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DOI
10.1038/s44221-024-00318-2

Publication date
2024

Document Version
Final published version

Published in
Nature Water

Citation (APA)
Song, C., Zhu, J. J., Yuan, Z., van Loosdrecht, M. C. M., & Ren, Z. J. (2024). Defining and achieving net-zero emissions in the wastewater sector. *Nature Water*, *2*(10), 927-935. Article 113818. https://doi.org/10.1038/s44221-024-00318-2

nature water

Review article

https://doi.org/10.1038/s44221-024-00318-2

Defining and achieving net-zero emissions in the wastewater sector

Received: 28 April 2024

Accepted: 10 September 2024

Published online: 10 October 2024

Check for updates

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Here we delve into the challenges and innovative strategies for achieving net-zero emissions in the wastewater sector, a notable source of global greenhouse gases. Unlike other infrastructure sectors, wastewater management involves complex and variably quantifiable emissions across all scopes, making standardization difficult. This study provides a global overview of the sector's emissions profiles by leveraging literature mining, data analysis and case studies. It emphasizes the substantial variability in emissions, identifies key emission sources and locations, and advocates for tailored monitoring and mitigation strategies. It highlights the potential emissions shifting across scopes due to the adoption of new technologies and accounting practices, and it argues for a holistic analysis for optimization and integration to ensure a net benefit of the overall reductions in carbon footprints. This study underscores the urgency of rethinking current practices to align with ambitious mid-century net-zero targets, emphasizing the critical role of accurate emissions quantification and comprehensive decarbonization strategies.

Reporting and mitigating greenhouse gas (GHG) emissions is pivotal in efforts to achieve net-zero carbon goals for all countries, regions and industry sectors. Among the major GHG-contributing industries, the wastewater sector has been largely understudied, despite it being the fifth-largest source of CH_4 and the third-largest source of N_2O globally[1]. In addition, the wastewater sector consumes an estimated 0.8–4% of global electricity and, for many towns, wastewater facilities are among the largest energy consumers[2]. However, unlike other sectors, such as energy and transportation, where emissions can be straightforwardly quantified and mitigated by focusing on fossil-based CO_2, the nature of GHG emissions associated with wastewater management is much more complex, spanning all three emission scopes (discussed in the following) and beyond, and hard to measure and mitigate[3–6].

Current Intergovernmental Panel on Climate Change (IPCC) emissions guidelines for wastewater are focused at the country level and use a simple global emission factor (EF) or encourage country-specific EFs[7,8], but numerous research efforts have found that the actual direct emissions of wastewater treatment span four to six orders of magnitude depending on variations in site-specific factors such as treatment processes, operation conditions, geographical differences and seasons, among others[9,10]. The use of default EFs helps with country-level estimates but does not reflect the reality on the ground, and it is difficult for individual utilities, cities and regions to use them for mitigation practices. Moreover, without an accurate understanding of the GHG emissions of technologies and operations, long-lasting risks could be imposed. Wastewater technologies have long lifetimes, and the impacts and damage caused by installing inappropriate technologies will last for many decades, missing the critical window to achieve net zero by the middle of the century.

This Review provides a global analysis of the state of the art of GHG emissions from the wastewater sector, and it identifies the key knowledge gaps in emission quantification and mitigation.

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https://doi.org/10.1038/s44221-024-00318-2

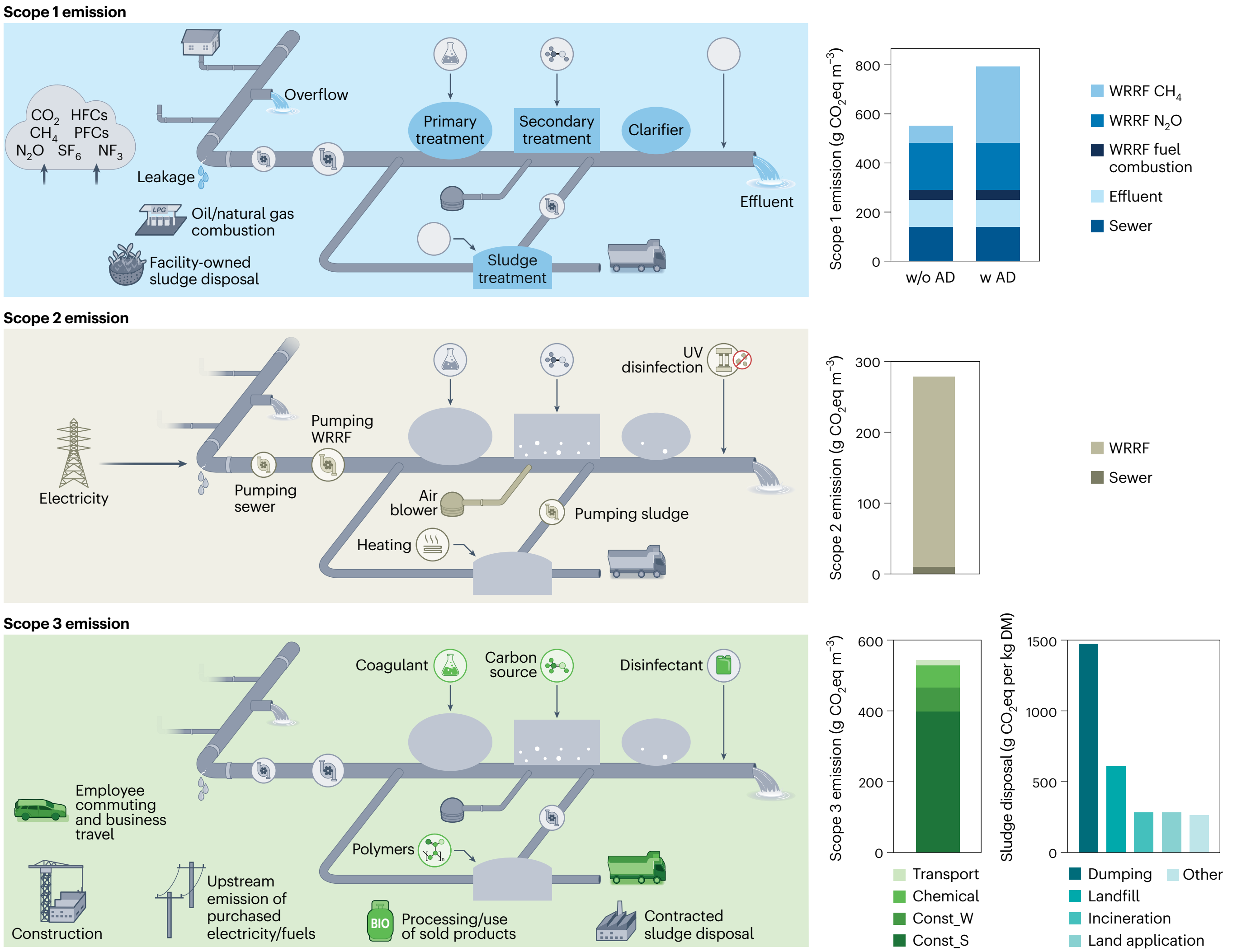

Fig. 1 | Summary of key sources and average GHG emissions by scope in the wastewater sector. Wastewater GHG emissions fall into scope 1 (top), scope 2 (middle) and scope 3 (bottom) categories. Analysis of scope 1 emissions is based on WRRFs with (w AD) and without anaerobic digestion (w/o AD). Const_S and Const_W refer to the construction of sewers and WRRF, respectively, over a 30-year lifespan to remain consistent with ref. 64. DM is dry matter of sludge. Raw data were collected from refs. 10,64,65, refs. 22,66–74 and refs. 22,64, 66–70,75 for scope 1, 2 and 3 emissions, respectively.

The current understanding and decarbonization strategies are summarized and analysed, and perspectives on short-, medium- and long-term opportunities for decarbonization are discussed. Moreover, pivotal questions and unknowns are explored with the goal of stimulating discussions and actions to decarbonize this critical infrastructure sector.

The unique emission profile of the wastewater sector

With applications in the residential, commercial and industrial sectors, wastewater management is a crucial service that aims to ensure public and environmental health[11]. It also supports a circular economy through the recovery of resources such as water, energy, chemicals and other products[6,12–14]. Wastewater from various sources is transported via the sewerage network to water resource recovery facilities (WRRFs), where it is treated by physical, chemical and biological processes to eliminate contaminants and recover value-added products before release into the environment. In these processes, GHG emissions occur in relation to three scopes. The main sources of emissions from scopes 1, 2 and 3 emissions are shown in Fig. 1. Scope 1 involves direct emissions from utility-owned facilities, including CH_4, N_2O and fossil-based CO_2 emissions from wastewater treatment and discharges, biogas and natural gas combustion, utility vehicle emissions, and other sources that are owned/controlled by WRRFs such as sewerage networks and onsite sludge disposal (for example, composting and land application). Despite direct CO_2 emissions during wastewater treatment being largely considered carbon-neutral, studies show that 4–15% may come from fossil sources such as soaps and detergents[15,16]. Scope 2 covers indirect emissions from using purchased electricity, heat or steam for operations such as pumping and aeration. Scope 3 encompasses emissions from the value chain, including construction, chemicals, by-product use (for example, biomethane) and offsite sludge management, among others[3].

The current evaluation of wastewater GHG emissions is based on the inventory methods outlined by the IPCC or national/regional guidelines aligned with the IPCC Protocols (2006, 2019)[7,8]. Due to the focus on standardized frameworks for countries or industrial sectors, single EFs are generally assigned, and specific guidance tailored to the wastewater sector remains limited, despite its complexity. Currently, accounting and reporting scopes 1 and 2 emissions is mandatory, whereas scope 3 reporting remains optional[17]. Based on the comprehensive datasets of previous monitoring campaigns and WRRF activity data across the globe, scope 1 emissions average at 550 g CO_2eq per m^3 of treated wastewater, including emissions from

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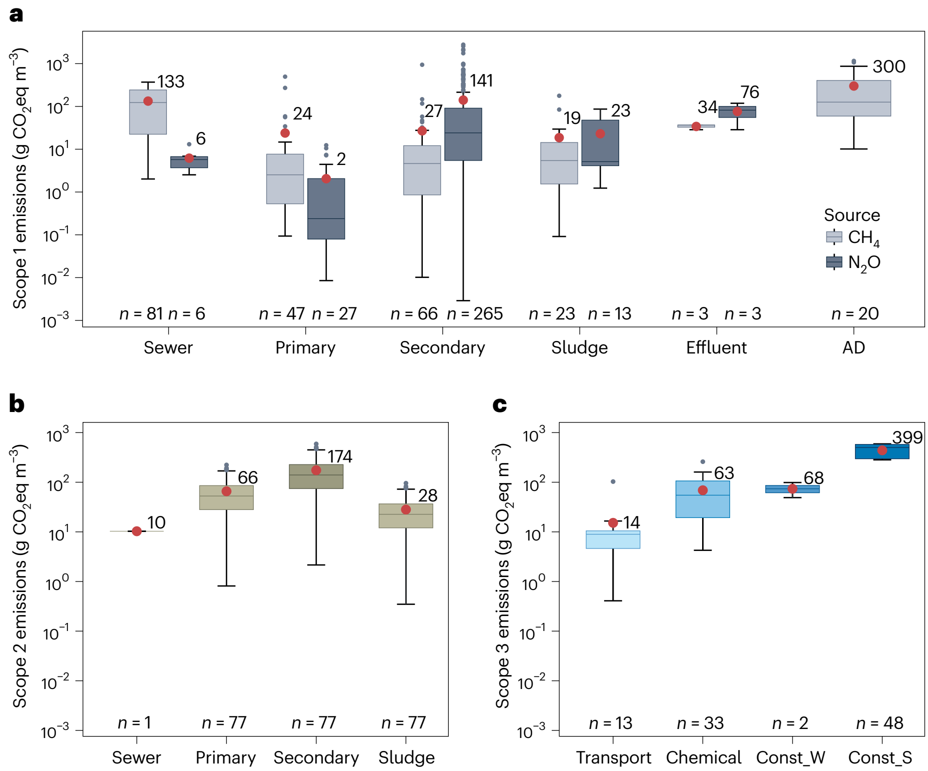

Fig. 2 | Facility-level GHG emissions from different stages of wastewater collection and treatment. **a**–**c**, Magnitude and distribution of emissions for each stage within scope 1 (**a**), scope 2 (**b**) and scope 3 (**c**). The boxplots show the 25th, 50th and 75th percentiles, and outlier bounds are based on 1.5 × IQR (interquartile range). Const_S and Const_W refer to the construction of sewer and WRRF, respectively, over a 30-year lifespan to remain consistent with ref. 64. Red dots represent the arithmetic mean, as indicated by the text above the boxes. *n*, number of monitoring data. Raw data were collected from refs. 10,64,65, refs. 22,66–74 and refs. 22,64,66–70,75 for scope 1, 2, and 3 emissions, respectively.

sewer networks, WRRFs and discharged effluent. Higher emissions are associated with WRRFs equipped with anaerobic digestion (AD) (790 g CO_2eq m^{-3}; Fig. 1). Sewer networks and AD are major sources of direct CH_4 emissions due to the anaerobic conditions, whereas N_2O emissions primarily arise from biological nutrient removal and effluent discharge (Fig. 2a). Scope 2 emissions are mainly attributed to electricity use from pumping, aeration and sludge handling, and a total of 280 g CO_2eq per m^3 of treated wastewater is estimated (Fig. 2b). Although not required to be reported now, of all evaluated scope 3 emissions, the largest contributors include the construction of sewer pipelines (400 g CO_2eq m^{-3}) and WRRFs (68 g CO_2eq m^{-3}) over a 30-year lifespan (Figs. 1 and 2c), as well as sludge disposal (0.3–680 g CO_2eq m^{-3}, assuming an average sludge production rate of 0.24 kg dry solids per m^3 according to ref. 18, Fig. 1). Chemical usage and sludge transportation are the main operational emissions reported in previous studies[8–11], contributing emissions of 63 and 14 g CO_2eq m^{-3} on average (Fig. 2c). It is difficult to give an overall contribution of the wastewater sector in terms of the total GHG emissions, as it is one of the least studied sectors, and very limited data are available. However, if one just considers the 359 km^3 of municipal wastewater generated globally each year, of which 63% (226 km^3) is collected and 52% (188 km^3) is treated[19], the contributions will be substantial. The total GHG emissions associated with centrally treated municipal wastewater are estimated to be 0.28–0.36 Gt CO_2eq per year based on simple EFs. If emissions from decentralized, uncollected, untreated and industrial wastewater are counted, these figures will probably more than double or triple, but, again, there are limited data available. Consequently, the wastewater sector, accounting for 2–3% of global GHG emissions (44.7 Gt CO_2eq; ref. 20), will become a priority in industrial decarbonization efforts after major sectors such as energy, transportation and construction are decarbonized.

Not every utility is created equal

Although single EFs are effective in estimating national GHG inventories, numerous studies have found that the actual GHG emissions from different utilities are very site-specific[21,22] and can vary by several orders of magnitude[9,10,23]. This creates substantial difficulties and disparities when utilities and the entire industry work to evaluate and mitigate their carbon footprints. For example, plant-level N_2O EFs span six orders of magnitude, ranging from 0.00003%[24] to ~25%[25] kg N_2O-N per kg total nitrogen (TN), influenced by factors such as seasonal variations, treatment processes, various monitoring campaigns, microbial community diversity, the ratio of carbon/nitrogen (C/N), effluent NO_2^- concentration, among others[9,10,21,25]. The mean N_2O EFs of certain processes such as sequencing batch reactors (SBRs) and membrane bioreactors (MBRs) with nutrient removal showed approximately threefold higher EFs than modified Ludzack–Ettinger (MLE) or oxidation ditches[9], so the uniform EF approach used by the IPCC would overestimate the emissions from some utilities while underestimating others. In addition, the 50 times increase in the default N_2O EF from IPCC2006 (0.00032 kg N_2O-N per kg TN) to IPCC2019 (0.016 kg N_2O-N per kg TN) elevated the wastewater sector into the top non-agricultural sources of N_2O overnight, further confusing the already complicated estimates. Similarly, agreement was reached by two separate studies that either directly measured 63 facilities in North America or used literature mining analysis; these studies found high variations in CH_4 emissions, with the actual CH_4 emission from the US centralized municipal wastewater treatment being about twice the IPCC2019 estimate[10,26]. Therefore, rather than a top–down approach, we argue for bottom–up, facility-level monitoring networks for precise and representative GHG inventory building, so that utilities can quantify their own emissions and develop their own decarbonization plans, which will collectively help provide a more accurate and actionable sector GHG inventory.

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BOX 1

Emission shift

Emission shift occurs when emissions transfer from one scope category to another due to changes in operations, technologies or practices within an organization. Tracking these shifts is essential for accurately assessing the net environmental impact of an organization's carbon footprint. This is especially relevant in complex scenarios like wastewater-related emissions, where a comprehensive analysis across all emission scopes is necessary before making important decisions and building GHG inventories. For instance, the Blue Plains Advanced Wastewater Treatment Plant in Washington DC experienced an increase in methanol use of 54% after installing thermal hydrolysis to enhance sludge digestibility, leading to higher ammonium loading in its A/B activated sludge process[76]. If the facility only reported mandatory scopes 1 and 2 emissions, the EF of the plant would appear to decrease due to the enhanced recovery of biogas energy. However, this would not account for the rise in scope 3 emissions due to increased methanol consumption. Fortunately, a comprehensive analysis carried out by the facility revealed that total emissions fell by 45,000 Mt CO_2eq per year, thanks to reductions from purchased electricity, decreased biosolids hauling and lower lime consumption. Therefore, while reporting scope 3 emissions is voluntary, excluding them can lead to a misleading portrayal of a net reduction if only scopes 1 and 2 are covered. Yet, the overall environmental impact may be more intricate than it appears.

The disparity in GHG footprints and decarbonization priorities within the wastewater industry is also reflected across the different scopes, depending on many factors, including geographical location, power-grid carbon intensity, treatment process, procurement of chemicals and materials, sludge disposal methods, among others. We can consider Chicago and Toronto as examples, as both are leaders in building GHG inventories and implementing decarbonization plans. Both districts have implemented advanced biological nutrient removal and anaerobic sludge digestion, and also follow the IPCC2019 tier 2 method to account for their GHG emissions. They have similar unit-level N_2O (0.016 versus 0.015 kg N_2O-N per kg TN for aerobic WRRFs at Chicago and Toronto) and CH_4 (0.018–0.48 versus 0.011–0.29 kg CH_4 per kg biological oxygen demand (BOD) for WRRFs at Chicago and Toronto) emissions[27,28]. However, because Chicago primarily uses a natural gas-based electricity source (269 kg CO_2eq per MWh), its scope 2 emissions are ~12 times higher per volume of wastewater treated than in Toronto, where the power is almost exclusively derived from low-carbon energy, including nuclear, hydropower, wind and solar (25 kg CO_2eq per MWh). Therefore, in the near term, Chicago is focusing on sourcing clean electricity, while Toronto is prioritizing limiting fugitive emissions.

As the electricity grids continue to decarbonize and WRRFs increasingly adopt renewable energy, it is natural that scope 2 contributions decrease, while scopes 1 and 3 contributions are poised to become the primary source of GHG emissions. However, another issue is beginning to emerge for some WRRFs—emission transfer across scopes and organizational boundaries. This emission transfer is relatively unique to the wastewater sector, as a holistic consideration of all three scopes of emissions is needed when considering net-zero emissions. It is hard to claim that emissions are zero if mandatory scope 1 (direct) and scope 2 (indirect electricity-related) emissions are shifted to the optionally reported scope 3 emissions (for example, increased chemical uses or offsite sludge disposal; one case study is described in Box 1). To avoid emission transfer, accurate accounting of emissions from all scopes is essential. This can be achieved by developing accurate and representative accounting methods, ensuring comprehensive and reliable data collection, enhancing data transparency and availability, and promoting clear policies and regulations.

IPCC2019 assumes that both CH_4 and N_2O emissions from free-flow sewers are negligible due to the lack of a suitable quantifying method[7], but many studies have reported that sewer networks can be important sources of fugitive CH_4 emissions. For example, previous studies found that sewers could contribute 15% of WRRF plant-wide CH_4 emission[29] or 33% of the urban street-level CH_4 emissions, with sources mainly from natural gas leakage, sewer networks and the heating furnaces of buildings[30]. Neglecting sewer systems will lead to an underestimation of GHG emissions from the wastewater sector, but monitoring and quantifying the emissions in sewer pipelines poses major challenges, as these lines are underground and closed, and they often experience dynamic hydraulic conditions. In addition, depending on the ownership of sewer infrastructures, who is responsible for such emissions is very unclear and so hard to study.

Net-zero carbon starts with net-zero energy

Until recently, net zero in the wastewater sector mostly referred to energy neutrality, which could be achieved by many utilities with a combination of increased energy efficiency, reduced energy consumption, onsite energy production via biogas, or purchased and generated renewable energy[31,32]. The current wastewater sector is energy-intensive and consumes 0.8–4% of electricity globally[2]. In many cases, WRRFs are among the largest energy consumers of a municipality, and some studies show electricity-related emissions constitute 13–21% of government operation emissions[33]. Given that scope 2 emissions account for a large percentage of the mandatory reporting emissions (~43% of scopes 1 + 2, on average, on a global scale, Fig. 3a), achieving net-zero energy is indeed a critical milestone towards achieving net-zero carbon in wastewater treatment. Considering that the power and heat sectors will achieve ~49% emission reduction by 2030 in the world, and that complete decarbonization is targeted for around 2040[34], such practices, in combination with increased energy efficiency in wastewater treatment and sewer pumping, present the most promising short-term (<10 years) opportunities, resulting in a total of 59% reduction in scope 2 emissions (Fig. 3c). By further developing and widely implementing heat recovery and biogas-based energy recovery[35], scope 2 emissions could be reduced by up to 99% in the medium term (10–20 years) and long term (>20 years). About 432 MW of clean electric capacity is realized in combined heat and power systems from ADs in 215 WRRFs in the United States[36], which offsets ~18% of electricity-related emissions. This could be further expanded to more utilities, especially in areas where renewable grid electricity is not readily available. However, investing millions of dollars to install biogas-powered engines that last 30 years may not align with the best strategies for reducing overall emissions across different scopes and operations, considering grid electricity has a much faster decarbonization rate and price drops. For utilities situated in regions with low-carbon grid electricity or small utilities without AD, funds can be used in other more impactful areas, such as reducing N_2O emissions or reducing chemical use, to advance their net-zero ambitions.

Reduce process emission through operation optimization

Optimizing process operations has been an easy and popular approach to reducing GHG emissions. Many studies have reported notable reductions in N_2O emissions through the optimization of operational settings such as dissolved oxygen (DO), substrate (C/N loadings and ratio), pH/temperature or microbial composition. For example, lowering DO levels has resulted in up to 77% reduction in N_2O emissions at full-scale SBR and MBR facilities, which also reduced electricity consumption

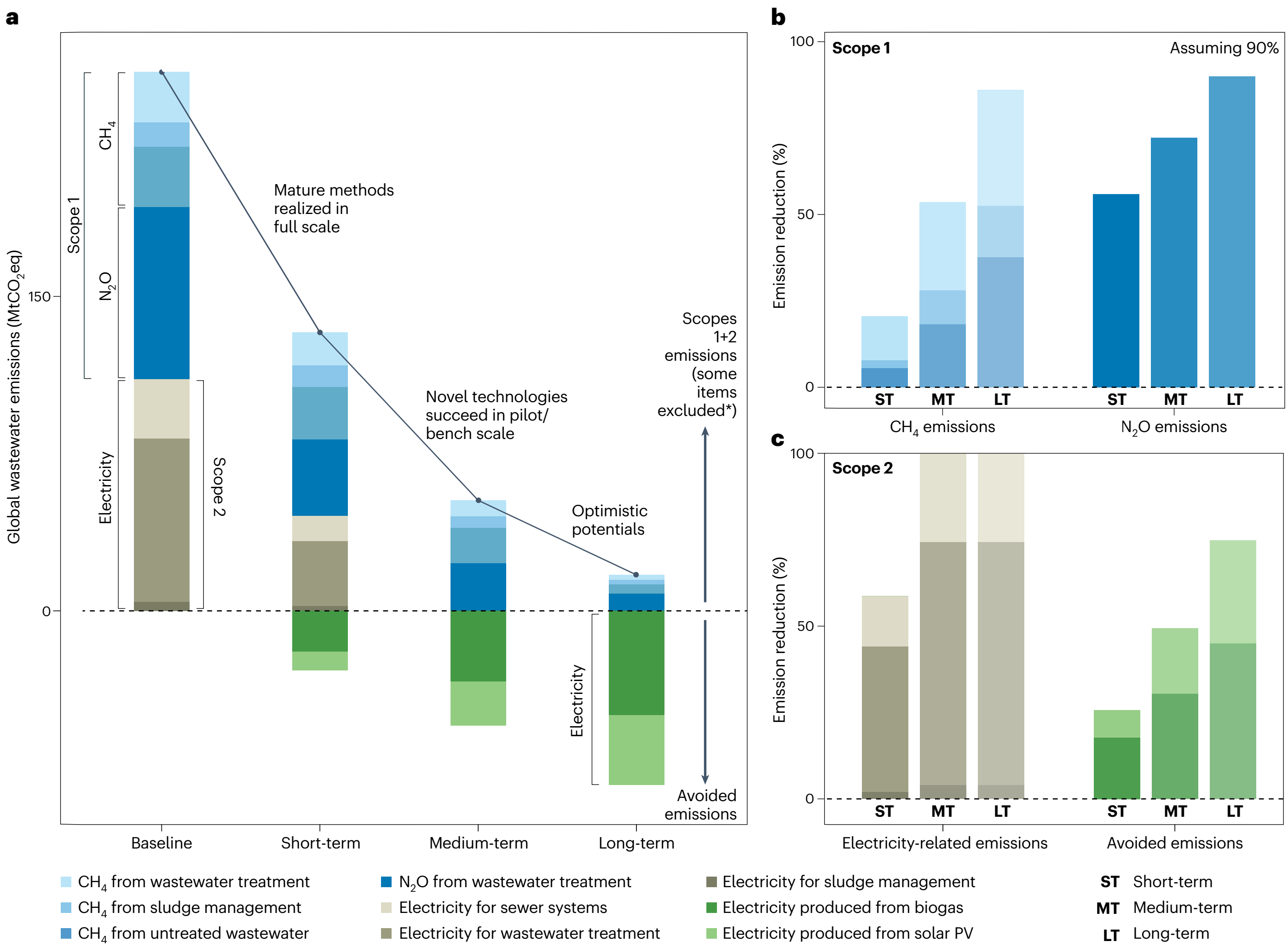

Fig. 3 | Sector-level GHG reduction potential for centralized municipal wastewater treatment in the short (<10 years), medium (10–20 years) and long (>20 years) terms. a, The decarbonization wedge for carbon footprint mitigation. Only scopes 1 and 2 are included. *Some items (for example, sewer emission) as well as scope 3 are excluded due to a lack of data. PV, photovoltaics. **b**, Emission reduction percentage in scope 1 from baseline to the short term, medium term and long term for CH_4 and N_2O emissions. **c**, Emission reduction percentage in scope 2 from baseline to the short term, medium term and long term for electricity-related and avoided emissions.

for aeration by 20%[37,38]. If these operational optimization strategies are applied at a global scale, total N_2O emissions from wastewater treatment are expected to reduce by 56% in the short term (Fig. 3a,b). However, achieving the same level of emissions reductions across all treatment processes can be challenging due to the diverse conditions required for optimal results, and prolonged testing is needed[39,40]. New developments, such as using membrane contactors or off-gas bio-scrubbers for dissolved N_2O removal and recovery, or SBRs, the Bio-denipho process and membrane aerated biofilm reactors for precisely controlled nutrient removal are promising, but full-scale applications need further investigation[41].

Compared to N_2O emissions, in-plant fugitive CH_4 emissions for WRRFs with AD can be relatively easily detected and prevented, as more than 80% of the in-plant CH_4 emission occurs at ADs and sludge storage units[10]. Equipment such as optical gas imaging infrared video cameras and portable CH_4 analysers can be easily applied to detect possible leaking locations and followed by appropriate preventive measures, such as installing thermal oxidizers, enclosing open digestate storage areas, providing a gas collection apparatus, and repairing potential leakage holes. With such management strategies, 14–83% of CH_4 leakage reduction has been achieved[42]. Low-efficiency gas flaring is another main concern; the CH_4 destruction/removal efficiency can range from <60% to nearly 100%, so upgrading equipment could greatly reduce fugitive CH_4 emission. Such practices have been widely used in the oil and gas industries, so they can be easily adopted by the wastewater sector when resources are available[43].

We note that monitoring and reducing process emissions is not necessarily a burden for plant operators, as reducing CH_4 emissions by collecting the ventilation air of sludge handling and storage facilities and using the ventilation air to run biogas heat/power units gives a higher recovery of biogas and thus some economic benefit. It is also worth noting that two other major sources of CH_4 emissions are untreated wastewater (11% of total studied scopes 1 + 2 emissions, as shown in Fig. 3a) and sewer systems. According to the limited available full-scale measurements of sewer emissions[29,44–49], CH_4 emissions from segments of sewer systems (an average value of 0.13 kg CO_2eq m^{-3}) may constitute up to 35% of direct CH_4 and N_2O emissions from wastewater treatment and discharge at WRRFs without AD (Fig. 2a). At the city scale, sewer systems in Paris have been found to emit approximately 63 metric tonnes of CH_4 per year[30]. However, emissions from untreated wastewater and sewer systems are extremely understudied, and limited research indicates that overflows from combined sewer systems and leakage from aged sewer pipelines can be major causes of GHG emissions. To reduce such emissions, policies and investment would be more substantial drivers than technological advancements. For example, de Foy and colleagues found that high CH_4 emissions from 61 urban areas closely correlate with the estimated rates of untreated wastewater based on measurements using the TROPOspheric Monitoring Instrument[50]. If this correlation was confirmed by higher-resolution remote sensing and in situ monitoring, they estimated that some urban areas could reduce emissions by >50% by completely treating the wastewater[50].

The interplay between resource recovery and decarbonization

Recognizing the rich carbon resources, nutrients, as well as other resources in wastewater, resource recovery has become an important mission for WRRFs besides wastewater treatment. A range of products, including energy, fuels, cellulose, fertilizers, minerals, biopolymers, food additives and of course clean water, have been investigated using different technologies[51,52]. Resource recovery transforms wastewater treatment from a cost-intensive process to a revenue-generating activity, and it makes a circular economy a reality. On the one hand, resource recovery is very synergistic with decarbonization, because these technologies recover value-added products, which reduce the emissions associated with the electricity or chemicals otherwise needed to produce such products from the beginning of their life cycle. For example, biogas or hydrogen-gas recovery offsets utility energy use, substantially reducing scope 2 emissions[31,53]. Emerging technologies that recover biopolymers, organic acids and animal protein would greatly reduce the use of fossil fuels or agricultural biomass as feedstocks and so carry carbon benefits across scopes. For example, a recent study found that polyhydroxybutyrate (PHB) production from wastewater can achieve similar environmental and economic benefits to traditional sugar-based PHB production, with a production cost of €1.40, a global warming potential of 2.4 kg CO_2eq, and a non-renewable energy use of 106 MJ in producing 1 kg of PHB[54]. Furthermore, the development of innovative biosolid management techniques, such as converting biosolids to biochar, biocrude and struvite, also supports a circular economy by conserving landfill space, reducing the reliance on non-renewable resources and fuels compared to traditional methods like landfill, incineration and land application[14]. It is worth noting, however, that the actual environmental and economic benefits remain uncertain in these early-stage technologies, and more pilot and full-scale deployments would greatly reduce the uncertainty.

The net impacts in terms of carbon footprint are more complex than the direct benefits for some technologies, and deeper and more holistic analyses are needed. For example, anammox-based processes are increasingly deployed at full scale due to their excellent performance in nitrogen removal, with reduced demands in terms of energy, carbon source and alkalinity, but numerous studies have reported higher N_2O emissions of such processes compared to traditional biological nutrient-removal processes, although some also report lower numbers[55]. For example, pilot- and full-scale comparative studies have reported that the EF increased from 0.3% to 1% kg N_2O-N per kg TN after switching from traditional nitrification–denitrification to mainstream anammox-based N removal[56]. Full-scale studies in Denmark reported that, although the overall average EF of WRRFs was 0.84% kg N_2O-N per kg TN, anammox sidestream processes had an EF of 5–6% kg N_2O-N per kg TN due to high loading and removal rates. Similarly, anaerobic treatment processes, such as the anaerobic membrane bioreactor (AnMBR), have gained popularity due to their energy savings and ability to recover biogas. However, dissolved CH_4 in the effluent remains a major issue, as it leads to energy losses, increased GHG emissions and potential safety hazards. Studies indicate that between 40% and 60% of total CH_4 could be lost during effluent discharge[57,58]. Considering that the 20-year global warming potential of $CH_{4\ \text{non fossil origin}}$ is 81 times that of CO_2 according to the IPCC Sixth Assessment Report[59], the release of such dissolved CH_4 could not only negate the benefits derived from biogas utilization, but also cause ~15 times the damage in terms of additional carbon footprint. Although technologies such as membrane contactors can recover a substantial portion of the dissolved CH_4 (57% to nearly 100%[41,60]), this may still be insufficient to completely mitigate this negative impact. Additionally, the implementation of these technologies involves increased energy consumption and equipment costs, with few commercial applications reported so far. Although it is still rather early to draw conclusions regarding which processes have higher overall carbon footprints, as current data vary significantly, we must be wary of pursuing some savings at the cost of higher emissions in other categories.

> **BOX 2**
>
> ### Emission reduction in the context of the urban water cycle
>
> Recent studies in Australia highlighted that water heating for residential, industrial and commercial uses accounted for 7% of the nation's GHG emissions[77]. This figure alone is more than five times the scope 1 and 2 combined emissions from wastewater treatment. Although household water heating is not considered by the wastewater industry, reducing hot-water usage effectively decreases what could be termed 'scope 4' emissions by lowering the volume of wastewater entering the system. Investing in water saving may thus be a more cost-effective way to reduce overall emissions for the whole water cycle compared to the current focus on 'within gate' strategies. However, challenges exist in defining boundaries and identifying the responsible and benefiting parties.

Beyond the gates and beyond the scopes

So far, most studies have focused on the three scopes of emissions related to wastewater conveyance and treatment, but a broader understanding is necessary, as carbon accounting should extend beyond the confines of facility gates to encompass the entire urban water cycle. There is, however, a lack of clarity and some confusion. For example, liquid discharges are generally classified as scope 1 emissions, because such effluent is a direct product of the WRRF operation, and its quality can be controlled by the utility. On the other hand, solid discharges from WRRFs can be either scope 1 if disposed of on site, or scope 3 if sludge disposals occur at locations beyond the utility's control.

It is not only the physical barriers that need to be removed when considering the carbon footprint; the expanded scopes of GHG emissions, or so-called scope 4 emissions, can be important for wastewater infrastructure. Although not officially defined by the IPCC and GHG Protocol Standard, scope 4 emissions represent avoided emissions associated with a service or products[61,62]. Similar to the case of remote conference calls avoiding emissions associated with commuting and travel, water conservation can indirectly reduce emissions in the wastewater sector. By lowering the volume of wastewater that needs treatment, it lowers the emissions tied to the use of energy and chemicals, and it may reduce fugitive emissions too. Furthermore, the recovery of heat, nutrients and chemicals can also be considered scope 4 emissions, as such recovered products reduce and avoid the GHG emissions otherwise associated with synthetic fertilizer or chemical productions from fossil or other sources (Box 2).

Popular carbon offsets also include direct carbon capture, such as natural sequestration through tree planting and active engineered carbon capture. In 2019, water companies in England announced plans to plant 11 million trees as a part of a broader commitment to improve

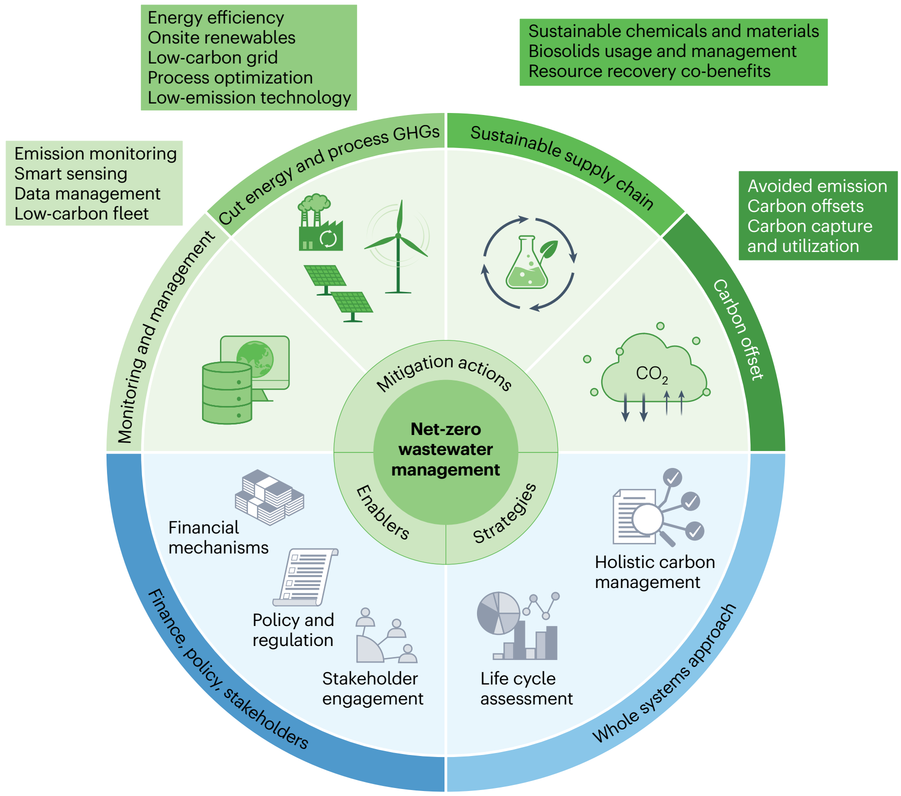

Fig. 4 | Mitigation actions, strategies and enablers for achieving net-zero emissions in the wastewater sector. A holistic analysis and system understanding, underpinned by robust finance, policy frameworks and stakeholder engagement, are essential for the effective design, implementation and verification of diverse mitigation strategies to maximize GHG reduction.

the natural environment and support their net-zero goals, but they projected such efforts would have limited near-term mitigation potential (0.005 Mt CO_2eq per year) in the first decade. Greater benefits are expected in the next 20–30 years (0.086 Mt CO_2eq per year) as the trees mature[63]. In the short term, emerging processes such as alkalinity enhancement in wastewater treatment are being explored to capture and stabilize CO_2 by forming bicarbonate and carbonate ions. Such practices can be applied either during wastewater treatment or to the wastewater effluent. However, it is worth noting that current corporate reporting guidelines require utilities to separately report avoided emissions (or scope 4 emissions) and carbon credits without netting off their impacts. Such separation ensures that the emission reductions are accurately accounted for in line with science-based reporting frameworks.

Towards net-zero emissions

Achieving net-zero GHG emissions is an inspiring mission that requires holistic analyses and system understanding to design, implement and verify diverse mitigation strategies, with support from finance, policy and stakeholder perspectives (Fig. 4). This study, although not exhaustive, aims to present the latest developments and stimulate critical reflection on the existing gaps in both knowledge and practice in terms of achieving net-zero emissions. The discussed mitigation strategies include implementing advanced sensing technologies and robust frameworks for real-time monitoring to achieve a more accurate quantification of direct emissions. To increase energy efficiency and cut scope 2 emissions, it is essential to replace old equipment, upgrade infrastructure and integrate onsite renewable energy production while sourcing low-carbon electricity. Developing sustainable supply chains, adopting new low-emission technologies and enabling resource recovery are also critical steps. Additionally, exploring opportunities for carbon offset and carbon capture, as well as considering emissions across the entire life cycle of operations, would further support decarbonization efforts. Beyond the technical aspects, engaging with the public, policymakers and other stakeholders is also critical for knowledge sharing and goal alignment. These combined efforts will substantially contribute to achieving net-zero goals in the wastewater industry, transforming decarbonization from an inspiring concept into a practical and achievable reality.

Data availability

The raw dataset used in this study, along with documentation of data collection and processing, is publicly available on the Open Science Framework at https://osf.io/bydnv/.

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Acknowledgements

C.S., J.-J.Z. and Z.J.R. appreciate the support from the Water Research Foundation Paul L. Busch Award, Project 5188, and the Andlinger Center for Energy and the Environment at Princeton University. Z.Y. is a Global STEM Professor funded by the Government of the Hong Kong Special Administrative Region, China.

Author contributions

Z.J.R. conceived the initial idea, with input from all co-authors. C.S., J.-J.Z. and Z.J.R. conducted data analysis. C.S., J.-J.Z. and Z.J.R. wrote the draft, and Z.Y. and M.C.M.v.L. edited and commented on the manuscript.

Competing interests

The authors declare no competing interests.

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Peer review information *Nature Water* thanks Wayne Parker, Glen Daigger and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.