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# Balancing energy recovery and greenhouse gas emissions in wastewater treatment with model-assisted analysis

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**Abstract:** Achieving net-zero emissions is a critical goal for the water industry. This study utilizes mechanistic modelling to provide a comprehensive evaluation of energy recovery and direct greenhouse gas (GHG) emissions from a full-scale wastewater treatment plant (WWTP), emphasizing the balance between carbon capture and emissions reduction. Long-term monitoring results revealed that upstream carbon capture, while recovering significant energy for carbon offset (40% of total emission), significantly stimulated downstream nitrous oxide ($N_2O$) emissions, a major contributor to Scope 1 emissions. In response, integrated mitigation strategies were developed through mechanistic modelling, considering process optimization and retrofitting solutions. The identified strategy reduced $N_2O$ emissions by 50% and the overall carbon footprint by 40%, despite a 31% decrease in energy recovery, compared with the baseline case. The findings demonstrated the need for a holistic assessment of carbon capture, energy recovery, and GHG emissions across the entire treatment process. The outcome offers actionable insights to guide WWTP operations toward achieving net-zero emissions.

**Keywords**: mechanistic modelling; model-assisted analysis; greenhouse gas; mitigation

## Introduction

The wastewater treatment sector must address the growing climate crisis by reducing greenhouse gas (GHG) emissions, particularly Scope 1 (nitrous oxide [$N_2O$] and methane [$CH_4$]) and Scope 2 emissions (energy-related). A-B wastewater processes, which capture carbon in the A-stage for energy recovery and focus on nitrogen removal in the B-stage, are gaining attention for their potential to maximize energy recovery and reduce Scope 2 emissions (McCarty et al., 2011). However, carbon capture and energy recovery in the A-stage poses a significant risk of depleting COD needed for denitrification in the B-stage, potentially increasing $N_2O$ emissions due to incomplete denitrification under COD-limited conditions (Law et al., 2012). This trade-off between energy recovery and $N_2O$ emissions remains poorly understood, with no systematic analysis of the impact of upstream carbon capture on downstream emissions.

While reducing Scope 2 emissions through energy recovery is essential, directly mitigating Scope 1 emissions, especially $N_2O$ emissions, is critical to reduce the net carbon footprint. Various $N_2O$ mitigation strategies have been developed to reduce $N_2O$ productions (Duan et al., 2021). However, these mitigation strategies were mostly developed and assessed on a single unit or a single scope of emissions, rather than adopting a comprehensive, system-wide evaluation.

This study addresses these gaps by conducting two years of GHG and performance monitoring on a full-scale four-step-feed bioreactor treating effluent from an upstream carbon capture process (anaerobic lagoon). Using these monitoring results, a model-assisted approach was applied to holistically investigate the balance and trade-offs between upstream carbon capture and downstream GHG emissions, providing integrated strategies to effectively reduce net emissions.

## Material and Methods

This study collected data from a full-scale anaerobic lagoon and step-feed bioreactor in Australia. The bioreactor, treating effluent from the anaerobic lagoon, is divided into four passes that alternate between anoxic and aerobic zones to achieve nitrogen removal. Scope 1 emissions ($N_2O$ and $CH_4$) were monitored with floating hoods, and electricity use and generation were converted to Scope 2 emissions and energy recovery as $CO_2$ equivalents using local grid factors (0.79–0.96 kg $CO_2$-eq/kWh). Net system emissions were calculated by combining Scope 1 and Scope 2 emissions, subtracting energy recovery, and normalizing by flow rate (kg $CO_2$-eq/ML). Operational data were monitored online, and hourly samples of key parameters were collected during intensive sampling campaign for model calibration and validation.

The activated sludge model used in this work combined the modified classic Activated Sludge Model (ASM) No. 1 (Henze et al., 2006), the four-step denitrification model (ASMN) (Hiatt and Grady, 2008) and the modified two-pathway $N_2O$ production by AOB model (Pocquet et al., 2016). After calibration and validation, the model was used to evaluate the effectiveness of the proposed mitigation strategies. These strategies were categorized into process optimization and retrofitting, with the best approaches identified based on their potential to reduce GHG emissions and maintain nitrogen removal efficiency.

## Results and Discussion

Figure 1(A) presents the monthly average combined Scope 1 and Scope 2 emissions, energy recovery and net emissions for the monitored timeframe from anaerobic lagoon and secondary bioreactors. The average net emissions were 360.3 kg $CO_2$-e per ML of raw influent. The figure shows that energy recovery from biogas combustion in the anaerobic lagoon offset Scope 2 emissions in 15 out of the 23 months monitored. Figure 1(B) provides a detailed breakdown of the average net emissions and offset emissions (energy recovery) over the entire monitoring period, along with the contributions of different emission sources to the total emissions. The majority of total emissions originated from Scope 1 $N_2O$ emissions in secondary treatment (62.3%). Scope 2 emissions from secondary treatment also made a significant contribution (34.9%), while the contributions from Scope 1 $CH_4$ emissions and Scope 2 emissions from the anaerobic lagoon were relatively minor. From a long-term perspective, the offset emissions (39.5%) could successfully counterbalance Scope 2 emissions (a total of 35.5%), leaving $N_2O$ emissions as the primary contributor to net emissions. This highlights the critical importance of targeting $N_2O$ emissions for mitigation to achieve further reductions in net carbon footprints.

Understanding $N_2O$ emissions is essential for developing mitigation strategies. Figure 2(A) shows a strong correlation between dissolved $N_2O$ concentrations and nitrite accumulation across all four aerobic passes, where nitrite accumulation stimulates $N_2O$ emissions via the AOB nitrifier denitrification pathway (Law et al., 2012). Emissions from aerobics 3 and 4 were also influenced by $N_2O$ carried over from the preceding anoxic zone. Incomplete denitrification in later passes likely results from COD deficiency, caused by upstream COD removal for biogas generation in the anaerobic lagoon. Figure 2(C) highlights a significant reduction in organic material, particularly soluble COD after the anaerobic lagoon.

Based on the understanding of $N_2O$ emissions from various locations of the step-feed bioreactor, four types of mitigation strategies were developed: changing the bioreactor split ratio, adjusting DO setpoints, modifying the influent mixing ratio and diverting raw wastewater directly to bioreactor bypassing the anaerobic lagoon. Each strategy was tested in the calibrated model, with

the best results achieved by combining all four. As seen from Figure 3(A), the integrated solution successfully reduced the $N_2O$ emission factor to 0.65% TKN load, which was a 50% reduction from the baseline scenario. The ammonia and total nitrogen removal remained stable after mitigation. Additionally, net emissions were reduced from 354.29 kg $CO_2$-e/ML to 211.82 kg $CO_2$-e/ML, achieving a 40% overall reduction, though the energy recovery was reduced by 31% as seen from Figure 3(B) These results emphasize the need for mitigation strategies that account for Scope 1 while also addressing Scope 2 and energy recovery.

## Conclusion

Carbon capture and energy recovery have been increasingly applied in WWTPs to improve energy efficiency (Gu and Liu, 2020). Despite the benefits of carbon recovery, this work showed that there is a potential risk to stimulate downstream $N_2O$ emissions, especially in step-feed configurations where later stages receive less influent. Conversely, completely avoiding upstream carbon capture eliminates energy recovery and increases the net carbon footprint. It is essential to use a model-assisted approach to holistically evaluate the balance and trade-offs between upstream energy recovery and downstream emissions, ensuring the lowest net emissions are identified during the design phase.

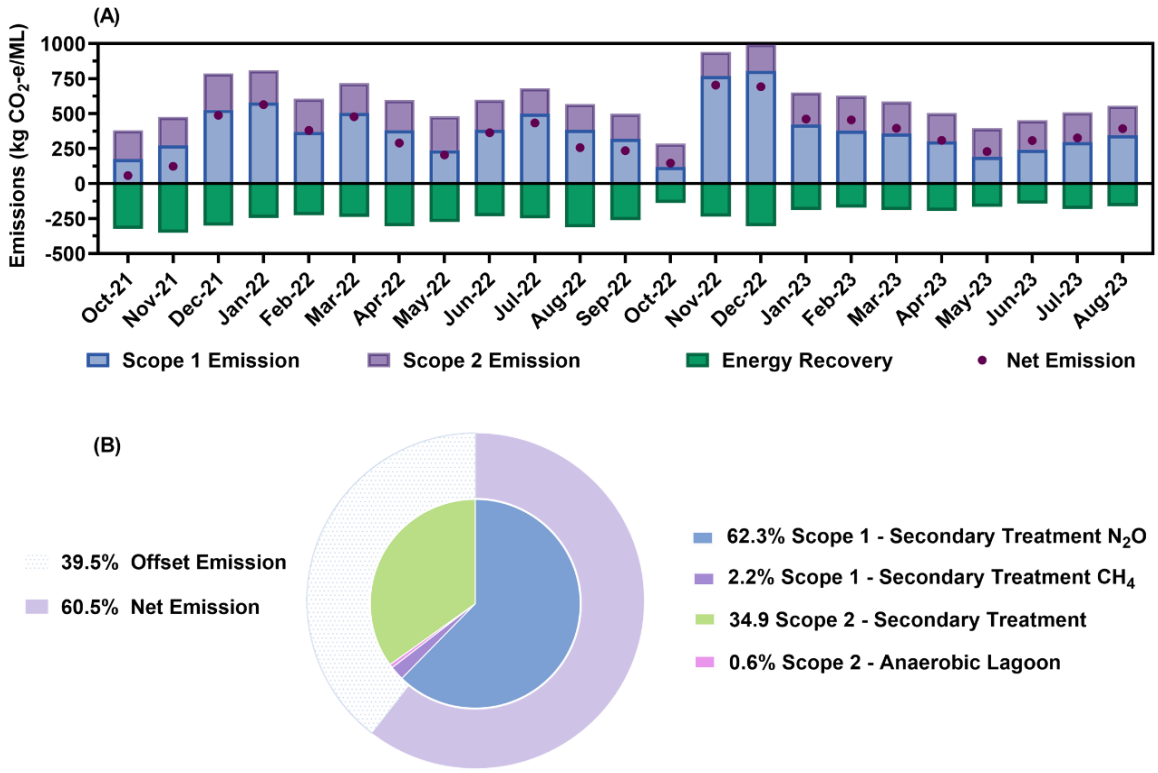


**Figure 1.** (A) Scope 1 emission, Scope 2 emission, energy recovery and net emission from anaerobic lagoon and secondary treatment; (B) Double pie-chart illustrating average emissions breakdown for entire monitoring period. The outer pie chart shows offset and net emissions. The inner pie chart details contributions for each type of emission.

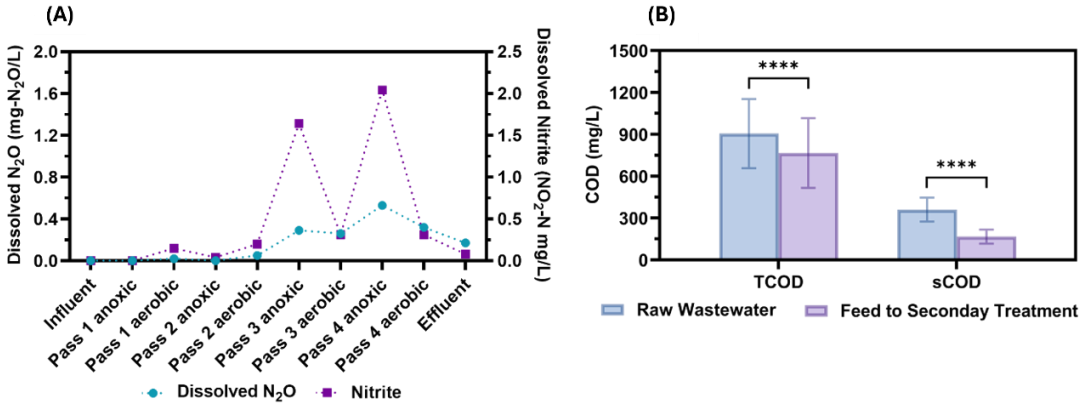


**Figure 2.** (A) intensive sampling results from a typical hour; (B) TCOD and sCOD concentrations before and after anaerobic lagoon. The significance of the results was evaluated by an analysis of variance (n = 89 for TCOD and n=36 for sCOD). ****: p<0.0001.

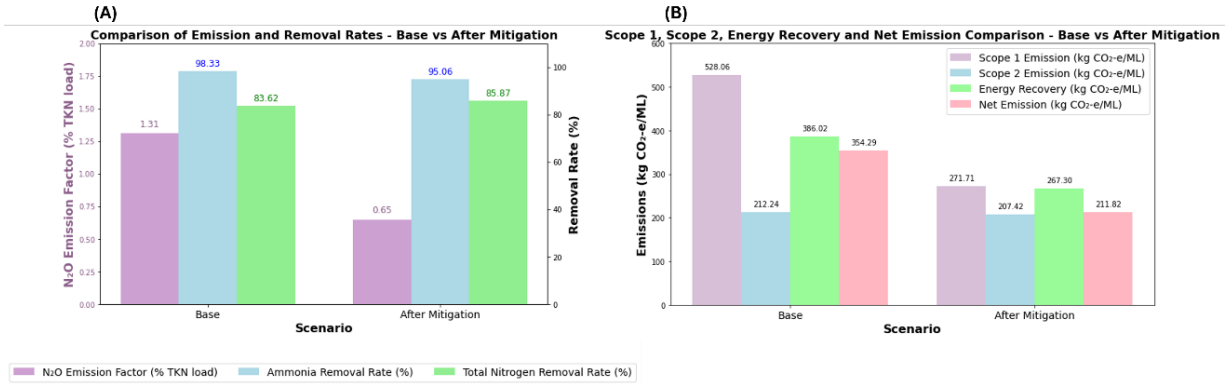


**Figure 3.** (A) Comparison of $N_2O$ emission factor, ammonia and total nitrogen removal rate for base and model-predicted mitigation scenarios; (B) Comparison of Scope 1, Scope 2, energy recovery and net emission for base and model-predicted mitigation scenarios.

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