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Review

Path to zero emission of nitrous oxide in sewage treatment: is nitrification controllable or avoidable?

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Amid growing concerns over climate change, the need to reduce nitrous oxide (N_2O) emissions from sewage treatment is more urgent than ever. Sewage treatment plants are significant sources of N_2O due to its production as an intermediate in nitrification and its release into the air during aeration. Effective management of the nitrification process is therefore vital for controlling or eliminating these emissions. Despite substantial efforts to quantify and understand N_2O emissions from sewage treatment, success in reducing them has been limited. This review discusses and proposes promising solutions for reducing N_2O emissions in sewage treatment, evaluates the potential of various strategies, and identifies ways to accelerate their development and implementation.

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Introduction

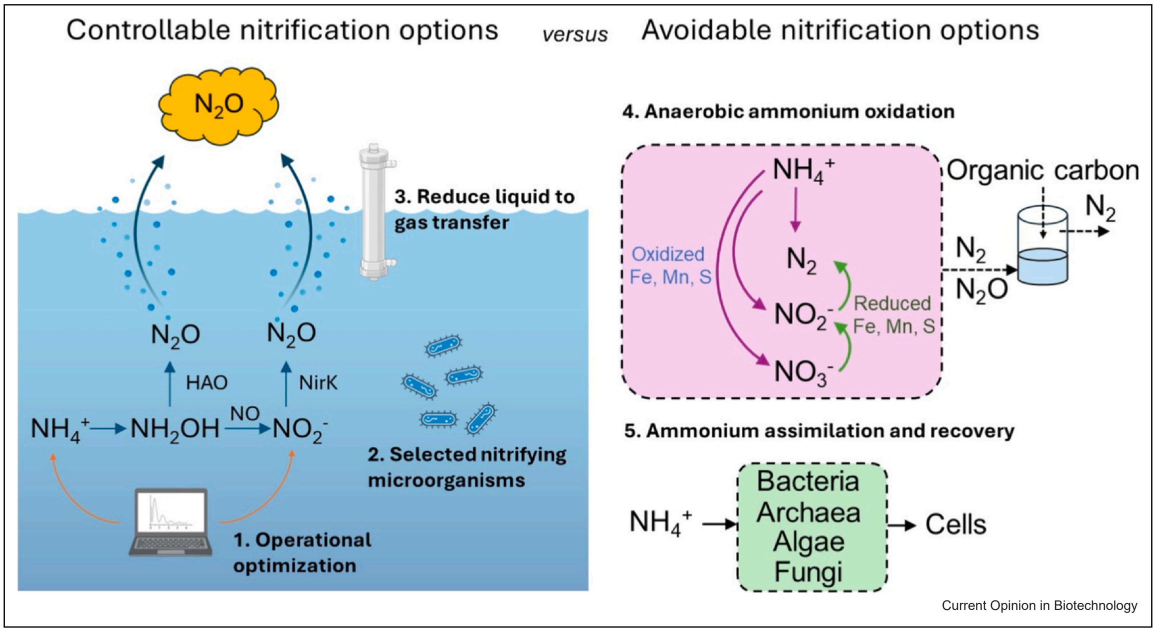
Nitrous oxide (N_2O) is a potent greenhouse gas (GHG) that has a global warming potential estimated to be approximately 273 times greater than carbon dioxide over a 100-year time frame [1]. N_2O emissions significantly contribute to climate change, accounting for approximately 6% of anthropogenic GHG emissions worldwide [1]. This underscores the importance and urgency of reducing N_2O emissions to combat climate change effectively. As the sixth-largest emitter, the wastewater sector contributes 3% of total N_2O emissions (Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021). Setting path to zero emission of N_2O is therefore critically needed for the wastewater industry.

Nitrification, the biological oxidation of ammonium (NH_4^+) to nitrite (NO_2^-) and subsequently to nitrate (NO_3^-), is a central process in global nitrogen cycling. For decades, sewage treatment plants (STPs) worldwide have employed the nitrification process to remove NH_4^+ from sewage. When coupled with subsequent denitrification — the biological reduction of NO_3^- to dinitrogen gas (N_2) — this process effectively safeguards natural water bodies from eutrophication due to treated water discharge.

However, the nitrification unit presents a hotspot for N_2O emissions, with an Intergovernmental Panel on Climate Change (IPCC)-estimated average emission level of 1.6% of total nitrogen removed in global STPs, although lower emission levels have been observed in cases with reduced influent nitrogen loads [1]. Microbial nitrification inherently produces N_2O as an intermediate by incorporating two common pathways of hydroxylamine oxidation and nitrifier denitrification [2,3]. Furthermore, nitrification occurs with aeration, providing the oxygen necessary for nitrifying microorganisms to thrive. Diffused bubbling and surface aeration, which have been commonly installed in STPs, transfer liquid N_2O into the air, leading to N_2O emissions [4]. Controlling or avoiding N_2O emissions through better management of the nitrification process is therefore vital.

Therefore, this paper aims to provide insights into solutions of controllable and avoidable nitrification for achieving the ambitious goal of nearly zero N_2O emissions in sewage management in the next decades, as illustrated in Figure 1. Notably, the focus is primarily on biological solutions, and thus, many promising physicochemical processes — such as membrane absorption or adsorption — are not covered.

Figure 1



Potential solutions to address GHG N_2O emissions from wastewater treatment.

Controllable nitrification: operational optimization

During nitrification, intermediate compounds such as nitrite can enhance the formation of N_2O, especially under suboptimal conditions like low oxygen levels or high ammonia concentrations [5]. Numerous laboratory, pilot, and full-scale studies have tested optimizing operational parameters for reducing N_2O emissions [6,7]. These include aeration control, feed scheme optimization, and process optimization, with full-scale STPs showing N_2O emission reductions of 30%–60% [7,8]. Understanding the mechanisms of N_2O generation pathways is crucial, as operational parameters affect these pathways differently. This understanding can be achieved through close monitoring of N_2O emissions and biological nitrogen removal performance. Analyzing and correlating the monitored results with plant operation control can help develop effective strategies. Additionally, the complexity of N_2O generation mechanisms necessitates using mathematical models to evaluate the consequences of optimization on N_2O emissions and treatment performance, yet it needs to be cautious with model predictions on absolute emissions. However, the extensive efforts required for monitoring, data analysis, and mathematical modeling can be prohibitive for implementing operational optimizations at STPs. Limited mitigation practices have been implemented due to the multiple challenges in process control optimization.

Controllable nitrification: introducing selected nitrifying microorganisms

Nitrification is catalyzed by various nitrifying microorganisms, including the canonical ammonia-oxidizing bacteria (AOB) *Nitrosomonas*, commonly found in activated sludge of STPs [9]. *Nitrosomonas* in activated sludge produces N_2O as a by-product, constituting several percentages of ammonia oxidized [10]. However, other ammonia oxidizers exhibit distinct nitrogen metabolism characteristics. For instance, complete ammonia-oxidizing (comammox) *Nitrospira* [11,12] and ammonia-oxidizing archaea (AOA) [13] lack the N_2O-producing nitrifier denitrification pathway due to the absence of nitric oxide (NO) reductase in their genomes. Similarly, acid-tolerant AOB, such as *Candidatus* Nitrosacidococcus and *Candidatus* Nitrosoglobus, lack NO-producing nitrite reductase (NirK) [14,15]. Consequently, ammonia oxidation processes dominated by comammox [16–18], AOA, and acid-tolerant AOB [19] could exhibit lower N_2O emissions compared to those led by canonical AOB *Nitrosomonas* [20,21].

An important research question of this solution is how to apply these low N_2O producers for ammonia oxidation in sewage treatment. Comammox *Nitrospira* are ubiquitous in activated sludge and can become the dominant nitrifying microorganism in long sludge retention time or attached biofilm systems [22,23]. Additionally, comammox bacteria facilitate cost-effective nitrogen removal by cooperating with anammox bacteria under oxygen-limited conditions [24,25], a potential that AOA may also share [26]. Acid-tolerant AOB are advantageous for performing robust, high-rate nitritation processes, providing nitrite for subsequent nitrogen removal by anammox bacteria [19,27]. Creating appropriate operating conditions can facilitate the replacement of canonical AOB with these alternative ammonia oxidizers, leading to substantially reduced N_2O generation from nitrification.

Controllable nitrification: reducing liquid nitrous oxide transfer into air

As N_2O is highly soluble in the aqueous phase (up to 1.5 g N/l at 15°C), liquid N_2O generated during nitrification could theoretically be reduced to N_2 through subsequent denitrification, serving as a sink for N_2O [28]. Significant reduction of N_2O emissions can be achieved by mitigating the transfer of dissolved N_2O from liquid to air. Managing liquid turbulence to lower the gas–liquid transfer coefficient (kLa) is crucial for controllable nitrification [29]. Reducing liquid turbulence must also ensure adequate oxygen supply to maintain effective nitrification.

A potential solution is the membrane-based aeration. Researchers have developed membrane-aerated biofilm reactors (MABR) as an emerging technology for air supply without forming bubbles, thereby reducing liquid turbulence compared with conventional bubbling methods. Membranes also promote biofilm formation, hosting diverse microbial communities, with nitrifiers growing inside the biofilm and denitrifiers on the outside. This arrangement theoretically allows most of the N_2O produced within the biofilm to be consumed by denitrification before it reaches the bulk liquid. However, large-scale demonstrations remain limited, and further validation is needed for its potential as a low N_2O emission process. A recent full-scale MABR study reported only 0.8% of the influent nitrogen load emitted as N_2O but did not cover overall N_2O emissions from the integrated process [30]. Moreover, design of full-scale MABR usually requires coarse bubble aeration for biofilm scouring, which could lead to additional N_2O emissions [31]. More research is still needed to evaluate the effectiveness of MABR in mitigating N_2O emissions.

Avoid nitrification through anaerobic ammonium conversion

Although nitrification has been an essential process in wastewater treatment for decades, eliminating it could be a potential solution for achieving zero N_2O emissions. This would require an alternative nitrogen removal process. Recent studies have reported the phenomenon of ammonium oxidation using electron acceptors such as sulfate [32,33], ferric iron [34,35], and manganese [36] instead of oxygen, For example,

$$2NH_4^+ + SO_4^{2-} \rightarrow S^0 + N_2 + 4H_2O$$

$$8NH_4^+ + 3SO_4^{2-} \rightarrow 4N_2 + 3HS^- + 12H_2O + 5H^+$$

$$NH_4^+ + 6Fe^{3+} + 4H_2O \rightarrow N_2 + 6Fe^{2+} + 10H^+$$

$$NH_4^+ + 3MnO_2 + 2H_2O \rightarrow N_2 + 3Mn^{2+} + 4OH^-$$

These preliminary findings have laid a foundation for NH_4^+ conversion to NO_2^-, NO_3^-, or even N_2 in the absence of oxygen. Consequently, aeration would no longer be necessary. This dramatic paradigm shift could significantly mitigate N_2O emissions by minimizing liquid turbulence and reducing the likelihood of N_2O being stripped into the air. Moreover, these anaerobic nitrogen-converting processes may not produce N_2O as an intermediate, although the functional microorganisms responsible for them have not been fully identified or understood. Even if N_2O is generated, it can be easily reduced to N_2 through denitrification treatment of the off-gas due to the absence of oxygen, ensuring complete elimination of N_2O emissions in sewage management. While recent studies have explored novel anaerobic ammonium conversion, most have been limited to observational phenomena and have rarely investigated N_2O emissions in depth [36,37]. At this stage, this approach to mitigating N_2O emissions remains in its infancy. However, if successful, it could revolutionize century-old sewage treatment practices. Further research is essential to identify the microorganisms responsible for these anaerobic processes, understand the involved nitrogen metabolisms, and evaluate the feasibility and effectiveness of using these reactions for sewage treatment.

Avoid nitrification through ammonium assimilation and recovery

Another approach to avoid nitrification is to incorporate NH_4^+ into biomass, that is, assimilation, rather than oxidizing it to NO_2^- or NO_3^-, thereby preventing the formation of N_2O altogether. Various microorganisms, including bacteria, archaea, algae, and fungi, assimilate NH_4^+ as a nitrogen source for growth. For instance, algae-based systems and heterotrophic bacteria can be employed to uptake NH_4^+ directly from sewage, with high yields of up to 0.45 g of biomass per gram of NH_4^+-N [38]. Algae, in particular, can assimilate NH_4^+ rapidly and convert it into biomass, which can then be harvested and used as biofuel or fertilizer, creating a circular economy. Assimilation of NH_4^+ can be enhanced by optimizing the conditions for microbial growth, particularly in systems where microbial communities are tailored to efficiently assimilate NH_4^+. Studies have identified high NH_4^+-assimilating strains [39], indicating bioaugmentation may be a feasible strategy to enhance the efficiency of ammonium assimilation in existing facilities such as the high-rate activated sludge process for organic carbon and nitrogen removal. Additionally, purple phototrophic bacteria are capable of NH_4^+ assimilation under anaerobic and light conditions, with biomass yields often ranging from 0.3 to 0.6 g per g of NH_4^+-N assimilated. Novel microbes, such as fungi, although less studied for NH_4^+ assimilation in wastewater contexts, may have the potential to meet the requirement for less organic carbon, necessitating further fundamental and applied research. Notably, a key limitation of these NH_4^+ assimilation processes is the requirement for substantial organic carbon, which is often insufficient in sewage.

Utilizing ion exchange to recover NH_4^+ can prevent nitrification and usually requires a semi-abiotic process to replace traditional biological nitrogen removal. This process could achieve high NH_4^+ removal efficiency [40] and avoid N_2O emissions. However, despite these promising results, significant challenges remain in developing and scaling up this innovative treatment approach.

End-of-pipe techniques

End-of-the-pipe approaches offer a promising opportunity to achieve nearly zero N_2O emissions by removing emitted N_2O from off-gas. In some STPs in Australia, treatment facilities are fully covered to collect almost all off-gases emitted from the plant. Although off-gas treatment is primarily designed for odor control, it rarely addresses the issue of N_2O. In industrial plants for nitric and adipic acid production, catalytic decomposition of NO_x, including Selective Catalytic Reduction and Selective Non-Catalytic Reductions, has been widely implemented and proven effective in N_2O removal [41]. However, these catalytic methods have not been reported for sewage off-gas treatment due to the significant oxygen and moisture content in sewage off-gas, which can significantly affect the effectiveness of the catalytic conversion of N_2O [42]. Additionally, the high-temperature requirement (typically > 500 K) for catalytic decomposition implies high energy costs for preheating off-gas, challenging its economic feasibility.

Biological technologies usually offer a cost-effective option for sewage treatment. Studies have demonstrated the effectiveness of biological N_2O removal in sewage off-gas, which relies on anoxic microbial reduction of N_2O in the absence of oxygen [43–46]. However, removing oxygen from sewage off-gas is a costly step that requires substantial external organic carbons. This makes end-of-the-pipe biological technologies difficult to apply at current STPs with significant aeration and collection of significant oxygen in off-gas. In contrast, these technologies are feasible in treatment systems of anaerobic ammonium conversion, which does not require aeration with oxygen supply.

Some studies have aimed to promote N_2O generation in sewage treatment, recovering N_2O as an energy resource, in contrast to reducing N_2O generation [47–49]. The heterotrophic coupled aerobic-anoxic nitrous decomposition operation process is the most investigated for N_2O recovery, while autotrophic processes, such as photoelectrotrophic denitrification, sulfur-driven denitrification, and hydrogenotrophic denitrification, are also presented as alternative [50]. Nonetheless, recovering N_2O from both heterotrophic and autotrophic denitrification processes still requires either NO_2^- or NO_3^-, leaving N_2O generated from the prior nitrification process unregulated.

Technical maturity of solutions to reduce nitrous oxide

While some strategies for reducing N_2O emissions in sewage treatment are commercially available and effective, many approaches aimed at avoiding nitrification are still in early stages of development. Controllable nitrification methods, which focus on optimizing the process of converting NH_4^+ into NO_3^-, are already being used in many STPs. These methods include strategies like adjusting aeration to lower N_2O emissions. However, these methods still require careful monitoring and complex management to be fully effective, which can be challenging and costly. On the other hand, methods that avoid nitrification altogether, such as using alternative microbial processes to treat NH_4^+ or using chemical treatments like ion exchange to capture NH_4^+, are still in the experimental phase. These techniques hold great potential because they could prevent N_2O from forming in the first place, but they require more testing to prove their feasibility in large-scale sewage plants. For example, using microbes that produce much less N_2O during NH_4^+ conversion, like Comammox bacteria, could revolutionize treatment processes, but applying these organisms on a large scale has not yet been fully validated. Similarly, ion exchange systems could capture NH_4^+ efficiently, but their high cost and the need for further optimization have limited their widespread adoption. Overall, while controllable nitrification solutions are relatively mature, promising strategies for avoiding nitrification still need further research and refinement before they can be widely implemented.

Conclusions

Minimizing N_2O emissions from sewage treatment is crucial for mitigating climate impacts. This paper highlights the nitrification unit as a hotspot for N_2O emissions in current STPs and suggests either controllable or avoidable nitrification as potential strategies for mitigation. Achieving controllable nitrification with low N_2O emissions requires a comprehensive approach, including operational optimization, strategic management of nitrifying microorganisms, and membrane-based aeration. Avoiding nitrification offers substantial promise for reducing emissions by one to two orders of magnitude compared to current levels. This can be accomplished through anaerobic ammonium conversion for removal or ammonium assimilation for recovery, both of which show promise but necessitate further fundamental and applied research. End-of-pipe techniques can play a critical role when combined with other approaches to achieve the ultimate goal of nearly zero N_2O emissions in future sewage management. Successfully integrating these diverse strategies is essential for the wastewater sector to significantly reduce its carbon footprint and contribute meaningfully to global climate mitigation efforts.

CRediT authorship contribution statement

Min Zheng: Conceptualization, Writing – original draft preparation, Writing – review & editing. **James Lloyd**: Writing – original draft preparation. **Peter Wardrop**: Writing – original draft preparation. **Haoran Duan**: Writing – original draft preparation. **Tao Liu**: Writing – original draft preparation. **Liu Ye:** Writing – review & editing. **Bing-jie Ni:** Writing – review & editing.

Data Availability

No data were used for the research described in the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Intergovernmental Panel on Climate Change (IPCC): **Climate Change 2021 — The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change**. Cambridge University Press; 2023.

2. Ni BJ, Peng L, Law Y, Guo J, Yuan Z: **Modeling of nitrous oxide production by autotrophic ammonia-oxidizing bacteria with multiple production pathways**. *Environ Sci Technol* 2014, **48**:3916-3924.

3. Blum JM, Su Q, Ma Y, Valverde-Pérez B, Domingo-Félez C, Jensen MM, Smets BF: **The pH dependency of N-converting enzymatic processes, pathways and microbes: effect on net N_2O production**. *Environ Microbiol* 2018, **20**:1623-1640.

4. •• Duan H, Zhao Y, Koch K, Wells GF, Zheng M, Yuan Z, Ye L: **Insights into nitrous oxide mitigation strategies in wastewater treatment and challenges for wider implementation**. *Environ Sci Technol* 2021, **55**:7208-7224.

The authors provided critical insights into N_2O mitigation strategies in wastewater treatment and discussed the challenges associated with their broader implementation.

5. Chen H, Zeng L, Wang D, Zhou Y, Yang X: **Recent advances in nitrous oxide production and mitigation in wastewater treatment**. *Water Res* 2020, **184**:116168.

6. Su Q, Domingo-Félez C, Jensen MM, Smets BF: **Abiotic nitrous oxide (N_2O) production is strongly pH dependent, but contributes little to overall N_2O emissions in biological nitrogen removal systems**. *Environ Sci Technol* 2019, **53**:3508-3516.

7. Chen X, Mielczarek AT, Habicht K, Andersen MH, Thornberg D, Sin G: **Assessment of full-scale N_2O emission characteristics and testing of control concepts in an activated sludge wastewater treatment plant with alternating aerobic and anoxic phases**. *Environ Sci Technol* 2019, **53**:12485-12494.

8. Duan H, van den Akker B, Thwaites BJ, Peng L, Herman C, Pan Y, Ni B-J, Watt S, Yuan Z, Ye L: **Mitigating nitrous oxide emissions at a full-scale wastewater treatment plant**. *Water Res* 2020, **185**:116196.

9. Su Z, Liu T, Guo J, Zheng M: **Nitrite oxidation in wastewater treatment: microbial adaptation and suppression challenges**. *Environ Sci Technol* 2023, **57**:12557-12570.

10. Law Y, Ni BJ, Lant P, Yuan Z: **Nitrous oxide (N_2O) production by an enriched culture of ammonia oxidising bacteria depends on its ammonia oxidation rate**. *Water Res* 2012, **46**:3409-3419.

11. Daims H, Lebedeva EV, Pjevac P, Han P, Herbold C, Albertsen M, Jehmlich N, Palatinszky M, Vierheilig J, Bulaev A, Kirkegaard RH, von Bergen M, Rattei T, Bendinger B, Nielsen PH, Wagner M: **Complete nitrification by *Nitrospira* bacteria**. *Nature* 2015, **528**:504-509.

12. van Kessel MA, Speth DR, Albertsen M, Nielsen PH, Op den Camp HJ, Kartal B, Jetten MS, Lucker S: **Complete nitrification by a single microorganism**. *Nature* 2015, **528**:555-559.

13. Prosser JI, Nicol GW: **Archaeal and bacterial ammonia-oxidisers in soil: the quest for niche specialisation and differentiation**. *Trends Microbiol* 2012, **20**:523-531.

14. Hayatsu M, Tago K, Uchiyama I, Toyoda A, Wang Y, Shimomura Y, Okubo T, Kurisu F, Hirono Y, Nonaka K, Akiyama H: **An acid-tolerant ammonia-oxidizing γ-proteobacterium from soil**. *ISME J* 2017, **11**:1130-1141.

15. Picone N, Pol A, Mesman R, van Kessel MA, Cremers G, van Gelder AH, van Alen TA, Jetten MS, Lücker S, Op den Camp HJ: **Ammonia oxidation at pH 2.5 by a new gammaproteobacterial ammonia-oxidizing bacterium**. *ISME J* 2021, **15**:1150-1164.

16. • Kits KD, Jung M-Y, Vierheilig J, Pjevac P, Sedlacek CJ, Liu S, Herbold C, Stein LY, Richter A, Wissel H: **Low yield and abiotic origin of N_2O formed by the complete nitrifier *Nitrospira inopinata***. *Nat Commun* 2019, **10**:1-12.

The authors reported the low yield and abiotic origins of N_2O produced by comammox Nitrospira.

17. Han P, Wu D, Sun D, Zhao M, Wang M, Wen T, Zhang J, Hou L, Liu M, Klümper U: **N_2O and NO_y production by the comammox bacterium *Nitrospira inopinata* in comparison with canonical ammonia oxidizers**. *Water Res* 2021, **190**:116728.

18. Li D, Fang F, Liu G: **Efficient nitrification and low-level N_2O emission in a weakly acidic bioreactor at low dissolved-oxygen levels are due to comammox**. *Appl Environ Microbiol* 2021, **87**:e00154-21.

19. Wang Z, Zheng M, Meng J, Hu Z, Ni G, Guerrero Calderon A, Li H, De Clippeleir H, Al-Omari A, Hu S: **Robust nitritation sustained by acid-tolerant ammonia-oxidizing bacteria**. *Environ Sci Technol* 2021, **55**:2048-2056.

20. Wu L, Chen X, Wei W, Liu Y, Wang D, Ni BJ: **A critical review on nitrous oxide production by ammonia-oxidizing archaea**. *Environ Sci Technol* 2020, **54**:9175-9190.

21. Liu T, Duan H, Lücker S, Zheng M, Daims H, Yuan Z, Guo J: **Sustainable wastewater management through nitrogen-cycling microorganisms**. *Nat Water* 2024, **2**:936-952.

22. •• Cotto I, Dai Z, Huo L, Anderson CL, Vilardi KJ, Ijaz U, Khunjar W, Wilson C, De Clippeleir H, Gilmore K, Bailey E: **Long solids retention times and attached growth phase favor prevalence of comammox bacteria in nitrogen removal systems**. *Water Res* 2020, **169**:115268.
The authors revealed that long solids retention times and attached growth phases enhance the prevalence of comammox bacteria in nitrogen removal systems.

23. Zhao J, Zheng M, Su Z, Liu T, Li J, Guo J, Yuan Z, Hu S: **Selective enrichment of comammox *Nitrospira* in a moving bed biofilm reactor with sufficient oxygen supply**. *Environ Sci Technol* 2022, **56**:13338-13346.

24. Shao YH, Wu JH: **Comammox Nitrospira species dominate in an efficient partial nitrification–anammox bioreactor for treating ammonium at low loadings**. *Environ Sci Technol* 2021, **55**:2087-2098.

25. Gottshall EY, Bryson SJ, Cogert KI, Landreau M, Sedlacek CJ, Stahl DA, Daims H, Winkler M: **Sustained nitrogen loss in a symbiotic association of Comammox *Nitrospira* and Anammox bacteria**. *Water Res* 2021, **202**:117426.

26. Straka LL, Meinhardt KA, Bollmann A, Stahl DA, Winkler MKH: **Affinity informs environmental cooperation between ammonia-oxidizing archaea (AOA) and anaerobic ammonia-oxidizing (Anammox) bacteria**. *ISME J* 2019, **13**:1997-2004.

27. Niu C, Ying Y, Zhao J, Zheng M, Guo J, Yuan Z, Hu S, Liu T: **Superior mainstream partial nitritation in an acidic membrane-aerated biofilm reactor**. *Water Res* 2024, **257**:121692.

28. • Conthe M, Lycus P, Arntzen MØ, da Silva AR, Frostegård Å, Bakken LR, Kleerebezem R, van Loosdrecht MC: **Denitrification as an N_2O sink**. *Water Res* 2019, **151**:381-387.
The authors investigated denitrification as a sink for N_2O, offering insights into its role in nitrogen cycling and GHG mitigation.

29. Chen W-H, Yang J-H, Yuan C-S, Yang Y-H: **Toward better understanding and feasibility of controlling greenhouse gas emissions from treatment of industrial wastewater with activated sludge**. *Environ Sci Pollut Res* 2016, **23**:20449-20461.

30. Uri-Carreño N, Nielsen PH, Gernaey KV, Domingo-Félez C, Flores-Alsina X: **Nitrous oxide emissions from two full-scale membrane-aerated biofilm reactors**. *Sci Total Environ* 2024, **908**:168030.

31. Latschbacher M: **Evaluation of N_2O Emissions of MABR Treating SDE**. *Wien* 2017,.

32. Grubba D, Majtacz J, Mąkinia J: **Sulfate reducing ammonium oxidation (SULFAMMOX) process under anaerobic conditions**. *Environ Technol Innov* 2021, **22**:101416.

33. Feng F, Liu Z, Tang X, Wu X, Qu C, How SW, Wu D, Xiao R, Tang CJ, Lin Z, Chai L: **Dosing with pyrite significantly increases anammox performance: its role in the electron transfer enhancement and the functions of the Fe-NS cycle**. *Water Res* 2023, **229**:119393.

34. • Yang Y, Xiao C, Lu J, Zhang Y: **Fe (III)/Fe (II) forwarding a new anammox-like process to remove high-concentration ammonium using nitrate as terminal electron acceptor**. *Water Res* 2020, **172**:115528.
The authors introduce a novel anammox-like process using iron to anaerobically remove ammonium with nitrate as the terminal electron acceptor.

35. Zhen J, Zheng M, Wei W, Ni SQ, Ni BJ: **Extracellular electron transfer (EET) enhanced anammox process for progressive nitrogen removal: a review**. *Chem Eng J* 2024, **482**:148886.

36. Li Y, Liu Y, Feng L, Zhang L: **A review: manganese-driven bioprocess for simultaneous removal of nitrogen and organic contaminants from polluted waters**. *Chemosphere* 2023, **314**:137655.

37. Xia Q, Ai Z, Huang W, Yang F, Liu F, Lei Z, Huang W: **Recent progress in applications of Feammox technology for nitrogen removal from wastewaters: a review**. *Bioresour Technol* 2022, **362**:127868.

38. Mathew MM, Khatana K, Vats V, Dhanker R, Kumar R, Dahms HU, Hwang JS: **Biological approaches integrating algae and bacteria for the degradation of wastewater contaminants — a review**. *Front Microbiol* 2022, **12**:801051.

39. Zhang LJ, Xie Y, Ding LY, Qiao XJ, Tao HC: **Highly efficient ammonium removal through nitrogen assimilation by a hydrogen-oxidizing bacterium, Ideonella sp. TH17**. *Environ Res* 2020, **191**:110059.

40. Guida S, Conzelmann L, Remy C, Vale P, Jefferson B, Soares A: **Resilience and life cycle assessment of ion exchange process for ammonium removal from municipal wastewater**. *Sci Total Environ* 2021, **783**:146834.

41. Brandenberger S, Kröcher O, Tissler A, Althoff R: **The state of the art in selective catalytic reduction of NOx by ammonia using metal-exchanged zeolite catalysts**. *Catal Rev* 2008, **50**:492-531.

42. Frutos OD, Quijano G, Aizpuru A, Munoz R: **A state-of-the-art review on nitrous oxide control from waste treatment and industrial sources**. *Biotechnol Adv* 2018, **36**:1025-1037.

43. Akdeniz N, Janni KA, Salnikov IA: **Biofilter performance of pine nuggets and lava rock as media**. *Bioresour Technol* 2011, **102**:4974-4980.

44. Frutos OD, Quijano G, Pérez R, Muñoz R: **Simultaneous biological nitrous oxide abatement and wastewater treatment in a denitrifying off-gas bioscrubber**. *Chem Eng J* 2016, **288**:28-37.

45. Frutos OD, Cortes I, Cantera S, Arnaiz E, Lebrero R, Muñoz R: **Nitrous oxide abatement coupled with biopolymer production as a model GHG biorefinery for cost-effective climate change mitigation**. *Environ Sci Technol* 2017, **51**:6319-6325.

46. Han H, Kim DD, Song MJ, Yun T, Yoon H, Lee HW, Kim YM, Laureni M, Yoon S: **Biotrickling filtration for the reduction of N_2O emitted during wastewater treatment: results from a long-term in situ pilot-scale testing**. *Environ Sci Technol* 2023, **57**:3883-3892.

47. Scherson YD, Wells GF, Woo S-G, Lee J, Park J, Cantwell BJ, Criddle CS: **Nitrogen removal with energy recovery through N2O decomposition**. *Energy Environ Sci* 2013, **6**:241-248.

48. Scherson YD, Woo S-G, Criddle CS: **Production of nitrous oxide from anaerobic digester centrate and its use as a co-oxidant of biogas to enhance energy recovery**. *Environ Sci Technol* 2014, **48**:5612-5619.

49. Wu L, Peng L, Wei W, Wang D, Ni BJ: **Nitrous oxide production from wastewater treatment: the potential as energy resource rather than potent greenhouse gas**. *J Hazard Mater* 2020, **387**:121694.

50. Duan H, Zhao Y, Koch K, Wells GF, Weißbach M, Yuan Z, Ye L: **Recovery of nitrous oxide from wastewater treatment: current status and perspectives**. *ACS EST Water* 2020, **1**:240-250.