

Deammonification Synthesis report 2014

R&D at Hammarby Sjöstadsverk



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Preface

This report presents an overview of studies on deammonification processes performed by the joint research group from Royal Institute of Technology (KTH) and IVL Swedish Environmental Research Institute during the years 2008 - 2014 at the Research and Development Facility Hammarby Sjöstadsverk in Stockholm, Sweden (www.hammarbysjostadsverk.se). The Water and Sewage Technology Research Group at KTH has been working with wastewater technologies based on the deammonification process since 1999. Their earlier investigations have resulted in the first full-scale application in Scandinavia of deammonification for supernatant treatment at Himmerfjärden Wastewater Treatment Plant (2007). Studies performed by IVL/KTH at Hammarby Sjöstadsverk have contributed to gather more knowledge about implementation of the deammonification process for both supernatant and mainstream treatment. The experimental work has resulted in three licentiate-theses (Jingjing Yang, Andriy Malovanyy, and Razia Sultana), 10 master thesis and several publications in pre-reviewed international journals and conference presentations, among others.

Financial support has been granted by the Foundation for IVL Swedish Environmental Research Institute (SIVL), Swedish Water Development (SVU), the Swedish Research Council Formas, Vinnova, Swedish Institute (SI Visby Programme), Lars Erik Lundberg Foundation, KTH (Land and Water Resources Department), and Chalmers University of Technology (Department of Civil and Environmental Engineering). Moreover, research grants for exchange post-doctoral researchers, exchange PhD students and master students have been obtained from: EU in the framework of European Social Fund through Warsaw University of Technology Development Program (scholarship for Monika Zubrowska-Sudol), EU in framework of EU ESF (European Science Foundation) through University of Santiago de Compostela, Spain (scholarship for Isaac Fernandez Rodriguez), Ministry of Education and Science of Ukraine (scholarship for Andriy Malovanyy), EU in framework of ERASMUS programme (exchange master students).

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Stockholm, October 2014

Summary

Nitrogen removal in wastewater treatment plants (WWTPs) is one of the most crucial end-of-pipe actions by which society can protect the environment from anthropogenic nitrogen loads that would otherwise have a negative impact on natural water systems. Without nitrogen removal from municipal wastewater, many ecosystems would have more problems with eutrophication and oxygen depletion and algae blooming as result, as challenges in regions such as the Baltic Sea illustrate. An increasing population and the restoration, or at least maintenance, of our ecosystem will in the future require even more stringent nitrogen removal targets than we have today.

Nitrogen removal in WWTPs is also one of the most resource-intensive processes, which requires both a high amount of energy needed for aeration in the nitrification process as well as external carbon sources addition in the form of methanol/ethanol for the denitrification process. As the use of these resources contributes to impacts on our environment, reducing energy and resource consumption in nitrogen removal is one of the most focused research and development (R&D) areas in wastewater treatment worldwide.

The most significant step towards a more sustainable nitrogen removal has been accomplished with the implementation of the deammonification process based on nitrification/anammox in side-stream treatment, i.e. the treatment of ammonium-rich supernatant from digested sludge dewatering. However, the process can be improved further in many different ways.

The upcoming application of the deammonification process is for the mainstream, i.e. wastewater with low concentration and temperature. The pioneering work by a group consisting of researchers and experts from the Royal Institute of Technology (KTH) and IVL Swedish Environmental Research Institute has a significant share in this research field.

This Synthesis report provides an overview of the work performed by the KTH/IVL R&D-group at the R&D-facility Hammarby Sjöstadverk in Stockholm since the collaborative activities were initiated in 2008. The expertise of KTH stretches longer back than this (starting from year 1999 with first studies in laboratory scale), but this report has the aim to present the KTH/IVL research of the last years (2008-2014) and provide an overview of the expertise and potential that the group has within the field of deammonification in all its applications.

The main competences and research focus of the KTH/IVL group includes:

1. Side-stream deammonification process operation and control
2. Mainstream deammonification process operation and control
3. GHG-emissions measurement and control from deammonification processes
4. Holistic WWTP-system approaches including deammonification processes

This Synthesis report does not include a review of the research groups' activities in relation to other international research. However, the included review of performed

research and listed publications will provide an indication of the group's activities. In addition, interested collaboration partner are invited to see the actual work at the R&D-facility Hammarby Sjöstadsværk.

The shared goal by the group members is clear: Side-stream and Mainstream Deammonification process for Energy Positive Nitrogen Removal as a part of creating water resource recovery facilities previously known as wastewater treatment plants.

Sammanfattning

Kvävereduktion i kommunala avloppsreningsverk (ARV) är en av samhällets viktigaste uppgifter för att minska den negativa miljöpåverkan antropogent (mänskligt orsakat) kväve annars har i naturliga vattensystem. Utan kvävereduktion skulle utsläppt avloppsvatten orsaka övergödning med syrebrist och algblooming som följd. Detta kan tydligt ses i regioner där kvävereduktion i ARV ej ännu är implementerat, men även i regioner såsom Östersjön där det redan finns implementerat i hög grad. En ökad befolkning i kombination med ett återställande, eller åtminstone bibehållande av befintlig vattenkvalité, kommer i framtiden innebära krav för ytterligare förbättrad kvävereduktion.

Kvävereduktion i ARV är en väldigt resursintensiv process. Det krävs resurser både i form av energi till luftning i nitrifikationsprocessen samt metanol eller etanol som tillsätts som kolkälla i denitrifikationsprocessen. En stor förbrukning av dessa resurser medför således också en negativ miljöpåverkan vilket ger att det är en balansgång att uppnå en god kvävereduktion med så liten resursförbrukning som möjligt. Denna balansgång har medfört att kvävereduktion i ARV numera är ett av de största forskningsområdena i världen idag.

Det tydligaste steget mot en mer resurseffektiv kvävereduktion har åstadkommit genom fullskaleimplementering av deammonifikationsprocessen för rening av sidoströmmar, det vill säga koncentrerat tempererat rejektivatten från slamavvattning.

Deammonifikationsprocessen för rejektivattenbehandling kan dock ytterligare förbättras med avseende på flera aspekter, vilket forskning visat. Ett annat viktigt bidrag mot en mer resurseffektiv kvävereduktion sker just nu genom forskning inom området för rening av huvudströmsvatten med deammonifikationsprocessen, det vill säga vanligt avloppsvatten med lägre koncentration och temperatur jämfört med rejektivatten. En stor del av arbetet i båda dessa områden har utförts av en grupp bestående av forskare och experter från Kungliga Tekniska Högskolan och IVL Svenska Miljöinstitutet. I forskargruppens främsta kompetenser och fokusområden ingår:

- Sidoströmsdeammonifikation, drift och styrning
- Huvudströmsdeammonifikation, drift och styrning
- Utsläpp av växthusgaser från deammonifikationsprocessen, mätning och styrning
- Kompletta avloppsvattenreningsystem med deammonifikationsprocessen inkluderad

Denna rapport innehåller en sammanfattning av arbete och studier utförda av forskargruppen, sedan initiativet om gemensamma forskningsaktiviteter på forskningsanläggningen Hammarby Sjöstadverk startade år 2008 fram tills idag, år 2014. Expertisen inom gruppen sträcker sig dock längre bak i tiden (med de första studierna i labbskala år 1999), men en sammanfattning från de senaste åren (2008-2014) ger en god översikt över den expertis och potential som denna grupp har inom området deammonifikation och dess möjliga applikationer.

Det gemensamma målet inom forskargruppen är tydligt: Sidoströms- och huvudströmsdeammonifikation för energipositiv kvävereduktion som en del av att utveckla resurseffektiva vattenanläggningar, tidigare benämnda avloppsvattenreningsverk.

1 Introduction and background

1.1 General

Large efforts are made in the field of nitrogen removal in wastewater treatment plants (WWTPs) since nitrogen is one of the main target substances that have to be removed in order to prevent negative effects in the environment. Both, direct nitrogen loads to WWTPs from the sewer system and internal loadings from e.g. sludge dewatering are in focus of worldwide research activities in order to make the resource-intensive removal of nitrogen more resource-efficient and to decrease the total environmental impact by considering all kinds of direct and indirect emissions from nitrogen removal processes.

The majority of WWTPs, also in Sweden, remove nitrogen by using traditional activated sludge nitrification/denitrification processes. Many facilities also add a carbon source in the denitrification step, both as external (for example methanol) and internal carbon source (from hydrolysis of sludge). Only about 23% (16 facilities; status year 2013) of Swedish facilities have a separate supernatant treatment and apply sequencing batch reactor (SBR) technology and 3 facilities use deammonification process of which the first installation in Sweden (at Himmerfjärden WWTP) was based on work from KTH research group (see section 1.5). New requirements on nitrogen treatment will probably imply an increased number of installations for separate supernatant treatment.

1.2 Deammonification as a new pathway for nitrogen removal

The Deammonification process is based on nitrification (oxidation of about half of influent ammonium nitrogen to nitrite nitrogen without further oxidation of nitrite) and the Anammox process (Anaerobic ammonium oxidation, reaction between formed nitrite and remaining ammonium to nitrogen gas). The process opens for a more cost-effective nitrogen removal from wastewater. Deammonification is considered more environmental friendly compared with conventional nitrification/denitrification processes due to decreased energy requirements, no need for an external carbon source and lower emission of greenhouse gases (Table 1.1).

The recently discovered autotrophic bacteria responsible for Anammox reaction belong to the order of the Planctomycetales (Strous *et al.*, 1999a). Before they were identified by microbiologists, the existence of Anammox bacteria was preliminary predicted by Engelbert Broda in 1977 (Broda, 1977).

Table 1.1. Comparison of traditional nitrification/denitrification and deammonification processes in terms of sustainability indicators (Trela *et al.*, 2004c).

	Energy [kWh/kg N]	External C (methanol) [kg/kg N]	CO ₂ emission [ton/ton N]	Nitrous oxide emission
Traditional nitrification/denitrification	1.3	2.3	3.5	High
Deammonification	0.5	0	0.4	Low

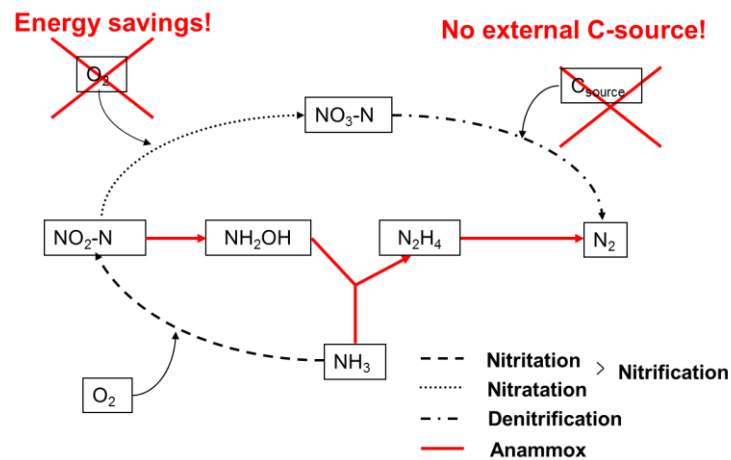


Figure 1.1. Scheme of nitrification/denitrification and deammonification processes. The nitrification is common for both processes, but anammox (red arrows) replaces both nitratation and denitrification, which saves both energy and addition of carbon (modified Trela *et al.*, 2005).

Deammonification can be performed as a one-stage or a two-stage process. In a one-stage deammonification process, the biomass normally forms a biofilm to allow simultaneous performance of nitritation and anammox processes. The biofilm can either be in granule (Winkler *et al.*, 2012) form or grow on carriers, like Kaldnes carriers. In a one-stage deammonification process, ammonium oxidizers exist in the outer layer of the biofilm and anammox bacteria are present in the inner layer. Therefore, anammox bacteria can avoid oxygen, which can cause inhibition effect on anammox bacteria.

1.3 R&D-facility Hammarby Sjöstadsverk

Because the majority of activities referred to in this report are based on work carried out at the R&D-facility Hammarby Sjöstadsverk (www.hammarbysjostadsverk.se) a brief introduction to this facility is provided.

Hammarby Sjöstadsverk is a platform for research, development, and exchange of knowledge and technologies in water treatment and related environmental technology. It promotes cooperation among companies, experts/researchers, and municipal sewage treatment plants to meet future challenges in the water and wastewater sector and aims to increase export of Swedish knowledge and technology. The facility is used for long-term national and international research programs and projects and for consultancy, testing, and development for the industry and other collaborators.

The facility is owned and operated by a consortium led by IVL Swedish Environmental Research Institute and the Royal Institute of Technology (KTH). Hammarby Sjöstadsverk is Sweden's leading and internationally renowned research and development facility in water purification technology. The facility contributes through research and demonstration to a profiling and increase of Swedish know-how related to water and environmental technology.

At the Hammarby Sjöstadsværk plant, research and development work within wastewater treatment is undertaken within the scope of various projects:

- Requirements on incoming water (causes for operational disturbance)
- Optimization of existing aerobic and anaerobic processes
- Complementary treatment of outgoing wastewater
- Process control and monitoring technology
- Treatment of secondary flows
- Climate-effective treatment technologies
- Increased biogas production
- Development of new techniques and processes to meet more stringent water quality requirements

Hammarby Sjöstadsværk plant is also used:

- for applied research and development
- as reference and demonstration plant
- as training and knowledge exchange platform

1.4 Studied Pilot-scale system

Two moving bed biofilm reactors (MBBRs), with a total working volume of 200 L each, have been operated at the R&D-facility Hammarby Sjöstadsværk (since 2008). Forty percent (80 L) of the reactor volume was filled with Kaldnes K1 biofilm carriers. Air was supplied from the bottom of the reactors and DO concentration was controlled/regulated by a PID controller. Sufficient mixing was achieved with a mechanical stirrer and the targeted water temperature was controlled with a heater. Influent supernatant was continuously fed into the reactors that were equipped with online instruments to measure pH, redox, conductivity, temperature, and DO concentration.

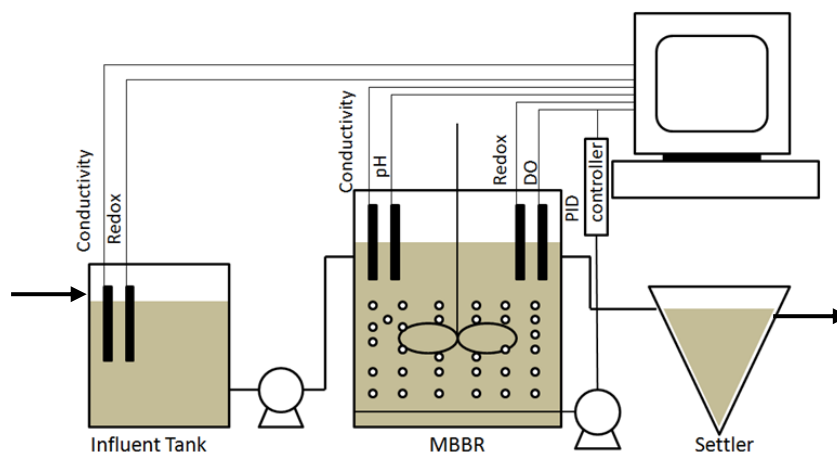


Figure 1.2. The scheme of pilot-scale MBBR (Yang *et al.*, 2011a).

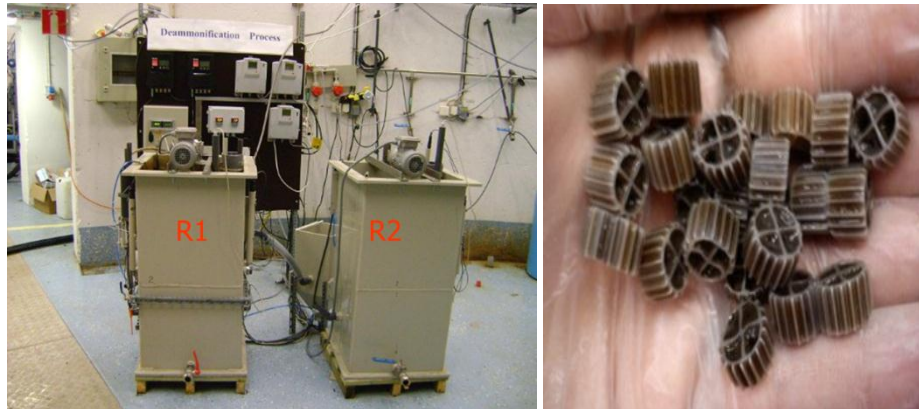


Figure 1.3. Pilot reactors at Hammarby Sjöstadsverk (left) and Kaldnes biofilm carriers K1 (right).

1.5 Studied Full-scale system

Much experience and knowledge of the current work is based on laboratory scale and pilot scale experiments and later on full-scale implementation of the deammonification process at Himmerfjärden wastewater treatment plant (SYVAB) that is still in operation. Here, the Royal Institute of Technology (KTH) initially conducted research on developing a cost-effective nitrogen treatment method for supernatant obtained from dewatering of digested sludge. Experiments were first performed in a pilot plant built by PURAC AB.

The initial studies included experiments in lab-scale (two 8 L reactors) since 1999 at KTH. Those were completed with pilot-scale (2 x 2.1 m³) at Himmerfjärdsverket in 2001-2007, and finally the first full-scale plant in Sweden with deammonification in 2007. Initially, both two-stage and one-stage processes were tested. However, due to several advantages, the one-stage process was later selected for the full-scale implementation and it still makes the basis of the on-going research.



Figure 1.4. Used deammonification systems at Himmerfjärdsverket, from lab-scale over pilot-scale to full-scale treatment of supernatant.

More information about this R&D-work including a more comprehensive background, relevance of the work compared to other activities in the field, methods, results, and evaluation can be found in following publications by the R&D-group:

- Cema, G. 2009. Comparative study on different Anammox systems. Land and Water Resources Engineering, KTH, Stockholm, TRITA-LWR PhD Thesis 1053.

- Cema, G., Szatkowska, B., Płaza, E., Trela, J. and Surmacz-Górska, J. 2006. Nitrogen removal rates at a technical-scale pilot plant with the one-stage partial nitrification/Anammox process. *Water Science and Technology* 54(8), 209-217.
- Cema, G., Płaza, E., Surmacz-Górska, J., Trela, J and Miksch, K. 2005. Study on evaluation of kinetic parameters for Anammox process. In: Proceedings of the IWA Specialized Conference “Nutrient Management in Wastewater Treatment, Processes and Recycle Streams”, 19-21 September 2005, Kraków, Poland.
- Gut, L., Plaza, E. Hultman, B. 2007. Assessment of a two-step partial nitrification/Anammox system with implementation of multivariate data analysis, Chemometrics and intelligent laboratory systems, 86, 26-34.
- Gut, L. 2006. Assessment of a partial nitrification/Anammox system for nitrogen removal, Licentiate Thesis TRITA-LWR LIC 2031.
- Gut, L., Plaza, E., Trela, J., Hultman, B. & Bosander, J. 2005a. Combined partial nitrification/Anammox system for treatment of digester supernatant. *Water Science and Technology*, 53(12), 149-159.
- Gut, L., Plaza, E., Długolecka, M. & Hultman, B. 2005b. Partial nitrification process assessment. *Vatten*, 61(3), 175-182.
- Plaza, E., Stridh, S., Örnmark, J., Kandars, L. & Trela, J. 2011. Swedish experience of the deammonification process in a biofilm system. Proc. of the IWA/WEF Specialized conference “Nutrient recovery and management 2011”. 9-12 January 2011, Miami, Florida, USA, 1333-1345.
- Szatkowska, B., Cema, G., Plaza, E., Trela, J. & Hultman, B. 2007a. One-stage system with partial nitrification and Anammox processes in moving-bed reactor. *Water Science and Technology*, 55, (8-9), 19-26.
- Szatkowska, B. 2007b. Performance and control of biofilm systems with partial nitrification and Anammox for supernatant treatment. Land and Water Resources Engineering, KTH, Stockholm, TRITA-LWR PhD Thesis 1035.
- Szatkowska, B. Płaza, E., Trela, J., Hultman, B. and Bosander, J. 2007c. Combined partial nitrification and Anammox biofilm system as a sustainable solution for supernatant treatment. *Water Practice and Technology*, 2(1) doi10.2166/wpt.2007.0005.
- Szatkowska B., Cema G., Płaza, E., Trela J. and Hultman B. 2006a. One-stage system with partial nitrification and Anammox processes in moving-bed biofilm reactor. In: Proceedings of the IWA Specialized Conference “Biofilm Systems VI”, 24 – 27 September 2006, Amsterdam, The Nederland.
- Szatkowska, B., Płaza, E. & Trela, J. 2004a. Nitrogen removal rates in the deammonification process: batch experiments. In: Proceedings of the “4th IWA World Water Congress and Exhibition”, Marrakech, 19-24 September 2004.
- Szatkowska, B. 2004. Treatment of ammonium-rich wastewater by partial nitrification/Anammox in a biofilm system. Land and Water Resources Engineering, KTH, Stockholm, Licentiate thesis, TRITA-LWR.LIC 2023.
- Szatkowska, B., Płaza, E., Trela, J. & Hultman, B. 2004b. Monitoring of nitrogen removal processes by use of conductivity measurements. *Vatten* 60(2), 111-118.
- Trela, J., Hultman, B., Plaza E., Levlin, E., Fernandez, I. 2009. Mätteknik för att styra och optimera deammonifikation. (Measurements for monitoring, controlling and optimisation of deammonification). *Svenskt Vatten Utveckling* 2009-11.

- Trela, J., Plaza, E., Hultman, B., Cema, G., Bosander, J., Levlin, E. 2008. Utvärdering av enstegsprocess för deammonifikation. Svenskt Vatten Utveckling 2008-1.
- Trela, J., Hultman, B., Plaza, E., Szatkowska, B., Cema G., Gut L. & Bosander, J. 2006. Framtagande av underlag för dimensionering, drift och processövervakning av deammonifikation vid kommunala avloppsverk Stockholm. VA-Forsk 2006-15.
- Trela, J., Plaza, E., Gut, L., Szatkowska B., Hultman, B. & Bosander, J. 2005. Deammonifikation, en ny process för behandling av avloppsströmmar med hög kvävehalt – fortsatta pilot-plant experiment. VA-Forsk 2005-14.
- Trela, J., Plaza, E., Szatkowska, B., Hultman, B., Bosander, J. & Dahlberg, A. G. 2004a. Pilot-plant experiments with combined nitrification and anaerobic ammonium oxidation (Anammox) in biofilm system. In: Proceedings of the “4th IWA World Water Congress and Exhibition”, Marrakech, 19-24 September 2004.
- Trela, J., Plaza, E., Szatkowska, B., Hultman, B., Bosander, J. & Dahlberg, A. G. 2004b. Deammonification as a new process for treatment of wastewater with high nitrogen content. Vatten 60(2), 119-127.
- Trela, J., Plaza, E., Szatkowska, B., Gut, L. & Hulman, B. 2004c. Deammonifikation som en ny process för behandling av avloppsströmmar med hög kvävehalt – experiment i pilot-skala. Stockholm. VA-FORSK 2004-09.

2 Key working fields and results

The following pages provide an overview of the work, including focus areas, the research team at KTH/IVL has been working with. This includes the majority of activities that have been carried out since the startup at the R&D-facility Hammarby Sjöstadswerk (www.hammarbysjostadsverk.se). However, some of the previous work prior to 2008 is referred to as well, if relevant and connected to the subject.

Key working topics covered during the considered period include:

- Side-stream treatment by deammonification process
 - Deammonification control by different aeration strategies
 - Deammonification control by ORP value
 - Evaluate microbial activity in deammonification process
- Nitrous oxide (N₂O) emissions
 - Emissions from pilot-scale deammonification systems for supernatant treatment
 - Emissions from full-scale deammonification systems for supernatant treatment
- Mainstream treatment by deammonification process
 - Deammonification process after ammonium concentration by ion exchange
 - Temperature influence on deammonification performance
 - Deammonification process at low concentrations and low temperatures
 - Combination of anaerobic treatment with UASB and mainstream deammonification process

2.1 Side-stream treatment by deammonification process

2.1.1 Introduction

Sludge handling at WWTPs after dewatering of digested sludge generates ammonium-rich water, called reject water or supernatant. Often anaerobic sludge digestion is used at larger WWTPs for sludge stabilization and biogas production. The ammonium concentration in the supernatant can be as high as up to 2 000 g/m³. Returning this supernatant to the inflow of the WWTP, which is commonly practiced in smaller and medium size WWTP, implies an increase in nitrogen load by about 15–20% on average, with reference to the total inlet nitrogen load. Therefore, mostly larger facilities have started to setup a separate supernatant treatment to reduce the internal load significantly and thus being able to achieve lower effluent nitrogen concentrations.

Physical-chemical methods such as ammonia stripping or ion exchange etc. have some drawbacks if compared to biological nitrogen removal. This includes higher treatment costs, small capacity, and release of secondary pollutants or products that are difficult to handle. The high nitrogen concentration and temperature of supernatant favors biological methods of which deammonification was identified as one of the most promising applications for supernatant treatment in the last decades.

2.1.2 Deammonification control by different aeration strategies

2.1.2.1 Background

The aeration is one of the key parameters in stable deammonification process operation and therefore much focus was placed here, carrying out experiments in both laboratory and pilot-scale.

2.1.2.2 Materials and methods

To investigate removal rates under different aeration strategies, three series of batch tests were carried out in lab-scale experiment based on different DO concentrations (2, 3 and 4 mg/L). Four tests have been done for each series of tests with different ratios of duration between the non-aerated phase and aerated phase in 1 hour cycle ($R = 0, 1/3, 1$ and 3). R stands for the ratio of duration between non-aerated and aerated phase in each one hour. Each batch test was operated in cycle of 4 h distributed according to a certain scheme.

2.1.2.3 Results and discussion

The results indicated that the highest deammonification rates were achieved at $R=1/3$ and DO concentration of 4 mg/L, which was $3.4 \text{ g N/m}^2 \text{ d}$ (Figure 2.1). The obtained results indicated that the impact of dissolved oxygen on deammonification was dependent on the R -value. With a proper intermittent aeration, nitrogen removal efficiency was able to reach the similar nitrogen removal efficiency under continuous aeration with the same DO concentration. DO concentration also played an important role to maintain high nitrogen removal. At R equal to 0 and $1/3$, an increase of DO from 3 mg/L to 4 mg/L caused a significant increase in nitrogen removal rate. At R equal to 1 and 3, similar rates of the process were however observed irrespectively of the DO.

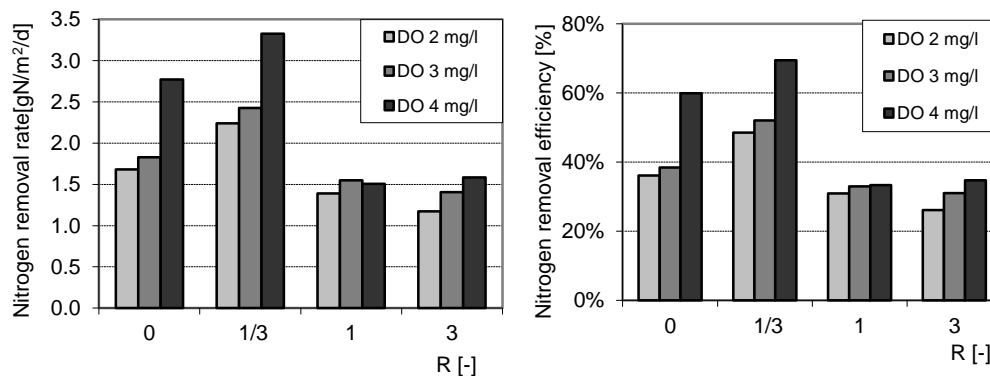


Figure 2.1. Nitrogen removal rate (a) and nitrogen removal efficiency (b) in batch tests (Zubrowska-Sudol *et al.*, 2010).

2.1.2.4 Conclusions

The research work by the KTH/IVL group has shown that:

- In a deammonification process, partial nitrification and Anammox are occurring simultaneously in the biofilm and nitrite production is the bottleneck of the whole process.
- The DO-concentration together with an R -value is two crucial parameters for deammonification process performance and efficiency.

- The highest nitrogen removal rate and efficiency were achieved at $R=1/3$ and DO concentration of 4 mg/L, although only 75% of airflow was used compared with continuous aeration.
- Taking into account that the aeration costs are a significant part of the total operational costs of WWTP, the use of an appropriately selected intermittent aeration strategy could imply significant savings at no negative impacts on the process performance.

2.1.2.5 Further Study

More information about this R&D-work including a more comprehensive background, relevance of the work compared to other activities in the field, methods, results, and evaluation can be found in following publications by the R&D-group:

- Yang, J. 2012. Controlling and monitoring of deammonification process in moving bed biofilm reactor. Licentiate thesis. KTH TRITA LWR LIC 2065.
- Yang, J., Trela, J., Plaza, E. 2011a. Activity of different groups of microorganisms in moving-bed biofilm reactor with one stage deammonification process. In: Proceedings of the IWA Specialized Conference “Biofilm 2011”, 27-30 October 2011, Shanghai, China. 113-124.
- Yang, J., Trela, J., Plaza, E. 2011b. Influence of aeration strategy on behaviour of different microorganisms in deammonification process. In: Proceedings of the international conference “Environmental Biotechnology”, 7-9 September 2011b, Gdansk, Poland. Paper 10.
- Yang, J., Zubrowska-Sudol, M., Trela, J., Plaza, E. 2011c. Influence of aeration conditions on nitrogen removal rate in one-stage partial nitrification/anammox process. In: Proceedings of the IWA Specialized Conference “Nutrient Recovery and Management 2011”, 9-12 January 2011, Miami, Florida. 1307-1320.
- Zubrowska-Sudol, M., Yang, J., Trela, J., Plaza, E. 2010. Evaluation of deammonification process performance at different aeration strategies. *Water Science & Technology*. 63(6), 1168-1176.

Also earlier studied in:

- Cema, G., Plaza, E., Trela, J. and Surmacz-Górska, J. 2011. Dissolved oxygen as a factor influencing nitrogen removal rates in a one-stage system with partial nitrification and Anammox process. *Water Science & Technology*. Vol. 64(5), 1009-1015.

2.1.3 Deammonification control by ORP value

2.1.3.1 Background

In a one-stage deammonification process applied in a moving bed biofilm reactor (MBBR), the redox potential value can be used as a monitoring parameter for process performance and efficiency. The objective of this research topic was to investigate the possibility of using the redox value as a control parameter to operate one-stage deammonification process.

2.1.3.2 Material and methods

The redox value was fixed by a PID controller at various set-points. Different combinations of nitrogen loads and redox potential values were tested in the pilot-scale system treating reject water.

2.1.3.3 Results and discussion

The tested combinations revealed that redox value closed to $pe=0$ (corresponds to 0 mV, 1 $pe=59.2$ mV) was the most suitable case in term of process performance at 25°C. The performance was stable during the complete experimental period and reached nitrogen removal efficiency above 80% except the case when $pe=-1$. With the fixed redox potential value ($pe=0$) used in the system, air supply adjusted automatically with the different nitrogen loads. Theoretical calculations showed that pe higher than 0.15 (at $pH=7$) offers a condition for nitrite transferring into nitrate at 25°C.

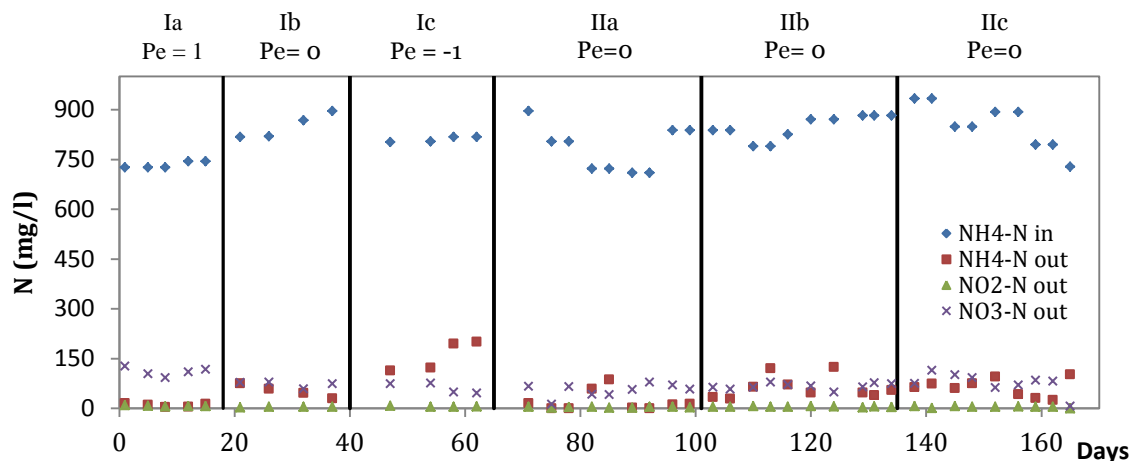


Figure 2.2. Concentrations of different nitrogen compounds in the influent and effluent from MBBR (Yang *et al.*, 2014).

2.1.4 Conclusions

The research work by the KTH/IVL group has shown that:

- The Redox value can be used as a control parameter for treating supernatant by one-stage deammonification process. The highest nitrogen removal rate and efficiency were obtained when redox value of 0 was applied among the tested redox values ($pe= -1, 0, +1$)
- When the redox value was fixed at 0, the nitrogen removal efficiency was higher than 70% with different nitrogen loads applied. Air supply into the system showed linear correlation with nitrogen loads at the fixed redox value.
- Theoretical optimum pe value for preventing nitrate production is 0.15 when $pH=7$ and temperature of 25°C.
- Compared with the aeration control, redox control needs longer reaction time.

2.1.4.1 Further study

More information about this R&D-work including a more comprehensive background, relevance of the work compared to other activities in the field, methods, results, and evaluation can be found in following publications by the R&D-group:

- Yang, J., Trela, J., Plaza, E., Wahlberg, O., Levlin, E., 2014. Using oxidation-reduction potential (ORP) as a control parameter in a single stage deammonification process at room temperature. (Manuscript).

2.1.5 Evaluate microbial activity in deammonification process

2.1.5.1 Background

In an MBBR with one-stage deammonification process, ammonium-oxidizing bacteria (AOB) and anammox bacteria (AnAOB) play the dominating roles for the process performance and efficiency. However, heterotrophic bacteria and nitrite oxidizing bacteria (NOB) are very hard to avoid due to the presence of small amounts of organic matter and nitrite.

2.1.5.2 Materials and methods

In this study, an investigation has been carried out to evaluate the activity of nitrifiers, heterotrophic bacteria, anammox bacteria, and denitrifiers in the biofilm of one-stage deammonification MBBR under various aeration strategies and different nitrogen loads. The methodology has been described in Yang *et al.* (2012a).

2.1.5.3 Results and discussion

The results showed that introduction of anaerobic phase (under intermittent aeration) and high nitrogen load could enhance the activity of anammox bacteria. Oxygen concentration in the bulk liquid of the reactor influenced the activity of AOB. It was possible to limit the NOB activity in the deammonification process by providing regular anaerobic phases. Heterotrophic bacteria activity was low when limited amount of organic carbon was available.

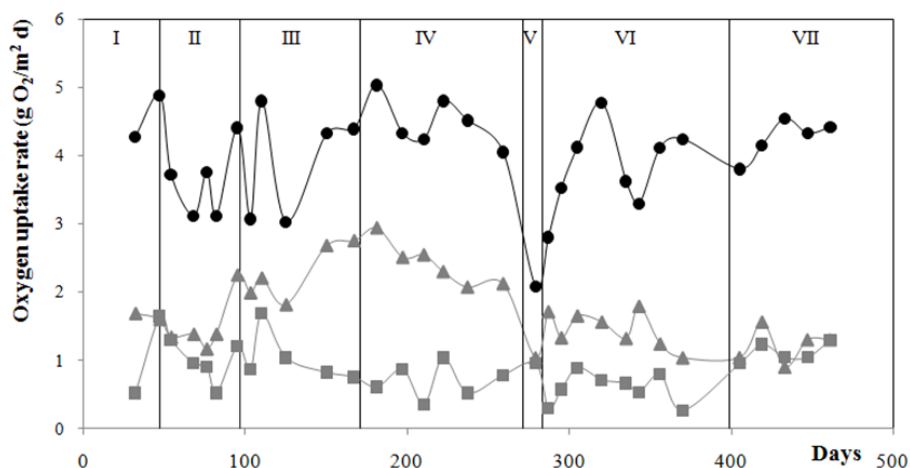


Figure 2.3. Variation of AOB (●), NOB (■) and heterotrophic bacteria (▲) activity (Yang *et al.*, 2011a).

2.1.5.4 Conclusions

The research work by the KTH/IVL group has shown that:

- Deammonification involves the use of oxygen for partial nitrification and the use of produced nitrite and remaining ammonium for the anammox reaction. To keep anammox bacteria and AOB as dominating bacteria inside the system, most strategies are directed towards ways to diminish the concentration of electron donor and electron acceptor for competing bacteria (NOB, denitrifiers, and heterotrophic bacteria).

2.1.5.5 Further study

More information about this R&D-work including a more comprehensive background, relevance of the work compared to other activities in the field, methods, results, and evaluation can be found in following publications by the R&D-group:

- Fernández, I., Plaza, E., Trela, J., Hultman, B. & Méndez, R. 2011. Evaluation of deammonification process by response surface models. *Water, Air, and Soil Pollution* 215 (1-4), 299-309.
- Fernandez, I., Plaza, E., Trela, J., Hultman, B. & Mendez, R. 2009. Evaluation of deammonification process by Anammox activity measurement. In: Proc. of the IWA 2nd Specialized Conference “Nutrient Management in Wastewater Treatment Plants”, Krakow, Poland, 7-9 September 2009, 501-508.
- Trela, J., Yang, J., Plaza, E., Levlin, E. 2014 Nitritation/anammox-processen för rejektivattenbehandling. *Svenskt Vatten Utveckling* accepted for publication.
- Trela, J., Hultman, B., Plaza E., Levlin, E., Fernandez, I. 2009. Mätteknik för att styra och optimera deammonifikation. (Measurements for monitoring, controlling and optimisation of deammonification). *Svenskt Vatten Utveckling* 2009-11.
- Winkler, M., Yang, J., Kleerebezem, R., Plaza, E., Trela, J., Hultman, B., van Loosdrecht, M. C. M. 2012. Nitrate reduction by organotrophic anammox bacteria in a partial nitrifying granular sludge and a moving bed biofilm reactor. *Bioresource Technology*. 114, 217-223.
- Yang, J., Trela, J., Plaza, E. 2011a. Activity of different groups of microorganisms in moving-bed biofilm reactor with one stage deammonification process. In: Proceedings of the IWA Specialized Conference “Biofilm 2011”, 27-30 October 2011, Shanghai, China. 113-124.
- Yang, J. 2012. Controlling and monitoring of deammonification process in moving bed biofilm reactor. Licentiate thesis, KTH TRITA LWR LIC 2065.
- Wójcik, W. 2011. Evaluation of microbiological activity during the deammonification process for nitrogen removal. TRITA LWR Degree Project, 11:26.

Also earlier studied in:

- Cema, G., Szatkowska, B., Plaza, E., Trela, J. & Surmacz-Górska, J. 2006. Nitrogen removal rates at a technical-scale pilot plant with the one-stage partial nitrification/Anammox process. *Water Science and Technology*. 54(8), 209-217.
- Cema, G., Plaza, E., Surmacz-Górska, J., Trela, J & Miksch, K. 2005. Study on evaluation of kinetic parameters for Anammox process. In: Proceedings of the IWA Specialized Conference “Nutrient Management in Wastewater Treatment, Processes and Recycle Streams”, 19-21 September 2005, Kraków, Poland, 379-388.

- Szatkowska, B., Cema, G., Plaza, E., Trela, J. & Hultman, B. 2007a. One-stage system with partial nitritation and Anammox processes in moving-bed reactor. *Water Science and Technology*, 55(8-9), 19-26.
- Szatkowska, B., Cema, G., Plaza, E., Trela, J. & Hulman, B. 2006a. One-stage system with partial nitritation and Anammox processes in moving-bed biofilm reactor. In: Proceedings of the IWA Specialized Conference “Biofilm Systems VI”, 24 – 27 September 2006, Amsterdam, The Nederland.

2.2 Nitrous oxide (N₂O) emissions

2.2.1 Introduction

Greenhouse gas (GHG) emissions are an increased concern within all sectors of today's society. Even though treating wastewater is essentially positive for the environment since it removes harmful substances that might cause damage to the receiving waters, the treatment process itself has an impact on the environment, for instance through greenhouse gas emissions. Special attention is given to nitrous oxide (N₂O) emissions, since it is a greenhouse gas about 300 times stronger than CO₂. As deammonification process so far only have been implemented in side stream applications (with regard to full-scale plants), emissions from supernatant treatment have mostly been investigated.

It is important to mention that the formation of N₂O is not a specific phenomenon for supernatant treatment but a common problem for all biological nitrogen removal processes. Important is the amount of such emissions related to the treated nitrogen flux and possibilities to reduce these emissions at maintained removal efficiency. The reader can be informed that the R&D-group also has performed substantial work within measuring, understanding, and reducing GHG-emissions from other biological treatment steps in both pilot and full-scale applications.

Among the bacteria groups present in one-stage deammonification biofilm, nitrous oxide can be produced as by-product or reaction intermediate only by AOB, NOB and denitrifying bacteria, since it has been proven that N₂O is not a metabolite of anammox reaction (Firestone *et al.*, 1979; Freitag *et al.*, 1990; Desloover *et al.*, 2012). Reported N₂O production in full-scale supernatant treatment varies between 0.6-2.6% for the partial nitritation but are as low as 0.6% of nitrogen loads from anammox process (Chandran, 2011; Okabe *et al.*, 2011). Although deammonification is attractive for its low operation cost and energy demand, it has to be optimized against the higher carbon footprint due to N₂O emissions.

2.2.2 Emissions from pilot-scale deammonification systems for supernatant treatment

2.2.2.1 Background

Measurements under controlled conditions and with the ability to measure entire flows are necessary to understand the fundamentals of emission creation, dynamics, and influencing factors.

2.2.2.2 Materials and methods

The measurement of N_2O emissions from deammonification process to the atmosphere and in discharge was carried out in two pilot-scale one-stage deammonification MBBRs. One reactor (R1) was operated with intermittent aeration under $25^\circ C$ and the other (R2) was operated with continuous aeration at temperature $19-22^\circ C$.

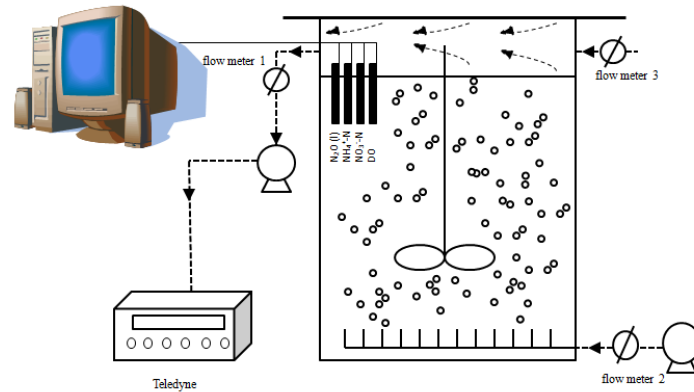


Figure 2.4. Setup of N_2O emissions in pilot-scale system (Yang *et al.*, 2013a).

During the measurements, the reactor was sealed to achieve a closed system. Air was supplied from the bottom of the reactor and an external pump, which delivered a constant airflow rate, was used to collect the off-air above the water surface. Considering that there are periods without air supply during intermittent aeration, an extra inlet of air (for dilution and constant airflow) and a flow meter were installed. Unisense nitrous oxide microelectrode and Teledyne analytical instruments (Model GFC-7002E) were used to measure the nitrous oxide concentration in the liquid and the gas phase, respectively.

2.2.2.3 Results and discussion

The results based on the measurements during several months showed that 0.4-2% of nitrogen load was emitted as N_2O to the atmosphere and less than 0.05% was released as N_2O dissolved in the outgoing water, which is comparable with the results obtained by other studies. The range of N_2O emissions in R1 and R2 was 0.09-2.34 g N_2O/d and 0.4-1.4 g N_2O/d , respectively, which was lower comparing with the results obtained when measuring emission from a full-scale plant in the Netherlands (Kampschreur *et al.*, 2008).

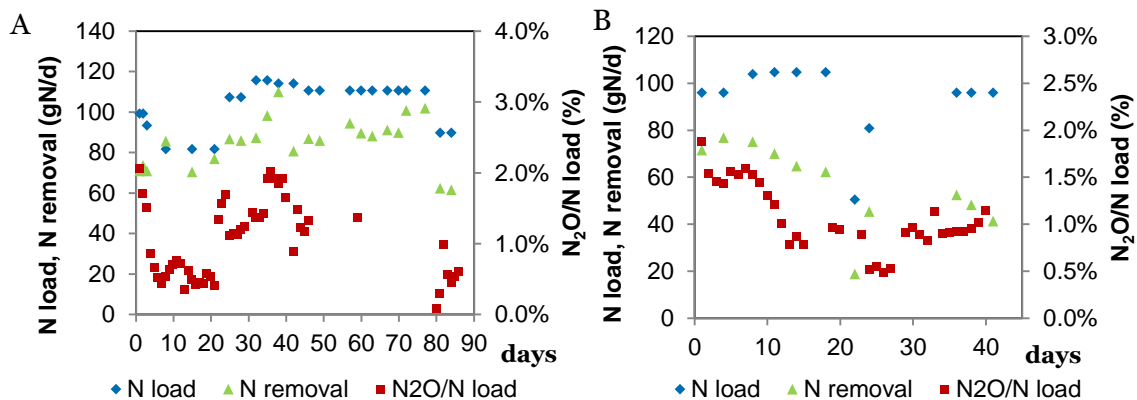


Figure 2.5. Nitrogen loads and removal rates, and emissions of N_2O from R1 (A) and R2 (B) (Yang *et al.*, 2013a).

2.2.2.4 Conclusions

The research work by the KTH/IVL group has shown that:

- Nitrous oxide emissions were related to the nitrogen loads, dissolved oxygen concentrations, and ratio between non-aerated phase and aerated phase (R).
- Large fraction of nitrous oxide is emitted into the air and only a minor part of nitrous oxide emitted with effluent.
- In pilot-scale deammonification MBBR, around 0.4-2 % of the nitrogen load was converted into nitrous oxide gas.
- Nitrous oxide emissions under intermittent and continuous aeration were comparable.

2.2.2.5 Further study

More information about this R&D-work including a more comprehensive background, relevance of the work compared to other activities in the field, methods, results, and evaluation can be found in following publications by the R&D-group:

- Jönsson, H., Baresel, C., Willén, A., Yang, J., Trela, J., Junestedt, C., Tjus, K., Ek, M., Rodhe, L. 2014. Reduce the greenhouse gas emissions from Swedish wastewater and sewage sludge management. Svenskt Vatten AB, accepted for publication.
- Tjus, K., Yang, J., Ek, M., Baresel, C., Trela, J. 2011. Minimize emissions of greenhouse gas from municipal wastewater treatment. In Proceedings of "The 12th Nordic/NORDIWA Wastewater Conference, 365-370.
- Yang, J., Trela, J., Plaza, E., Tjus, K., 2013a. N_2O emissions from a one stage partial nitrification/anammox process in moving bed biofilm reactors. *Water Science & Technology*. 68(1), 144-152.

2.2.3 Emissions from full-scale deammonification systems for supernatant treatment

2.2.3.1 Background

Measurements of emissions at full-scale systems provide information about actual emissions under normal dynamics and impacts of treatment processes. This is not only necessary to map emissions but also to understand dynamics and with help of general knowledge gained from pilot-studied to mitigate emission production.

2.2.3.2 Materials and methods

Emission measurements were performed at the full-scale deammonification processes for supernatant treatment at Himmerfjärden WWTP, Stockholm. The treatment process consisted of two parallel lines (L1 and L2) filled with about 32% of biofilm carriers (K1). DO concentration, pH, conductivity, and temperature were monitored on-line in both treatment lines. As the treatment was used as part of the WWTP, fluctuations in load and other process parameters existed. During the emission measurements the average ammonium concentration of the influent supernatant was 1476 mg N/L, the DOC 380 mg/L, the alkalinity 4705 mg CaCO₃/L and the pH 7.8. The average temperature was 28 °C.

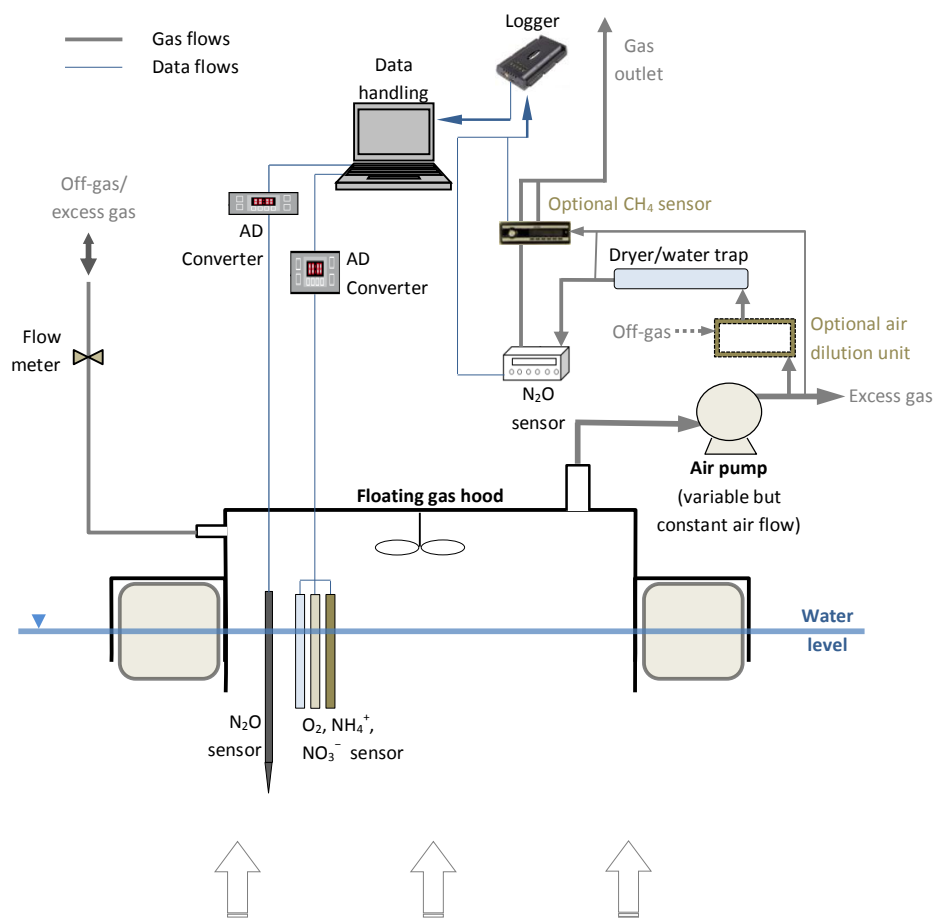


Figure 2.6. Set-up of N₂O emissions measurement in full-scale deammonification system (Yang *et al.*, 2013a).

Emissions to the atmosphere and the effluent water were measured utilizing the set-up designed by the research team (Figure 2.6). This setup, including a floating gas hood to collect the gas from the water surface and micro sensors for the online measurement of N_2O concentration in water and other influencing parameters, facilitates the collection of the emission data dynamic in both space and time. This is not possible with traditional measuring methods that create results with high uncertainties. An extra air inlet was introduced to the hood to enable gas flow to the off-gas analyzer during periods without aeration. A dilution system was used to measure high N_2O concentrations in the off-gas. Various nitrous oxide analyzer (e.g. GFC-7002E; Teledyne Analytical Instruments; MIRAN 1B; Foxboro) were used for the online measurement of N_2O concentration in off-gas to ensure the accuracy of the obtained results.

2.2.3.3 Results and discussion

Higher N_2O emission at the beginning of the measurement and the period of day 23-25, and at some days were related to changes/problems with the DO concentration. When the aeration was stopped for a certain period of time, N_2O emissions were much lower comparing to the other days because most of the produced N_2O remained in the liquid phase and was consumed biologically leading to very little N_2O stripping. The average nitrogen removal efficiency of the process was around 81%. The average value of N_2O emissions was 1.31 kg N/d, which was 0.7 % of the nitrogen loads, 0.86% of the removed nitrogen.

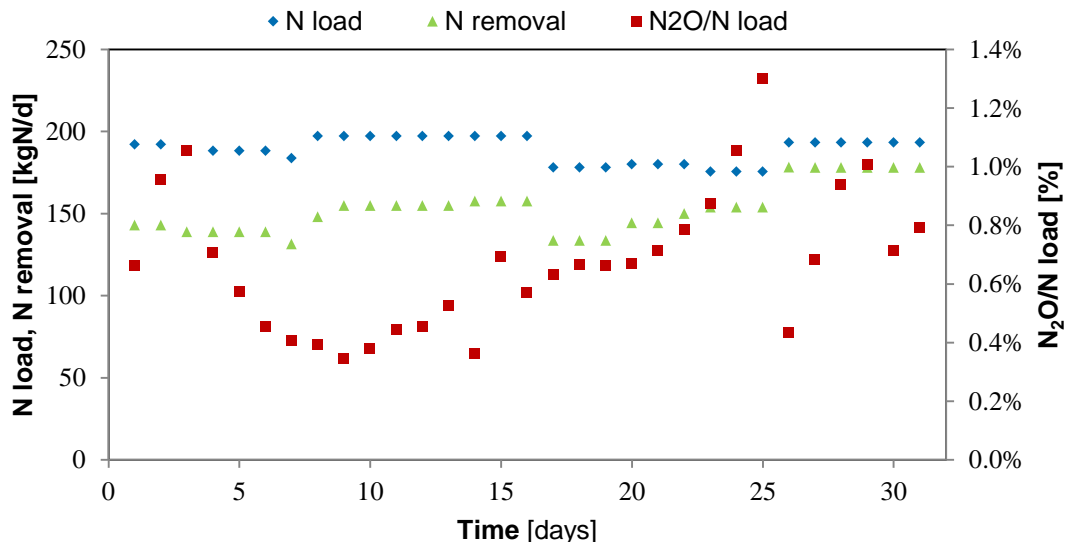


Figure 2.7. Nitrogen loads, removal rates, and emissions of N_2O from full-scale deammonification reactor (Yang *et al.*, 2013a).

2.2.3.4 Conclusions

The research work by the KTH/IVL group has shown that:

- The presented N_2O concentration profiles in process water and process gas clearly illustrate the dynamics in the formation of N_2O in supernatant treatment.
- Aerated and non-aerated periods were related with the increase or decrease of N_2O concentrations. Changes in the process will more or less directly influence

the formation of N_2O . Thus, N_2O production is not only related to the nitrogen loads and aeration but also to the stability of the process configuration.

- There is a consistency in N_2O concentrations in both water and gas phase for the pilot and full-scale MBBR.
- The variations in N_2O concentrations, especially in the one-stage deammonification MBBR, require real-time monitoring over a longer time in order to include different operation conditions and process parameters affecting the formation of N_2O .

Emissions measurements have also been carried out for two-stage deammonification process in full-scale and for traditional nitrification/denitrification treatment of supernatant, as well as on mainstream nitrification/denitrification processes.

2.2.3.5 Further study

More information about this R&D-work including a more comprehensive background, relevance of the work compared to other activities in the field, methods, results, and evaluation can be found in following publications by the R&D-group:

- Jönsson, H., Baresel, C., Willén, A., Yang, J., Trela, J., Junestedt, C., Tjus, K., Ek, M., Rodhe, L. 2014. Reduce the greenhouse gas emissions from Swedish wastewater and sewage sludge management. Svenskt Vatten AB, accepted for publication.
- Sambola, A. 2012. N_2O emission in a full-scale partial nitrification/anammox process, TRITA LWR Degree Project 12:30.
- Stenström, F., Tjus, K., la Cour Jansen, J., 2014. Oxygen-induced dynamics of nitrous oxide in water and off-gas during the treatment of digester supernatant. *Water Science & Technology* 69, 84. doi:10.2166/wst.2013.558.
- Stenström, F., Tjus, K., la Cour Jansen, J. 2013a. Oxygen-induced dynamics of nitrous oxide in water and off-gas during the treatment of digester supernatant. IWA 2013 Holistic Sludge Management Conference, May 6-8, 2013 Västerås, Sweden.
- Stenström, F., Baresel, C., Jansen, J. la C., 2013b. Nitrous oxide production under varied C/N-ratio and DO in an SBR treating digester supernatant, in: NordIWA 2013. Presented at the NordIWA 2013, Malmö.
- Tjus, K., Ek, M., Baresel, C. 2013a. Emissions of greenhouse gases from sewage treatment at SYVAB Himmerfjärdsverket. Technical report, IVL Swedish Environmental Research Institute, U4113, (in Swedish).
- Tjus, K., Baresel, C., Ek, M. 2013b. Measurement of methane emission from the sludge tank at Slottshagen WWTP, Norrköping, IVL Swedish Environmental Research Institute, Stockholm, (in Swedish).
- Yang, J., Trela, J., Plaza, E., Tjus, K., 2013a. N_2O emissions from a one stage partial nitrification/anammox process in moving bed biofilm reactors. *Water Science & Technology*. 68(1), 144-152.
- Yang, J., Baresel, C., Tjus, K., Trela, J., 2013b. Nitrous oxide emissions from different biological nitrogen removal processes treating reject water from sludge dewatering. In Proceedings of IWA Specialized Conference Holistic Sludge Management, May 6-8, 2013 Västerås, Sweden.

2.3 Mainstream treatment by deammonification process

2.3.1 Introduction

While a number of wastewater treatment plants have begun to implement the side stream deammonification as a cost-effective, efficient, and reliable option to treat high-strength ammonia wastewater streams, in particular streams from dewatering of anaerobic digested sludge, the techniques by which to sustain deammonification in the colder and more dilute mainstream wastewater are yet to be defined. The application of deammonification process is especially interesting in two-step systems where organic matter is removed in the first stage by using techniques such as high rate activated sludge, precipitation of organic matter by metal salt and polymer addition, Upflow Anaerobic Sludge Blanket (UASB) reactor or a combination of these methods. The nitrogen removal is then accomplished in a separate step followed by phosphorous removal.

However, there are several challenges to master before deammonification processes can be implemented in mainstream wastewater treatment:

1. The dominance of NOB growth at lower temperatures makes the selection of AOB over NOB not always successful. Moreover, NOB suppression by free ammonia inhibition is not possible because of low ammonium concentration. If NOB out-competes AOB, it leads to nitrate accumulation, which significantly decreases nitrogen removal efficiency. Based on literature and results of research done at Sjöstadsverket, this is the biggest challenge for reaching high efficiency of nitrogen removal treating mainstream wastewater.
The possible solution for out-competing NOB is to optimize operation parameters (DO, intermittent aeration phase duration, pH, inorganic carbon concentration) for stimulating AOB growth and suppression of NOB growth. Using IFAS system instead of MBBR is also a possible way for NOB out-competition.
2. An effective retention of the Anammox biomass in a reactor is required. This is because inflow nitrogen concentration in mainstream wastewater is low (25-50 mg NH₄⁺-N/L) and together with low yield and growth rate of Anammox bacteria this leads to low Anammox biomass production.
One of the possible solutions is to use an attached growth systems where Anammox bacteria grow as a biofilm on moving or fixed carriers.
3. Nitrogen transformation rates are about 70-80 % lower for mainstream wastewater with yearly average temperature of 15 °C comparing to supernatant treatment at 30 °C based on activation energies of deammonification reactions. Moreover, because of lower ammonium and nitrite concentrations in the process, even lower rate can be expected.
The solution for increasing nitrogen conversion can be based on either increasing reaction rate by heating wastewater or treating wastewater at actual temperature but increasing biomass concentration.

2.3.2 Investigated process configurations

There are several possibilities of the application of deammonification process for the mainstream wastewater treatment. The phosphorous removal is not a primary problem

because it is not disturbing the deammonification process in the same way as high concentration of organics do. Therefore, focus is on a functional deammonification process in the mainstream. The options, which have been included in our ongoing research work, are (Figure 2.8):

- I. High rate activated sludge (HRAS) systems > up-concentration of the effluent > one-stage deammonification
- II. Upflow anaerobic sludge blanket (UASB) > up-concentration of the effluent > one-stage deammonification
- III. Upflow anaerobic sludge blanket (UASB) > one-stage MBBR deammonification
- IV. Upflow anaerobic sludge blanket (UASB) > one-stage IFAS deammonification

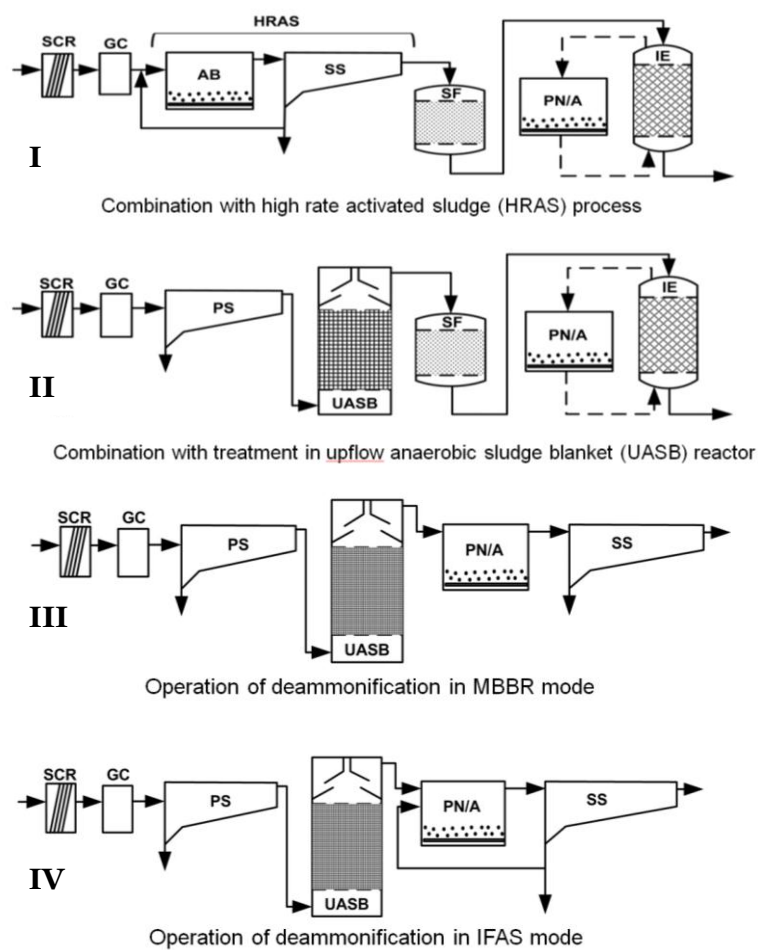


Figure 2.8. Investigated process configuration with mainstream deammonification application.

2.3.3 Deammonification process after ammonium concentration by ion exchange

2.3.3.1 Background

One of the tested approaches for nitrogen removal from mainstream wastewater by one-stage deammonification is a combination of biological treatment with ammonium up-concentration by ion exchange. In such a system, deammonification is applied on concentrated wastewater, which gives the advantage that the existing knowledge of deammonification process operation for side-stream treatment can be used. Moreover, the possibility of increasing the temperature of the wastewater, to reach comparable conditions as for supernatant treatment, is more feasible since the wastewater volume is significantly reduced.

2.3.3.2 Materials and method

Ammonium concentration by ion exchange was studied using four types of ion exchange materials: strong acid cation (SAC) resin, weak acid cation (WAC), natural zeolite of clinoptilolite type and synthetic zeolite of type NaA. Both synthetic wastewater of different content and pre-treated municipal wastewater were used in different stages of the research on ammonium concentration. Further, different aspects of ammonium concentration by ion exchange were studied and regeneration of the exchange material was investigated.

2.3.3.3 Results and discussion

Based on the obtained results the most suitable ion exchange materials for ammonium concentration from municipal wastewater are SAC resin and natural zeolite. The advantage of natural zeolite is that it is highly selective for ammonium ion which in practice means that mostly ammonium is removed from wastewater. On the other hand, SAC resin allows obtaining much higher ammonium content in concentrated stream but other ions (for instance Ca^{2+} and Mg^{2+}) are also transferred.

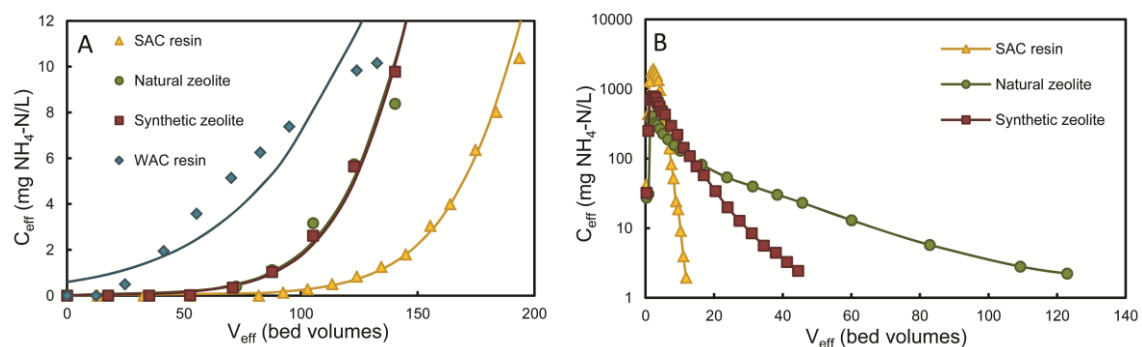


Figure 2.9. Concentration of ammonium from synthetic wastewater using different ion exchange materials: A – saturation from synthetic wastewater; B – regeneration with 30 g/L NaCl solution (Malovanyy *et al.*, 2013).

2.3.3.4 Conclusions

The research work has shown that:

- SAC resin and natural zeolite are the most promising ion exchange materials for the technology of ammonium concentration with ion exchange, where the former offers higher concentration increase and the latter can concentrate ammonium selectively.
- The combined technology was tested in batch mode with the achieved nitrogen removal efficiencies of 83-91%.
- The main disadvantages of the technology are the long bacteria adaptation period and need of chemicals addition for regenerating exchange and alkalinity source dosing.

2.3.3.5 Further study

More information about this R&D-work including a more comprehensive background, relevance of the work compared to other activities in the field, methods, results, and evaluation can be found in following publications by the R&D-group:

- Malovanyy, A. 2014a. Ammonium removal from municipal wastewater with application of ion exchange and partial nitritation/Anammox process. TRITA-LWR LIC-2014:01.
- Malovanyy, A., Plaza, E., Trela, J., Malovanyy, M. 2014b. Combination of ion exchange and partial nitritation/Anammox process for ammonium removal from mainstream municipal wastewater. Accepted to Water Science and Technology.
- Malovanyy, A., Plaza, E., Trela, J., Malovanyy, M. 2014c. Combination of ion exchange and deammonification processes as an innovative way of nitrogen removal. In Proceedings of 11th IWA Leading Edge Conference on Water and Wastewater Technologies, May 26-30, 2014 Abu-Dhabi, United Arab Emirates.
- Malovanyy, A., Plaza, E., Trela, J., Malovanyy M. 2014d. Ammonium removal by partial nitritation and Anammox processes from wastewater with increased salinity. Accepted to Environmental Technology.
- Malovanyy, A., Sakalova, H., Yatchyshyn, Y., Plaza, E., Malovanyy, M. 2013. Concentration of ammonium from municipal wastewater using ion exchange process. Desalination. 329, 93-102.
- Malovanyy, A., Plaza, E., Yatchyshyn, Y., Trela, J., Malovanyy, M. 2012. Removal of nitrogen from the main stream of municipal wastewater treatment plant with combination of Ion Exchange and CANON process (IE-CANON) - effect of NaCl concentration. Proceedings of Polish-Ukrainian-Swedish seminar "Future urban sanitation to meet new requirements for water quality in the Baltic Sea region", Krakow, Poland. E. Plaza, E. Levlin (editors). TRITA-LWR.REPORT 3031.
- Malovanyy, A., Plaza, E., Yatchyshyn, Y. 2011. Concentration of ammonium from wastewater using ion exchange materials as a preceding step to partial nitritation / Anammox process. Proceedings of International Conference "Environmental (Bio)Technologies", Gdansk, Poland.
- Owusu-Agyeman, I., 2012. Systems for ammonium concentration for further removal in the partial nitritation/anammox technology. TRITA LWR Degree Project. 12:19.
- Zhang, X., 2012. Application of Partial Nitritation/Anammox Process for Treatment of Wastewater with High Salinity. TRITA-LWR Degree Project 12:20.

2.3.4 Temperature influence on deammonification performance

2.3.4.1 Background

The temperature of wastewater is one of the most important technological parameter for deammonification process because of the influence on the activity of autotrophic bacteria, which take part in ammonium nitrogen oxidation (AOB, NOB) and nitrite reduction (anammox). The optimum temperature for operation of anammox process is from about 35°C to 40°C. Usually the temperature of supernatant from sludge dewatering after anaerobic digestion is above 25°C and because of this, most of the full-scale side stream deammonification systems work under such conditions. Decreasing the temperature of the treated wastewater has generally resulted in significantly decreased nitrogen conversion rate both in short term of alteration and long-term reactor operation (Szatkowska *et al.*, 2006). Better understanding of how to control the deammonification process to promote the required biomass activity at low temperatures is necessary in order to apply deammonification process successfully for mainstream treatment.

2.3.4.2 Materials and method

This research work focused on the long-term performance of deammonification process for supernatant treatment (high ammonium concentrations) at moderate to low temperatures (from 25°C down to 10°C) in a pilot-scale moving bed biofilm reactor (MBBR). The experimental set-up used in this research and in the research described in chapters 3.3.5 and 3.3.6 is the same as described in chapter 3.1.2. The duration of the study was about two years, divided into six periods, when the reactor was set to operate at 25, 22, 19, 16, 13, and 10 °C, respectively.

The temperature changes, loadings and other process configurations were controlled during the experimental period and the potential activities of heterotrophic bacteria, AOB and NOB were measured at different time intervals.

The microbial community in the MBBR biofilms was investigated by quantitative polymerase chain reaction (qPCR), sequencing of functional and ribosomal genes as well as fluorescence in situ hybridization (FISH) in conjunction with confocal scanning laser microscopy (CLSM).

2.3.4.3 Results and discussion

A moderate decrease of removal capacity was observed in the course of lowering temperature from 25°C to 16°C. At the same time, a less significant decrease in total inorganic nitrogen removal efficiency was measured since applied nitrogen loading rate (NLR) had been adjusted to measured bioreactor capacity. However, after changing temperature from 16°C to 13°C a sharp decrease in both nitrogen removal capacity and efficiency was recorded. The efficiency dropped to 55% at 13°C compared to removal efficiencies at 25°C and the process was totally suppressed at 10°C.

Suppression of AOB bacteria activity occurred when temperature decreased from 19 to 16°C, whereas the average NOB activity did not change significantly with decreasing temperature.

The microbial community composition, as well as the biofilm structure in the MBBR was stable throughout the experiments with decreasing temperatures. Anammox bacteria (*Brocadia* sp.) were dominating the biofilm community in the thick biofilms, with a much lower abundance of AOB (*Nitrosomonas* sp.) located near the oxygenated biofilm-water interface, where also NOB (*Nitrobacter* sp. and *Nitrospira* sp.) were situated (Persson *et al.*, 2014).

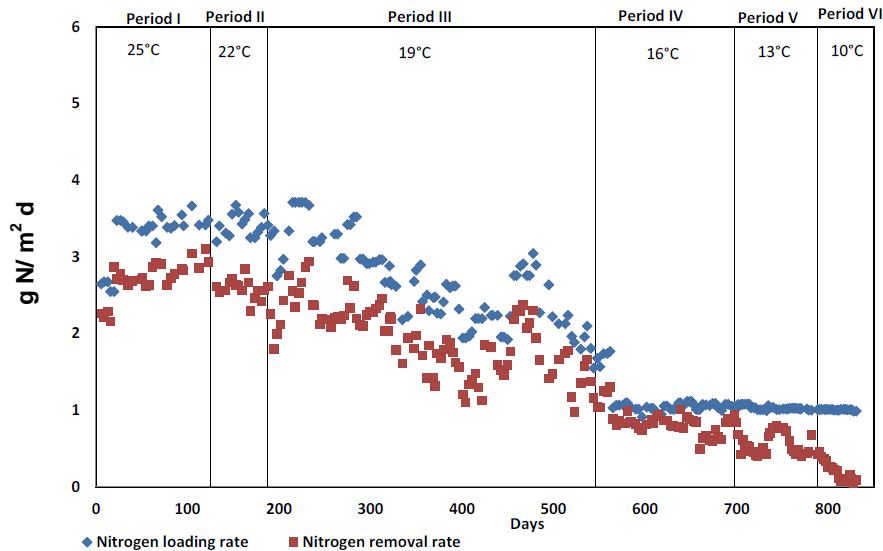


Figure 2.10. Nitrogen loading and nitrogen removal rates at different temperature during the study period (Sultana *et al.*, 2014a).

2.3.4.4 Conclusions

The research work by the KTH/IVL group has shown that:

- For high-content ammonium wastewater, only a moderate reduction of capacity (about 41%) of deammonification MBBR reactor was recorded when temperature decreased from 25 down to 16°C. At the same time an insignificant efficiency change occurred (about 6%) as the result of compensating lower bioreactor's capacity with reduced nitrogen loading rate.
- The threshold temperature below which capacity of deammonification process sharply decreased was 16°C.
- The deammonification process for reject water was totally suppressed at 10°C.
- The microbial community and the structure of the MBBR biofilms was stable throughout the study, indicating that the MBBR carriers provided a stable and protected environment for the microorganisms.
- No adaptation of anammox to low temperatures was recorded. This observation can be utilized for setting strategy for a start-up of a new system for reject water deammonification. It also implies that bio-augmentation may be utilized as a proper technique for increasing the capacity of deammonification bioreactor for wastewater treatment at low temperatures.
- Activity of anammox was recorded even at 5°C.

2.3.4.5 Further study

More information about this R&D-work including a more comprehensive background, relevance of the work compared to other activities in the field, methods, results, and evaluation can be found in following publications by the R&D-group:

- Bertino, A. 2010. Study on one stage partial nitritation-anammox process in Moving Bed Biofilm Reactors: a Sustainable Nitrogen Removal. TRITA LWR degree Project.
- Maloszewski, K. 2013. Application of on-line measurements and activity tests for the controlling and monitoring of the Nitritation/Anammox process. TRITA-LWR Degree Project 13:4.
- Persson, F., Sultana, R., Suarez, M., Hermansson, M., Plaza, E., & Wilén, B.M. (2014). Structure and composition of biofilm communities in a moving bed biofilm reactor for nitritation-anammox at low temperatures. *Bioresource Technology*. 154, 267-273.
- Rajkowski, M. 2012. Evaluation of the deammonification process operated at low temperatures. TRITA LWR Degree Project 12:26.
- Sultana, R., Yang, J., Trela, J., Plaza, E., Wilén, B.M., Persson, F. 2014a. Deammonification process performance and efficiency at moderate to low temperatures. Submitted to *Water Research Journal*.
- Sultana, R. 2014b. Partial Nitritation/Anammox process in a moving bed biofilm reactor operated at low temperatures. Licentiate thesis, TRITA-LWR LIC-2014:05, 33p.
- Sultana, R., Yang, J., Trela, J., Plaza, E. 2013. Deammonification process performance and efficiency at different temperatures. In *Proceedings of IWA Specialized Conference "Holistic Sludge Management, May 6-8, 2013 Västerås, Sweden*.
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2.3.5 Deammonification process at low concentrations and low temperatures

2.3.5.1 Background

Besides possible technological constraints related with low temperature as discussed in the previous chapter, low nitrogen concentration is the main challenge for mainstream implementation of the deammonification process. In such conditions (low substrates concentration, low temperature) kinetics of biotransformation processes will be altered from "zero-order" to "half-" or even "first-order". Consequently, expected microbial activity and nitrogen removal rates will probably be even lower. Because of that, problems keeping highly active and right-structured biota (active AOB and anammox bacteria, NOB's outcompeted) in the process may occur. Studies that observe response of the process in the course of reducing ammonia-nitrogen concentration at low temperature are necessary to develop efficient deammonification technology for a mainstream wastewater.

2.3.5.2 Materials and method

The aim of the presented research work in this section was to investigate the influence of moderate to low nitrogen concentrations at 13°C (targeting towards mainstream conditions) on the process performance of deammonification in a pilot-scale MBBR. The bioreactor operational time of 320 days was divided into six periods with decreasing influent concentration. The process performance was performed by a set of batch tests for the activity of the different groups of nitrogen converting microorganisms (AOB, NOB, anammox, H), besides standard chemical assays. For microbial analysis, see section 2.3.4.2.

2.3.5.3 Results and discussion

Nitrogen removal rates (NRR) throughout the periods from I to V of the study were stable. A drop in NRR was observed after decreasing ammonia nitrogen concentration in period VI. This suggests that in the first five periods, temperature was the main factor influencing the nitrogen removal capacity while in the last period other factor additionally reduced the nitrogen removal rate, e.g. low substrates concentration (ammonium ions and nitrites).

Despite stable nitrogen removal rates, the efficiency of the process dropped below 50 %. This was mainly caused by NOB growth in the biofilm, a problem that had already earlier been identified as an important parameter that has to be controlled.

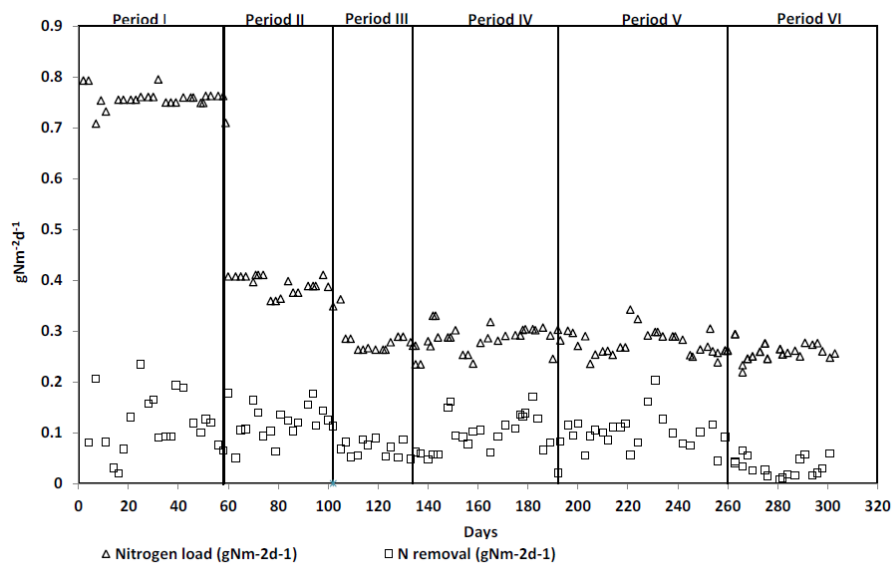


Figure 2.11. Nitrogen loading rate (NLR) and Nitrogen removal rate (NRR) during different periods of the test (Sultana *et al.*, 2014b)

The activity of anammox bacteria decreased significantly in the course of two first periods and a further reduction was recorded in the last period (VI). Substrate utilization capacity of ammonia oxidizing bacteria's (AOB) was rather stable throughout the whole time of experiment. The activity of NOB increased gradually from period III to V and finally started outcompeting both AOB and anammox in period VI.

The possible denitrification in the bioreactor was limited by low ratio of COD to N-NH₄ concentration in the influent. Microbial community analysis (qPCR and FISH analyses) showed that dominating group of microorganisms in biofilm was anammox bacteria throughout the study. NOB were present in the biofilm throughout the study period in stable but lower abundances than anammox bacteria and AOB, but apparently were active enough to have a large impact on the process performance.

2.3.5.4 Conclusions

The research work by the KTH/IVL group has shown that:

- It is possible to remove nitrogen from low strength wastewater at temperature of 13°C via deammonification with MBBR type processes.
- After decreasing ammonia nitrogen concentration in the reactor below about 45 mg/L NH₄⁺-N the other factor beside temperature additionally reduced the nitrogen removal rate – the most probably it was the low substrates concentration (ammonium ions, nitrites, inorganic carbon).
- NOB at low temperatures and low substrate concentration outcompete both anammox and AOB biota, despite a numerically lower abundance.
- In order to transform capacity of AOB and anammox biomass into efficiency of nitrogen removal in the reactor, suppression of NOB growth must be achieved.

2.3.5.5 Further study

More information about this R&D-work including a more comprehensive background, relevance of the work compared to other activities in the field, methods, results, and evaluation can be found in following publications by the R&D-group:

- Maloszewski, K. 2013. Application of on-line measurements and activity tests for the controlling and monitoring of the nitrification/ anammox process. TRITA-LWR Degree Project 13:41.
- Persson, F., Sultana, R., Wilén, B.M., Hermansson, M., Sörensson, F., Matsson, A., Plaza, E. 2013. One-stage nitrification-anaerobic ammonium oxidation at low temperatures in a moving bed biofilm reactor. In Proceedings of IWA Specialized Conference “Holistic Sludge Management, May 6-8, 2013 Västerås, Sweden.
- Rajkowski, M. 2012. Evaluation of the deammonification process operated at low temperatures. TRITA LWR Degree Project 12:26.
- Sultana, R., Yang, J., Trela, J., Plaza, E., Wilén, B.M., Persson, F. 2014a. Deammonification process performance and efficiency at moderate to low temperatures. Submitted to Water Research.
- Sultana, R. 2014b. Partial Nitrification/Anammox process in a moving bed biofilm reactor operated at low temperatures. Licentiate thesis, TRITA-LWR LIC-2014:05, 33p.
- Sultana, R., Plaza, E., Persson, F., Wilén, B.M. 2014c. Partial nitrification/anammox with moderate to low nitrogen concentrations at 13°C. (Manuscript).

2.3.6 Combination of anaerobic treatment with UASB and mainstream deammonification process

2.3.6.1 Background

One of the most promising wastewater treatment systems is, according to the research team, a combination of organic matter removal in an Upflow Anaerobic Sludge Blanket (UASB) and nitrogen removal via deammonification in a moving bed biofilm reactor (MBBR). In the UASB reactor operated at slightly increased ambient temperatures, most of biodegradable organic matter can be transformed to biogas while concentration of nutrients remains unchanged.

2.3.6.2 Materials and method

Application of deammonification process for nitrogen removal from UASB effluent has been studied during 2 years. The influent of a pilot-scale deammonification MBBR was gradually changed from reject water to UASB effluent during an adaptation period. After transition to UASB reactor effluent the MBBR was operated for roughly 1.5 years and different aeration modes in MBBR were tested aiming to promote aerobic ammonium oxidizing bacteria (AOB) and suppress nitrite oxidizing bacteria (NOB) to reach high efficiency of nitrogen removal.

A number of activity tests were performed and evaluated with the goal to improve the system operation. Optimal conditions for AOB/NOB competition, different aeration strategies including continuous and intermittent aeration with different duration of aerated and non-aerated phases were investigated.

2.3.6.3 Results and discussion

During the first five transition phases, nitrogen removal efficiency above 60% was reached and there was no substantial accumulation of nitrate (Table 2.1). When ammonium concentration was further decreased, nitrate started to accumulate and more than 30% of all the ammonium, oxidized by ammonium oxidizing bacteria (AOB), was converted by nitrate oxidizing bacteria (NOB). High nitrate production resulted in low removal efficiency during the last two transition phases (43% in average). When the MBBR was operated with undiluted UASB effluent, nitrate production became even higher. In average, nitrogen removal efficiency during first 200 days of operation with mainstream wastewater was 25% and 65% of all the oxidized ammonium was converted to nitrate.

After changing the inflow to un-spiked UASB reactor effluent it was found that with short aeration cycles NOB suppression due to intermittent aeration allows reaching the highest nitrogen removal efficiency (38% in average) in this system set-up.

Table 2.1. Performance of studied deammonification MBBR during transition phase from supernatant to UASB effluent.

		Phase (in total 200 days)							
		I	II	III	IV	V	VI	VII	VIII
MBBR inflow	NH ₄ -N (mg/L)	884	463	252	194	146	108	67	30
	COD (mg/L)	404	194	95	84	72	56	56	62
MBBR outflow	NH ₄ -N (mg/L)	51	143	80	30	39	23	16	8
	NO ₂ -N (mg/L)	4.5	3.7	2.6	1.8	1.3	0.4	0.3	0.2
	NO ₃ -N (mg/L)	66	25	21	34	18	38	22	14
	COD (mg/L)	275	148	94	70	61	48	37	39
Biomass quantity	VSS (g)	28.5	13.1	5.0	4.5	3.8	3.0	3.7	1.7
	Biofilm VS (g)	1147	1198	1198	1233	1275	1130	1104	856
NL (g N/m ² -d)		1.79	1.74	1.22	1.21	0.84	0.69	0.44	0.21
NRR (g N/m ² -d)		1.60	1.07	0.70	0.84	0.54	0.34	0.19	0.05
HRT (days)		2.45	1.33	1.06	0.81	0.95	0.78	0.76	0.72

2.3.6.4 Conclusions

The research work by the KTH/IVL group has shown that:

- In mainstream deammonification operated in one-stage MBBR reactor much lower removal rate comparing to treatment of supernatant must be expected due to decrease of AOB amount in the system.
- Washout of Anammox bacteria from the MBBR is not a significant problem as the stable specific activity during 1.5 years of continuous operation indicated.
- The main hinder to reach high efficiency is the increase of NOB activity.
- Intermittent aeration with short cycle can help to increase the efficiency. However, due to low influence of DO concentration on AOB/NOB competition in biofilm and AOB washout with suspended sludge, reaching high efficiency of nitrogen removal in reactor operated in MBBR mode with low influent nitrogen and low temperature is difficult.
- Based on findings of this part of research the operation of deammonification reactor was changed to integrated fixed film activated sludge (IFAS) mode, which is described more in the section of ongoing and future work (see Section 4.1.1)

2.3.6.5 Further study

More information about this R&D-work including a more comprehensive background, relevance of the work compared to other activities in the field, methods, results, and evaluation can be found in following publications by the R&D-group:

- Malovanyy, A., Yang, J., Trela, J., Plaza, E. 2014e. Combination of UASB reactor and partial nitrification/Anammox MBBR for municipal wastewater treatment. Manuscript.
- Malovanyy, A., Plaza, E., Rajkowski M., Trela, J., 2014f. Deammonification process combined with UASB reactor for treatment of mainstream wastewater. In Proceedings of 11th IWA Leading Edge Conference on Water and Wastewater Technologies, May 26-30, 2014 Abu-Dhabi, United Arab Emirates.
- Malovanyy, A., Trela, J., E. Plaza, E., 2014g. Competition between AOB and NOB in deammonification MBBR treating mainstream wastewater. Accepted for IWA Specialist Conference on Global Challenges for Sustainable Wastewater Treatment and Resource Recovery 2014 Kathmandu Nepal.

3 Ongoing and future work

This section lists some of the new topics the research group focuses on and that are directly related to the deammonification processes. The mentioned R&D areas are chosen towards the most current needs and requests from collaboration with different WWTPs.

3.1 Mainstream deammonification in IFAS system after organic matter removal in UASB reactor

Based on the tests presented in section 2.3.6 It indicated that the ratio of AOB/NOB is higher in suspended biomass, it would be preferred to keep high concentration of suspended sludge in the reactor. Since diffusion of DO into suspended biomass flocks is not a rate-limiting step, it is possible to control AOB/NOB competition by keeping DO concentration that stimulates NOB out-selection. Moreover, sludge age of suspended biomass can be controlled, which is not possible for biofilm, and this provides more possibilities for testing different NOB out-selection mechanisms.

The research group therefore converted the utilized pilot deammonification MBBR to IFAS mode by recirculating sludge from a post-sedimentation back to the reactor. Different modes of aeration (DO concentration, continues and intermittent aeration with different phases duration) are tested.

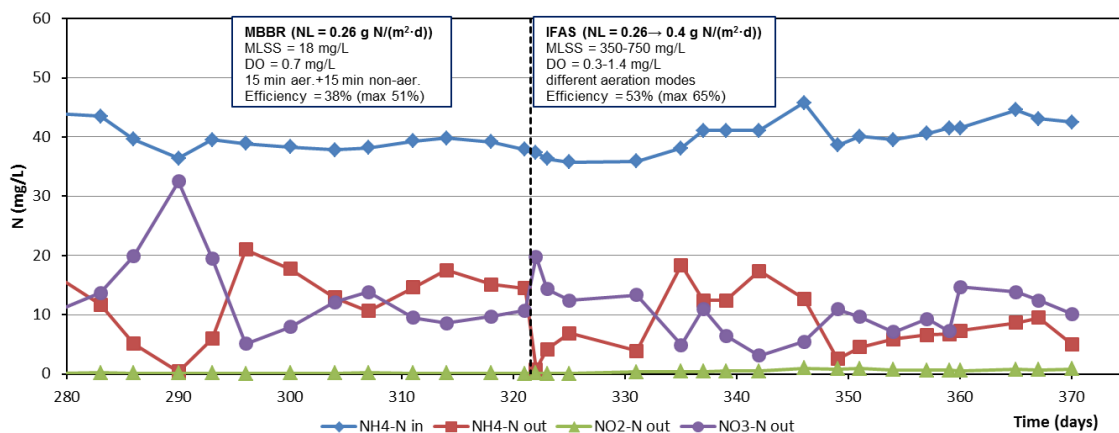


Figure 3.1. Influence of DO concentration on the rates of AOB and NOB in attached biomass (Malovyany *et al.*, 2014e).

The average efficiency during these tests was, with 53%, significantly higher than in the previously in MBBR mode (Figure 3.1). However, after initial testing, conditions that allow maintaining a stable efficiency of 60-65% were identified. The goal of the study is to reach average nitrogen removal efficiency of >75%.

This R&D is ongoing and publications are made available a.s.a.p.

3.2 Strategies for nitrate oxidation bacteria (NOB) suppression for mainstream deammonification

As it was emphasized earlier, the key factor for efficient mainstream deammonification is the suppression of NOB growth and at the same time keeping an active AOB and anammox biota. This becomes even more challenging at low temperatures of wastewater as NOB are less temperature sensitive than AOB and anammox (lower activation energy). Furthermore, taking into account basic kinetic parameters of bacterial growth (maximum growth rate (μ_{\max}) and yield coefficient (Y)), the theoretical NOB potential of nitrite oxidation (and resulting substrate utilization rates/substrate fluxes in the reactor) is one order of magnitude higher than for AOB and two orders of magnitude higher than for anammox. This implies that even low amounts of NOB in biofilm can successfully compete with (or even out-compete) AOB and anammox. The phenomena of generating high substrate fluxes by NOB will have higher influence at lower temperatures and under conditions of absence of inhibitors of NOB's growth (like free ammonia (FA) or free nitrous acid (FNA)). Lack of those inhibiting factors is certain in low strength mainstream wastewater.

Therefore, ways to suppress and out-compete NOB under such conditions have been identified as:

- Utilizing differences of substrate affinities (mainly oxygen) for AOB and NOB (unfortunately NOB are able to adapt to lower dissolved oxygen concentration).
- Changing physical-chemical conditions in reactor to induce inhibition of NOB (for example by increasing concentration of FA or FNA).
- Suppressing NOB growth by depriving them of one of the substrates (oxygen or nitrites). It was proved as possible and successful strategy with use of intermittent aeration control with short aerated and prolonged non-aerated periods.
- Increasing concentration of AOB/anammox bacteria, for example by sludge recirculation and running process in IFAS mode (enrichment with AOB) or bio-augmentation utilizing anammox-rich biofilm from side stream wastewater (enrichment with anammox).
- Mechanically decreasing NOB biomass concentration in the reactor (low solids retention time in IFAS reactor, abrasion or erosion of outer layer of biofilm by inducing higher shear stress in a bioreactor).
- Activating AOB and anammox by physical and chemical factors (for example: inorganic carbon, pH).
- Irreversibly suppressing NOB by chemical factors (hard to achieve in biofilm).

Based on this, the scopes of the on-going research is on finding an effective and feasible control method of NOB growth and then optimize the process at low temperatures and nitrogen concentrations. The following strategies and factors are being tested:

- intermittent aeration strategies,
- process running at increased pH,
- influence of inorganic carbon concentration on anammox bacteria activity,
- interactions between ammonia nitrogen concentration, pH and dissolved oxygen concentration and their influence on NOB suppression.

This R&D is on-going and publications are made available a.s.a.p.

3.3 Modelling mainstream deammonification

A mathematical model of deammonification processes in a moving bed biofilm reactor has been developed, calibrated, and verified. The model together with the results from experimental studies will be utilized to find a set of optimal values of technological parameters to operate and control efficiently the mainstream deammonification process.

This R&D is on-going and publications are made available a.s.a.p.

3.4 Mainstream deammonification combined with high rate activated sludge

Besides the already investigated mainstream deammonification coupled to anaerobic wastewater treatment for an energy-positive treatment alternative, the work of the research group further includes focus on mainstream application of deammonification in existing WWTPs. This implies the startup and operation of an enhanced one-stage deammonification process in the mainstream based on the existing infrastructure of a common activated sludge operated WWTP. The goal is, similar to the mainstream UASB-deammonification system, to remove organic matter, nitrogen, and phosphorus simultaneously from municipal wastewater reaching current discharge limits but at a significant lower consumption of both energy and other resources.

This R&D is on-going and publications are made available a.s.a.p.

3.5 Mainstream deammonification: Process control

Process monitoring and control are of increasing interest not only for deammonification processes but also for sewage treatment processes in general as targets becoming more stringent and advances in on-line monitoring and process control allows for further operation improvement. Especially, focus will be on the operation of the deammonification process in IFAS mode and for mainstream applications. As part of this, new on-line sensors and a control system will be installed at the pilot-scale reactors at Hammarby Sjöstadverk.

This research work overlaps with other activities such as the aeration control for minimizing GHG-emissions and strategies for nitrate oxidation bacteria (NOB) suppression. Different regulators and control strategies will be evaluated and, if possible, multivariate analyses (MVA), successfully implemented in a number of industrial processes by IVL, will be used.

This R&D is on-going and publications are made available a.s.a.p.

3.6 Mainstream deammonification startup/scale up strategy

As the deammonification process is successfully implemented in an increasing amount of WWTPs for supernatant treatment in the side stream, and as it in the future also will be in the mainstream treatment, the process startup will be a crucial stage, especially for the biofilm system. Both, seeding with bacteria from existing plants or a clean start-up may be applied which have its advantages and disadvantages that will be investigated.

The goal of this research is to develop fast start-up strategies for different prerequisites in order to facilitate the wide implementation of the deammonification process. For this, several pilot reactors will be used to test and compare various startup strategies.

This R&D is on-going and publications are made available a.s.a.p.

3.7 N₂O emissions from mainstream deammonification

Greenhouses gas emissions are not avoidable in the biological wastewater treatment processes. However, the process can be operated in a way to minimize the nitrous oxide and methane gas formation and emissions. Right now, it is considered that pH, organic matter, and DO concentration are the factors, which influence the nitrous oxide production. However, process operation and reactors configuration also play important role, which related to nitrous oxide production. In order to estimate and minimize the nitrous oxide emission, more measurement and modelling work based on the different processes and reactor configurations are expected to be done. For example, in the one-stage deammonification process, the layer structure of the biofilm system allows anaerobic and aerobic bacteria growing together and existing in the same reactor. Intermittent aeration offers time duration of aerobic and anaerobic phases. Since nitrous oxide producers exist both in the aerobic and anaerobic conditions, it is very difficult to avoid nitrous oxide production. When the oxygen concentration is low, AOB has a tendency to produce nitrous oxide; while when the DO concentration is high; oxygen can diffuse into the biofilm system and give inhibition effect on denitrifiers (Table 3.1). If the system is based on the suspended sludge, the production and emission of nitrous oxide will be easier to predict and minimize.

Table 3.1. Nitrous oxide production in one-stage deammonification biofilm systems under intermittent aeration.

Intermittent aeration biofilm system	Aerated phase		Non-aerated phase
	Insufficient aeration	Over aeration	
AOB (outer layer)	N ₂ O production happens.	No N ₂ O production.	Oxygen diffused into the reactor cause N ₂ O production.
Denitrifiers (inner layer)	Optimal condition that N ₂ O can be consumed	DO diffused into inner layer of the biofilm and cause N ₂ O production.	Optimal condition for N ₂ O consumption.

The ongoing and future research will include a focus on a better understanding of these mechanisms as they are crucial for the control of nitrous oxide emissions to the atmosphere. This is not only of interest for one-stage deammonification processes but also for hybrid systems such as the investigated IFAS-deammonification process.

R&D will focus on improving our understanding of emissions from deammonification processes in side-stream applications and gaining knowledge on emissions from deammonification processes in mainstream applications to facilitate proper measures for emission control.

This R&D is ongoing and publications are made available a.s.a.p.

4 Conclusions and Discussion

The report provides an overview of the activities by the KTH/IVL research group within the area of deammonification both in side-stream and mainstream applications. It indicates that the research activities are oriented on current demands from WWTPs and cover all related aspects in order to provide a holistic work. The research is also at the frontline even if considering the international scientific community. While collaborating with WWTPs to ensure a problem- and practical-oriented R&D-work, the knowledge buildup and future development is also ensured by educating PhDs and master students.

Some years ago, the research group was one of few that worked with deammonification and its application in WWTPs. Nowadays there are worldwide enormous amounts of research funding and research activities going on within this field.

For an optimal continuation of the high-level R&D, more collaboration partners are welcome, especially if they can accomplish the commercialization and spread of the deammonification applications developed by the group. As decades of working with WWTPs have shown, there is no such thing as a final optimal process configuration. The current research group is dedicated to, together with its partners; use all of its knowledge to serve for further development in this area in order to get a step closer to a more sustainable society.

This synthesis report will continuously be updated when new results are available and ready for dissemination.

5 References

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- Malovanyy, A., Plaza, E., Trela, J., Malovanyy, M. 2014c. Combination of ion exchange and deammonification processes as an innovative way of nitrogen removal. In *Proceedings of 11th IWA Leading Edge Conference on Water and Wastewater Technologies*, May 26-30, 2014 Abu-Dhabi, United Arab Emirates.
- Malovanyy, A., Plaza, E., Trela, J., Malovanyy M. 2014d. Ammonium removal by partial nitritation and Anammox processes from wastewater with increased salinity. Accepted to *Environmental Technology*.
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