WHITE PAPER

Significant cost savings through dynamic ventilation during nitrification in wastewater treatment

Wastewater treatment plants (WWTPs) play a vital role in safeguarding the environment by treating and purifying wastewater before it is discharged into water bodies. Among the various stages of wastewater treatment, the nitrification process is of utmost importance. Nitrification involves the bacterial conversion of ammonia (NH_3) and nitrite (NO_2^-) into nitrate (NO_3^-), a less harmful form of nitrogen. However, this process demands a significant amount of energy, primarily in the aeration stage.

In this context, aeration refers to the introduction of oxygen into the wastewater to support the growth and activity of nitrifying bacteria. These bacteria require oxygen for their metabolic processes, and oxygen supply regulation is essential to ensure they function optimally. Depending on the specific type of plant and its design, the energy consumption dedicated to the aeration of the nitrification process can range from 50% to 95% [**1**]. This White Paper discusses a solution that uses Metrohm Process Analytics single-method process analyzers to monitor ammonia levels online to enhance the efficiency of the nitrification process within WWTPs.

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INTRODUCTION

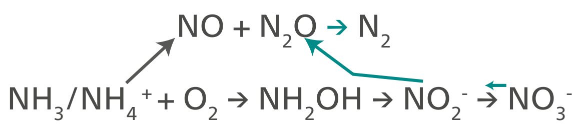
Water serves as a fundamental resource for agriculture, industrial processes, and domestic use. Its role as a solvent facilitates numerous chemical reactions, while its cooling properties are harnessed in various industrial applications. Additionally, water acts as a conduit for transportation and as a means of disposing effluents through complex drainage and sewage systems. However, the utilization of water in these ways results in contamination and the accumulation of pollutants, underlining the need for effective wastewater treatment.

Within the context of wastewater treatment, WWTPs are tasked with achieving two primary objectives: removing pollutants and reducing the environmental impact of the treated water. Among these objectives, the reduction of ammonia levels holds particular significance due to its toxicity to aquatic ecosystems. Ammonia-rich wastewater, if not properly treated, can lead to detrimental effects on aquatic life and compromise the overall health of water bodies.

The focus of this White Paper is to enhance the efficiency of the nitrification process within WWTPs without compromising the quality of the treated effluent or exacerbating the emission of harmful gases (nitrous oxide, N_2O). By implementing strategies such as real-time monitoring and dynamic aeration regulation, it becomes feasible to achieve these objectives. In doing so, not only can the discharge of harmful substances be minimized, but substantial energy savings can be realized. This comprehensive approach exemplifies the ongoing efforts to harmonize efficient wastewater treatment with environmental preservation and resource optimization.

To ensure efficient nitrification of wastewater, it is crucial to closely monitor the ammonia concentration. Ammonia serves as a key indicator of the nitrogen content and the overall efficiency of the nitrification process. By tracking ammonia levels and adjusting the aeration rate accordingly (**Figure 1**), WWTPs can tailor the oxygen supply to meet the specific requirements of different nitrifying bacteria species. Maintaining a low concentration of ammonia in the treatment system indicates adequate aeration, resulting in the successful nitrification of the wastewater.

Striking the right balance can be challenging. The absence of oxygen in the nitrification process can lead to the conversion of ammonia and nitrite into N_2O, a potent greenhouse gas (**Equation 1**). To mitigate this risk, many WWTPs adhere to the practice of maintaining a minimum oxygen concentration of 2 mg/L during the nitrification process [**2**]. While this practice helps prevent N_2O formation, it is important to note that this value is based on empirical data and might not always correlate precisely with the actual ammonia load of the wastewater and the bacterial requirements [**1**].



Equation 1. General reaction mechanism of the nitrification process from ammonia/ammonium. Green arrows indicate the denitrification route from nitrite into nitrous oxide.

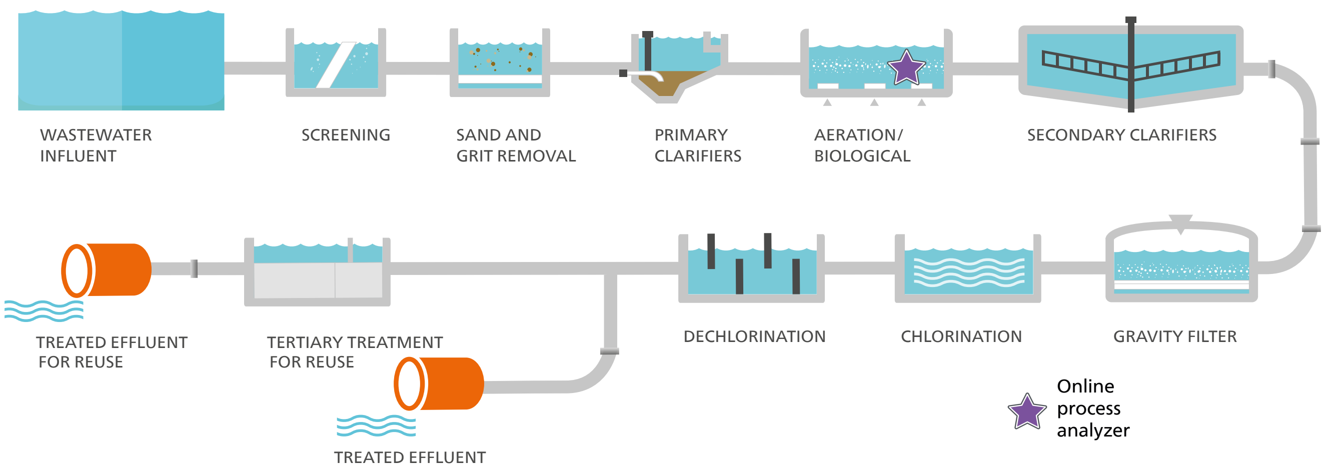


Figure 1. Illustrated diagram of a WWTP with an online process analyzer (star) for ammonia monitoring.

A promising approach to address these challenges involves the dynamic regulation of the aeration system based on real-time ammonia concentrations. By adopting this strategy, critical oxygen shortages can be minimized, reducing the likelihood of ammonia/nitrite breakthroughs and the subsequent formation of nitrous oxide. Moreover, this approach helps prevent the oversaturation of nitrification basins within the WWTP, leading to a reduction in energy consumption by the associated pumps in operation.

ANALYSIS TECHNIQUE

Ammonia (NH_3) and ammonium (NH_4^+) are fundamental nitrogen compounds encountered in wastewater treatment. Ammoniacal nitrogen can exist as ammonia (free ammonia, NH_3) or as an ammonium ion, depending on pH and temperature conditions. **Equation 2** highlights the dynamic interaction between these forms [**3**].

$$NH_3 + H^+ \Leftrightarrow NH_4^+$$

Equation 2. Chemical equation showing ammonia and ammonium in equilibrium.

The Dynamic Standard Addition (DSA) technique ensures the accuracy and reliability of ammonia concentration measurements, particularly within unfiltered wastewater samples.

DSA is an analytical method employing a high-precision burette and cutting-edge Ion Selective Electrodes (ISE). This technique adapts the standard addition volume to the actual sample concentration by means of a dynamic differential approach.

Moreover it takes into account ISE slope values over several ranges, allowing the use of ISEs within both low and high measuring ranges. To enhance accuracy, an integrated temperature measurement is employed to mitigate potential temperature-related effects on the analysis results.

For this application, ammonium ions are liberated and transformed into gaseous ammonia through the addition of excess caustic soda (**Equation 3**). This transformation allows for the subsequent diffusion of ammonia through the outer membrane of the electrode. As the pH value of the inner electrolyte solution is tracked using a combined glass electrode, this intricate process enables precise monitoring and determination of ammonia concentration levels in the sample.

$$NH_4^+{}_{(aq)} + OH^-{}_{(aq)} \rightarrow NH_{3\,(g)} + H_2O_{\,(l)}$$

Equation 3. Reaction equation for ammonia monitoring using Dynamic Standard Addition.

One of the outstanding features of this technique lies in its resilience and dependability. DSA is ideal for ammonia determination in unfiltered wastewater samples, where the presence of various impurities and particles can complicate measurements via other techniques. This analytical method ensures that accurate results are obtained even in such a complex matrix.

To facilitate the application of this technique on an industrial scale, process analyzers are used. The **2026 Ammonia Analyzer** from Metrohm Process Analytics is ideal for this application due to its exceptional accuracy and performance. This analyzer takes charge of the entire analysis cycle, from sample introduction (**Figure 2**) to results generation.

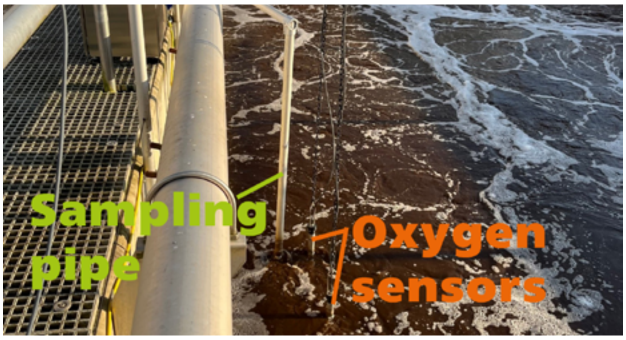


Figure 2. Location of the 2026 Ammonia Analyzer including sampling pipe and oxygen sensors.

The cleaning and calibration aspects, both critical for accurate measurements, are seamlessly executed by the analyzer itself. To prevent any potential issues arising from organic growth and contamination, the measuring cell and sampling pipes undergo an automated cleaning process with acid after every sixth measurement (**Figure 3**). Additionally, the ammonia sensor is calibrated once per day, ensuring the ongoing accuracy and reliability of the measurements.

Figure 3. Not even biological growth inside the measuring cell disturbs the analysis. (Manual cleaning is suggested after 3 months.)

To provide a comprehensive understanding of the various measurement options available, a comparison table is presented in the next section (**Table 1**), outlining the strengths and limitations of each approach.

DYNAMIC REGULATION VENTILATION SYSTEM

WWTPs encounter immense variability in influent volume. It is a complex task to implement optimal treatment strategies in the face of this variability, especially when considering the intricacies of the nitrification process. Nitrification, central to the wastewater purification process, depends on the provision of adequate aeration throughout various zones (**Figure 1**). Notably, it stands out as a prime candidate for process optimization due to its multifaceted impact on key operational objectives.

Table 1. Comparison table of the different measurement techniques.

Measurement technique	Photometry	Probe	Process Analyzer
Filtered sample	yes	no	no
Interval for manual cleaning	weekly	weekly	quarterly
Interval for manual calibration	weekly	weekly	no
Reagents required	yes (toxic)	yes	yes
Risk of carry-over	yes	no	no
Biofilm-sensitive	yes	yes	no
Interferences	amino acids, hydrazine, urea	potassium	no

To address the goals of energy efficiency, reduction in ammonia and nitrite levels, mitigation of nitrous oxide emissions, and overall plant safety, the dynamic regulation of aeration emerges as a pivotal strategy. Customizing aeration rates to correlate with influent loads can result in remarkable improvements in these areas.

The central requirement for effective aeration regulation is robustness. While considering diverse species of nitrifying bacteria, oxygen is predominant as the critical success factor for the nitrification process. Interestingly, not only does nitrification rely on oxygen, but the oxidation of organic carbon (Chemical Oxygen Demand, or COD) also consumes a substantial portion of this vital element. Of these two treatments that occur simultaneously (nitrification and oxidation), the nitrification process happens at the slowest rate. Therefore, the completion of ammonia oxidation signifies the culmination of the treatment process.

Understanding the kinetics of the nitrification reaction illuminates the intricacies of this optimization challenge. Reaction kinetics are closely tied to the concentration of oxygen, nitrifiers, and ammonia, as well as temperature. Of these factors, only oxygen concentration is directly controllable. This implies that oxygen levels offer the sole lever through which the reaction kinetics of ammonia reduction can be influenced.

It is important to note that the relationship between oxygen concentration and reaction kinetics is not linear. The Monod Kinetic Model [**4**] introduces the concept of a saturation coefficient for oxygen concentration, estimating it at 50% for maximum kinetics. If the provided oxygen concentration surpasses this coefficient, reaction speed accelerates; conversely, reducing oxygen concentration retards reaction kinetics.

Figure 4 shows the Monod Kinetic Mode in relation to the oxygen concentration. The thick line represents the established hypothesis of the saturation coefficient of 0.5 mg O_2/L. [**5**]

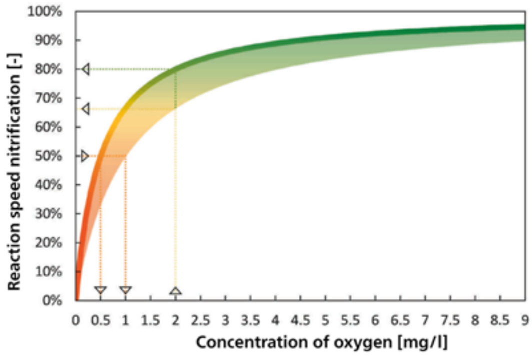


Figure 4. In presence of ammonia, the thick line indicates a reaction kinetic of 50% at 0.5 mg O_2/L (red dotted line) and 80% at 2 mg O_2/L (green dotted line). The transparent colored area illustrates the possible extension of a faulty saturation coefficient. The worst case scenario results in a reaction kinetic of 50% at 1 mg O_2/L and lower than 70% at 2 mg O_2/L. Extracted from [**6**].

Consider the impact of heavy rainfall events on a WWTP. Two factors can precipitate breakthroughs of ammonia in such scenarios:

- First, the ventilation system might struggle to deliver sufficient oxygen to sustain reaction kinetics.
- Second, increased flow rates can lead to inadequate retention time within the nitrification zone.

The maximum achievable aeration rate is also contingent on the capacity of aeration membranes, measured in Nm^3/h. A visualization of the decrease in oxygen transfer efficiency due to membrane overload can be observed in **Figure 5**.

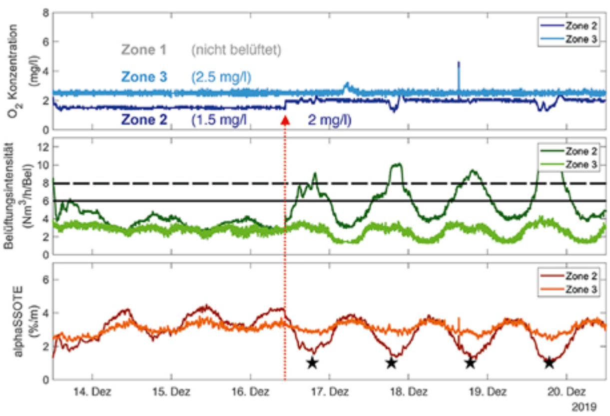


Figure 5. Top graph: oxygen concentration. Middle graph: aeration intensity of aeration membranes (black line: nominal rating, dashed line: max. admission aeration membranes). Bottom graph: oxygen transfer (stars indicate low periods), red arrow shows rising of the reference value for the oxygen concentration. Extracted from [**7**].

RESULTS: FIELD TEST ERZO WWTP OFTRINGEN

The determination of nitrogen content associated with ammonium is critical in WWTPs to calculate optimum «nitrogen loading» for an efficient nitrogen removal process. This parameter, known as ammonium nitrogen (NH_4-N), is essential in the complex nitrification processes of wastewater treatment.

In pursuit of refining wastewater treatment processes and achieving greater operational efficiency, real-world field tests provide invaluable insights. Such a test was conducted at the ERZO WWTP in Oftringen (Switzerland), starting in November 2022, where aeration was deliberately reduced from the conventional 2 mg O_2/L to 1.5 mg O_2/L. The outcome of this experiment is noteworthy, revealing not only an energy-saving potential but also the resilience of the system to handle such adjustments.

The results are intriguing. Despite the reduction in aeration levels, the test demonstrated a remarkable energy savings of 4.3% between January 2022 and January 2023 (**Table 2**). Equally remarkable is the virtually unchanged efficiency of ammonia (NH_4-N) degradation at approximately 99.5% despite a notable increase in load (**Table 2**). This reinforces the feasibility of optimizing aeration rates without compromising treatment efficacy.

Table 2. Despite the lower efficiency nitrification in January 2021, the ERZO WWTP in Oftringen was able to comply with the daily limit values.

	Period		
	Jan. 21	**Jan. 22**	**Jan. 23**
Energy consumption [kWh]	46,027	49,979	52,730
Load NH_4-N Inlet [kg]	12,949	13,515	14,916
Load NH_4-N Outlet [kg]	445	55.9	71.6
Load NH_4-N reduced [kg]	12,503	13,460	14,845
Nitrification efficiency NH_4-N [%]	96.56	99.59	99.52
Energy consumption per kg NH_4-N [kWh]	3.68	3.71	3.55

This trend is also seen in **Figure 6**, illustrating a shift in energy consumption per kg NH_4-N [kWh] from 11.8 in May 2022 to 6.3 in May 2023. This positive outcome not only demostrates the commitment to optimizing energy consumption but also positions process analyzers as a strategic investment.

The reported reduction in energy use, together with current energy costs, fits perfectly with estimates, indicating that ERZO WWTP may expect to realize a return on their process analyzer investment within a year.

Figure 6. Energy consumption in kWh/kg NH_4-N at ERZO WWTP in Oftringen (2022 vs. 2023).

RESULTS AND SUMMARY OF FIELD TEST

The field test conducted at ERZO WWTP in Oftringen, spanning from November 2022 to February 2023 (**Figure 7**), yielded valuable insights into the dynamics of wastewater treatment optimization. During this testing period, the system demonstrated a consistent correlation between the levels detected by the 2026 Ammonia Analyzer from Metrohm Process Analytics and the daily composite samples taken from the WWTP outlet and analyzed in the laboratory. This harmonious agreement underscores the reliability and accuracy of the 2026 Ammonia Analyzer's measurements, building confidence in the data-driven approach to process optimization.

A key component of this test was the monitoring of NH_4-N levels, a critical parameter in optimizing the nitrification process.

As shown in **Figure 8**, the temporal behavior of O_2 concentration during a breakthrough event is indicative of the aeration system's responsiveness. Notably, a brief dip in O_2 concentration occurs at the onset of the breakthrough. However, the aeration unit promptly responds to this challenge, quickly restoring the O_2 concentration to the target level of 1.5 mg O_2/L. This resilience is attributed to the aeration unit's ample capacity, ensuring its ability to tackle transient disturbances effectively.

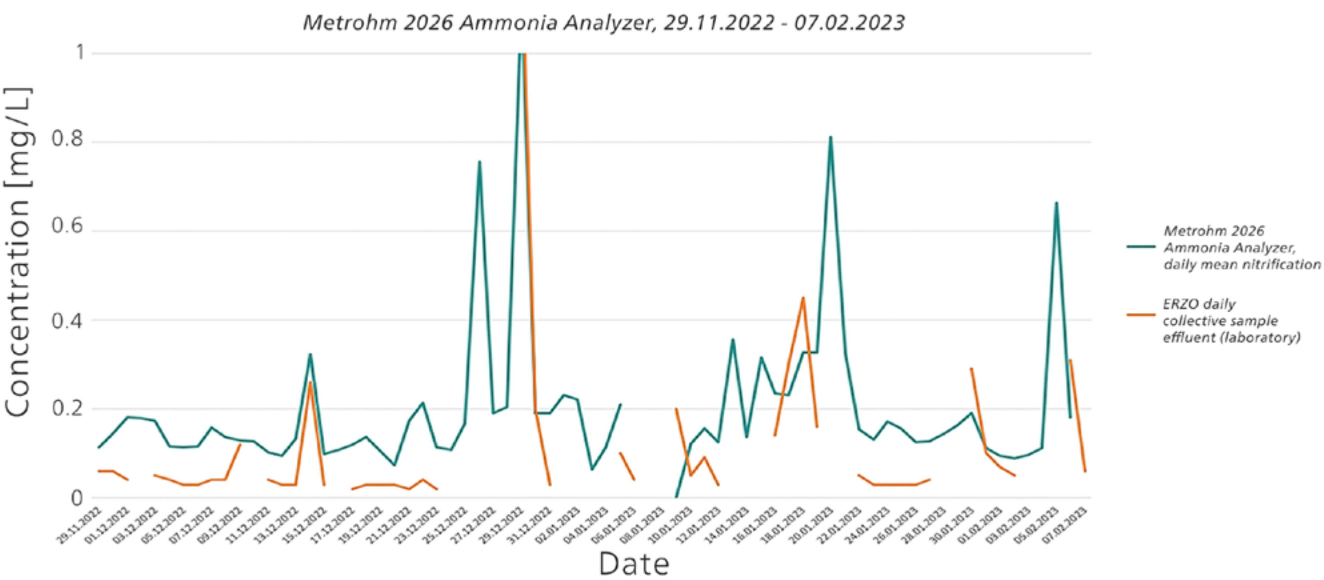


Figure 7. Comparison of analyzer results (nitrification) vs. daily samples (outlet).

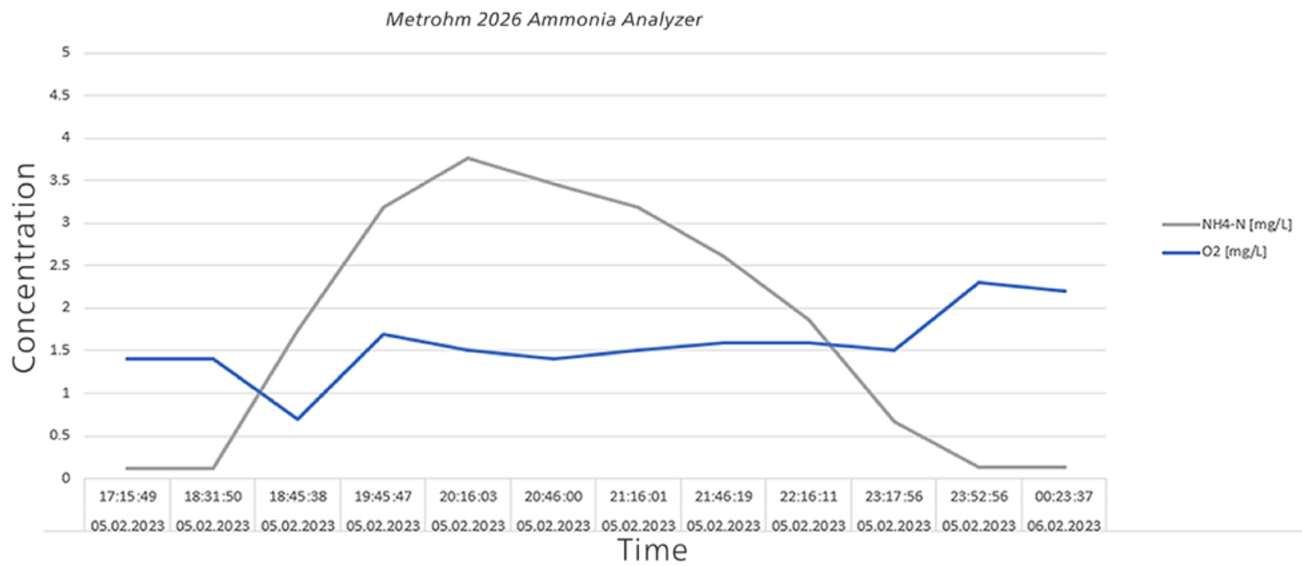


Figure 8. Breakthrough of NH_4-N in the nitrification process due to a heavy rainfall event.

Interestingly, the graph in **Figure 8** also reveals that the NH_4-N concentration continues to rise during such an event—a trend that might be challenging to discern without continuous monitoring. This emphasizes the indispensable role that near real-time data plays in capturing process dynamics and alerting operators to deviations from the norm. To amplify these benefits, dynamic control of the aeration system could potentially yield even higher O_2 concentrations, thus catalyzing enhanced reaction kinetics and expediting ammonium degradation.

A key takeaway from the field test is the remarkable robustness and user-friendliness of the entire system, encompassing both the process analyzer and associated components. Apart from periodic electrolyte replacement and reagent refills, the analysis system operates with minimal need for supervision. Moreover, its adaptability is noteworthy. The measuring system is well-suited for various treatment processes, including Sequencing Batch Reactors (SBR), Activated Sludge (A-I), classic activated sludge processes, and hybrid plant configurations. This versatility underscores the analysis system's potential to benefit a wide array of wastewater treatment facilities, regardless of their specific design and operational parameters.

Looking ahead, the integration of the process analyzer into the WWTP process control system marks an exciting step forward. This integration will empower the process control system to dynamically regulate aeration based on real-time ammonium content, further optimizing the nitrification process. This proactive approach holds the promise of not only enhancing wastewater treatment efficacy but also potentially yielding significant energy savings. By combining cutting-edge technology with a nuanced understanding of wastewater treatment dynamics, facilities like ERZO WWTP exemplify the ongoing evolution towards more sustainable, efficient, and environmentally responsible practices in wastewater management.

CONCLUSION

In conclusion, the ERZO WWTP Oftringen field test, spanning from November 2022 to February 2023, exemplifies the potential of dynamic aeration control in wastewater treatment optimization. Despite the reduction in aeration levels, there was a notable 4.3% decrease in energy consumption and a steady efficiency in ammonia (NH_4-N) degradation, remaining at approximately 99.5% despite an increased load.

The analytical system's resilience and user-friendliness, supported by compatibility across diverse treatment processes, underscore its versatility. Integration into the process control system heralds a new era of real-time optimization, further enhancing treatment efficacy and potentially yielding substantial energy savings. This success story at ERZO WWTP demonstrates the power of technology-driven solutions to propel wastewater treatment towards heightened sustainability and operational excellence.

References

[1] Müller, E. A.; Kobel, B.; Schmid, F. *Handbuch Energie in ARA*, Neuaufl. des Handbuchs Energie in ARA von 1994.; Verband Schweizer Abwasser- und Gewässerschutzfachleute (VSA), 2008.

[2] ECOS. *Wastewater Nitrification: How it works*. ECOS. **https://www.ecos.ie/wastewater-nitrification-how-it-works/** (accessed 2023-08-22).

[3] *Nitrogen Species*. HillLabs. **https://hill-labs.co.nz/resources/technical-notes/** (accessed 2023-11-07).

[4] Henze, M.; Gujer, W.; Mino, T.; et al. *Activated Sludge Models ASM1, ASM2, ASM2d and ASM3*; IWA Publishing: London, 2000.

[5] Koch, G.; Kühni, M.; Gujer, W.; et al. Calibration and Validation of Activated Sludge Model No. 3 for Swiss Municipal Wastewater. *Water Research* **2000**, *34* (14), 3580–3590. **https://doi.org/10.1016/S0043-1354(00)00105-6**.

[6] Weber, P.; von Känel, L.; Braun, D. *Sauerstoff – Treibstoff Für Die Nitrifikation*, Aqua&Gas 7/8.; 2016.

[7] Braun, D.; von Känel, L.; Biolley, L. *Dynamische Regelung der ARA Hofen.* SVGW. **https://www.aquaetgas.ch/wasser/abwasser/20220104_ag1_dynamische-regelung-der-ara-hofen/** (accessed 2023-08-22).

Further related Metrohm literature

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Contact

Yves Buchmüller
Metrohm Schweiz AG.; Zofingen, Switzerland
041-info@metrohm.com