Making the invisible visible.

**Case Study:**

# An optimized influent strategy reduces nitrous oxide emissions in the sidestream by approximately 70%

## Reutlingen

## Key facts

- A reduction of around 70% in nitrous oxide emissions is possible by adjusting the influent flow rate of process water
- Emission patterns indicate issues in denitrification.
- From initial measurement to first optimization measures in only six months.

## 1. Introduction

Sidestream treatment of highly concentrated nitrogen, for example digester sludge process water, represents a specific challenge. In many wastewater treatment plants, process water from sludge digestion with high ammonium ($NH_4^+$) concentrations (>1 g/L) is treated separately in sequencing batch reactors (SBR) or similar systems. Due to the high ammonium load and often low carbon availability, these processes can be stronger sources of nitrous oxide ($N_2O$) per unit of nitrogen than conventional mainstream processes. At the same time, they offer the opportunity to actively control emissions through targeted operation, as the influent load can be dosed separately.

Against the background of potentially high $N_2O$ emissions, the aim of this study was to investigate $N_2O$ emissions in a full-scale SBR sidestream process and to identify relationships with operational conditions. Starting with an observation phase, high emissions were detected. Between 20 and 30% of the incoming nitrogen was released as nitrous oxide, corresponding to the emission factor (EF). By correlating off-gas measurements with SBR process data, it became clear that high emissions were linked to high ammonium concentrations.

A correlation analysis of off-gas data with SBR process data showed that adding process water during the first 30 minutes of nitrification led to high ammonium concentrations in the SBR. These concentrations showed a positive correlation with nitrous oxide emissions.

Based on this, the focus shifted to systematically analyzing the influent strategy and optimizing the process with regard to nitrous oxide emissions. The study specifically compared a reduced, time-distributed addition of process water with a concentrated, pulse-like addition in terms of resulting emissions. This also addressed a knowledge gap, as only limited practical data exists on how dosing strategies influence $N_2O$ emissions.

For this study, the EmiCo lite measurement device from Variolytics was used to analyze the SBR off-gas. In addition, the Variolytics software EmiCo Insight was used to evaluate more than one year of data.

The objectives were to quantify total $N_2O$ emissions and specific emission factors in the system, to compare emission characteristics between the two influent strategies using cluster analysis, and to derive recommendations for emission reduction.

The findings were intended not only to improve scientific understanding of the process but also to provide practical guidance for reducing climate-relevant emissions in wastewater treatment plants.

## 2. Measurement and setup of the investigated biology

### Operation and design of the investigated SBR

**Figure 1:** Aerial view of the investigated SBR with schematic hood placement

The investigated reactor is a full-scale sequencing batch reactor (SBR) for sidestream treatment of ammonium-rich process water from sludge dewatering. It operates cyclically with clearly separated filling, anoxic, aerobic, and discharge phases. This results in changing redox conditions over time. Due to the operating mode and mixing, SBR reactors show little to no spatial gradient of nitrous oxide emissions at the surface. Therefore, measurement hoods can be placed close to each other.

The initial operating state of the SBR was as follows. After decanting the treated wastewater, a new cycle started. Each cycle was divided into two phases. Each phase consisted of approximately three hours of nitrification followed by three hours of denitrification. During the first 30 minutes of nitrification, process water was added. After denitrification in the second phase, the reactor was emptied and the cycle restarted (see Figure 5).

The supplied process water had very high ammonium concentrations and low carbon availability. To ensure denitrification, an external carbon source based on glycerin was added. Due to the high nitrogen load and dynamic operation, the SBR is particularly prone to nitrite accumulation and unstable nitrification conditions. Aeration is not strictly controlled by dissolved oxygen, which can lead to transient oxygen limitations, especially at the beginning of aerobic phases. This combination of high $NH_4^+$ load, cyclic operation, and variable influent strategy makes the reactor a relevant source of nitrous oxide emissions.

The specific emission factor of the investigated SBR is 11.8 kg $CO_2$-eq/$m^3$, corresponding to approximately 2–3% $N_2O$-N per total nitrogen. This lies within the range reported in studies but is higher than default values previously used for inventories. For comparison, the IPCC default factor from 2019 assumes 1.6% nitrogen loss as $N_2O$-N. The observed value is slightly higher, which is typical for sidestream treatment with high ammonium loads.

## Measurement system and principle

Nitrous oxide emissions were measured using the EmiCo lite online measurement system. The system is specifically designed for wastewater treatment plants and enables continuous real-time monitoring of $N_2O$ and $CH_4$ concentrations in the off-gas of biological reactors. It is based on a non-dispersive infrared (NDIR) gas analyzer for detecting $N_2O$, $CO_2$, and methane, combined with additional $O_2$ sensors. In this application, two measurement points in the SBR tank were covered with hoods. Gas samples were continuously extracted and transported via sampling lines of approximately 10 meters to a weather-protected, temperature-controlled analyzer. In addition to $N_2O$ concentration, the system also measured airflow, $CO_2$ concentration, and oxygen content.

**Figure 2:** Setup of the EmiCo lite system at the investigated SBR.

## 3. Results: Data analysis and process optimization

Figure 3 shows the daily $N_2O$ emission factor, the average ammonium concentration, and the influent flow rate of process water in the SBR over an 11-month period in 2025, from January to November. Nitrous oxide measurements can also be used for process optimization. In this case, off-gas measurements were combined with process data to derive concrete recommendations for reducing emissions. The approach and results are described below.

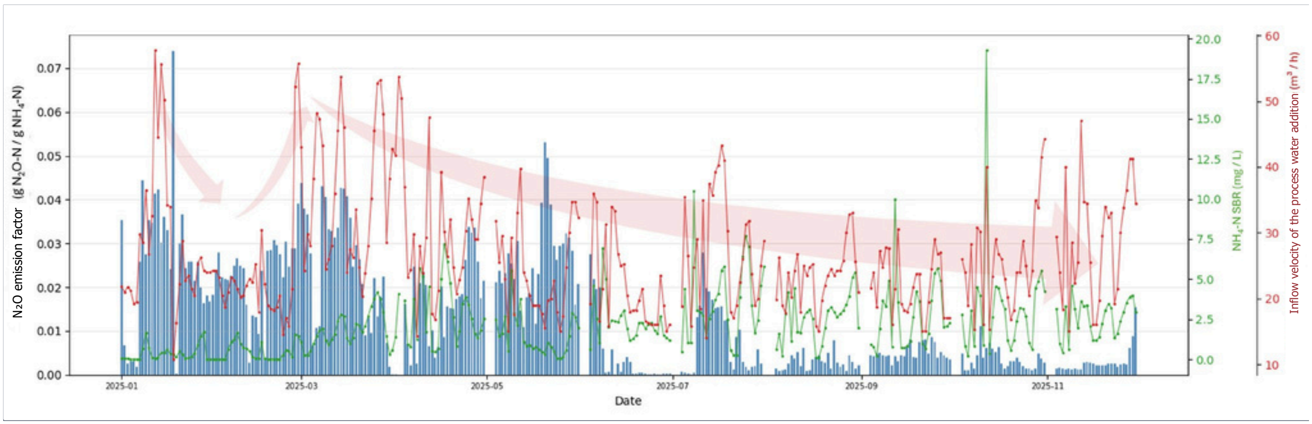

**Figure 3:** Daily $N_2O$ emission factor (blue), average ammonium concentration (green), and influent flow rate of process water (red) from January to November 2025. The flow rate could only be reduced using a manual valve, leading to stepwise adjustments and occasional spikes.

For data evaluation, total emissions over the observation period were first calculated by integrating emission rates over time. These values were then related to the treated process water volume. The total volume of process water fed to the SBR was summed, and a specific emission factor in kg $CO_2$-eq per $m^3$ of process water was calculated. The dataset was then analyzed with respect to influent characteristics. Operating phases were classified based on influent flow rate into three categories:

- Low influent flow rates were below 21.5 $m^3/h$.
- Medium flow rates ranged from 21.5 to 28.3 $m^3/h$.
- High flow rates were above 28.3 $m^3/h$.

Figure 4 clearly shows that fast addition is associated with significantly higher emission factors.

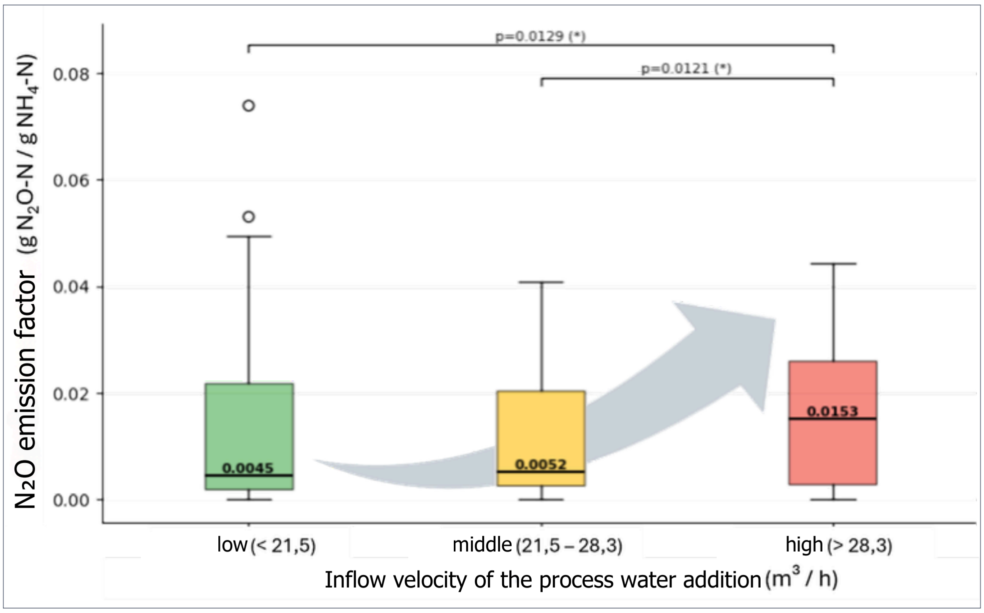

**Figure 4:** $N_2O$ emission factors for different process states, classified by influent flow rate. High flow rates result in significantly higher emissions ($p < 0.05$).

The effect of the implemented optimization is already visible in Figure 3. As a result, slowing down the process water addition was recommended. This led to a significant reduction in nitrous oxide emissions, as shown in Figure 4. However, Figure 3 also shows that it is not yet possible to maintain a consistently low influent flow rate. The currently installed pump is oversized, and flow control is only possible using a manual valve. This increases mechanical stress on the pump and prevents stable flow conditions. The installation of a smaller pump was identified as a concrete improvement measure.

During the measurement period, total emissions of 271.35 t $CO_2$-eq were recorded. Without the implemented optimization, emissions could have reached up to 328.69 t $CO_2$-eq under consistently high influent flow. This already corresponds to a reduction of 57.34 t $CO_2$-eq. With a consistently low influent flow rate enabled by a new pump, emissions could have been reduced further to 97.06 t $CO_2$-eq. This corresponds to a reduction of 234.63 t $CO_2$-eq, or approximately 70%.

This clear result demonstrates a direct relationship between emission factor and influent strategy. However, even with reduced addition, both zero emissions and emission peaks with daily factors up to 10% were observed. As described earlier, different emission patterns were identified. Emissions can also result from $N_2O$ accumulation during denitrification. This accumulated $N_2O$ can be released at the start of aeration in nitrification. This is characterized by a sudden peak in emission rate followed by a decrease during nitrification. Figures 5 and 6 illustrate these patterns.

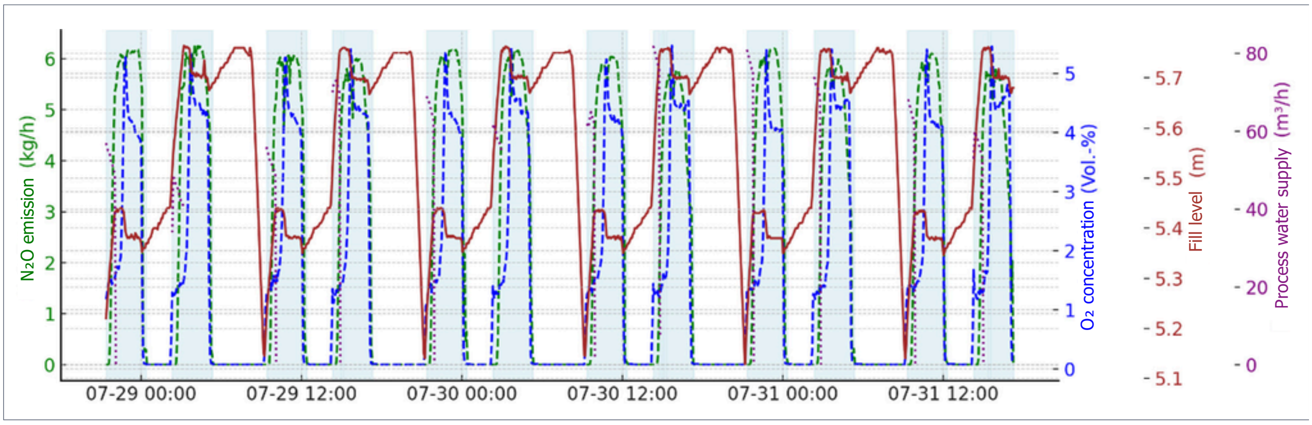

**Figure 5:** $N_2O$ emissions (green), $O_2$ concentration (blue), tank level (brown), and influent flow (violet). During the shown period, process water was added rapidly (>28.8 m$^3$/h). Nitrification phases are highlighted. Strong nitrous oxide formation occurs during nitrification due to pulse loading. The highest emission factor of the entire campaign was recorded in the shown time period.

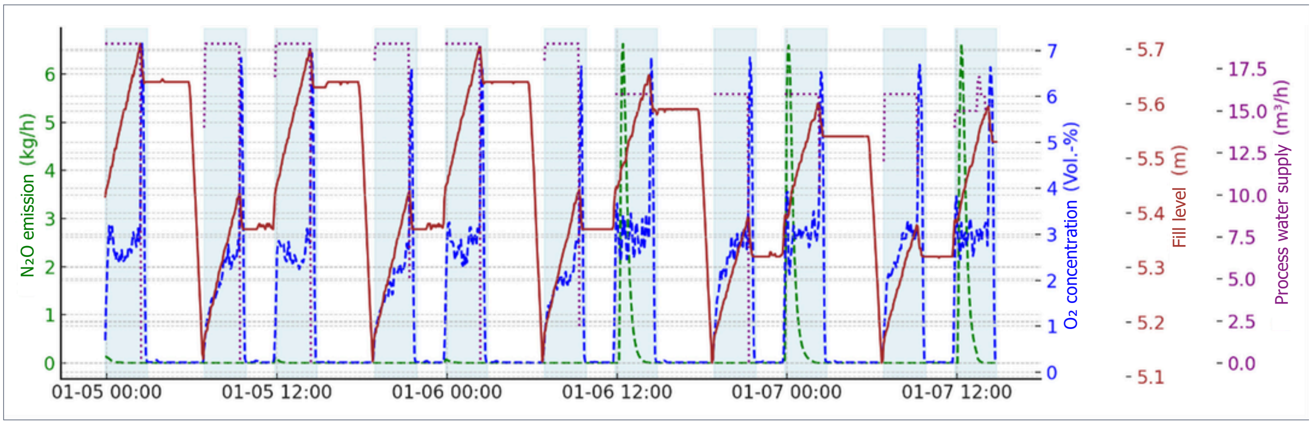

**Figure 6:** $N_2O$ emissions (green), $O_2$ concentration (blue), tank level (brown), and influent flow (violet). During this period, process water was added slowly (<21.8 $m^3/h$). No emissions occurred in early cycles. From January 6 onward, sharp emission peaks appear at the start of nitrification. This indicates $N_2O$ accumulation during denitrification and release at aeration start.

The change in tank level due to process water addition during nitrification in Figure 6 shows that decreasing emission rates are independent of continuous $NH_4$-N input. This indicates that emissions under reduced influent conditions are mainly caused by accumulation during denitrification followed by release during aeration. And the optimization continiues.

## 4. Summary

This case study shows that a full-scale SBR for sidestream treatment of ammonium-rich process water has significant but controllable potential for nitrous oxide emissions. The results demonstrate that the influent strategy has a decisive impact on both the magnitude and dynamics of emissions. Pulse-like loading leads to strongly increased emission factors, while a time-distributed influent strategy enables significantly lower emissions. In addition, it was shown that nitrous oxide is not only formed during nitrification but can also accumulate during anoxic phases and be released at the start of aeration. Continuous online off-gas measurements proved to be a key tool for clearly identifying emission patterns, process states, and root causes. Overall, the study shows that operational optimization, like through adjusted influent strategies, is an effective lever for reducing nitrous oxide emissions without major structural changes. At the same time, it provides valuable insights for more climate-friendly operation of sidestream SBR systems.