JUNE 2026
R: 26-05-C

WHITEPAPER

Understanding and abating nitrous oxide and methane emissions from wastewater

Author: Caroline Kim

NRDC
NATURAL RESOURCES DEFENSE COUNCIL

Acknowledgments

The author would like to thank the following peer reviewers for their contributions:

Amanda Lake, Jacobs

Dr. Pingyu Wang, Stanford University

Steve Fleischli, NRDC

Alex Hillbrand, NRDC

Dr. Daniel Rath, NRDC

Additionally, the author would like to give special thanks to all involved in the NRDC publications process, especially Leah Stecher and Laurie Geller.

About NRDC

NRDC (Natural Resources Defense Council) is an international nonprofit environmental organization with more than 3 million members and online activists. Established in 1970, NRDC uses science, policy, law, and people power to confront the climate crisis, protect public health, and safeguard nature. NRDC has offices in New York City, Washington, D.C., Los Angeles, San Francisco, Chicago, Beijing and Delhi (an office of NRDC India Pvt. Ltd). Visit us at www.nrdc.org and follow us on Instagram @nrdc_org.

NRDC Senior Policy Publications Editor: Leah Stecher
NRDC Director of Peer Review, Science Office: Laurie Geller

Design and Production: www.suerossi.com

Table of Contents

Executive summary

Nitrous oxide and methane are extremely potent greenhouse gases (GHGs) that contribute significantly to climate change. The global wastewater sector (inclusive of both treated and untreated wastewater) emits large quantities of methane and nitrous oxide, so understanding how to abate these emissions is important for addressing climate change.

Untreated wastewater accounts for 90 percent of the methane emissions from the wastewater sector. To address methane emissions, the most impactful abatement solution is therefore to build new wastewater treatment facilities and modernize water treatment infrastructure, especially for countries in the Global South that lack access to wastewater treatment. By building new treatment facilities and upgrading infrastructure, almost 80 percent of the sector's methane emissions can be abated. In addition to providing climate benefits, these abatement measures will improve global public health outcomes by increasing access to clean water and sanitation.

In contrast, nitrous oxide emissions originate largely from centralized wastewater treatment facilities and have historically been underestimated. (As more of the global population has moved to urban areas with greater access to centralized wastewater treatment, historical data accordingly show that methane emissions from wastewater sources have decreased and that nitrous oxide emissions have increased.) Nitrous oxide is formed under suboptimal conditions during biological nitrogen removal processes, but further study is required to fully understand its formation pathways. Generally, improved monitoring methods must be developed to better quantify nitrous oxide emissions as a way to facilitate better mitigation outcomes. Still, fully understanding nitrous oxide emissions is not a prerequisite for beginning abatement, and mitigation efforts are already underway at various stages of deployment.

Wastewater treatment plants can also be a significant source of methane, though less so than untreated wastewater. Anaerobic digestion, which uses microbes to break down waste into methane-rich biogas, disproportionately accounts for methane emissions from wastewater treatment plants. Evidence suggests these emissions too have been underestimated, and better monitoring of methane emissions from wastewater treatment plants would lead to more effective mitigation strategies. Current mitigation strategies include preventing leaks through better equipment and process optimization.

Advancing abatement of nitrous oxide and methane from wastewater will likely require new funding, policies, and regulations. To build new wastewater treatment facilities in the Global South, a significant amount of capital is required from financial institutions such as multilateral development funds. Addressing emissions from wastewater treatment plants may be more complicated. The primary objective of these facilities is to remain in compliance with mandatory effluent discharge limits, not to reduce GHG emissions. Additionally, water utilities are accountable to ratepayers and are therefore averse to actions that could increase costs for their customers. As a result, policies and regulations that require action on mitigation (e.g., mandating monitoring or imposing emissions limits) are crucial to stimulating action in an otherwise conservative industry. Still, mitigation action can 1) lead to cost savings from operational improvements and 2) allow wastewater treatment plants to participate in carbon markets. Currently, there is one emissions crediting scheme that covers wastewater treatment: the Swiss emissions crediting scheme, which funds abatement projects at wastewater treatment plants. This type of financial mechanism can provide an extra incentive to abate.

Finally, it is important to consider methane and nitrous oxide emissions that are outside the scope of the wastewater treatment facility. Sewers and landfills (where biosolids end up post-processing) are likely significant sources of additional GHGs that are not currently included in monitoring methodologies. Therefore, a systems-level perspective can lead to a more holistic understanding of emissions sources and solutions beyond the boundaries of the wastewater treatment plant.

Introduction

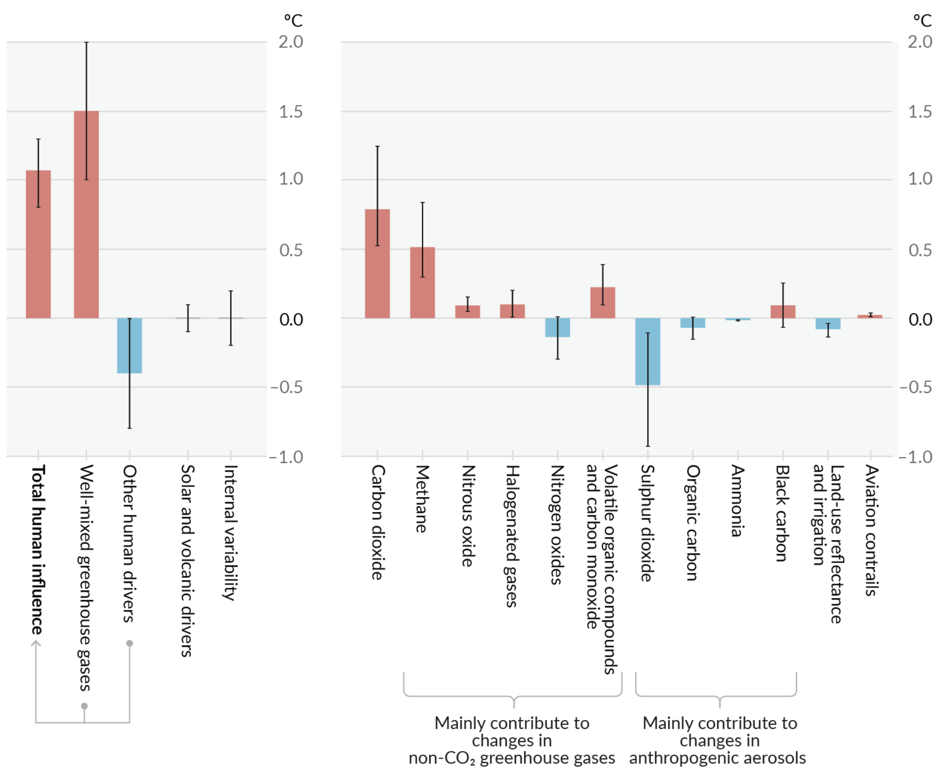
While carbon dioxide is the most common greenhouse gas (GHG), nitrous oxide and methane are both extremely potent GHGs that must be addressed as part of the effort to mitigate climate change. Nitrous oxide has a global warming potential (GWP) 270 times that of carbon dioxide on a 100-year basis, and it lasts in the atmosphere for roughly 120 years.[1] Not only does nitrous oxide contribute to climate change, but it also contributes to destruction of the stratospheric ozone layer that protects us from harmful UV radiation. Methane doesn't last as long as carbon dioxide in the atmosphere, but its GWP is roughly 80 times that of carbon dioxide over a 20-year timeframe. Therefore, addressing methane emissions as quickly as possible will have an enormous near-term climate impact.

Both methane and nitrous oxide are emitted in sufficient quantities to have a significant impact on warming. According to the most recent IPCC Assessment Report, the combined contributions of methane and nitrous oxide to warming from 2010 to 2019 were similar to the contribution of carbon dioxide (figure 1).[2]

The wastewater sector (including both treated and untreated wastewater) is responsible for significant methane and nitrous oxide emissions. According to the U.S. Environmental Protection Agency (EPA), methane and nitrous oxide emissions from the global wastewater sector alone accounted for 6 percent of total global non-CO_2 GHG emissions in 2025.[3] Both methane and nitrous oxide emissions from wastewater are expected to increase in the coming decades, due to increasing urbanization and population growth (table 1).[4] Given the large contributions of methane and nitrous oxide to warming and the notable fraction of those emissions originating from the wastewater sector, it is clear that abating methane and nitrous oxide emissions from wastewater will play an important role in curbing climate change.

FIGURE 1: CONTRIBUTIONS OF VARIOUS GASES TO GLOBAL WARMING (°C), 2010 TO 2019

Methane and nitrous oxide contributed to a similar amount of warming as CO_2 from 2010 to 2019.



Source: IPCC 2021 (panel C), https://www.ipcc.ch/report/ar6/wg1/figures/summary-for-policymakers/figure-spm-2.

TABLE 1: MODELED GLOBAL NON-CO_2 (METHANE AND NITROUS OXIDE) EMISSIONS FROM WASTEWATER IN 2020 AND 2050 FROM THE EPA'S JANUARY 2025 NON-CO_2 REPORT AND THE GLOBAL NITROUS OXIDE ASSESSMENT (GNA)[5]

GNA's nitrous oxide values come from the International Nitrogen Management System's scenarios, which were implemented by the International Institute for Applied Systems Analysis (IIASA) Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model. Nitrous oxide emissions are shown in million metric tons (Mt) CO_2-equivalent (CO_2e) using GWP values from IPCC's Assessment Report 5 (AR5 values) to be consistent with the EPA's report. Wastewater non-CO_2 GHG emissions are expected to increase modestly as urban populations grow and utilization of wastewater treatment and collection technologies increases in these urban areas.[6]

	2020		2050	
	EPA	GNA	EPA	GNA
Methane emissions (Mt CO_2e [AR5])	569	–	667	–
Nitrous oxide emissions (Mt CO_2e [AR5])	145	205	169	258
Methane and N_2O emissions(Mt CO_2e [AR5])	714		836	

Emissions from the wastewater sector

Methane emissions arise from organic material decomposing under anaerobic conditions. Developed countries rely on centralized treatment systems that limit methane formation, whereas developing countries use a variety of wastewater treatment strategies such as latrines and septic tanks with higher methane emissions.[7]

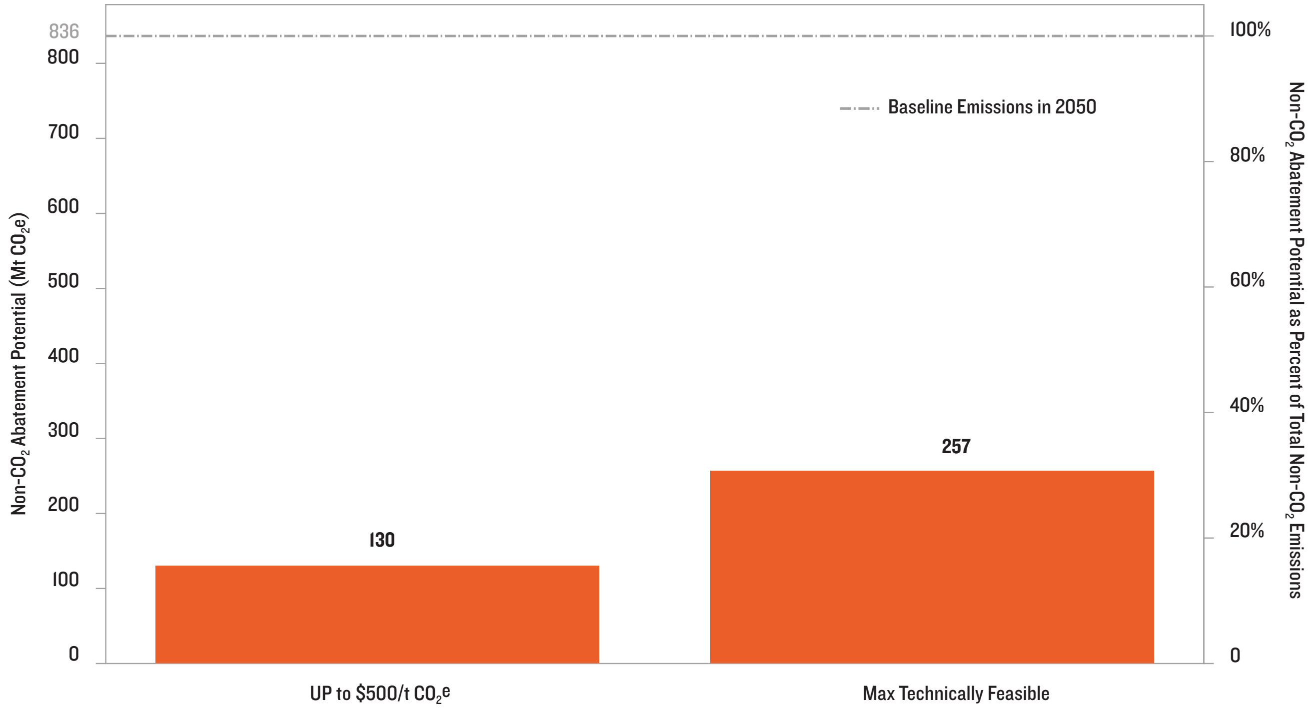
Nitrous oxide emissions arise from nitrogen compounds present in wastewater. As rates of urbanization around the world increased from 1990 to 2015, urban areas with access to centralized wastewater treatment have accounted for an increasing proportion of global wastewater emissions.[8] During this period, nitrous oxide emissions from wastewater increased by 69 percent, compared with a 6 percent decrease in methane emissions.[9] This evidence suggests that nitrous oxide emissions are more associated with large, centralized wastewater treatment, while methane emissions are more associated with less-centralized treatment. Therefore, there exists a tension wherein increasing access to centralized wastewater treatment can lead to a decrease in methane emissions but an increase in nitrous oxide emissions.

Evidence is conflicting on how effective mitigation solutions will be for non-CO_2 GHG emissions from wastewater. Mitigation assessments from the EPA indicate that less than 20 percent of non-CO_2 emissions from wastewater can be addressed at breakeven prices up to \$500/t CO_2e (i.e., abatement that costs \$500/t CO_2e or less) and that the maximum technically feasible emissions reduction is 31 percent in 2050 (figure 2).[10] Projected emissions from the sector increase from 836 million metric tons (Mt) CO_2e in 2050 to 1,035 Mt CO_2e in 2100, but maximum abatement remains at 31 percent.[11]

It is important to note that the EPA did not model any nitrous oxide abatement by 2100 in its report, yet there is evidence to suggest that some nitrous oxide mitigation could be accomplished today and could lead to cost savings.[12] There are also mitigation approaches that are not yet commercialized but, once scaled, could change the outlook for cost-efficient and effective wastewater emissions mitigation. Thus, the EPA's nitrous oxide emissions mitigation assessments underestimate what is likely possible with technology advancements.

FIGURE 2: GLOBAL ABATEMENT POTENTIAL OF NON-CO_2 GASES FROM WASTEWATER IN 2050

Bar plot of non-CO_2 abatement potential in Mt CO_2e (AR5 GWP values) and as a percentage of total non-CO_2 emissions from wastewater in 2050.



Source: EPA, 2025, https://www.epa.gov/system/files/other-files/2025-07/non-co2-report-data-annex-gloabl-domestic-072025.zip.

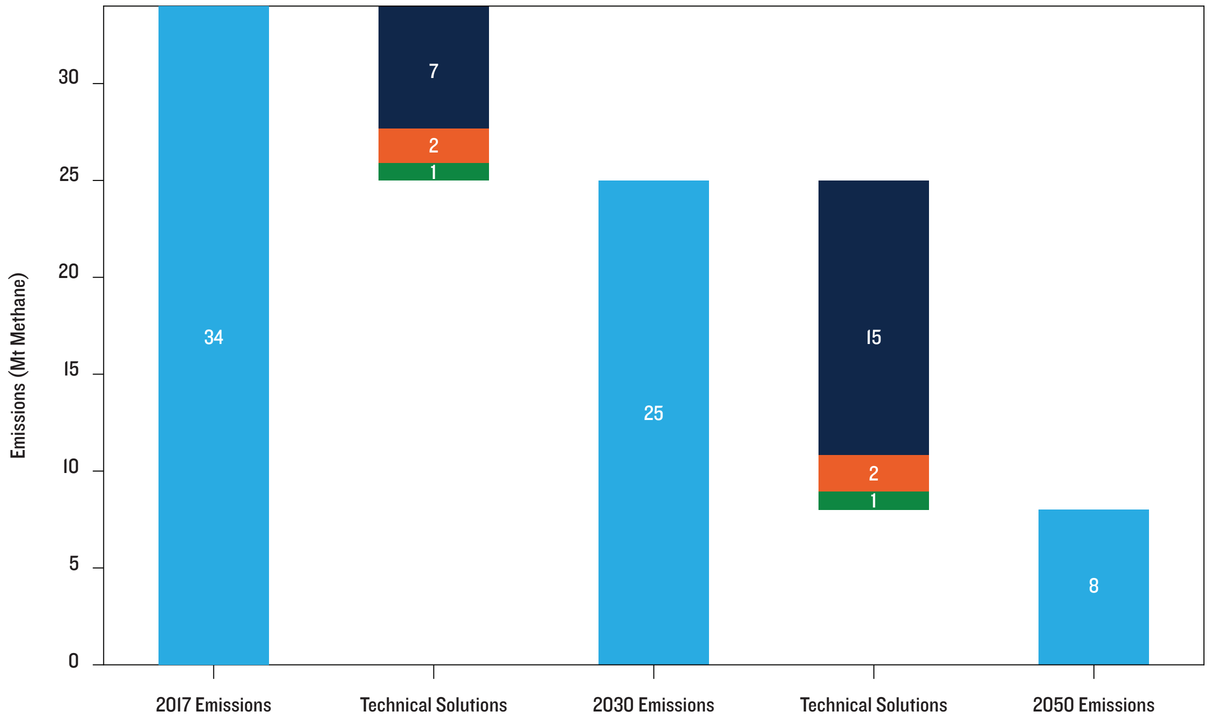
Abating wastewater methane emissions from non-wastewater treatment plant (WWTP) sources

The key to addressing methane emissions from wastewater is building new wastewater treatment plants (WWTPs[a]) and supporting infrastructure. Untreated wastewater accounts for 90 percent of the methane emissions from the wastewater sector globally.[13] Methane forms when organic matter in wastewater is either untreated or inadequately treated and decays.[14] Modernization of global water treatment infrastructure could abate almost 80 percent of wastewater methane emissions by 2050, from a 2017 baseline (figure 3).[15] In particular, constructing WWTPs and upgrading connections to treatment grids in developing economies can abate 65 percent of wastewater methane emissions by 2050 by eliminating significant emissions from less developed systems such as non-sewered sanitation systems.[16] Building new, centralized WWTPs will not only reduce wastewater methane emissions but also increase access to clean water and sanitation, thereby improving public health outcomes globally. Although centralized WWTPs carry an increased risk of nitrous oxide emissions, these emissions can be mitigated, as discussed in the following sections.

a For this report, WWTPs include publicly owned treatment works (POTWs), water resource recovery facilities (WRRFs), water recycling/reclamation facilities, and other centralized wastewater facilities.

FIGURE 3: WASTEWATER METHANE ABATEMENT POTENTIAL IN 2050

It is estimated that almost 80 percent of global wastewater methane emissions can be addressed through technical solutions by 2050 (relative to a 2017 baseline). The largest abatement lever is building new WWTPs and upgrading connections in developing economies that have less-developed wastewater treatment systems. (Note: Figures may not sum due to rounding.)



	Technical Solutions	Top Abatement Levers
■ (dark blue)	Build treatment facilities and upgrade connections	Construction of wastewater treatment facilities and connection to treatment grid in developing economies, especially in Asia and Latin America
■ (orange)	Implement advanced technologies	Improved efficiency and operating standards, such as improved membrane filtration, pressure settings, venting, etc., to prevent anerobic methane release
■ (green)	Make operational improvements	Advanced technologies, such as microalgae, covered lagoons, anaerobic sludge digesters, degassing effluent charge, etc., for biogas harvesting

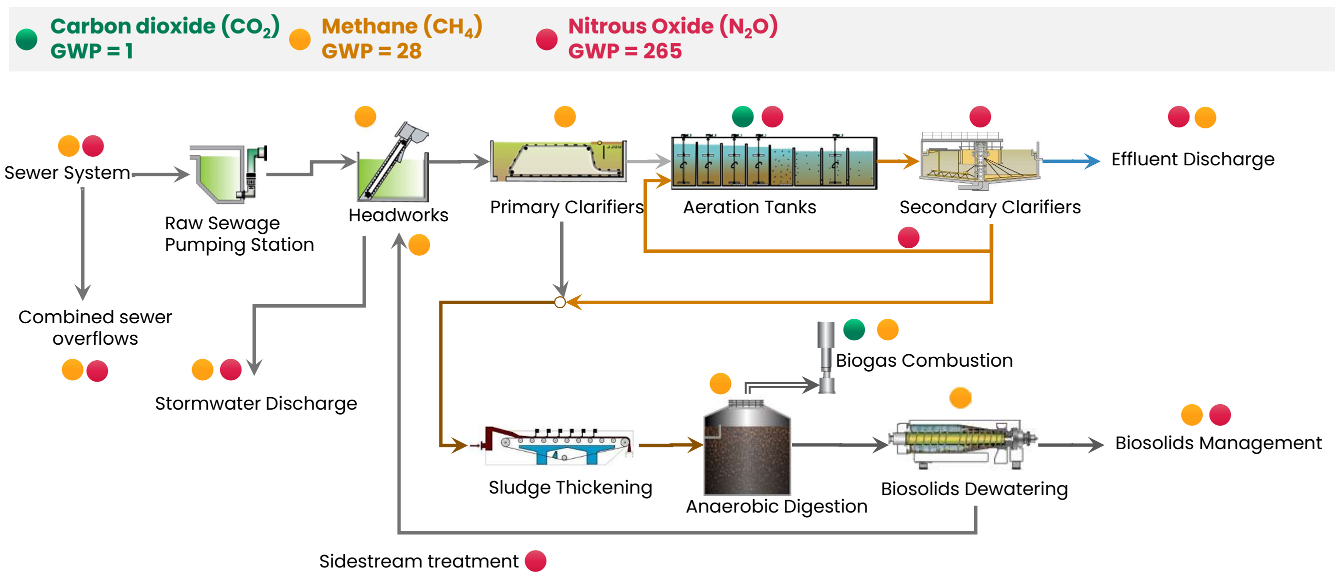
Source: DeFabrizio et al., 2021, https://www.mckinsey.com/capabilities/sustainability/our-insights/curbing-methane-emissions-how-five-industries-can-counter-a-major-climate-threat#/.

Abating non-CO2 emissions from centralized WWTPs

Centralized WWTPs are generally required to meet regulatory discharge limits for certain chemicals in their effluent. The processes used to meet these discharge limits can emit large quantities of nitrous oxide and methane. WWTPs may contribute to 3 percent of global nitrous oxide emissions.[17] Methane emissions from WWTPs are much lower than emissions from wastewater not treated in centralized facilities, but WWTPs can still emit significant amounts of methane—one study found that methane emissions from WWTPs in the United States account for 2.5 percent of the nation's total methane emissions.[18] Methane and nitrous oxide are produced at various points of a typical wastewater treatment configuration (figure 4). Importantly, different WWTPs use differing technologies and have differing operations, so not all WWTPs have the exact schematic shown in figure 4.[19]

FIGURE 4: GENERAL SCHEMATIC OF PROCESS EMISSIONS FROM WASTEWATER TREATMENT

Carbon dioxide, methane, and nitrous oxide are produced at various points throughout the wastewater treatment process. However, different WWTPs have differing technologies, layouts, components, and schemes.



Source: Amanda Lake, January 2024, https://www.energy.gov/sites/default/files/2024-03/iedo-ghg-workshop_jacobs.pdf.

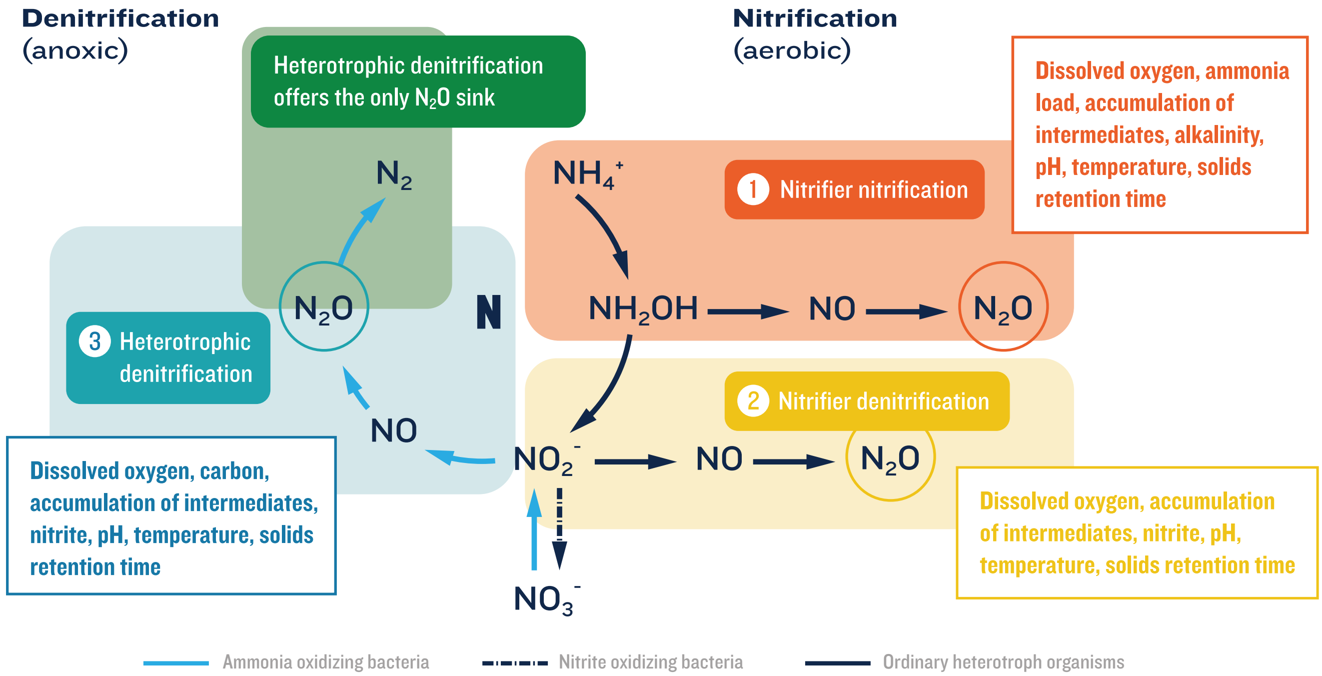
Accurate monitoring of nitrous oxide emissions to support more effective mitigation

Historically, nitrous oxide emissions from WWTPs have been underestimated.[20] Currently, emissions reporting from wastewater treatment facilities follows a three-tier framework developed by the IPCC: global emission factors (Tier 1), country emission factors (Tier 2), and facility-specific (Tier 3).[21] Unfortunately, the default emission factors (Tier 1 and Tier 2) are based on a very limited and inconsistent set of data that do not adequately account for site-specific variations.[22] Significant evidence has shown the need for facility-level measurements to "support accurate baselining, and . . . mitigation, which needs to happen" on a plant-by-plant basis.[23] For example, a recent Princeton University study monitored emissions from almost 100 WWTPs in the United States over a 14-month period. In addition to finding that the EPA was underestimating nitrous oxide emissions from WWTPs in the United States, the study found that emissions varied significantly among facilities, further highlighting the limitations of countrywide emissions factors in estimating emissions from the sector.[24]

Nitrous oxide is formed during biological treatment of wastewater in WWTPs, although the process is not yet fully understood. Generally, nitrous oxide formation is driven by suboptimal process conditions during this biological treatment.[25] As more WWTPs have implemented biological nitrogen removal, nitrous oxide emissions have increased.[26] Many WWTPs biologically treat wastewater with microbes that perform nitrification and denitrification to remove nitrogen and therefore prevent large releases of reactive nitrogen (e.g., ammonia, nitrates) into the surrounding environment.[27] In nitrification, ammonia (NH_4^+) is converted to nitrite then nitrate, and the process of denitrification converts nitrate into nitrogen gas. Although the exact production pathways of nitrous oxide are not fully understood, it is known that nitrous oxide can be created and consumed during this biological removal of nitrogen and that nitrous oxide formation is influenced by WWTP design and operational factors such as temperature, dissolved oxygen, pH, ammonium, carbon-to-nitrogen ratio, and perturbations/extremities in loading and feeding strategies (figure 5).[28] Nitrous oxide emissions at a single plant can also vary according to time of day, season, and the specific process.[29]

FIGURE 5: SIMPLIFIED BIOLOGICAL PATHWAYS AND POTENTIAL INFLUENCING PROCESS CONDITIONS FOR NITROUS OXIDE (N_2O) FORMATION FROM WASTEWATER TREATMENT[30]

Many WWTPs use microbes to nitrify ammonia into nitrate, then denitrify nitrate into nitrogen gas. During these processes, nitrous oxide can be produced and consumed. Although nitrous oxide production pathways are still being studied, it is known that suboptimal process conditions can lead to more nitrous oxide formation.[31]



Source: Amanda Lake, 2024, https://www.waterrf.org/resource/wastewater-process-emissions-fundamentals.

Therefore, developing accurate monitoring methods is crucial for first understanding when and where nitrous oxide is being formed and then determining how to mitigate those emissions. Using these data, mechanistic or data-driven models may eventually become useful in predicting N_2O emissions with more limited data, but this is not the case yet.[32] Already, process optimization made possible through accurate monitoring has demonstrated real emissions reductions.[33] Other proposed mitigation strategies involving monitoring include use of advanced control systems.[34]

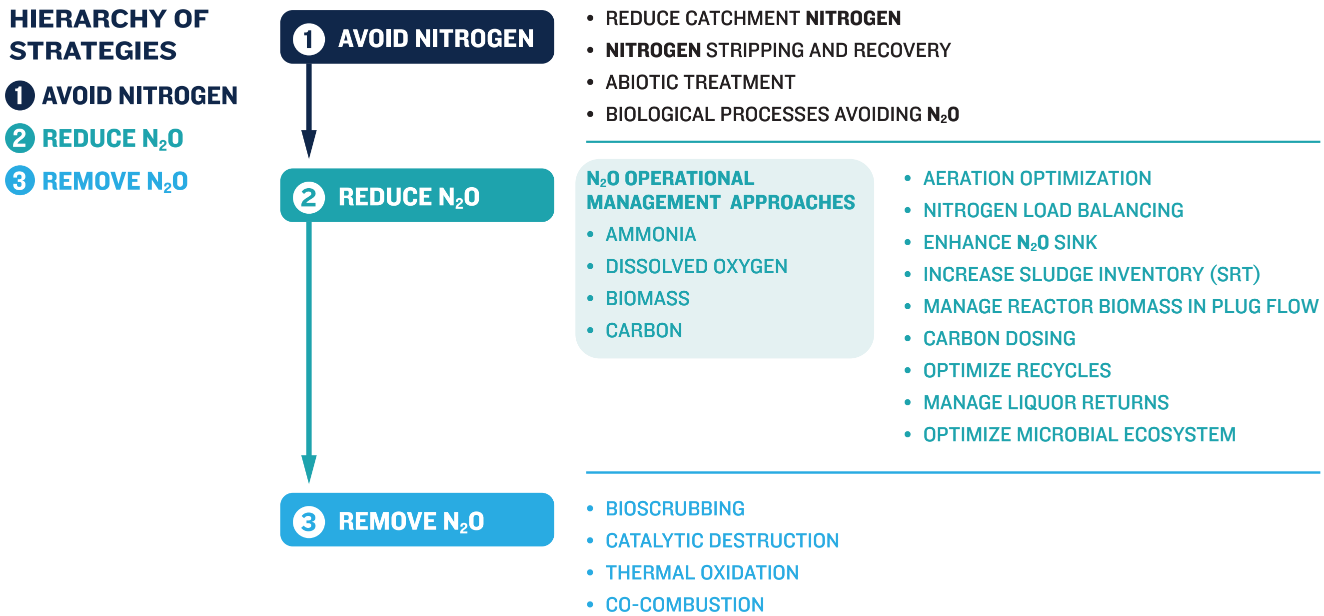
Promising nitrous oxide abatement technologies for WWTPs

Fortunately, comprehensive monitoring and full understanding of nitrous oxide emissions from WWTPs are not prerequisites to pursuing effective abatement, and abatement efforts are already underway. Nitrous oxide mitigation strategies can be viewed as part of a hierarchy of solutions: 1) avoid nitrous oxide formation, 2) reduce nitrous oxide formation through process optimization, and 3) remove formed nitrous oxide through destruction (figure 6).[35] While there are few examples of full-scale, sustained operating mitigation strategies for nitrous oxide in wastewater, promising strategies exist at various stages of deployment for all three levels of this hierarchy.

Nitrous oxide avoidance is achieved by reducing the amount of nitrogen that reaches the WWTP processes that produce nitrous oxide. Technical solutions inside WWTPs to prevent nitrous oxide formation include nitrogen stripping and recovery processes. These technologies recover some nitrogen from wastewater before it enters biological treatment, thereby reducing the amount of nitrogen that can be converted into nitrous oxide. Nitrogen recovery not only prevents nitrous oxide formation but also promotes nitrogen circularity. For example, nitrogen can be recovered from wastewater and converted into fertilizer, which could support the economics of nitrogen recovery once commercialized.[36] Nitrogen recovery technologies are in various stages of development and commercialization.[37]

FIGURE 6: HIERARCHY OF WASTEWATER NITROUS OXIDE (N_2O) MITIGATION STRATEGIES WITH EXAMPLES

Nitrous oxide mitigation can be approached through avoidance, reduction, and removal. The priority strategy is to prevent nitrous oxide formation through upstream nitrogen management approaches, but when formation is unavoidable, the next priority is to reduce nitrous oxide formation through operations management. Lastly, any remaining nitrous oxide is removed.



Source: Lake et al., 2024, https://www.thechemicalengineer.com/features/the-challenges-of-eliminating-nitrous-oxide-from-the-water-sector/.

When nitrous oxide formation cannot be avoided, process optimization can reduce the amount of nitrous oxide formed. Nitrous oxide reduction measures include "balancing ammonia loads, adjusting dissolved oxygen levels and ensuring sufficient carbon where denitrification is taking place," using strategies like monitoring methods and advanced control systems.[38] Water utilities in Finland and the Netherlands have shown success in preventing nitrous oxide formation through these methods.[39] Variolytics has developed a control system to monitor and analyze conditions during treatment processes and perform process optimization adjustments using artificial intelligence to reduce nitrous oxide emissions and lower costs.[40] Biotechnology company Microvi has developed a next-generation, biocatalyst wastewater treatment system. Microvi's system has been shown to reduce nitrous oxide emissions, in addition to improving treatment metrics, during a 2.5-year demonstration project at a WWTP in California.[41] An important co-benefit to process optimization to reduce nitrous oxide emissions is the potential for operational cost savings, as improved processes can lead to lower energy use.[42]

For the remaining nitrous oxide after avoidance and reduction measures have been implemented, destruction technologies are needed. While none have been fully commercialized, thermal and catalytic processes to destroy nitrous oxide have been piloted. Regenerative thermal oxidation (RTO) is a thermal destruction process that heats nitrous oxide-rich gases to 800–1000 °C and decomposes nitrous oxide into nitrogen and oxygen gas.[43] One challenge is that, due to the high heat, NO_x[b] can be produced and would need to be mitigated if its emissions exceed regulatory limits.[44] Pilot-scale research was successfully completed at the Swiss WWTP Bern, and a new RTO plant has been operating since 2025.[45] Another destruction method is catalytic processes that destroy nitrous oxide at lower temperatures. The catalyst speeds up the reaction and can sometimes be paired with a reductant to further support nitrous oxide destruction. Catalytic technologies have been piloted at WWTPs, including at three facilities in Denmark.[46]

b NO_x is shorthand for nitrogen oxides, which are air pollutants such as NO and NO_2.

Anaerobic digestion disproportionately emits methane at WWTPs

Anaerobic digesters can provide useful energy for WWTPs but are also prime sources of methane emissions from WWTPs. Anaerobic digesters contain microbes that break down waste into methane-rich biogas, which can be used for energy at WWTPs. Although anaerobic digesters are closed systems in theory, methane can still leak. One *Nature Water* study found that U.S. facilities with anaerobic digesters emitted 2.5 times more methane than U.S. facilities without anaerobic digestion, thus corroborating previous work showing that facilities with anaerobic digesters are disproportionately responsible for methane emissions from WWTPs.[47] Another study found that facilities with anaerobic digesters accounted for 72 percent of U.S. wastewater sectoral methane emissions despite only treating 55 percent of the country's wastewater.[48]

As with nitrous oxide, an important step in mitigating methane is better understanding and quantification of emissions through long-term, continuous monitoring studies. Methane emissions may be underestimated by current IPCC quantification guidelines.[49] The same *Nature Water* study found that U.S. WWTPs had methane emissions that were 2.4 times higher than current U.S. inventories.[50] Better monitoring of methane sources can lead to updated guidelines to accurately detect methane emissions and design effective mitigation strategies.[51]

Mitigation strategies already exist to an extent. Investing in robust biogas capture systems that do not leak, optimizing the anaerobic digestion process to minimize methane loss, and installing methane leak detectors are some methane abatement steps that WWTPs can take.[52]

Recommendations for reducing nitrous oxide and methane emissions from wastewater

Financial and policy levers are needed to catalyze nitrous oxide and methane abatement in the wastewater sector. Both GHG reduction mandates and financial incentives can encourage governments and municipalities to implement the abatement strategies described above, including building new WWTPs and installing emissions-reducing technologies in existing WWTPs. These incentives should focus on both monitoring and mitigation activities (figure 7).

FIGURE 7: RECOMMENDATIONS TO REDUCE NON-WWTP EMISSIONS AND WWTP EMISSIONS

Non-WWTP emissions	WWTP emissions
• Build new WWTPs	• Develop policies and regulations mandating GHG monitoring and/or mitigation • Use financial mechanisms to fund abatement

Reducing wastewater methane emissions from untreated wastewater

The main technical solution to reducing methane emissions from untreated wastewater is to build new WWTPs. The capital costs can be a significant burden and therefore a barrier to doing so, especially in Global South countries with the least access to centralized wastewater treatment. One potential funding mechanism could be the use of multilateral development funds. For example, in 2024 the Nordic Development Fund granted €12 million to the African Water Facility (a fund managed by the African Development Bank) to support water sanitation projects in Africa.[53]

Reducing non-CO_2 emissions from WWTPs

Both the technological advancements and capital projects needed to mitigate nitrous oxide and methane emissions globally from WWTPs could be catalyzed with policies, regulations, and financial mechanisms. When designing these levers, the priorities of WWTPs must be understood. First and foremost, WWTPs must meet their obligations under their discharge permits.[54] WWTPs are also accountable to ratepayers, so minimizing rate increases is another priority.[55] Notably, reducing GHG emissions currently is not part of most WWTPs' operations or mandate. Interventions must, at the very least, be mindful of these considerations and should attempt to address them when possible.

Policies and regulations to mandate WWTP GHG reductions

Policies and regulations that mandate GHG emissions reductions or steps toward emissions reductions at WWTPs can catalyze action, including funding being made available for GHG mitigation.

Policies can motivate water utilities to adhere to climate goals. In 2019, the U.K. government set a legally binding commitment to reach net-zero GHG emissions by 2050; the following year, all water companies in England agreed to a "Public Interest Commitment" that included a pledge to reach net-zero operational emissions by 2030.[56] The Asset Management Plan 8 for U.K. water companies starting in April 2025 included £300 million specifically for reducing nitrous oxide from wastewater treatment.[57] Policies that make funding available for mitigation activities are important to incentivize cost-averse water utilities.

Regulations mandating monitoring and reporting or setting thresholds on emissions could push utilities to invest in monitoring campaigns, new technologies, and upgrades. Denmark is one of the first countries with plans to adopt nitrous oxide emissions limits for WWTPs, with a proposed 50 percent reduction in emissions.[58] Regulations are expected to follow from other entities, such as the European Union.[59] In addition to working on passing this new regulation (and perhaps because of this), the Danish Environmental Technology Development and Demonstration Program (funded by the Danish Ministry of Environment) is also supporting a new initiative to transform nitrous oxide monitoring at WWTPs by developing a new testing system, conducting measurement campaigns, and creating a standardized approach for estimating plant-wide baseline emissions.[60] Importantly, standardizing nitrous oxide monitoring protocols will provide a crucial foundation for regulation.[61]

Funding for GHG monitoring and mitigation at WWTPs

Given their sensitivity to cost, WWTPs may need tangible financial incentives to participate in monitoring campaigns and mitigation activities, both of which could lead to large capital and operating expenditures. Experts estimate that even a fairly limited monitoring campaign at fewer than 10 facilities in the United States could cost $5 million.[62] Generally, this may not be a huge cost for large water utilities, such as the Massachusetts Water Resources Authority, which provides water and sewer services to more than three million people in the metropolitan Boston area and whose FY26 proposed expense budget exceeded $900 million.[63] Still, water utilities are hesitant to spend money on measures that are not regulatorily required and that could raise customers' rates.[64] Fortunately, there are economic co-benefits from GHG measurements and sustainable operation of WWTPs. Monitoring can lead to process optimization strategies that reduce costs, and measurement and mitigation can allow WWTPs to participate in carbon credit programs to fund upgrades.[65]

There is only one example of an emissions crediting scheme being used to fund nitrous oxide abatement at WWTPs: the Foundation for Climate Protection and Carbon Offset KliK (KliK Foundation) in Switzerland.[66] One of the measures of the Swiss CO_2 Act, which regulates Switzerland's carbon dioxide emissions, is to mandate fossil fuel companies to offset some of the GHGs from transportation. The KliK Foundation is a private carbon offset grouping that fulfills this legal obligation on behalf of the fossil fuel companies it represents (36 as of January 1, 2025).[67] The foundation pays for mitigation activities approved by the Swiss government.[68] First the Swiss government issues attestations, or certificates, to mitigation activity owners for each ton of verified CO_2 reduced through the mitigation activity.[69] The KliK Foundation then buys attestations from activity owners at a predetermined, mutually agreed upon price; this is how it financially supports these mitigation activities.[70] The foundation annually gives a number of attestations to the Swiss government equal to the amount of CO_2 required to be offset by the participating companies.[71] For any remaining CO_2 that is not offset, the foundation must pay the Swiss government CHF 160 per ton of CO_2.[72]

The KliK Foundation supports nitrous oxide offsetting projects at WWTPs.[73] As of January 2026, 17 projects in various stages of planning and implementation were participating in the KliK program to reduce nitrous oxide from wastewater treatment.[74] The program issues CHF 145 per ton of CO_2e until investment costs are covered.[75] In 2023, attestations equal to 1,164 tons of CO_2e avoided were issued.[76] One funded project reduced nitrous oxide emissions by more than 90 percent through regenerative thermal oxidation.[77] Funding for implementing these technologies is important to overcome economic hurdles to abatement.

The KliK Foundation also finances a methane reduction program for WWTPs to capture and destroy methane.[78] Participating WWTPs receive a subsidy equal to CHF 140 per ton of CO_2e until their investment cost is amortized.[79] WWTPs continue to earn CHF 10,000 per year for continuing operation of methane abatement and CHF 25 per ton of CO_2e.[80] More than 20 WWTPs are already participating in this program, and in 2022, attestations equal to 12,423 tons of CO_2e avoided were issued.[81]

Beyond the WWTP

There is a growing realization that non-CO_2 emissions upstream and downstream of the WWTP itself must be better studied. For example, sewers and landfills (where biosolids are disposed after wastewater treatment) may be sources of additional GHG emissions but are not currently included in emissions calculations.[82] The United States alone has more than a million miles of sewers that could be a significant source of methane emissions, but these emissions are not accounted for in current GHG inventories and are more difficult to access and measure.[83] Management of biosolids including land disposal, incineration, or emerging thermal processes may not be accounted for in WWTP boundaries for carbon accounting but must be considered holistically using life-cycle carbon (and ideally wider life-cycle analysis) methods.[84]

Finally, it is important to note that the nitrous oxide and methane emissions from WWTPs come from carbon and nitrogen sources that originate elsewhere. Solely attributing these emissions to wastewater treatment plants may not lead to accurately understanding the full suite of mitigation solutions.[85] Therefore, while pursuing mitigation at WWTPs is essential, incorporating a more systems-level perspective can reveal more mitigation solutions outside of WWTPs.

Conclusion

The wastewater sector accounts for a significant portion of global nitrous oxide and methane emissions. Actions can be taken today to abate emissions by building new WWTPs, monitoring nitrous oxide and methane at WWTPs, and supporting deployment of new abatement technologies. Urgent abatement of these extremely potent GHGs is critical to achieve a climate-stable future.

Endnotes

1 United Nations Environment Programme and Food and Agriculture Organization of the United Nations, *Global Nitrous Oxide Assessment*, 2024, 15, 119, https://doi.org/10.59117/20.500.11822/46562.

2 V. Masson-Delmotte et al., eds., "Figure SPM.2 in IPCC, 2021: Summary for Policymakers," in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2023), https://doi.org/10.1017/9781009157896.001.

3 U.S. Environmental Protection Agency (hereinafter EPA), "NonCO$_2$ MACs—Summary Tables 2025," June 26, 2025, https://www.epa.gov/system/files/other-files/2025-07/non-co2-report-data-annex-gloabl-domestic-072025.zip.

4 EPA, Office of Atmospheric Programs, *Global Non-CO$_2$ Greenhouse Gas Emission Projections & Mitigation 2015–2050*, October 2019, 73, https://www.epa.gov/sites/default/files/2019-09/documents/epa_non-co2_greenhouse_gases_rpt-epa430r19010.pdf.

5 EPA, *Global Non-CO$_2$ Greenhouse Gas Emission Projections & Mitigation Potential: 2020–2080*, EPA-430-R-25-002, 2025, https://cfpub.epa.gov/ghgdata/nonco2/reports/; EPA, "Proj_annex," June 26, 2025, https://www.epa.gov/system/files/other-files/2025-07/non-co2-report-data-annex-gloabl-domestic-072025.zip; United Nations Environment Programme and Food and Agriculture Organization of the United Nations, *Global Nitrous Oxide Assessment*, 80.

6 EPA, *Global Non-CO$_2$ Greenhouse Gas Emission Projections & Mitigation 2015–2050*, 73.

7 Ibid., 72.

8 Ibid.

9 Ibid.

10 EPA, "NonCO$_2$ MACs—Summary Tables 2025."

11 Ibid.

12 EPA, *Global Non-CO$_2$ Greenhouse Gas Emission Projections & Mitigation 2015-2050*, 74; EPA, "macc_result_raw_WWR," June 26, 2025, https://www.epa.gov/system/files/other-files/2025-07/non-co2-report-data-annex-gloabl-domestic-072025.zip; United Nations Environment Programme and Food and Agriculture Organization of the United Nations, *Global Nitrous Oxide Assessment*, 158.

13 Sam DeFabrizio et al., *Curbing Methane Emissions: How Five Industries Can Counter a Major Climate Threat*, McKinsey Sustainability, September 23, 2021, 49, https://www.mckinsey.com/capabilities/sustainability/our-insights/curbing-methane-emissions-how-five-industries-can-counter-a-major-climate-threat.

14 Climate and Clean Air Coalition, "Methane Emission Mitigation in the Wastewater Sector," 1, accessed August 21, 2025, https://www.ccacoalition.org/sites/default/files/resources//Methane%20Mitigation%20in%20the%20Wastewater%20Sector%20-%20Factsheet.pdf.

15 DeFabrizio et al., *Curbing Methane Emissions*, 22.

16 Ibid., 50; Climate and Clean Air Coalition, "Methane Emission Mitigation," 1–2.

17 Alexandre Alix et al., eds., *Reducing the Greenhouse Gas Emissions of Water and Sanitation Services: Overview of Emissions and Their Potential Reduction Illustrated by Utility Know-How* (IWA Publishing, 2022), 11, https://doi.org/10.2166/9781789063172.

18 John Sullivan, "Wastewater Plants Produce Twice as Much Greenhouse Gas as Estimated," Princeton Engineering, October 8, 2025, https://engineering.princeton.edu/news/2025/10/08/wastewater-plants-produce-twice-much-greenhouse-gas-estimated.

19 Ibid.

20 Amanda Lake et al., "The Challenges of Eliminating Nitrous Oxide from the Water Sector," *Chemical Engineer*, September 26, 2024, https://www.thechemicalengineer.com/features/the-challenges-of-eliminating-nitrous-oxide-from-the-water-sector/.

21 International Water Association, "Greenhouse Gas Emissions and Water Resource Recovery Facilities," 2023, 9, https://www.iwa-network.org/publications/greenhouse-gas-emissions-and-wwrfs.

22 Cuihong Song et al., "Oversimplification and Misestimation of Nitrous Oxide Emissions from Wastewater Treatment Plants," *Nature Sustainability* 7, no. 10 (2024): 1349, https://doi.org/10.1038/s41893-024-01420-9; Liu Ye et al., eds., *Quantification and Modelling of Fugitive Greenhouse Gas Emissions from Urban Water Systems* (IWA Publishing, 2022), 249, https://doi.org/10.2166/9781789060461.

23 Lake et al., "The Challenges of Eliminating Nitrous Oxide."

24 Daniel P. Moore et al., "Comprehensive Assessment of the Contribution of Wastewater Treatment to Urban Greenhouse Gas and Ammonia Emissions," *Nature Water* 3, no. 10 (2025): 1114–24, https://doi.org/10.1038/s44221-025-00490-z.

25 Lake et al., "The Challenges of Eliminating Nitrous Oxide."

26 Moore et al., "Comprehensive Assessment," at 1119.

27 Ye et al., *Quantification and Modelling*, at 13.

28 Song et al., "Oversimplification and Misestimation," at 1348.

29 Water Research Foundation, "Nitrous Oxide Emissions from Wastewater Treatment," October 31, 2024, 17, https://www.waterrf.org/resource/nitrous-oxide-emissions-wastewater-treatment.

30 David Ponder et al., "Wastewater Process Emissions Fundamentals," Water Research Foundation, July 18, 2024, 49, https://www.waterrf.org/resource/wastewater-process-emissions-fundamentals.

31 Lake et al., "The Challenges of Eliminating Nitrous Oxide."

32 Ye et al., *Quantification and Modelling*, at 247.

33 Lake et al., "The Challenges of Eliminating Nitrous Oxide."

34 Amanda Lake and Thomas Binninger, "Tackling Nitrous Oxide in Wastewater: New Strategies for Decarbonising AMP8 and Beyond," Chartered Institution of Water and Environmental Management, June 2, 2025, https://www.ciwem.org/news/tackling-nitrous-oxide-in-wastewater-new-strategies-for-decarbonising-amp8-and-beyond.

35 Lake et al., "The Challenges of Eliminating Nitrous Oxide."

36 Cambi, "Nitrogen Recovery in Wastewater Treatment," November 5, 2025, https://www.cambi.com/blog/nitrogen-recovery-wastewater.

37 Ibid.

38 Lake and Binninger, "Tackling Nitrous Oxide in Wastewater."

39 Ibid.

40 Monique Opetz, *KI macht Kläranlagen sauber*, August 2024, https://variolytics.com/wp-content/uploads/2025/11/CHIP_Variolytics_082024.pdf.

41 Microvi, "Celebrating 2024—A New Era of Biosolutions," February 11, 2025, https://www.microvi.com/latest-news/2025/02/11/celebrating-a-new-era-of-biosolutions; Microvi, "MicroNiche Engineering™ to Unlock the Power of Biology," accessed March 20, 2026, https://www.microvi.com/technology-1; Microvi, "Microvi MNE™ Achieves Breakthrough Results in 2.5-Year Full-Scale Demonstration of Low-Carbon Nitrogen Removal and Carbon Diversion," June 9, 2025, https://www.microvi.com/latest-news/2026/2/17/ljbvg9oo4gykdum1jf7irq7bex9cw3.

42 United Nations Environment Programme and Food and Agriculture Organization of the United Nations, *Global Nitrous Oxide Assessment*, at 158.

43 Lake and Binninger, "Tackling Nitrous Oxide in Wastewater"; Ali Valipoor et al., "Critical Review on End-of-Pipe Technologies for Nitrous Oxide Removal as Part of a Novel Comprehensive Concept for Greenhouse Gas Emission Mitigation at Wastewater Treatment Plants," *Water Science and Technology* 92, no. 5 (2025): 737–38, https://doi.org/10.2166/wst.2025.124.

44 Lake and Binninger, "Tackling Nitrous Oxide in Wastewater."

45 Valipoor et al., "Critical Review on End-of-Pipe Technologies," at 738; KliK Foundation, "Carbon Offsetting in Switzerland and Abroad: Proven and Effective," August 19, 2025, https://www.klik.ch/en/news/news-article/carbon-offsetting-in-switzerland-and-abroad-proven-and-effective/; Lake and Binninger, "Tackling Nitrous Oxide in Wastewater"; "ARA Bern Reduces Nitrous Oxide Emissions with RTO Technology," MQ Management and Quality, April 22, 2026, https://www.m-q.ch/en/ara-bern-reduces-nitrous-oxide-emissions-with-rto-technology/.

46 Valipoor et al., "Critical Review on End-of-Pipe Technologies," at 737.

47 Moore et al., "Comprehensive Assessment," at 1116–17.

48 Song et al., "Methane Emissions from Municipal Wastewater Collection and Treatment Systems," *Environmental Science & Technology* 57, no. 6 (2023): 2248-2261, https://doi.org/10.1021/acs.est.2c04388 at 2257.

49 Colton Poore, "Wastewater Sector Emits Nearly Twice as Much Methane as Previously Thought," Princeton Engineering, February 28, 2023, https://engineering.princeton.edu/news/2023/02/28/wastewater-sector-emits-nearly-twice-much-methane-previously-thought.

50 Moore et al., "Comprehensive Assessment," at 1114.

51 Poore, "Wastewater Sector Emits Nearly Twice as Much Methane."

52 Cambi, "Fugitive Emissions in Wastewater Treatment: A Climate Threat," November 14, 2024, https://www.cambi.com/blog/fugitive-emissions-wastewater.

53 African Development Bank Group, "African Water Facility Secures 12 Million Euros to Invest in Urban Sanitation in Africa," September 5, 2024, https://www.afdb.org/en/news-and-events/press-releases/african-water-facility-secures-12-million-euros-invest-urban-sanitation-africa-73929.

54 Bria Jamison et al., *Measuring Life Cycle Greenhouse Gas Emissions from Water Resource Recovery Facilities Workshop Report*, U.S. Department of Energy, August 2024, 6, https://doi.org/10.2172/2437707.

55 Ibid.

56 Water UK, "Net Zero 2030 Routemap Summary for Policymakers," 2020, 7, https://www.water.org.uk/sites/default/files/2023-08/Water-UK-Net-Zero-2030-Routemap-Summary-updated.pdf.

57 Lake and Binninger, "Tackling Nitrous Oxide in Wastewater."

58 Unisense Environment, "Innovation to Bridge Critical Gap in N_2O Regulation Enforcement," May 8, 2025, https://unisense-environment.com/innovation-to-bridge-critical-gap-in-n2o-regulation-enforcement-in-wastewater-sector/; Unisense Environment, "Nitrous Oxide Measurement as Key Step Towards Climate-Neutral Wastewater Treatment," April 2024, 1, https://unisense-environment.com/wp-content/uploads/2024/04/2024.04-Nitrous-oxide-measurement_web.pdf; Carina Cupit Bayley et al., eds., *Proposals for Regulatory Methods to Reduce Nitrous Oxide Emissions from Treatment Facilities* (Danish Environmental Protection Agency, 2025), 5.

59 Unisense Environment, "Nitrous Oxide Measurement as Key Step," at 1.

60 Unisense Environment, "Innovation to Bridge Critical Gap."

61 Ibid.

62 Jamison et al., *Measuring Life Cycle Greenhouse Gas Emissions From Water Resource Recovery Facilities Workshop Report*, 23–24, 28–29.

63 "About MWRA," MWRA, accessed December 23, 2025, https://www.mwra.com/about-mwra; "MWRA Fiscal Year 2026 Proposed Current Expense Budget," March 28, 2025, 2, https://www.mwra.com/media/file/032825-cebcip.

64 Jamison et al., *Measuring Life Cycle Greenhouse Gas Emissions*, at viii.

65 Ibid., at 9.

66 Lake and Binninger, "Tackling Nitrous Oxide in Wastewater."

67 KliK Foundation, *Carbon Offset Mechanism*, 2025, 03:07, https://www.youtube.com/watch?v=ftvdRLrU4wc; KliK Foundation, *Annual Report 2024*, 28, accessed November 20, 2025, https://a.storyblok.com/f/246794/x/5c88f24a1f/jahresbericht_2024_en.pdf.

68 KliK Foundation, *Carbon Offset Mechanism*.

69 Ibid.

70 Ibid.; KliK Foundation, "About the KliK Foundation," accessed November 21, 2025, https://www.klik.ch/en/foundation/.

71 KliK Foundation, *Carbon Offset Mechanism*.

72 Ibid., at 2:48.

73 KliK Foundation, *Annual Report 2024*, at 9; Lake and Binninger, "Tackling Nitrous Oxide in Wastewater."

74 InfraConcept, "Programm 0174: Reduktion von Lachgasemissionen in Der Abwasserreinigung," September 19, 2024, https://www.infraconcept.ch/de/portfolio/projekte/9-no2-emissions.

75 Ibid.

76 KliK Foundation, *Annual Report 2024*, at 9.

77 Lake and Binninger, "Tackling Nitrous Oxide in Wastewater."

78 KliK Foundation, *Annual Report 2024*, at 8; South Pole, "Case Study: Climate Protection Funding for Sewage Treatment Plants," accessed November 20, 2025, https://www.southpole.com/work/reduce-methane-emissions.

79 South Pole, "Case Study: Climate Protection Funding for Sewage Treatment Plants"; KliK Foundation, "KliK Journal," no. 3, 2025, https://journal.klik.ch/en/.

80 KliK Foundation, "KliK Journal"; South Pole, "Case Study: Climate Protection Funding for Sewage Treatment Plants."

81 South Pole, "Case Study: Climate Protection Funding for Sewage Treatment Plants"; KliK Foundation, *Annual Report 2024*, at 8.

82 Jamison et al., *Measuring Life Cycle Greenhouse Gas Emissions*, at 30–31.

83 Poore, "Wastewater Sector Emits Nearly Twice as Much Methane."

84 Jamison et al., *Measuring Life Cycle Greenhouse Gas Emissions*, at 30–31.

85 Leon Downing et al., "Making Waves: Rethinking Our Mission for N_2O Emissions at WRRFs," *Water Research X* 28 (September 2025): 4, https://doi.org/10.1016/j.wroa.2025.100320.