相互之间存在促进吸附的作用,共存时表现出一定的湿地净化优势[162],但整体上,复合污染物之间的协同去除、转化产物的毒性强弱及其对湿地功能的影响仍缺乏系统评估。

3 结论和展望

人工湿地在处理污染物类型方面,研究重点集中在氮、磷和有机物的去除,而针对无机盐 (如氟化

物、氯化物、硫酸盐) 和石油烃的研究相对较少。人工湿地污染物去除机制多样且主导作用明确: 微生物是氮素去除的主要驱动因子, 贡献率超过 80%, 主要通过固氮、氨化、硝化和反硝化作用等途径实现; 基质通过吸附、沉淀等过程去除污水中 70% ~ 87% 的磷; 有机物以微生物降解为主, 贡献占比大于 70%; 重金属主要通过植物吸收和基质吸附去除; 新污染物和石油烃去除主要依赖微生物代谢, 贡献率分别为 40% ~ 70% 与 60% 以上。人工湿地去除无机盐类污染物的方式相对单一: 氟主要通过基质吸附与共沉淀作用去除, 氯化物依赖植物吸收与填料吸附, 人工湿地中大约 50% 的输入硫可以通过底物积累去除, 硫酸盐还原菌、硫氧化菌和碳降解菌等微生物也在硫酸盐的去除中起着重要作用。

前人对人工湿地去除单一污染物的研究较多, 而对复合污染物的关注较少, 由于废水中污染物种类的多样性以及水体理化性质的复杂性, 将来可有针对性地设置人工湿地考察其对复合污染物的去除效果并深入剖析净化机制。新污染物和石油烃类污染物种类繁杂, 虽然人工湿地对其具有一定净化效果, 但处理后的产物是否具有更大的生物毒性还不明确, 且净化过程虽已统计原有污染物的去除率, 但新生成污染物的浓度及其后续转化过程仍需进一步定量分析。人工湿地中填料、植物和微生物单元在净化污水时作用各异, 且不同污染物的去除过程相互影响, 所以有必要进一步量化人工湿地中微生物、植物和填料对去除效果的贡献, 探究其在多介质与多过程作用中的耦合关系。

A Review of Research Progress on the Application and Mechanism of Constructed Wetlands in Purifying Pollutants

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HIGHLIGHTS

(1) Due to the limitations of small generation and high technical requirements, the application of constructed wetlands in the treatment of industrial wastewater and other types of wastewater is still relatively limited.

(2) The removal of pollutants from wastewater by constructed wetlands mainly relies on the synergistic action of microorganisms, plants and substrate units.

(3) In the future, the contribution of each unit of constructed wetlands to pollutant removal can be further quantified, and the toxicological risks of the transformation products after the treatment of complex pollutants and new pollutants can be analyzed with emphasis.

ABSTRACT: Constructed wetlands are complex ecological treatment systems, and their pollutant purification process is the combined effect of physical, chemical and biological processes. However, the types and concentrations of pollutants in wastewater from different sources vary significantly, resulting in complexity and differences in the pollutant removal effect and mechanism of constructed wetlands, which restricts the promotion and application of constructed wetland technology. This review summarizes the research results on the treatment of industrial, agricultural and domestic wastewater from different sources by constructed wetlands. It concludes that the pollutants that can be treated include nutrients, organic matter, heavy metals, emerging pollutants, fluorides, sulfates and chlorides, among which the proportion of research literature related to domestic wastewater is as high as

64.45%. Pollutants are mainly concentrated in nitrogen, phosphorus and organic matter. The purification mechanisms of each functional unit of constructed wetlands are mainly summarized as follows: (1) Microorganisms remove nitrogen and organic matter through degradation and transformation processes. (2) The filler matrix removes phosphorus, heavy metals and fluorides through filtration, adsorption, sedimentation and ion exchange, etc. (3) Plants, while providing a living environment for microorganisms, also participate in the absorption and transformation of pollutants. (4) For petroleum and new pollutants, it relies on the biodegradation of domesticated microorganisms and the assistance of plants in absorption. The removal of sulfates also depends on the synergistic action of sulfur-metabolizing microorganisms such as sulfate-reducing bacteria and sulfur-oxidizing bacteria. In actual wastewater, there often exists complex pollution problems where multiple pollutants such as nitrogen, phosphorus, organic matter, and heavy metals coexist. Traditional constructed wetland systems still lack a systematic understanding of the collaborative removal mechanism of multiple pollutants. In the future, constructed wetland systems suitable for complex pollution scenarios can be constructed to enhance their collaborative purification capacity and anti-shock performance. Although some pollutants such as petroleum hydrocarbons and new pollutants can be effectively removed in wetlands, their transformation pathways and final products during the treatment process are still unclear. It is necessary to strengthen the quantitative detection and toxicological assessment of the transformation products of such pollutants after treatment. In constructed wetlands, microorganisms, plants and fillers play a synergistic role in the process of pollutant removal. However, at present, there is a lack of quantitative and mechanistic understanding of their respective contributions and the coupling mechanisms in multiple media and processes. Future research should focus on the analysis and optimal regulation of multi-component interaction processes to provide theoretical support for the structural design and functional improvement of constructed wetlands. The BRIEF REPORT is available for this paper at http://www.ykcs.ac.cn/en/article/doi/10.15898/j.ykcs.202504290110.

KEY WORDS: constructed wetlands; pollutants; nutritional elements; heavy metal; emerging pollutants; purification mechanism; collaborative purification

BRIEF REPORT

With global population growth, the acceleration of urbanization and the development of industrialization, the problem of water environmental pollution is becoming increasingly serious. Traditional sewage treatment technologies are facing challenges such as high energy consumption, large facility investment and poor adaptability to complex pollutants[1]. As a green and low-carbon technology integrating ecological engineering concepts, constructed wetlands have advantages such as simple construction, economical operation, convenient maintenance and high ecological landscape value[2]. They have received extensive international attention in the field of wastewater resource utilization and sustainable treatment[3]. However, the mechanisms for the coordinated purification of multiple pollutants and the removal of emerging pollutants remain unclear.

This review systematically assesses the main pollutants in wastewater from different sources, summarizes the purification mechanisms of plants, microorganisms and fillers for the main pollutants in wastewater, and explores the removal potential of constructed wetlands for emerging pollutants such as microplastics and antibiotics. It has significant scientific value and practical significance for improving the efficiency of wastewater treatment and the level of ecological environment governance.

1. The main pollutants in different sewage sources

Constructed wetlands, as an eco-friendly sewage treatment technology, are widely applied in the treatment of industrial, agricultural, domestic and other sources of sewage. Overall, constructed wetlands demonstrate high stability and adaptability in removing common pollutants such as nitrogen, phosphorus, and organic matter.

However, in terms of differences, composition, concentration, and degradability of pollutants in wastewater from different sources vary significantly. Industrial wastewater often contains heavy metals[28], inorganic salts and petroleum hydrocarbons, etc., and requires enhanced treatment in combination with specific tolerant plants and functional microorganisms. Agricultural and aquaculture wastewater also contains pollutants such as antibiotics, hormones and pesticide residues[29]. In addition to biodegradable organic matter and nutrients[30], domestic sewage also contains emerging pollutants such as antibiotics, microplastics and personal care products, and the treatment load is relatively stable. Other types of sewage (such as landscape wastewater, stormwater runoff, and low-pollution river water) often present the characteristics of large fluctuations in water quality and complex pollution types, and the wetland structure and operation mode need to be designed in accordance with local conditions.

2. The mechanism of artificial wetlands in purifying major pollutants

Based on the analysis of the treatment of various types of sewage sources by constructed wetlands and in combination with the proportion of literature research, the pollutants they treat are classified into five major categories: nutrients, organic matter, heavy metals, emerging pollutants, and typical anions, and their main purification mechanisms are explored. Nitrogen and phosphorus are the most important nutrient pollutants in constructed wetlands. The removal of nitrogen mainly relies on various biological processes mediated by microorganisms and some chemical pathways. The removal of phosphorus mainly relies on the physical and chemical effects of the substrate, supplemented by plant absorption and microbial assimilation. Both are significantly affected by factors such as substrate type, plant-microbial interaction and operating conditions. The removal of organic matter in constructed wetlands is centered on microbial degradation, with a contribution rate of microbial degradation exceeding 70%[12]. Under different oxygen conditions, functional bacteria can convert organic matter into nutrients, CO_2 and H_2O. Heavy metals, due to their high toxicity, biodegradability and easy accumulation, pose a serious threat to ecosystems and human health[11]. The removal of heavy metals by constructed wetlands mainly relies on plant absorption and substrate adsorption. In sewage, fluoride (F^-), sulfate (SO_4^{2-}) and chloride (Cl^-) are common inorganic anions. The removal of these anions by constructed wetland systems mainly relies on processes such as plant absorption, substrate adsorption, and microbial transformation. In addition to individual pollutants, relevant analyses on the purification mechanisms of complex pollutants in sewage are also conducted.

3. The purification potential of constructed wetlands for emerging pollutants

Constructed wetlands show significant potential in the removal of emerging pollutants. Microbial degradation is its main removal mechanism, contributing 40% to 70% to emerging pollutants such as antibiotics, hormones, pesticides and surfactants, while matrix adsorption can further remove 20% to 40%, of pollutants such as sulfonamide drugs, pesticide residues and microplastics[36]. Plants can assist in removing pollutants such as acetaminophen and caffeine through root absorption and enzymatic conversion[16]. Physical and chemical processes such as photodegradation, complexation, hydrolysis and oxidation-reduction also have a promoting effect under specific conditions. In terms of microplastic removal, the removal rates of polyvinyl chloride, polystyrene, polypropylene and polyethylene in large-scale multi-stage wetlands all exceed 89%. Under the action of water pressure, the microfibers can be entangled with each other to form coils, which is conducive to interception[22]. The removal of emerging pollutants from wastewater by constructed wetlands has become a research hotspot in the past two years, but the specific purification mechanism and the analysis of post-purification products still need further study.

4. Conclusions and prospects

In terms of the types of pollutants treated by constructed wetlands, research focuses mainly on the removal of nitrogen, phosphorus and organic matter, while studies on inorganic salts (such as fluorides, chlorides and sulfates) and petroleum hydrocarbons are relatively scarce. The purification of pollutants by constructed wetlands mainly relies on the combined effect of microbial degradation, filler adsorption and plant absorption. Although constructed wetland technology is widely applied, it still faces the following challenges: Previous studies have focused more on the removal of single pollutants by constructed wetlands, while less attention has been paid to complex pollutants. The types of emerging pollutants and petroleum hydrocarbon pollutants are complex. Although constructed wetlands have a certain purification effect on them, it is still unclear whether the treated products have greater biological toxicity. The fillers, plants and microbial units in constructed wetlands play different roles in purifying wastewater, and the removal processes of different pollutants influence each other. It is necessary to further quantify the contributions of microorganisms, plants and fillers in constructed wetlands to the removal effect and explore their coupling relationship in the multi-media and multi-process action.

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