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# Mitigating Nitrous Oxide Emissions in a Full-scale Industrial Activated Sludge Reactor Using Advanced Aeration Control Strategies under Multiple COD/N Ratios

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**Abstract:** Digital tools have become essential for quantifying and predicting greenhouse gas (GHG) emissions in urban wastewater treatment plants (WWTPs), enabling the development of strategies with a high probability of achieving net-zero targets. However, comprehensive studies documenting validation of model predictions remain scarce within full-scale industrial settings. This study aims to develop a decision support tool (DST) for predicting nitrous oxide ($N_2O$) emissions and suggesting mitigation strategies in full-scale industrial activated sludge reactors (ASRs). The DST, incorporating mathematical models and key performance indicator (KPI) assessment tools, was developed and validated using full-scale data (across multiple aeration control strategies and influent COD/N ratios) collected at the largest industrial wastewater treatment system (iWTS) in Northern Europe. Results show that the simulations reproduced high-frequency dynamics of multiple nitrogen species ($NH_x$, $NO_2^-$, $NO_3^-$, dissolved and gaseous $N_2O$), dissolved oxygen (DO), and airflow (NRMSE <0.16). Analysis indicates that the correlation ($R^2$ up to 0.9) between $N_2O$ emission factors (EF) and influent COD/N ratios is significantly influenced by the aeration strategies. These EFs range from 0.2% to 1.5%. Furthermore, the DST generated response surfaces illustrating the variations in EF, nitrification rates (NR), total nitrogen (TN) removal, and aeration efficiency (AE) as functions of different aeration control setpoints (DO and $NO_2^-$), suggesting a feasible aeration control strategy to achieve 71% reduction of $N_2O$ emission and performance improvements.

**Keywords**: Digital twin; net zero; performance optimization

## Background and Relevance

Carbon neutral vision and the introduction of climate change adaptation/mitigation aspects within EU legislation will force the wastewater industry to take a closer look at $N_2O$ production, which could account for up to 80% of plant total direct GHG emissions (**Ye et al., 2022**). Digital tools have become essential for reproducing data and suggesting strategies to achieve net-zero targets. However, existing research predominantly addresses municipal wastewater treatment plants (WWTPs). Industrial settings with unique influent characteristic and process configurations need a large extent. Moreover, various aeration control strategies have been introduced for $N_2O$ mitigation (**Flores-Alsina et al., 2025**), while the aeration patterns need further validation.

## Material and Methods

This case study focuses on the largest industrial wastewater treatment facility (iWTS) in Northern Europe, responsible for handling a pollution load equivalent to 2.5 million population equivalents (PE) within a compact inflow of 12,000 $m^3$/day. The focus of this study is on the activated sludge bioreactors (ASR) where the nitrogen conversion processes occur. The ASR is operated with alternating airflow based on ammonium ($NH_X$) and nitrite ($NO_2^-$) signals, switching ON and OFF for the nitrification/denitrification processes. **Figure 1** shows that the ASR receives effluent from anaerobic granular sludge reactors ($AnGSR_{Eff}$) and dewatering systems ($DEW_{Over}$), while sending its effluent to the secondary clarifier for water-sludge separation ($SEC_{Over}$ and $SEC_{WAS}$) (**Monje et al., 2022**).

A set of mathematical tools were developed and combined to (dynamically) predict treatment processes for both reactor mass-balances and high-frequency dynamics. The proposed approach accounts for three $N_2O$ production pathways: 1) nitrifier nitrification ($NH_2OH$ oxidation) (NN) pathway, nitrifier denitrification (ND) pathway and heterotrophic denitrification (DEN) pathway (**Solís et al., 2022**). The model is calibrated / validated using two data sets. The first (**#D1**) was obtained during a five-week measuring campaign with grab and flow proportional samples. The second (**#D2**) involved collecting sensor data to monitor high frequency dynamics within the ASR, including dissolved oxygen (DO), $NH_X$, $NO_2^-$, $NO_3^-$ and both dissolved & gaseous $N_2O$. The **#D2** represented three aeration controls strategies: Normal Operation Control (*Baseline*), Low DO Control (*Scenario #1*) and Low DO + Low $NO_2^-$ Control (*Scenario #2*) (See **Table 1**).

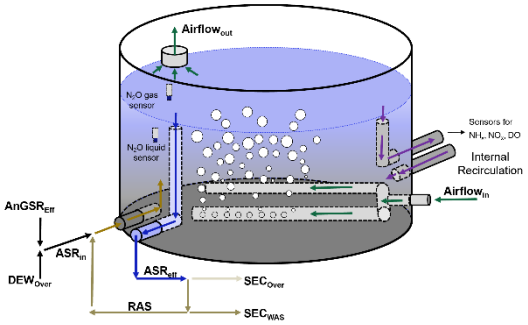


**Figure 1**. Configuration and sensor location for the industrial active sludge reactor (ASR).

**Table 1**. Scenario descriptions and aeration control settings

| | | | *Baseline* | *Scenario#1* | *Scenario#2* | Model-based Scenarios |
|---|---|---|---|---|---|---|
| **Manipulated** | | | DO ($NH_x$ in the model) | | | DO |
| **Controlled** | | | $NH_x$ (DO in the model), $NO_2^-$ | | | $NH_x$, $NO_2^-$ |
| **COD/N ratio** | | | 8.5 | 7.6 | 7.4 | 6.5, 8.5, 10 |
| **Setpoints ($g/m^3$)** | ON | $NH_x$ | 6 | 6 | 6 | 4 - 14 |
| | | $NO_2^-$ | 0 | 0 | 0 | 0 |
| | | DO | 5 | 2 | 2 | 2 - 5.5 |
| | OFF | $NH_x$ | 3 | 3 | 3 | 3 - 13 |
| | | $NO_2^-$ | 10 | 10 | 5 | 2 - 15 |
| | | DO | 0 | 0 | 0 | 0 |

## Key Findings

**1)** The DST successfully replicates daily mass-balances of chemical oxygen demand (COD) and nitrogen (N) removal, phosphorus (P) precipitation and sulfur (S) transformation (deviation 8.6%) (**Lei et al., 2025**). Specifically for N, an average total load of 6 tonsN/day is treated, 70 % is denitrified and on average 1% is emitted as $N_2O$ (**#D1**).

**2)** The DST accurately captures aeration variables (DO, airflow), nitrogen oxidation species ($NH_x$, $NO_2^-$, $NO_3^-$, dissolved and gaseous $N_2O$). These predictions are validated across various aeration controls (**#D1, #D2**): Normal Operation Control (*Baseline*) (See **Figure 2**), Low DO Control (*Scenario #1*) and Low DO+$NO_2^-$ Control (*Scenario #2*) (See **Figure 3**) with NRMSE values of 0.16, 0.14 and 0.11.

**3)** EFs from both plant data and DST predictions for the three aeration scenarios range from 0.2% to 1.4%. *Scenario #1*, with a low DO level, achieves a 22% reduction in $N_2O$ emissions relative to Baseline, while *Scenario #2*, with both low DO and $NO_2^-$ levels, yields an 80% reduction (See **Figure 4**).

**4)** A strong negative correlation ($R^2$ up to 0.9) between influent COD/N ratios and $N_2O$ emission factor (EF) is observed in *Baseline* and *Scenario #1*, while no evidence for the correlation in *Scenario #2*. Moreover, model predictions in *Scenario #2* tend to overestimate EFs under low COD/N (See **Figure 4**), probably due to the dissolved $N_2O$ peak levels bellowing sensor detecting limit (< 0.05 g $N/m^3$).

**5)** The DST examines KPIs including EF, nitrification rate (NR), total denitrified nitrogen ($TN_{DN}$) ratio, and aeration efficiency (AE) in response surfaces (generated in the model) based on DO and $NO_2^-$ setpoints (See **Figure 5**). The EFs generally decrease as those two setpoints are lower, while $NO_2^-$ setpoints seem more influential than DO.

**6)** Considering maintaining the NR to be robust for treating potential high N load, the DST recommends high DO setpoints (4 - 5.5 $g/m^3$) to achieve minimal EFs with $NO_2^-$ setpoints between 4 and 5 g $N/m^3$. This strategy reduces $N_2O$ emission by 71%, improves effluent quality and AE, and is also robust under different COD/N ratios (See **Figure 5**), which has been successfully implemented in our industrial partner.

## Outlook

This DST has provided strategies on mitigating GHG from one of the most contributing processes in the industrial partner's Scope 1 emission. This DST will be further developed to assess the sustainability in the iWTS, considering redirecting flows, sludge handling, chemical dosing, effluent quality, as well as energy recovery, with a potential application to other waste/wastewater treatment facilities.

## References

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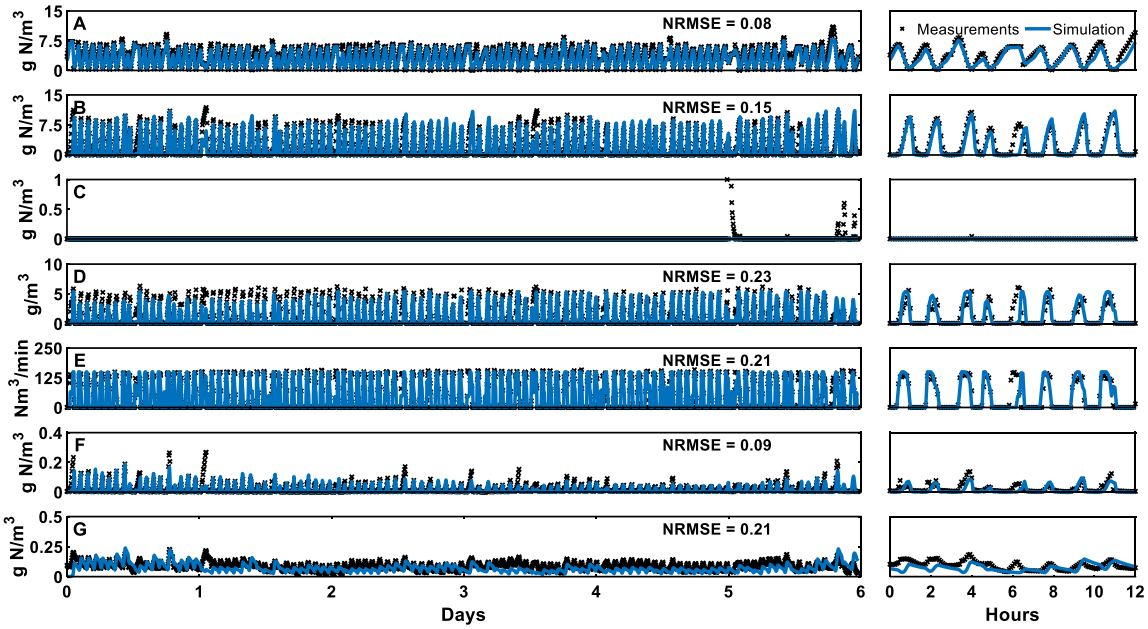


**Figure 2.** High resolution dynamic model prediction (blue solid lines) and on-line sensor measurement data (black crosses) comparison for **A**: $NH_x$, **B**: $NO_2^-$, **C**: $NO_3^-$, **D**: DO, **E**: airflow, **F**: dissolved and **G**: Gas $N_2O$ in **#D2** *Baseline*

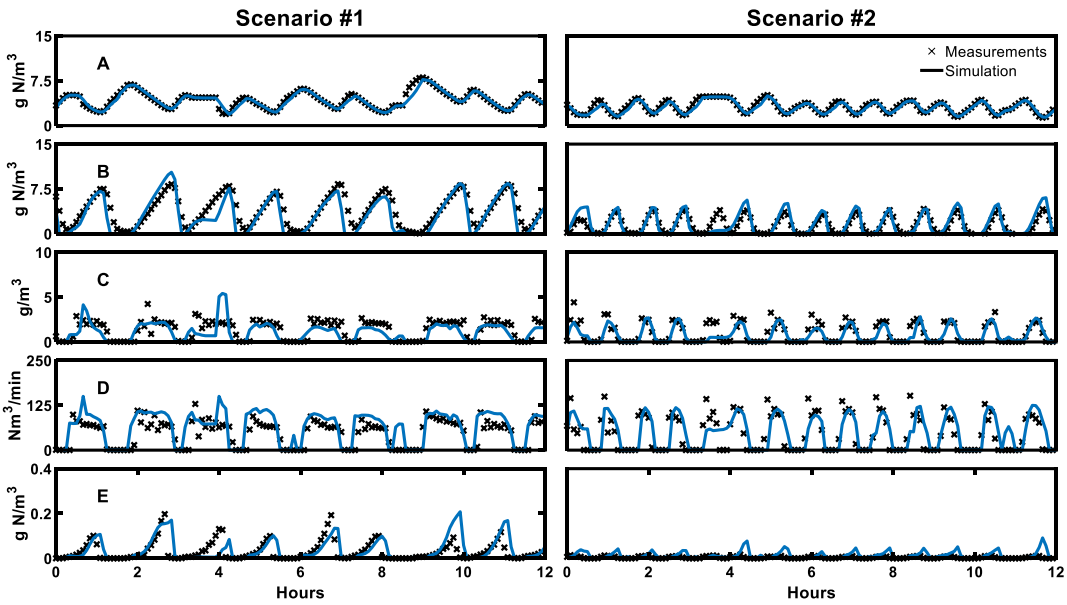


**Figure 3**. Twelve-hour simulations (solid lines) and measurements (crosses) for **A.** $NH_4^+$, **B.** $NO_2^-$, **C.** DO, **D.** airflow and **E.** dissolved $N_2O$ under *Scenario #1* (column 1) and *Scenario #2* (column 2).

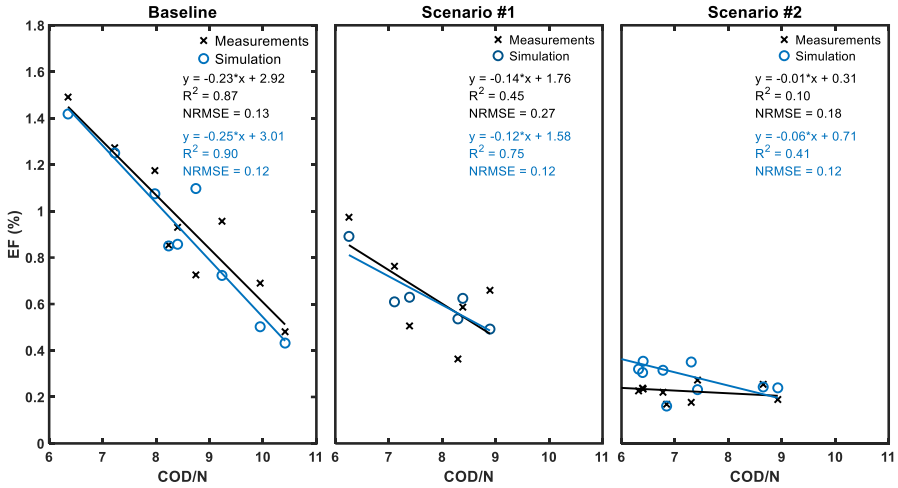


**Figure 4**. Simulation results (circles) and measurements (crosses) for daily emission factors of $N_2O$ (EF) vs daily influent COD/N ratios under *Baseline*, *Scenario #1* and *Scenario #2*.

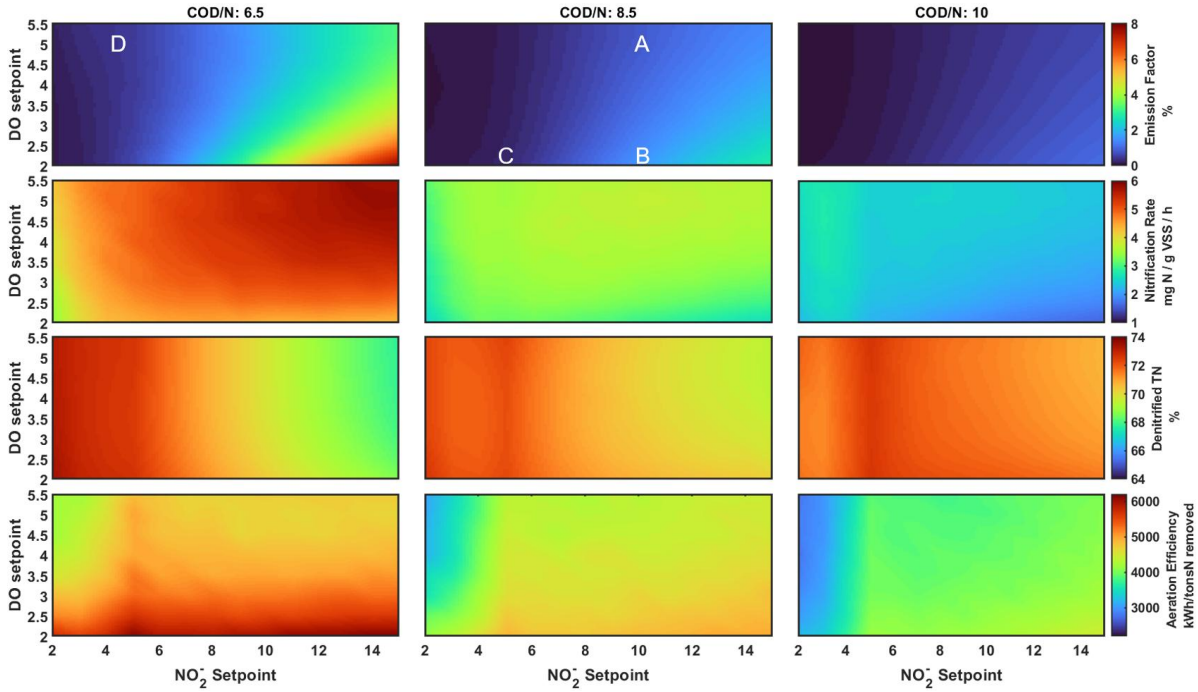


**Figure 5**. Four KPIs: EF, NR, $TN_{DN}$ ratio, and AE (rows top to bottom) under a combination of different DO and $NO_2^-$ setpoints for aeration patterns with different COD/N ratios (columns left to right). Strategies in **A:** *Baseline*, **B:** *Scenario #1*, **C:** *Scenario #2*, **D:** DST optimized strategy