

厌氧氨氧化组合脱氮工艺研究进展

万家秀¹, 王家骥², 郑平², 胡宝兰², 石振华³

1 兰州资源环境职业技术大学 环境与化工学院, 甘肃 兰州 730000

2 浙江大学 环境与资源学院, 浙江 杭州 310012

3 中石化宁波工程有限公司兰州分公司, 甘肃 兰州 730060

万家秀, 王家骥, 郑平, 胡宝兰, 石振华. 厌氧氨氧化组合脱氮工艺研究进展. 生物工程学报, 2022, 38(4): 1351-1359.

WAN JX, WANG JQ, ZHENG P, HU BL, SHI ZH. Research progress of combined anaerobic ammonium oxidation (ANAMMOX) process for nitrogen removal. Chin J Biotech, 2022, 38(4): 1351-1359.

摘 要: 厌氧氨氧化工艺是一项高效、低耗的生物脱氮工艺, 但受限于底物类型、硝氮积累等问题, 其在主流应用中仍然面临一些挑战。近些年来, 针对上述问题, 厌氧氨氧化组合工艺得到了广泛关注。通过对近年来所开发的厌氧氨氧化组合工艺, 从工艺原理、优缺点、影响因素、工艺拓展性及其在推广应用中存在的关键瓶颈等角度进行探讨, 并结合课题组相关工作, 展望了厌氧氨氧化组合工艺在城市生活污水处理中的发展前景。

关键词: 厌氧氨氧化; 污水处理; 生物脱氮; 组合工艺

Research progress of combined anaerobic ammonium oxidation (ANAMMOX) process for nitrogen removal

WAN Jiaxiu¹, WANG Jiaqi², ZHENG Ping², HU Baolan², SHI Zhenhua³

1 Lanzhou Resources & Environment Voc-Tech University, Lanzhou 730000, Gansu, China

2 College of Environmental and Resource Sciences, Zhejiang University, Hangzhou 310012, Zhejiang, China

3 Sinopec Ningbo Engineering Co., Ltd, Lanzhou Branch, Lanzhou 730060, Gansu, China

Abstract: Anaerobic ammonia oxidation (ANAMMOX) process is an efficient and low-cost biological nitrogen removal process. However, it still faces some challenges in mainstream applications due to the limitation of substrate types and nitrate accumulation. In recent years, the combined process of

Received: June 26, 2021; **Accepted:** September 23, 2021; **Published online:** November 20, 2021

Supported by: National Natural Science Foundation of China (41773074); Open Project of State Key Laboratory of Urban Water Resource and Environment, Harbin Institute of Technology (HCK202001)

Corresponding author: HU Baolan. Tel/Fax: +86-571-88982340; E-mail: blhu@zju.edu.cn

基金项目: 国家自然科学基金 (41773074); 哈尔滨工业大学城市水资源与水环境国家重点实验室开放基金 (HCK202001)

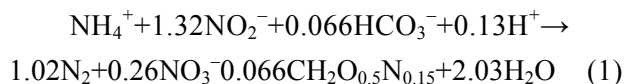
anammox has been widely studied to solve the above problems. In this paper, the combined processes of anammox developed in recent years are reviewed, and discussed from the process principle, advantages and disadvantages, influencing factors, process extensibility and the key bottlenecks existing in the promotion and application, as well as the relevant work of the subject group. Finally, we take an outlook on the development of the combined anaerobic ammonia oxidation process in municipal domestic wastewater treatment.

Keywords: anammox process; wastewater treatment; denitrification process; combined process

1 厌氧氨氧化 (anaerobic ammonia oxidation, anammox) 工艺

水体中输入过量氮素是引起水体富营养化的重要因素,氮素的脱除是污水处理厂的基本目标之一。传统的生物脱氮工艺需要消耗大量的能源和碳源,同时释放大量的温室气体氧化亚氮,这与高效、低耗、清洁的目标相背离。厌氧条件下,厌氧氨氧化菌 (anaerobic ammonia oxidizing bacteria, AnAOB) 以 $\text{NH}_4^+\text{-N}$ 为电子供体,以 $\text{NO}_2^-\text{-N}$ 为电子受体,最终将氮素转化为 N_2 。与传统脱氮工艺比较,anammox 工艺是一种不需要补充有机碳源、也不需要曝气的自养脱氮工艺。

但是城市生活污水中氮的主要形态是有机氮、 $\text{NH}_4^+\text{-N}$ 及少量 $\text{NO}_2^-\text{-N}$ 和 $\text{NO}_3^-\text{-N}$, $\text{NO}_2^-\text{-N}$ 浓度不能满足 anammox 的需求。此外,由于 AnAOB 在合成代谢过程中会产生硝酸盐 (式 1),这导致 anammox 工艺的理论脱氮效率最高仅能达到 88%。底物类型局限性及其硝氮积累问题制约了 anammox 工艺的广泛应用,针对上述问题,围绕 anammox 的组合工艺应运而生,有效解决了这两大难题。



2 厌氧氨氧化组合脱氮工艺

围绕上述两大问题,研究者通过工艺组合的方式将 anammox 工艺进一步完善补充并进行拓展性研究,表 1 为常见厌氧氨氧化组合工艺。其中包括已经得到广泛研究和应用的部分短程硝化-厌氧氨氧化 (partial nitrification anammox, PNA) 工艺,该组合工艺有效解决了 anammox 的底物问题;另一方面,anammox 还与短程反硝化、甲烷型反硝化工艺进行组合,这些组合工艺有效解决了 anammox 硝氮积累的问题。以下就几种常见的厌氧氨氧化组合工艺进行综述。

2.1 部分短程硝化-厌氧氨氧化 (partial nitrification anammox, PNA)

1998 年荷兰 Jetten 团队^[1]首先尝试了 PNA 工艺研究,2002 年荷兰鹿特丹的污水厂进行规模化应用^[2]。PNA 工艺可节约近 60% 的供氧量和 100% 的外部碳源,且污泥产量减少了 80%^[3]。PNA 工艺适用于中温条件下高浓度氨氮废水如厌氧消化上清液的处理,因此被认为是处理侧流废水的成熟工艺。目前 PNA 工艺在较高温度条件下高氨氮工业废水处理中也得到了应用^[4]。2012 年 Shen 在味精废水 PNA 处理工艺中针对 anammox 的启动,使用实际污水培养富集 AnAOB,证实颗粒污泥能显著提高 anammox 在反应器的生物量浓度,为 PNA 工艺的工程应

用提供了新思路^[5]。然而 PNA 工艺在主流废水处理工程应用时, 仍然存在一些有待解决的问题^[6]。低温不仅影响功能微生物的生长和代谢, 而且当温度小于 20 °C 时亚硝酸盐氧化菌 (nitrite-oxidizing bacteria, NOB) 的生长速率开始超过氨氧化细菌 (ammonia-oxidizing bacteria, AOB), 且温度越低差异越大^[7], 因此低温条件下抑制 NOB 十分困难。Qiu 等^[8]总结了温度在 25 °C 左右时氮去除率 (nitrogen removal efficiency, NRE) 可以达 51%–81%, 然而当温度小于 15 °C 时, NRE 甚至下降至 25% 且运行不稳定、出水水质差。因此低温运行 PNA 工艺时, NOB 的抑制和 NO_2^- -N 的稳定供给均是其应用于主流废水处理的挑战。目前通常通过调控溶解氧 (dissolved oxygen, DO)、污泥停留时间及氨氮或多种策略相结合的方式抑制 NOB^[9-10]。

PNA 工艺仅能解除 anammox 工艺底物类型的限制, 但随着愈发严格的废水排放标准, PNA 工艺仍存在出水总氮不达标的问题。针对这一问题, 2009 年 Chen 等^[11]提出将反硝化工艺与 PNA 进行耦合, 产生了同时部分硝化-厌氧氨氧化-反硝化工艺 (simultaneous nitrification anammox and denitrification, SNAD)。其作用机理是: AOB 将 NH_4^+ -N 部分氧化成 NO_2^- -N, 在 AnAOB 作用下将 NH_4^+ -N 和 NO_2^- -N 转化为 N_2 和 NO_3^- -N, 再由反硝化菌以有机物为电子供体将 NO_3^- -N 转化为 NO_2^- -N, 在充足的电子供体条件下, 反硝化最终产物仅为 N_2 。该工艺不仅具备 PNA 工艺的优点, 而且由于在一个反应器中进行, 占地面积小, 基建费用低。目前 SNAD 适用于低 C/N、氨氮废水处理, 如在养殖废水消化液、垃圾渗滤液及光电工业废水中均有较好的处理效果^[12]。有学者进行了深入研究, Du 等^[13]采用固定生物膜活性污泥反应器 (integrated fixed-biofilm activated sludge, IFAS) 运行 SNAD

工艺处理高氨氮城市生活污水, NRE 达 92.8%, 同时化学需氧量 (chemical oxygen demand, COD) 去除率为 78.8%。Xu 等^[14]采用厌氧水解酸化耦合 SNAD 强化生物除磷, 采用升流式厌氧活性污泥 (up-flow anaerobic sludge blanket, UASB)+IFAS 反应器, 总氮 (total nitrogen, TN)、总磷 (total phosphorus, TP) 和 COD 去除率分别达到 93.70%、97.71% 和 79.93%。但需要指出的是, 体系中过于复杂的微生物群落结构及种间关系, 会给工艺协调运作、长期稳定运行带来挑战。

2.2 短程反硝化-厌氧氨氧化 (partial denitrification anammox, PDA)

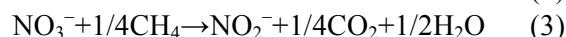
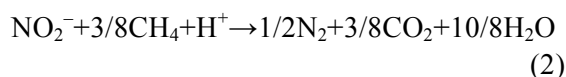
在 SNAD 工艺中 DO 控制十分关键, DO 的过量会导致 NO_2^- -N 被氧化为 NO_3^- -N, 因此, 如果在厌氧环境中能直接生成 NO_2^- -N, 不仅经济而且更加稳定。2006 年 Sumino 等^[15]提出 PDA 工艺, 利用短程反硝化工艺将反硝化限定在 NO_3^- -N 转化 NO_2^- -N 阶段并组合 anammox 工艺, 不仅具有 SNAD 的优势又简化了反应过程, 全程无需曝气。研究表明, 在交替的厌氧缺氧环境下, 缺乏 NO_2^- -N 还原酶的短程反硝化菌占主导地位, 以有机质作为电子供体时, NO_3^- -N 转化 NO_2^- -N 的比例可达到 80% 以上^[16]。据报道以生活污水中有机质为电子供体, 短程反硝化工艺 NO_2^- -N 转化率达 88.0%^[17], 且反硝化菌更倾向于以 NO_3^- -N 为电子受体^[18], 即 PDA 工艺的亚硝酸盐产生比 PNA 更稳定。此外, 有研究提出 PDA 在处理城市污水方面, 可降低 50% 的曝气量和 80% 的有机物投加量^[19]。相较于 PNA 工艺, PDA 工艺首先不再受 NOB 影响, 其次 PDA 理论脱氮率高达 100%, 并且有效降低了温室气体 N_2O 的排放, 此外 PDA 工艺对温度的要求也没有 PNA 高, 因此也可以在高纬度地区应用^[20]。然而适宜的 C/N 是实现短程反硝化的关键^[21]。当 C/N 为 4 时, AnAOB 受到

抑制,当 C/N 为 2 时,AnAOB 和反硝化菌可以很好地协同工作^[22]。马斌等^[23]采用序批式反应器 (sequencing batch reactor, SBR),进水 COD/TN 保持为 2.28, TN 去除率高达 92.6%。有研究者通过厌氧氨氧化载体与分段式厌氧好氧系统结合的反应器运行 PDA 工艺,处理 COD/TIN (总无机氮) 在 2.5 左右的生活污水,脱氮效率达到了 77.8%±4.3%^[24]。Ma 等^[25]使用生物膜反应器处理 C/N 为 2.6、TN 浓度 60.5 mg/L 的污水,最终 NRE 达 80%±4%。可见 PDA 工艺能够在低 C/N 的废水处理中发挥作用。

2.3 反硝化型甲烷氧化-厌氧氨氧化工艺

依赖 NO_3^- -N/ NO_2^- -N 的反硝化型厌氧甲烷氧化 (denitrifying anaerobic methane oxidation, DAMO) 工艺具有同时去除 NO_3^- -N/ NO_2^- -N 和 CH_4 的能力,最终产物仅为 N_2 和 CO_2 ,是一项潜在的绿色生物脱氮技术^[26]。2011 年 Zhu 等^[27]证明了 DAMO 和 anammox 组合工艺是可行的,当 NO_2^- -N 和 NH_4^+ -N 比例大于 1.32 时,可以同时脱氮和甲烷。Ettwig 等^[28]证实了 DAMO 细菌能将 NO_2^- -N 还原为一氧化氮 (NO) 然后转化为 N_2 和 O_2 ,最终利用 O_2 将 CH_4 氧化为 CO_2 (式 2)。Haroon 等^[29]随后证实了 DAMO 古菌通过逆向产甲烷进行甲烷氧化,并将甲烷提供的电子用于 NO_3^- -N 还原至 NO_2^- -N (式 3)。因为 DAMO 古菌可将 AnAOB 所产生的硝态氮还原为 NO_2^- -N,另一方面由于 DAMO 细菌的存在,可以对 NO_2^- -N 进行消耗,因此 NH_4^+ -N、 NO_2^- -N 并不需要严格按照 anammox 化学计量比添加,一定程度上降低了底物类型限制。然而 DAMO 功能菌缓慢的生长速度是该组合工艺的一个重要限制因子。笔者课题组通过矿物质营养浓度改进的培养基和 pH 的控制提高了 DAMO 工艺性能^[30],还研究了生长因子、微量金属元素对 DAMO 微生物活性的影响,其中

Fe(II) 浓度 20 $\mu\text{mol/L}$ 时对其活性有促进作用^[31-32]。此外本课题组还通过优化反应器构型强化了 CH_4 传质,提出通过膜组件等改变生物聚集形式保留生物质^[33]。 CH_4 的传质效率也是这一组合工艺的重要限制因子。目前,随着膜材料的发展,膜生物膜反应器 (membrane biofilm reactor, MBfR) 中无气泡透气纤维膜显著提高了 CH_4 传质,同时膜作为微生物附着的载体保证微生物的持留量。



有研究者发现 MBfR 显著提高了 DAMO 古菌和 AnAOB 的活性,脱氮速率达到 6.1 $\text{kg}/(\text{m}^3 \cdot \text{d})$ ^[34]。Cai 等^[35]将 AnAOB 和 DAMO 微生物进行组合,选用 MBfR, NO_2^- -N 和 NH_4^+ -N 的脱氮速率分别达 330 $\text{mg}/(\text{L} \cdot \text{d})$ 、268 $\text{mg}/(\text{L} \cdot \text{d})$ 。Xie 等^[36]以 MBfR 为基础耦合厌氧氨氧化和 DAMO 工艺,选用了可渗透性中空纤维膜输送甲烷,脱氮速率为 280 $\text{mg}/(\text{m}^3 \cdot \text{d})$,通过化学计量衡算得到 AnAOB 和 DAMO 菌对 NO_2^- -N 去除的贡献分别为 90% 和 10%,此外,当 NO_2^- -N 与 NH_4^+ -N 比例在 1.22–1.55 范围内变化时, NH_4^+ -N 和 NO_2^- -N 的去除率均能达到 96%。以上案例表明反硝化型甲烷氧化-厌氧氨氧化工艺耦合在污水脱氮方面具备较强的潜力。Peng 等^[37]选用两个不同运行条件的膜颗粒污泥反应器进行建模,提出较短的水力停留时间如在 4.8 h,较小的颗粒尺寸以及较低的 NO_2^- -N/ NH_4^+ -N,可以降低反硝化型甲烷氧化-厌氧氨氧化工艺运行成本。

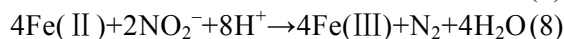
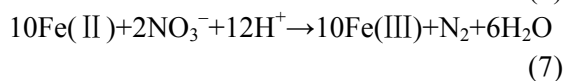
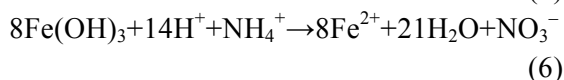
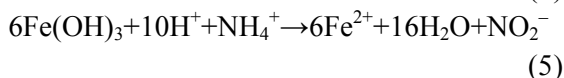
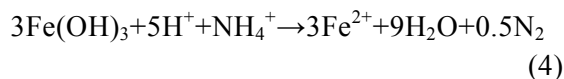
2.4 厌氧氨氧化-新型反硝化工艺耦合

2006 年 Mulder 等^[38]提出由硫化物驱动的部分反硝化和厌氧氨氧化工艺理念 (sulfide-driven partial denitrification and anammox, SPDA)。这是利用几种硫氧化细菌 (sulfur oxidizing bacteria,

SOB) 通过氧化硫化物, 将 NO_3^- -N 还原为 NO_2^- -N, 为 AnAOB 提供可利用基质。由于 SOB 具有较低的生物量产量 ((0.15–0.57) g 生物量/g NO_3^- -N) 和生长速率 (0.04–0.27/h)^[39], 此过程不会与 AnAOB 产生竞争。SOB 以硫单质 (S) 和 $\text{S}_2\text{O}_3^{2-}$ 作为电子供体, 为 AnAOB 提供稳定的 NO_2^- -N, 并且可以降低 AnAOB 受到额外有机质的抑制作用^[40]。虽然硫化物对 AnAOB 的活性有抑制作用, 但与 SOB 共同合作为 AnAOB 创造了低毒环境。Li 等^[41]和 Chen 等^[42]都成功启动了以硫单质或硫代硫酸盐为电子供体的 SPDA 工艺。Qin 等^[43]研究 SPDA 工艺时发现硫化物在体系中被完全氧化为硫酸盐。Deng 等^[44]选用 UASB 反应器运行 SPDA 工艺同时脱除硫化物和氮, 氮负荷保持在 0.36 kg/(m³·d), 最终 NRE 达 79.6%±3.0%。由此可见 SPDA 在污水处理中具有可行性。

2006 年 Sawayama^[45]证实在铁铵氧化 (iron reducing ammonium oxidation, Feammox) 过程中, Fe(III) 还原菌可以利用 Fe(III) 将铵离子氧化为 NO_2^- 、 NO_3^- 、 N_2 。这一概念之后被引入到污水处理中, 2018 年有报道称在厌氧消化池中添加三价铁氧化物, NH_4^+ 能显著降低, 分析可能是 Feammox 在厌氧条件下利用 NH_4^+ -N 还原 Fe(III), 而且铁还原菌 (iron reducing bacteria, IRB) 起到关键作用^[46]。其反应过程可由方程式 4–6 说明, 酸性条件下有利于铁还原^[47]。而硝酸盐依赖性铁氧化 (nitrate-dependent iron oxidation, NDFO) 可以通过 NO_3^- 氧化 Fe(II) 为 Fe(III) 并且产生 N_2 (式 7), 同时存在非生物化学反硝化将 Fe(II) 和 NO_2^- 转化为 N_2 和 Fe(III) (式 8), 那么将 Feammox、NDFO 和非生物化学反硝化耦合在一起, Fe(II) 和 Fe(III) 可以循环使用, 在没有 AnAOB 的情况下也可以实现厌氧氨氧化^[48]。也可将 Feammox、NDFO 与

anammox 工艺结合, 利用三价铁将氨氮氧化至亚硝氮, 解决 anammox 底物类型限制问题, 同时可以利用二价铁对 anammox 积累的确态氮进行还原, 解决硝态氮积累问题。



3 展望

厌氧氨氧化工艺虽然已经是一项成熟的技术, 但是在主流应用中仍然面临一些挑战。例如, 季节性温度变化对厌氧氨氧化细菌生长、活性提出了更高的要求, 越来越严格的氮排放要求则需要厌氧氨氧化工艺向深度脱氮方向发展。

通过各种手段对 anammox 工艺功能菌群活性的强化, 在水处理行业仍是研究的热点。目前有使用外加电场和磁场对 AnAOB 活性进行强化, 也有添加化学物质进行 AnAOB 的强化操作^[49]。以上对 anammox 均有良好的促进作用。此外, 有研究提出 anammox 的生理特性受到群体感应的控制, 而且 N-酰基高丝氨酸内脂类信号分子对 anammox 工艺有正调控作用, 那么, 通过外源信号分子的强化和工程细菌的合成可作为对 anammox 强化的手段, 提高可应用性^[50]。本课题组通过微量金属浓度调控强化 anammox 工艺时, 通过强化细胞间电子传递可有效提高 anammox 工艺性能, 发现添加铁载体能提高 anammox 工艺 50% 左右的氮去除速率 (数据未发表)。此外, 本课题组通过优化反应器

表 1 常见厌氧氨氧化组合工艺

Table 1 Combined anaerobic ammonia oxidation processes

Combination process	Main functional microorganism	Advantages	Disadvantages	Total nitrogen removal rate	References
PNA	<i>Candidatus Kuenenia</i> <i>Candidatus Brocadia</i> , <i>Nitrosomonas</i> , <i>Nitrospira</i>	Low operating cost, less N ₂ O emission, stable performance	Not suitable for low temperature environment	46%–95%	[3, 51-53]
SNAD	<i>Candidatus Kuenenia</i> , <i>Candidatus Brocadia</i> , <i>Pseudomonas</i> , <i>Flavobacterium</i> , <i>Bdellovibrio</i> , <i>Thauera</i> , <i>Denitratisoma</i> , <i>Rhodobacteraceae</i>	High efficiency, low consumption, small footprint, low capital construction cost	Slow start, unstable operation, difficult to control	77.9%–92.8%	[13-14, 54]
PDA	<i>Thauera</i> , <i>Alishewanella</i> , <i>Ornatilinea</i> , <i>Comamonas</i> , <i>Candidatus Kuenenia</i>	Low cost, high total nitrogen removal efficiency, strong impact load resistance	Organic matter inhibits autotrophic bacteria	84.8%–97.8%	[19, 55-56]
DAMO-anammox	<i>Candidatus Kuenenia</i> , <i>Candidatus Brocadia</i> , <i>Candidatus M. oxyfera</i> , <i>Candidatus M. nitroreducens</i>	The total nitrogen removal efficiency is high	Slow startup and low CH ₄ mass transfer efficiency	90%–99.9%	[35-36, 57]

构型和操作, 实现了 anammox 工艺对低浓度含氮废水 (<10 mg/L) 的高效脱氮^[58-59], 有望实现 anammox 工艺在主流废水中的应用。

然而底物类型限制与硝态氮积累问题无法通过强化厌氧氨氧化工艺完全消除, 因此, 厌氧氨氧化组合工艺为污水处理带了新的机遇, 更多工艺拓展性组合, 可成为探索我国可持续发展污水处理技术的载体。Wu 等^[60]用厌氧折流反应器 (anaerobic baffled reactor, ABR)+全混合厌氧反应器 (completely mixed anaerobic reaction, CSTR) 开发了一种反硝化除磷 (denitrifying phosphorus removal, DPR) 耦合 PDA 的节能工艺, TIN 和总无机磷去除率高达 97.57%和 95.66%。Du 等^[61]使用两段式硝化耦合 PDA 工艺, NRE 达到 93.7%。Ji 等^[62]使用强化部分反硝化+厌氧氨氧化+原位发酵 (synergistic partial-denitrification, anammox, and *in situ* fermentation, SPDAF) 工艺处理加入硝酸盐的实际生活污水, 在没有外部碳源和曝气

的条件下, NRE 可达 93.1%。由此可见在实践中如何通过工艺拓展组合, 来相互弥补缺陷及进行共同协作, 是污水处理技术可持续发展的未来研究方向。但需要注意的是, 组合工艺带来了更加复杂的微生物群落组成与工艺参数, 如何避免 AnAOB 竞争劣势, 如何实现组合工艺的长期稳定运行仍具有挑战性, 如果能够通过构建细胞间通讯和稳定可控的 anammox 组合工艺微生物群落系统, 有望实现 anammox 组合工艺运行设计目标, 达到长期稳定运行。

REFERENCES

- [1] Jetten MSM, Strous M, van de Pas-Schoonen KT, et al. The anaerobic oxidation of ammonium. FEMS Microbiol Rev, 1998, 22(5): 421-437.
- [2] Van Der Star WRL, Abma WR, Blommers D, et al. Startup of reactors for anoxic ammonium oxidation: experiences from the first full-scale anammox reactor in Rotterdam. Water Res, 2007, 41(18): 4149-4163.
- [3] Chen H, Wang H, Chen R, et al. Unveiling performance stability and its recovery mechanisms of

- one-stage partial nitrification-anammox process with airlift enhanced micro-granules. *Bioresour Technol*, 2021, 330: 124961.
- [4] Tan H, Wang YY, Tang X, et al. Quantitative determination of cavitation formation and sludge flotation in Anammox granules by using a new diffusion-reaction integrated mathematical model. *Water Res*, 2020, 174: 115632.
- [5] Shen LD, Hu AH, Jin RC, et al. Enrichment of anammox bacteria from three sludge sources for the startup of monosodium glutamate industrial wastewater treatment system. *J Hazard Mater*, 2012, 199/200: 193-199.
- [6] Tomaszewski M, Cema G, Ziemińska-Buczyńska A. Influence of temperature and pH on the anammox process: a review and meta-analysis. *Chemosphere*, 2017, 182: 203-214.
- [7] Zhu GB, Peng YZ, Li BK, et al. Biological removal of nitrogen from wastewater. *Reviews of Environmental Contamination and Toxicology*. New York, NY: Springer New York, 2008: 159-195.
- [8] Qiu SK, Li ZB, Hu YS, et al. What's the best way to achieve successful mainstream partial nitrification-anammox application? *Crit Rev Environ Sci Technol*, 2021, 51(10): 1045-1077.
- [9] Pellicer-Nàcher C, Sun SP, Lackner S, et al. Sequential aeration of membrane-aerated biofilm reactors for high-rate autotrophic nitrogen removal: experimental demonstration. *Environ Sci Technol*, 2010, 44(19): 7628-7634.
- [10] Laurenzi M, Falås P, Robin O, et al. Mainstream partial nitrification and anammox: long-term process stability and effluent quality at low temperatures. *Water Res*, 2016, 101: 628-639.
- [11] Chen H, Liu S, Yang F, et al. The development of simultaneous partial nitrification, ANAMMOX and denitrification (SNAD) process in a single reactor for nitrogen removal. *Bioresour Technol*, 2009, 100(4): 1548-1554.
- [12] 林志英. 基于 SBBR 的 SNAD 工艺的启动和运行性能[D]. 西安: 长安大学, 2019.
- Lin ZY. Start-up and operational performance of SNAD process based on SBBR[D]. Xi'an: Changan University, 2019 (in Chinese).
- [13] Du YQ, Yu DS, Wang XX, et al. Achieving simultaneous nitrification, anammox and denitrification (SNAD) in an integrated fixed-biofilm activated sludge (IFAS) reactor: quickly culturing self-generated anammox bacteria. *Sci Total Environ*, 2021, 768: 144446.
- [14] Xu X, Ma S, Jiang H, et al. Start-up of the anaerobic hydrolysis acidification (ANHA)-simultaneous partial nitrification, anammox and denitrification (SNAD)/enhanced biological phosphorus removal (EBPR) process for simultaneous nitrogen and phosphorus removal for domestic sewage treatment. *Chemosphere*, 2021, 275: 130094.
- [15] Sumino T, Isaka K, Ikuta H, et al. Nitrogen removal from wastewater using simultaneous nitrate reduction and anaerobic ammonium oxidation in single reactor. *J Biosci Bioeng*, 2006, 102(4): 346-351.
- [16] Cao S, Wang S, Peng Y, et al. Achieving partial denitrification with sludge fermentation liquid as carbon source: the effect of seeding sludge. *Bioresour Technol*, 2013, 149: 570-574.
- [17] Shi L, Du R, Peng Y. Achieving partial denitrification using carbon sources in domestic wastewater with waste-activated sludge as inoculum. *Bioresour Technol*, 2019, 283: 18-27.
- [18] Du R, Peng Y, Cao S, et al. Mechanisms and microbial structure of partial denitrification with high nitrite accumulation. *Appl Microbiol Biotechnol*, 2016, 100(4): 2011-2021.
- [19] Jiang H, Wang Z, Ren S, et al. Enrichment and retention of key functional bacteria of partial denitrification-Anammox (PD/A) process via cell immobilization: a novel strategy for fast PD/A application. *Bioresour Technol*, 2021, 326: 124744.
- [20] Wang ZB, Liu XL, Bu CN, et al. Microbial diversity reveals the partial denitrification-anammox process serves as a new pathway in the first mainstream anammox plant. *Sci Total Environ*, 2021, 764: 142917.
- [21] Ge SJ, Peng YZ, Wang SY, et al. Nitrite accumulation under constant temperature in anoxic denitrification process: the effects of carbon sources and COD/NO₃⁻-N. *Bioresour Technol*, 2012, 114: 137-143.
- [22] Du R, Peng Y, Cao S, et al. Advanced nitrogen removal with simultaneous Anammox and denitrification in sequencing batch reactor. *Bioresour Technol*, 2014, 162: 316-322.
- [23] 马斌, 许鑫鑫, 高茂鸿, 等. 基于短程反硝化厌氧氨氧化的低碳源城市污水深度脱氮特性. *环境科学*, 2020, 41(3): 1377-1383.
- Ma B, Xu XX, Gao MH, et al. Advanced Nitrogen removal characteristics of low carbon source municipal wastewater treatment via partial-denitrification coupled

- with ANAMMOX. *Environ Sci*, 2020, 41(3): 1377-1383 (in Chinese).
- [24] Gao RT, Peng YZ, Li JW, et al. Nitrogen removal from low COD/TIN real municipal sewage by coupling partial denitrification with anammox in mainstream. *Chem. Eng. J*, 2021, 410: 128221.
- [25] Ma B, Qian W, Yuan C, et al. Achieving mainstream nitrogen removal through coupling anammox with denitrification. *Environ Sci Technol*, 2017, 51(15): 8405-8413.
- [26] Raghoebarsing AA, Pol A, Van De Pas-Schoonen KT, et al. A microbial consortium couples anaerobic methane oxidation to denitrification. *Nature*, 2006, 440(7086): 918-921.
- [27] Zhu BL, Sánchez J, van Alen TA, et al. Combined anaerobic ammonium and methane oxidation for nitrogen and methane removal. *Biochem Soc Trans*, 2011, 39(6): 1822-1825.
- [28] Ettwig KF, Butler MK, Le Paslier D, et al. Nitrite-driven anaerobic methane oxidation by oxygenic bacteria. *Nature*, 2010, 464(7288): 543-548.
- [29] Haroon MF, Hu SH, Shi Y, et al. Anaerobic oxidation of methane coupled to nitrate reduction in a novel archaeal lineage. *Nature*, 2013, 500(7464): 567-570.
- [30] He ZF, Geng S, Wang LQ, et al. Improvement of mineral nutrient concentrations and pH control for the nitrite-dependent anaerobic methane oxidation process. *Sep Purif Technol*, 2016, 162: 148-153.
- [31] Wang JQ, Hua ML, Li YF, et al. Achieving high nitrogen removal efficiency by optimizing nitrite-dependent anaerobic methane oxidation process with growth factors. *Water Res*, 2019, 161: 35-42.
- [32] He Z, Geng S, Pan Y, et al. Improvement of the trace metal composition of medium for nitrite-dependent anaerobic methane oxidation bacteria: iron (II) and copper (II) make a difference. *Water Res*, 2015, 85: 235-243.
- [33] Hu B, He Z, Geng S, et al. Cultivation of nitrite-dependent anaerobic methane-oxidizing bacteria: impact of reactor configuration. *Appl Microbiol Biotechnol*, 2014, 98(18): 7983-7991.
- [34] Nie WB, Xie GJ, Ding J, et al. Operation strategies of n-DAMO and Anammox process based on microbial interactions for high rate nitrogen removal from landfill leachate. *Environ Int*, 2020, 139: 105596.
- [35] Cai C, Hu S, Guo J, et al. Nitrate reduction by denitrifying anaerobic methane oxidizing microorganisms can reach a practically useful rate. *Water Res*, 2015, 87: 211-217.
- [36] Xie GJ, Liu T, Cai C, et al. Achieving high-level nitrogen removal in mainstream by coupling anammox with denitrifying anaerobic methane oxidation in a membrane biofilm reactor. *Water Res*, 2018, 131: 196-204.
- [37] Peng L, Fan SQ, Xie GJ, et al. Modeling nitrate/nitrite dependent anaerobic methane oxidation and Anammox process in a membrane granular sludge reactor. *Chem Eng J*, 2021, 403: 125822.
- [38] Mulder A. Biological denitrification of wastewater comprises a nitrifying reactor and a denitrifying reactor, where an ammonium ion containing wastewater stream is partly fed to the denitrifying reactor and partly to the nitrifying reactor: WO, 022539. 2006-05-02.
- [39] Cui YX, Biswal BK, Guo G, et al. Biological nitrogen removal from wastewater using sulphur-driven autotrophic denitrification. *Appl Microbiol Biotechnol*, 2019, 103(15): 6023-6039.
- [40] Chen FM, Li X, Gu CW, et al. Selectivity control of nitrite and nitrate with the reaction of S^0 and achieved nitrite accumulation in the sulfur autotrophic denitrification process. *Bioresour Technol*, 2018, 266: 211-219.
- [41] Li X, Li X, Yuan Y, et al. Simultaneous removal of ammonia and nitrate by coupled S^0 -driven autotrophic denitrification and Anammox process in fluorine-containing semiconductor wastewater. *Sci Total Environ*, 2019, 661: 235-242.
- [42] Chen FM, Li X, Yuan Y, et al. An efficient way to enhance the total nitrogen removal efficiency of the Anammox process by S^0 -based short-cut autotrophic denitrification. *J Environ Sci*, 2019, 81: 214-224.
- [43] Qin Y, Wu C, Chen B, et al. Short term performance and microbial community of a sulfide-based denitrification and Anammox coupling system at different N/S ratios. *Bioresour Technol*, 2019, 294: 122130.
- [44] Deng YF, Wu D, Huang H, et al. Exploration and verification of the feasibility of sulfide-driven partial denitrification coupled with anammox for wastewater treatment. *Water Res*, 2021, 193: 116905.
- [45] Sawayama S. Possibility of anoxic ferric ammonium oxidation. *J Biosci Bioeng*, 2006, 101(1): 70-72.
- [46] Yang YF, Jin Z, Quan X, et al. Transformation of nitrogen and iron species during nitrogen removal from wastewater via feammox by adding ferrihydrite. *ACS Sustain Chem Eng*, 2018, 6(11): 14394-14402.

- [47] Zhou GW, Yang XR, Li H, et al. Electron shuttles enhance anaerobic ammonium oxidation coupled to iron(III) reduction. *Environ Sci Technol*, 2016, 50(17): 9298-9307.
- [48] Yang YF, Xiao CC, Yu Q, et al. Using Fe(II)/Fe(III) as catalyst to drive a novel anammox process with no need of anammox bacteria. *Water Res*, 2021, 189: 116626.
- [49] 刘朋朋. 低频电磁场强化短程硝化和厌氧氨氧化工艺性能与机理研究[D]. 济南: 山东大学, 2020.
Liu PP. The study on the performance and mechanism of the process of partial nitrification and anammox enhanced by low frequency electromagnetic field[D]. Jinan: Shandong University, 2020 (in Chinese).
- [50] Zhang Q, Fan NS, Fu JJ, et al. Role and application of quorum sensing in anaerobic ammonium oxidation (anammox) process: a review. *Crit Rev Environ Sci Technol*, 2021, 51(6): 626-648.
- [51] Akaboci TRV, Gich F, Rusalleda M, et al. Assessment of operational conditions towards mainstream partial nitrification-anammox stability at moderate to low temperature: reactor performance and bacterial community. *Chem Eng J*, 2018, 350: 192-200.
- [52] Lotti T, Kleerebezem R, Hu Z, et al. Simultaneous partial nitrification and anammox at low temperature with granular sludge. *Water Res*, 2014, 66: 111-121.
- [53] Gao DW, Huang XL, Tao Y, et al. Sewage treatment by an UAFB-EGSB biosystem with energy recovery and autotrophic nitrogen removal under different temperatures. *Bioresour Technol*, 2015, 181: 26-31.
- [54] 张凯. MBR-SNAD 生物脱氮工艺特性与优化控制研究[D]. 邯郸: 河北工程大学, 2018.
Zhang K. Study on the characterizations and regulation optimizations for biological nitrogen removal MBR-SNAD process[D]. Handan: Hebei University of Engineering, 2018 (in Chinese).
- [55] Cao SB, Du R, Niu M, et al. Integrated anaerobic ammonium oxidization with partial denitrification process for advanced nitrogen removal from high-strength wastewater. *Bioresour Technol*, 2016, 221: 37-46.
- [56] Wang Z, Zhang L, Zhang FZ, et al. Enhanced nitrogen removal from nitrate-rich mature leachate via partial denitrification (PD)-anammox under real-time control. *Bioresour Technol*, 2019, 289: 121615.
- [57] ie GJ, Cai C, Hu SH, et al. Complete nitrogen removal from synthetic anaerobic sludge digestion liquor through integrating anammox and denitrifying anaerobic methane oxidation in a membrane biofilm reactor. *Environ Sci Technol*, 2017, 51(2): 819-827.
- [58] Li Y, Yu T, Kang D, et al. Sources of anammox granular sludge and their sustainability in treating low-strength wastewater. *Chemosphere*, 2019, 226: 229-237.
- [59] Li YY, Zhang M, Xu DD, et al. Potential of anammox process towards high-efficient nitrogen removal in wastewater treatment: theoretical analysis and practical case with a SBR. *Chemosphere*, 2021, 281: 130729.
- [60] Wu P, Zhang X, Wang Y, et al. Development of a novel denitrifying phosphorus removal and partial denitrification anammox (DPR+PDA) process for advanced nitrogen and phosphorus removal from domestic and nitrate wastewaters. *Bioresour Technol*, 2021, 327: 124795.
- [61] Du R, Cao S, Zhang H, et al. Flexible nitrite supply alternative for mainstream anammox: advances in enhancing process stability. *Environ Sci Technol*, 2020, 54(10): 6353-6364.
- [62] Ji J, Peng Y, Wang B, et al. Synergistic partial-denitrification, anammox, and *in situ* fermentation (SPDAF) process for advanced nitrogen removal from domestic and nitrate-containing wastewater. *Environ Sci Technol*, 2020, 54(6): 3702-3713.

(本文责编 郝丽芳)