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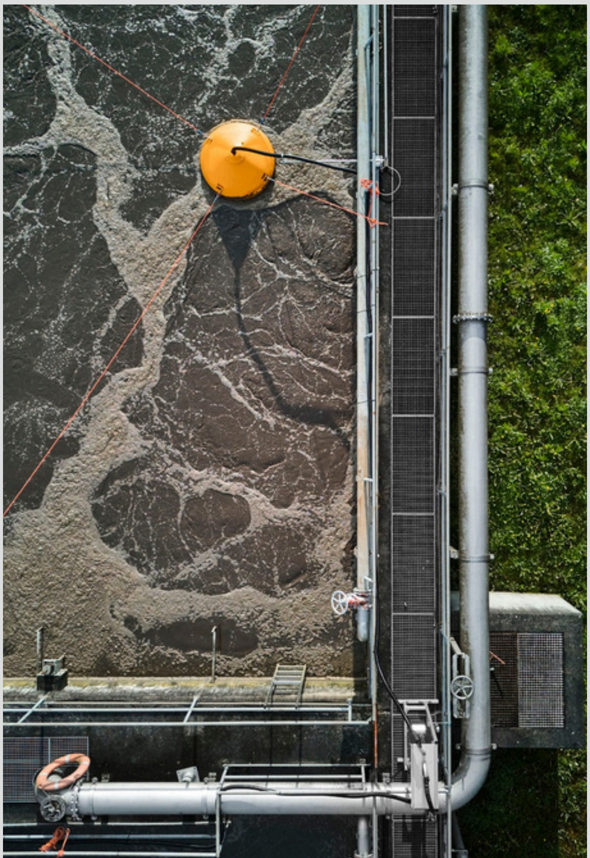
Case Study:

Year-round measurement identifies emission patterns and targeted optimization levers

Schweinfurt

Key facts

- Even in plants with low emission factors, the evaluation of nitrous oxide measurements can reveal optimization potential.
- The use of an industrial gateway enables high-resolution and synchronized integration of all data streams.
- In intermittently operated tanks, emission patterns can indicate whether nitrous oxide is formed during nitrification or denitrification.



1. Introduction

Nitrous oxide measurements are not only used for monitoring greenhouse gas emissions. They can also serve as a starting point for targeted process optimization. In this case, the objective was to identify which process conditions lead to increased nitrous oxide emissions and which operational measures can reduce them. The data analysis was based on measured nitrous oxide values as well as additional process and operational data from the plant. Based on this, optimization measures were developed to support a sustainable reduction of nitrous oxide emissions. In addition to the reduction of greenhouse gas emissions, such a process analysis can also be used to improve other operational parameters and the overall performance of the biological stage.

In this case study, emissions from the biological stage (aeration tanks) of a wastewater treatment plant with 165,000 population equivalents and without separate sidestream treatment were measured over one year. For the analysis, emissions were first estimated using the so-called "Vienna model." Based on standardized emission factors, annual nitrous oxide emissions of 65 t CO_2-eq. were calculated. However, real measurements showed that only around 55 t CO_2-eq. were emitted. Even though the difference between calculation and measurement is relatively small in this case, the result demonstrates the inaccuracy of model-based emission estimates. It also shows that the plant operates a highly efficient biological treatment stage.

2. Measurement and setup of the investigated biology

Measurement system and principle

Nitrous oxide and methane emissions were measured using hood-based measurements. An EmiCo lite system with two floating gas hoods was used. The system continuously measures N_2O and CH_4 concentrations in the off-gas. The measurement is based on a non-dispersive infrared (NDIR) gas analyzer for detecting N_2O and CH_4. Additional sensors capture CO_2, O_2, temperature, and flow.

Figure 1: Setup of the EmiCo lite system at the investigated aeration tank**.**

Measurement in an intermittent tank

The emission measurements were carried out in intermittently aerated tanks of the biological stage of a wastewater treatment plant with 165,000 population equivalents. Intermittent tanks are characterized by alternating aerated and non-aerated phases. As a result, nitrification and denitrification do not occur spatially separated, but sequentially in the same tank. This operating mode allows flexible control of nitrogen removal through alternating aerobic and anoxic conditions.

In intermittently operated tanks, emission patterns alone can already provide an initial indication of whether nitrous oxide is mainly formed during denitrification or nitrification (see figure 4).

Figure 2: Aerial view of the investigated aeration tank with schematic hood placement.

3. Results

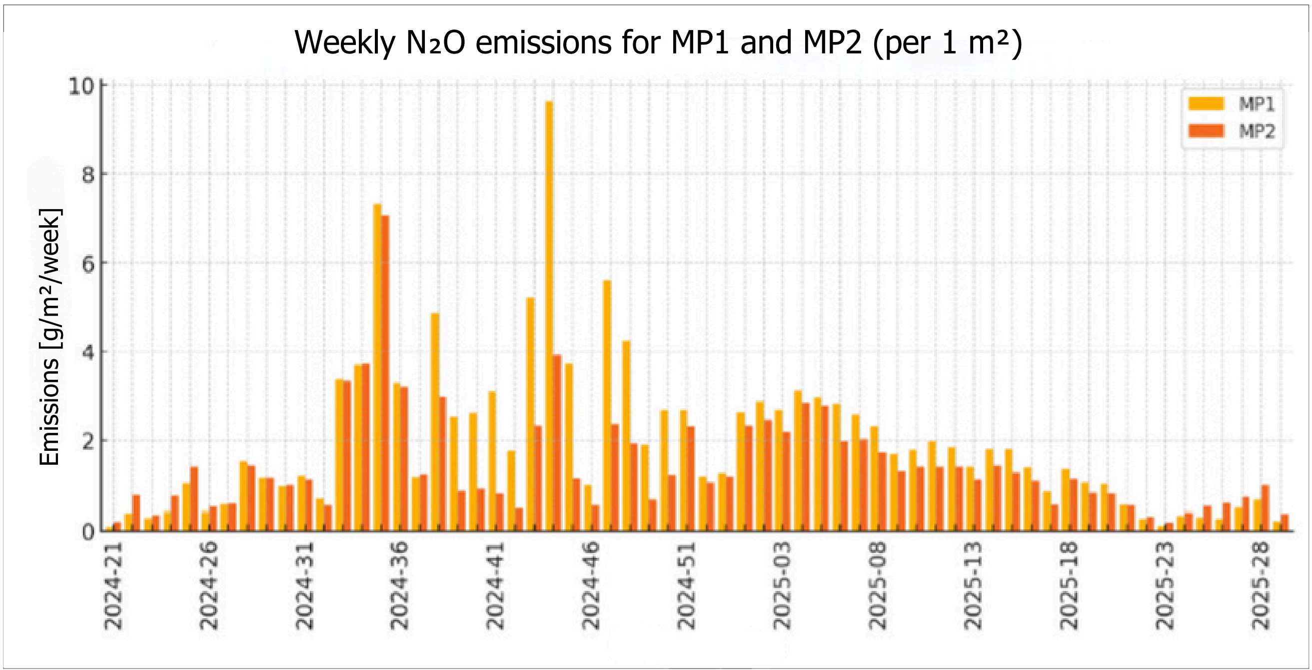


Figure 3: Weekly nitrous oxide emissions during the investigated period (calendar week 21 2024 to calendar week 29 2025).

The evaluated measurements were conducted from the end of May 2024 to the end of April 2025 (see Figure 3). This allowed seasonal variations to be observed. Greenhouse gas emissions showed clear seasonal fluctuations over the year (see Figure 1). Overall, the highest monthly emissions were observed between August and February.

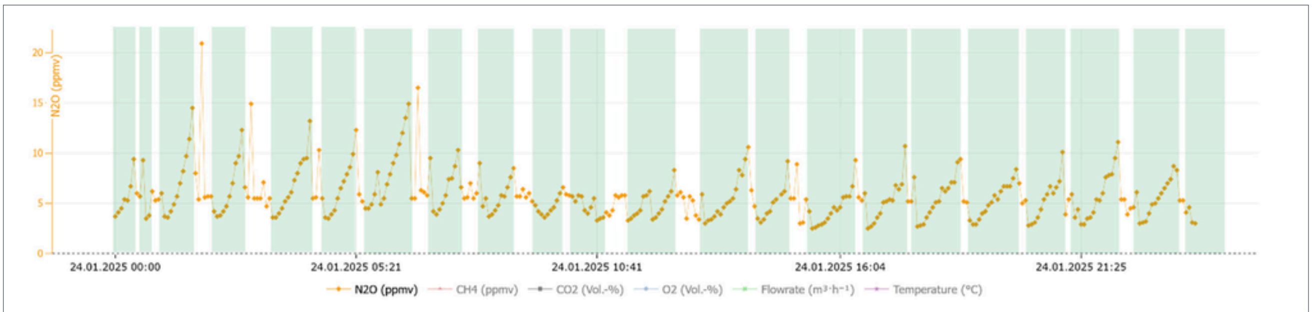


Figure 4: Typical daily profile of N_2O emissions. Aerated phases are highlighted in green. A clear increase in nitrous oxide concentration is visible during aerated phases. This emission pattern indicates that nitrous oxide is formed during nitrification.

The analysis of high-resolution data revealed characteristic daily emission patterns. Figure 4 shows the 24-hour profile of nitrous oxide concentration above a tank on a winter day (January 24, 2025). Nitrous oxide formation during nitrification is clearly visible. If nitrous oxide were formed during denitrification, it would accumulate and be stripped immediately at the start of aeration. In that case, the concentration would reach a peak immediately and then continuously decrease during nitrification.

Nitrous oxide emissions are often expressed as an emission factor relative to the treated nitrogen load (N_2O-N [%] of influent nitrogen load). The emission factor was calculated over the measurement period based on weekly average emission rates and nitrogen loads. In the reporting year, the factor was approximately 0.096%. For comparison, the IPCC default value is 1.6% N_2O-N relative to influent nitrogen. The calculated value for this plant is significantly lower, indicating a very well-performing biological treatment stage.

Process analysis and optimization

For detailed process analysis, continuously recorded emission data were evaluated together with relevant operational and process parameters. Off-gas data (N_2O, O_2, CO_2, flow rate) and selected process data from the control system were automatically collected via an industrial gateway system and transmitted in real time to a central cloud-based analysis environment.

The high temporal resolution and synchronization of all data streams enabled consistent correlation and state analysis. This made it possible to assign emission events precisely to specific operating conditions, such as aeration intensity, sludge age, C/N ratio, or return sludge rate.

Based on this integrated dataset, a dynamic state classification was implemented. Emission rates were statistically evaluated and categorized into low-emission ("good"), neutral, and high-emission ("bad") operating states (see Figure 5). This approach made it possible to identify recurring emission-relevant process patterns rather than focusing only on individual events.

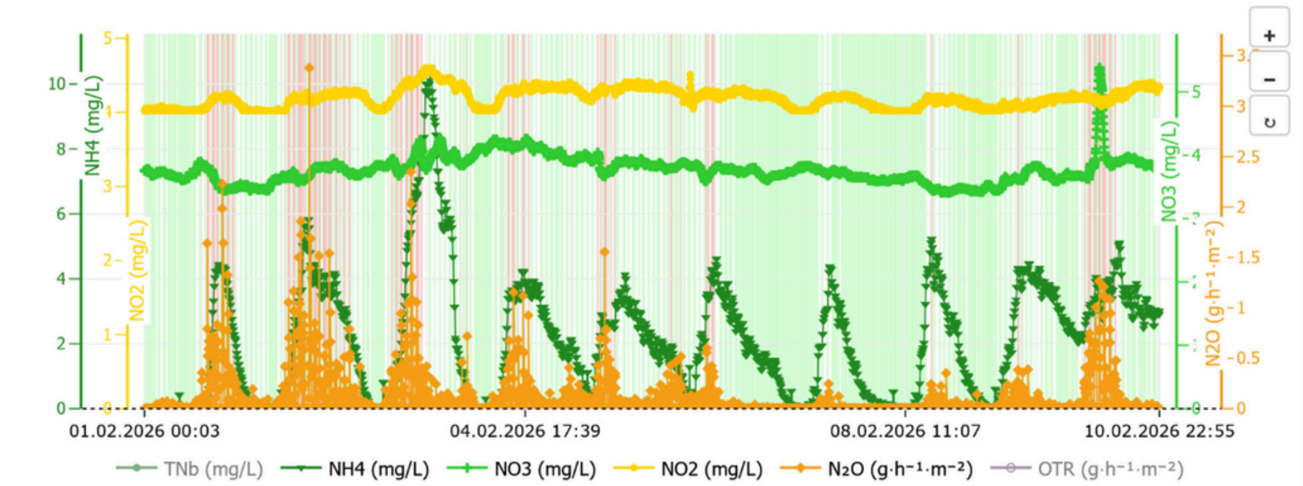


Figure 5: Example of state-based classification of plant operation based on N_2O emission rates, nitrogen parameters, and off-gas-based indicators. Time series and classification into low-emission (green), neutral (white), and high-emission (red) states are shown.

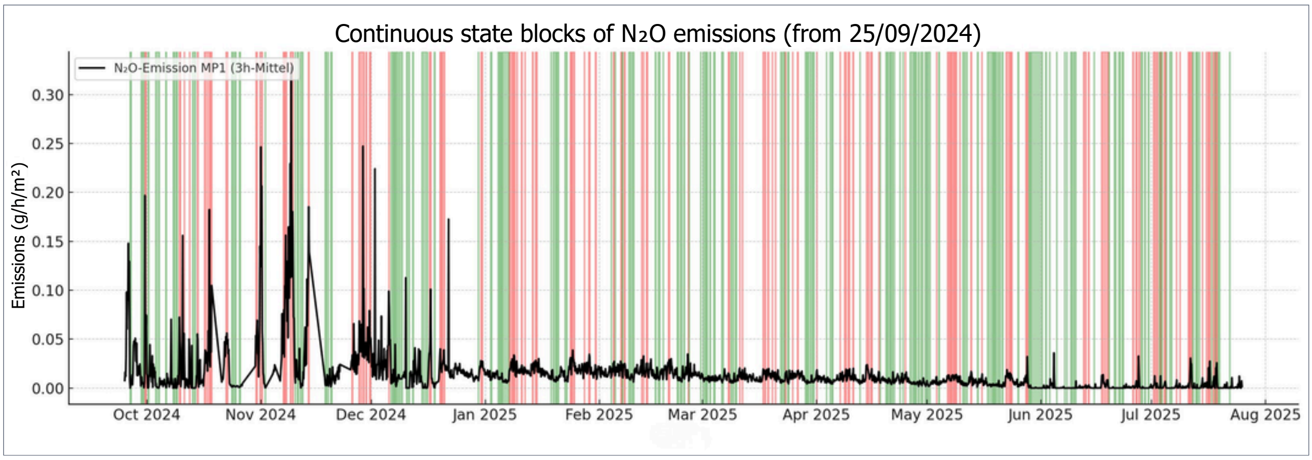


Figure 6: Classification of continuous process states based on N_2O emissions (3-hour average) at MP1 from September 25, 2024. Green indicates low-emission states, red indicates high-emission states. The classification is based on a dynamic analysis within a rolling two-week window.

Despite overall very good performance, phases with both high and low emission rates were identified. A rolling two-week window was used to analyze the distribution of averaged N_2O emission rates (see Figure 6). Based on this, "good" and "bad" states were defined.

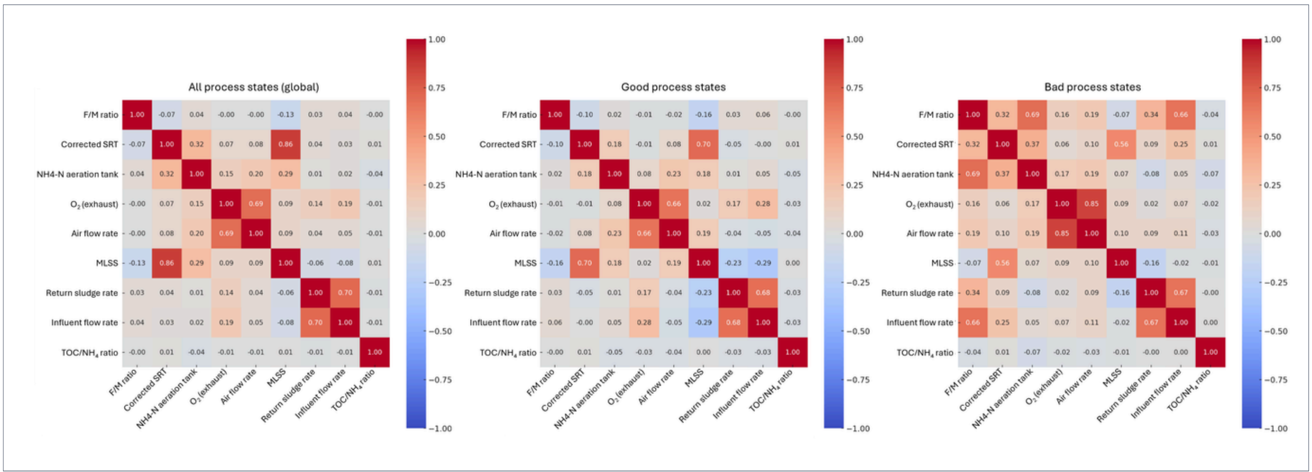


Figure 7: Results of the correlation analysis of operational parameters. Representation of all data (A) and separated into good (B) and bad (C) process states.

A comprehensive correlation analysis examined nine operational parameters of the biological treatment stage: sludge loading, corrected sludge age, ammonium concentration in the aeration tank, oxygen concentration, aeration rate, solids concentration, return sludge rate, influent flow, and the ratio of organic carbon availability to ammonium. Correlations were analyzed for the full dataset and separately for low-emission ("good") and high-emission ("bad") states. (see Figure 6)

Globally, expected relationships between control parameters were observed. Sludge age and sludge loading showed a strong negative correlation, meaning higher sludge age corresponds to lower F/M loading. Aeration intensity and dissolved oxygen showed a positive correlation, meaning increased aeration increased the oxygen concentration.

During bad operating conditions, some parameter relationships weakened or reversed. On days with disturbed biology, additional nitrous oxide formation occurred. This increase was no longer linear with nitrogen load but rose disproportionately. The highest emission factors occurred when denitrification was inhibited. In these "bad" states, nitrite accumulation in the effluent and a decrease in the TOC/NH_4 ratio were observed. This clearly indicates carbon limitation and incomplete denitrification.

The correlation analysis for bad states showed clear deviations. A strong negative correlation between TOC/NH_4 and N_2O emissions was observed. High nitrous oxide emissions were associated with low C/N ratios. This highlights the importance of sufficient carbon availability.

Parameter combinations related to nitrogen conversion and denitrification showed significant shifts. For example, a high return sludge rate no longer correlated positively with nitrate removal, as denitrification was impaired.

For denitrification, the key recommendation is to ensure effective anoxic conditions and sufficient organic carbon availability. A high TOC/N ratio supports complete reduction of nitrate to N_2. If the C/N ratio is too low, N_2O remains as an intermediate product. Increasing the C/N ratio, for example through adjusted recirculation rates, co-substrate addition, or optimized primary clarification, can reduce N_2O emissions. This allows more N_2O to be fully reduced to N_2. Extending non-aerated phases also provides sufficient anoxic time for denitrification.

Nitrous oxide was also formed during nitrification. The correlation analysis showed that oxygen limitation and insufficient sludge age must be avoided. According to DWA recommendations (DWA-M 229-1), aeration should ensure sufficient oxygen levels during nitrification phases, typically around 1–2 mg/L. Otherwise, nitrite formation and resulting nitrous oxide production can occur. In practice, this means identifying load peaks early and increasing aeration to prevent oxygen levels from dropping below critical thresholds. At the same time, biomass capacity must not become limiting. The temperature-corrected sludge age must be sufficiently high, especially in winter, to maintain nitrifying bacteria. If necessary, excess sludge withdrawal should be adjusted or tank inventory increased to prevent the sludge retention time from falling below the minimum value.

This case study shows that even in very well-operated plants, off-gas analysis and nitrous oxide signals can identify optimization potential. This leads to concrete measures to reduce emissions. The central objective is always to ensure stable and complete nitrification and denitrification.

4. Summary

This case study shows that even in a highly efficient large-scale wastewater treatment plant with a low emission factor, emission-relevant process states can be identified. Continuous hood measurements over one year revealed seasonal variations and characteristic daily patterns. These indicate that in the shown period nitrous oxide formation mainly occured during nitrification . At the same time, phases with increased emissions could be distinguished from stable operating conditions.

The combination of dynamic state classification and correlation analysis made it possible to identify key drivers of elevated N_2O emissions. Limited denitrification due to low carbon availability and oxygen limitation during nitrification were identified as major causes of emission peaks. Based on this, concrete operational measures can be derived, such as ensuring sufficient anoxic reaction time, improving the C/N ratio, and maintaining stable oxygen supply during nitrification.

Overall, the study highlights that online nitrous oxide measurements enable not only realistic emission assessment but also effective process diagnostics and optimization. Even in plants with very low total emissions, targeted measures can be developed to further reduce nitrous oxide formation and ensure long-term stability of biological nitrogen removal.

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