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Full-scale partial nitritation/anammox experiences – An application survey

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ABSTRACT

Partial nitritation/anammox (PN/A) has been one of the most innovative developments in biological wastewater treatment in recent years. With its discovery in the 1990s a completely new way of ammonium removal from wastewater became available. Over the past decade many technologies have been developed and studied for their applicability to the PN/A concept and several have made it into full-scale. With the perspective of reaching 100 full-scale installations in operation worldwide by 2014 this work presents a summary of PN/A technologies that have been successfully developed, implemented and optimized for high-strength ammonium wastewaters with low C:N ratios and elevated temperatures. The data revealed that more than 50% of all PN/A installations are sequencing batch reactors, 88% of all plants being operated as single-stage systems, and 75% for sidestream treatment of municipal wastewater. Additionally an in-depth survey of 14 full-scale installations was conducted to evaluate practical experiences and report on operational control and troubleshooting. Incoming solids, aeration control and nitrate built up were revealed as the main operational difficulties. The information provided gives a unique/new perspective throughout all the major technologies and discusses the remaining obstacles.

1. Introduction

Nitrogen removal from municipal and industrial wastewaters via the traditional nitrification/denitrification (N/DN) route has become a key stage in biological treatment trains over the past decades. The implementation of conventional nitrogen removal, i.e. the aerobic conversion of ammonium to nitrate (autotrophic nitrification) combined with the anaerobic conversion of nitrate to nitrogen gas in presence of organic carbon (heterotrophic denitrification), is, however, energy intensive, mainly due to aeration costs. In recent years a new pathway

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for ammonium removal has been discovered and widely studied for its potential engineering application: anaerobic ammonium oxidation, short anammox. In this process, ammonium as electron donor and nitrite as electron acceptor are converted anaerobically into mainly nitrogen gas and some nitrate by anammox bacteria (Strous et al., 1998).

These organisms belong to the phylum *Planctomycetes* and up to now five genera have been described: *Candidatus* Brodacia, *Ca*. Kuenenia, *Ca*. Anammoxoglobus, and *Ca*. Jettenia (Jetten et al., 2001; Kartal et al., 2007; Schmid et al., 2005) were all enriched from activated sludge plants; *Ca*. Scalindua occurs mainly in natural habitats (e.g. marine environments) (Jetten et al., 2009).

As strictly anaerobic organisms, anammox bacteria are inhibited by already low concentrations of dissolved oxygen (Egli et al., 2001; Strous et al., 1999). However, as Strous et al. (1997) concluded from experiments with intermittent aeration, anammox was reversibly inhibited by oxygen which makes single stage processes (i.e. the combination of partial nitritation and anammox in one reactor) possible (Third et al., 2005).

A crucial parameter for the anammox process is the nitrite concentration. Nitrite is an essential substrate but also inhibitory to the reaction. Many studies have focused on the effect of nitrite on anammox, however, reported threshold concentrations span over a wide range. Strous et al. (1999) reported complete inhibition for nitrite concentrations of more than 100 mg-N l^{-1}. A 50% inhibition of the anammox process at 350 mg-N l^{-1} nitrite was shown by Dapena-Mora et al. (2007) performing activity tests. Studies with *Ca*. Kuenenia stuttgartiensis by Egli et al. (2001) showed that anammox was only inhibited at nitrite concentrations higher than 182 mg-N l^{-1}. Prolonged high nitrite concentrations (6 days at 30–50 mg-N l^{-1}) as induced by Fux et al. (2004) seriously inhibited anammox activity with also lengthy recovery periods. Repeated additions of nitrite higher than 30 mg-N l^{-1} caused activity losses while short-term inhibition was found at concentrations higher than 60 mg-N l^{-1} by Bettazzi et al. (2010). Lotti et al. (2012) found inhibition increasing with exposure time and observed full recovery after removal of the nitrite. Recently the protective presence of ammonium was highlighted for nitrite inhibition, enhancing the nitrite concentration resulting in 50% inhibition by a factor of 7.2 (Carvajal-Arroyo et al., 2014). DEMON® plants keep nitrite concentrations well below 5 mg-N l^{-1}; inhibition was observed for nitrite >10 mg-N l^{-1} (Wett, 2007). Free nitrous acid has also been reported to have inhibitory effects on anammox bacteria (Fernández et al., 2012), however, within the normally applied pH range of anammox applications (pH > 7.0), nitrite rather than free nitrous acid seems to be the predominant cause of inhibition (Puyol et al., 2013).

Inhibitory effects of ammonium or nitrate on anammox bacteria were only reported for very high concentrations of several hundred milligrams per liter (Dapena-Mora et al., 2007) up to grams per liter (Strous et al., 1997). For ammonium this effect might be attributed to free ammonia inhibition as Fernández et al. (2012) report a 50% inhibition of anammox activity caused by free ammonia concentrations of 35–40 mg-N l^{-1} which also agrees with unpublished results by the authors indicating inhibition at 20–30 mg-N l^{-1} for centrate with 3 g-N l^{-1} influent ammonium concentration. Some researchers also observed inhibition of anammox activity by organic compounds, i.e. methanol (Guven et al., 2005; Isaka et al., 2008).

The engineering application of anammox bacteria is highly interesting, since their unique pathway entails significant advantages compared to classical N/DN. Indeed, the need for organic carbon decreases by 100%, aeration requirements by about 60% and sludge production by about 90% (Mulder, 2003; Siegrist et al., 2008; Van Loosdrecht and Salem, 2006).

The application of anammox is contingent on the ability to effectively shunt nitrification at nitrite. Only a partial oxidation of ammonium to nitrite (nitritation) is required for the successful application of partial nitritation/anammox (PN/A). Thereby, the balance between the different microbial groups involved is highly important. Aside from growing and sustaining the slow growing anammox bacteria, balanced activity of aerobic ammonium oxidizing bacteria needs to be established in line with a suppression or out-selection of nitrite oxidizing bacteria. The growth rates of ammonium oxidizing bacteria are usually higher than those of nitrite oxidizing bacteria at elevated temperatures (> 30°C) which makes selective wash-out of nitrite oxidizing bacteria possible in suspended biomass systems for partial nitritation by adjusting the solids retention time (SRT) at a minimum level (Hellinga et al., 1998). That concept, however, is not applicable for biofilm systems (Fux et al., 2004) because biofilms can sustain microorganisms with very different growth kinetics due to the undefined SRT and their distinct substrate gradients (Bryers, 2000); further also for combined PN/A SRT cannot be applied as sole selection criterion due to the significantly slower growth rate of the anammox biomass. The most practical approach to limit nitrite oxidation is considered to be reactor operation under oxygen limited conditions which favors growth of ammonium oxidizing bacteria versus nitrite oxidizing bacteria, as their oxygen affinity is higher (Blackburne et al., 2008; Wyffels et al., 2004) and combined with additionally competition for nitrite by the anammox bacteria.

Within the last decade several technologies have been developed and successfully implemented in full scale, e.g. sequencing batch reactors, granular reactors, and moving bed biofilm reactors.

This work intends to give an overview of the existing full scale PN/A technologies and to summarize/discuss experiences, operational aspects and remaining obstacles underlined and backed with real data gathered during a survey of 14 full-scale PN/A facilities. In comparison to other previously published review articles (Gustavsson et al., 2010; Terada et al., 2011; Van Hulle et al., 2010; Vlaeminck et al., 2012), this contribution focuses on technologies that are in full-scale operation and discusses control and operational troubleshooting.

2. Implementation of PN/A in full-scale

A variety of PN/A reactor configurations has been developed over the past decade. All full-scale installations using PN/A known to the authors are listed in Tables SI1–SI4. The majority of the PN/A installations is located in Europe, however, there is currently a strong interest in side-stream treatment implementation in North America. For better control of nitritation, early PN/A implementations used two-stage reactor configurations or made use of already existing nitritation systems (e.g. SHARON type reactors). With more full-scale experiences, focus has shifted mainly to single-stage systems. Current full-scale implementations include the moving bed biofilm reactor (MBBR) (Rosenwinkel and Cornelius, 2005), granular sludge processes (Abma et al., 2010) and SBR (Joss et al., 2009; Wett, 2007). Also few full-scale RBC (Hippen and Rosenwinkel, 1997) and activated sludge systems (Desloover et al., 2011) are operated. Fig. 1 compares the development of publications on anammox and the number of full-scale PN/A installations since 1995. There is only a short delay between the discovery and early publications on anammox and the first full-scale implementations (not considering plants where anammox was found coincidentally). The steady increase in new plants over the past years will result in more than 100 operating installations worldwide by 2014.

The distribution of installations between different configurations and technologies (Fig. 2) reveals that the SBR technology is the most commonly applied reactor type (more than 50% of all PN/A systems) followed by granular systems and MBBRs. The majority of all installations is realized in a one-stage configuration (88%) and for municipal wastewater treatment (75%). A different picture reveals itself when comparing the average nitrogen-load per plant. Then, granular systems treat by far the most nitrogen, the same applies for industrial sites (Fig. 2).

Among the SBR technologies, the DEMON® configuration is the most popular with more than 80% of all SBR systems. This process was first implemented in Strass, Austria, where reject water was originally treated in a nitritation/denitritation SBR with a pH-based control. DEMON® SBRs use of a patented pH-based feed control (Wett, 2006). A hydrocyclone allows to adjust the SRT for ammonium oxidizing bacteria and anammox bacteria separately and to separate the slow growing anammox bacteria from incoming solids (Wett et al., 2010).

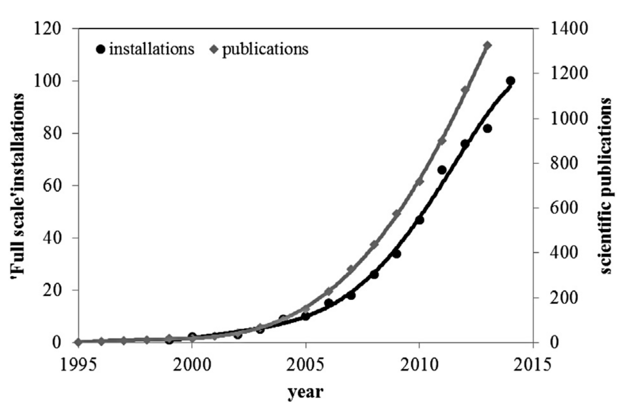

Fig. 1 – Cumulative development of full-scale partial nitritation-anammox installations (2014 represents known plants under design/construction) and scientific publications on the topic of anammox/demmonification (web of science and scopus, accessed on 10/24/2013).

This selective biomass retention enables wash-out of nitrite oxidizing bacteria in small flocs while retaining slowly growing anammox bacteria in larger aggregates.

Another well-known SBR technology is the NH_4^+ controlled partial nitritation/anammox process developed by eawag and first implemented in Zürich, Switzerland (Joss et al., 2011, 2009). In this process the SBR cycle is controlled via a NH_4^+ sensor resulting in variable cycle lengths. The feeding can be done at the beginning of each cycle or during the aeration phase. Yet unpublished results show that feeding throughout the aeration phase yields more stable operation; thereby the feed rate is controlled via a NH_4^+ set-point. The conductivity can be used as a surrogate for the NH_4^+ signal. The aeration is controlled volumetrically to allow for simultaneous nitritation and anammox, resulting in a dissolved oxygen (DO) concentration of <0.1 mg l^{-1}. Under normal operating conditions continuous aeration is preferred, while intermittent aeration is used during startup or periods of low sludge activity.

Additionally, several treatment facilities have implemented their own PN/A strategies, the differences residing primarily in intermittent vs. continuous feeding, suspended vs. attached biomass, control of aeration and one vs. two stage processes; e.g. the SBR at the WWTP Ingolstadt, Germany uses interval feeding (four times in a 6 h cycle) and interval aeration (6 min *on*/9 min *off*). In Gütersloh, Germany an old storage tank was converted into an SBR in 2004 with the purpose to perform nitritation on reject water. Later, microbial community examinations confirmed the presence of anammox bacteria in the reactor (Schröder, 2009). Their SBR cycle takes 24 h with more or less continuous feeding during daytime, depending on the reject water production. Aeration is activated when the ammonium concentration exceeds an upper limit and is stopped when either pH or ammonium concentration fall below a lower limit. DO is kept below 0.5 mg l^{-1}. Aqualia (ELAN®) and Degrémont (Cleargreen™) are also working on their own SBR technologies for PN/A. The procedure for Cleargreen™ consists of operation and control within 8 h reaction cycles according to a patented procedure. An aerated phase of about 60% of the reaction time (controlled at 0.3–0.8 mg-O_2 l^{-1}) followed by an anoxic stirred phase (about 40% of the reaction time) (Jeanningros et al., 2010). Fine-tuning towards reaching the ideal NO_2^-/NH_4^+ ratio is further assisted by online ammonium and nitrite/nitrate measurements. Two full-scale Cleargreen™ plants are expected to operate at full-scale in 2015.

Along with the SBR one of the first PN/A systems was the two-stage SHARON/ANAMMOX® process from Paques in Rotterdam, The Netherlands, where ANAMMOX® is realized as a granular sludge bed in two reactor compartments on top of each other (Van der Star et al., 2007). After 3.5 years of start-up, the second stage converted 90–95% of the nitrogen load of >10 kg m^{-3} d^{-1} (Zumbrägel et al., 2006). Since 2006 Paques has been designing granular reactors as one-stage implementations (Kormelinck, 2012), with the majority of their systems applied for industrial wastewater treatment. This shift from two to one stage installations was mainly driven by the lower investment costs.

Traditional biofilm technologies have also been successfully used for PN/A. Some of the first reactors where anammox activity was detected were rotating biological contactors

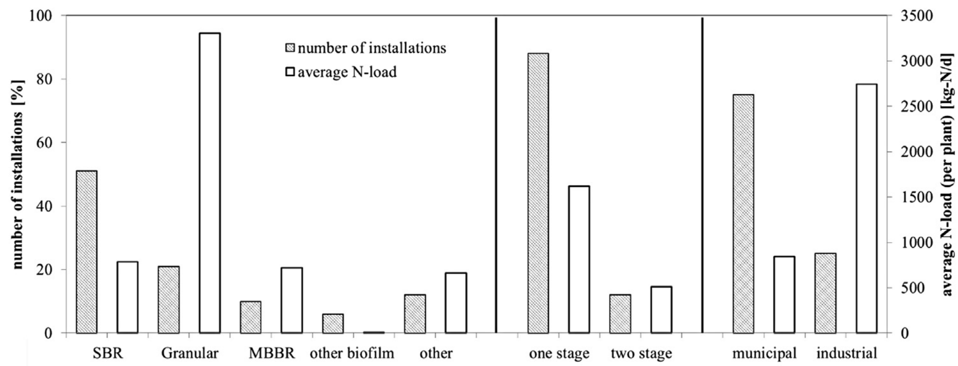

Fig. 2 – Distribution of PN/A applications, the number of installations with information on the N loads is also given and refers to the presented total N load in each category.

(RBC). In Mechernich, Germany (Hippen and Rosenwinkel, 1997), Kölliken, Switzerland (Siegrist et al., 1998) and Pitsea, Great Britain (Schmid et al., 2003) first high nitrogen losses appeared and later anammox bacteria were detected in those RBC treating landfill leachate. The RBC concept was followed up at Ghent University with the OLAND process (e.g. Vlaeminck et al., 2009). This configuration keeps operational costs low but process control flexibility is limited. Decentralized implementations were realized by DeSah BV, Sneek NL, for digested black water, with currently a 0.5 m^3 OLAND RBC serving 64 population equivalents (PE), and a 6 m^3 reactor for 464 PE, both in Sneek, The Netherlands. Process control is based on varying the rotation speed (1–4 rpm) in order to reach the DO concentration target (0.60–0.65 mg l^{-1} in the bulk liquid), and by setting the pH at 7.0–7.5 (NaOH addition). Another RBC technology was established by AWWS, Hulst, NL for treating wastewater of the fertilizer production industry, with a feeding strategy based on online ammonium measurements, and a DO control strategy based on variation of the rotation speed and disk submersion level. The pH is controlled through acid/base addition. The full-scale realization of this OLAND process treating 150 kg-N d^{-1} is expected in 2015.

One of the first full-scale biofilm PN/A plants was implemented by Purac in 2001 for reject water treatment at the WWTP in Hattingen, Germany. The DeAmmon® concept consists of a settler (upstream), three MBBR in row and a degasification (downstream). The MBBRs are filled with 40–50% carriers (AnoxKaldnes K1) and equipped with aeration and stirrers (Rosenwinkel and Cornelius, 2005; Szatkowska et al., 2007). DO, pH and temperature are monitored. The second DeAmmon® MBBR plant was constructed at Himmerfjärden WWTP, Sweden (Ling, 2009) in 2007.

The MBBR concept was also picked up by Veolia and AnoxKaldnes with the first implementation of their new single stage PN/A process ANITAMox™ in 2011 in Malmö, Sweden. This so-called BioFarm serves not only for treating reject water, but also growing carriers as seed material for other installations. The ANITAMox™ MBBRs are now designed with K5 as the carrier material and several new plants are underway. Aeration is controlled via a patented method using ratio of influent and effluent ammonium concentrations and nitrate production to control the DO. Further improvement of performance by 3–4 times was achieved using an integrated fixed film activated sludge (IFAS) configuration by incorporating a settler in the system. The suspended sludge retained from the effluent holds about 90% of the aerobic ammonium oxidizing bacteria and the system showed higher turnover than the pure biofilm system (Veuillet et al., 2013).

There are also some developments using suspended sludge concepts in a two- or multi-stage configuration for PN/A. Aquaconsult's two implementations of the partial augmented nitritation/denitritation with alkalinity recovery (PANDA) process in Weiβenfels and Rheda Wiedenbrück (Germany) were converted to PN/A (then termed PANDA$^+$) in 2007. Both are two-stage suspended sludge processes, consisting of an aerated reactor, a mixed reactor and settlers (Hartwig et al., 2009).

The new activated sludge concept (NAS®) by Colsen, The Netherlands, also uses suspended sludge and is based on a multi-stage principle. These installations consist of aerobic and anoxic, stirred compartments and rely on a hybrid combination of PN/A and N/DN reaching dischargeable effluents from digested food-processing wastewater (Desloover et al., 2011). Process control for NAS® is based on DO levels and SRT. In NAS® plants retro-fitted from existing multi-stage N/DN installations, solids/liquid separation is performed with the existing settlers. For newly designed NAS® plants, an MBR has been implemented, and the realization of a one-stage SBR is expected in 2014.

The TERRANA® concept by E&P, Germany, is another option, similar to the IFAS concept. Small splints of bentonitic clay, patented by Südchemie as TERRANA® are initially added to the suspended sludge, both in SBR or two-stage activated sludge processes. The TERRANA® material serves as substratum for attached growth to help retain anammox bacteria and improves the settleability (John, 2010). Due to its physical properties it also serves as an alkalinity source and enables treatment of poorly buffered wastewaters (John, 2012).

3. Operational aspects

3.1. *Plant overview (survey) and operational parameters*

Besides listing the full-scale implementations and control strategies, the core of this work was a survey including

Table 1 – Overview of the SBR plants surveyed for this study.

	Amersfort	Apeldoorn	Balingen	Heidelberg	Ingolstadt	Nieuwegein	Plettenberg	Zürich
	DEMON	DEMON	DEMON	DEMON	SBR	DEMON	DEMON	SBR
Source	Centrate	Centrate	Centrate	Centrate	Centrate	Centrate	Centrate	Centrate
Reactor volume [m^3]	780	2400	705	2 × 570	2 × 560	450	134	2 × 1400
TSS [$g\ l^{-1}$]	4.5	3.5–4	1.2	1.0–2.5	2.0–4.0	–	3	3.5–4.5
HRT [h]	26	58	94	114	75	42	40	45
Vol. loading operation [$kg_N\ m^{-3}\ d^{-1}$]	0.65	0.54	0.04–0.11	0.20	0.18–0.20	0.61	0.45	0.4
Sludge loading design/	194	161	142	150	129	–	159	107
operation [$g_N\ kg_{TSS}^{-1}\ d^{-1}$]	145	155	35–95	119	71	–	149	134
Energy demand [$kWh\ kg_N^{-1}$]	–	1.10	0.92	1.67	1.92	0.8	–	1.11

information and operators' experiences of 14 full-scale PN/A plants. The survey included eight SBR type systems (Table 1), which also are up to date the most common systems installed, two 1-stage biofilm systems, one MBBR and one granular based, and four 2-stage systems, where two of the anammox stages are granular based, and the other two are suspended sludge based (Table 2).

Table 3 (and for more details Table SI 5) summarizes the influent and effluent compositions of all plants. The ammonium influent concentration ranged from 500 to 1500 mg-N l^{-1} with the majority of the installations facing NH_4^+ concentrations of around 1000 mg-N l^{-1}. COD/N ratios remain <2 (with one exception) with most of the values being even below 1, resulting in N removal being the dominant electron acceptor.

There is only little data available on influent solids concentrations with known mean values being around 200–300 mg-TSS l^{-1}. Peak TSS loadings can cause severe operational problems, however no hard data is available on such observations. Effluent NH_4^+ concentrations vary in a wide range from more than 200 mg-N l^{-1} to as low as 5 mg-N l^{-1} which emphasizes the high substrate affinities. High removal efficiencies nevertheless can yield non-dischargeable effluent concentrations. However, this is usually not crucial, because the effluent of these sidestream installations is looped back to the inlet (often after primary clarification) of the wastewater treatment plant and hence treated further in the main line.

The SBR technology offers a wide range of operational concepts (summary of four concepts in Table SI 6). Within this survey information from six DEMON® type systems, the plant in Zürich and an alternative concept at the WWTP Ingolstadt, Germany was collected (Table 1). All of these systems were operated on digestor centrate in the side-stream, but with different SBR operation strategies. The feeding regime goes from continuous, over interval feeding to only one explicit feeding period at the start of the cycle. Aeration also differs: the DEMON® plants mostly relying on the patented pH-controlled feed with optional intermittent aeration; the Zürich SBR preferably using continuous aeration at very low DO levels, while shifting to intermittent aeration with pulses of 5–10 min and on a short term higher DO concentrations in case of start-up. Sludge age, sludge removal and retentions are also major factors characterizing different process options: in most DEMON® systems a cyclone is wasting fine particulate sludge while retaining larger anammox granules in the systems. The SBR in Zürich has no automated sludge removal under normal operation conditions and in Ingolstadt sludge is wasted with the effluent discharge by reducing settling times. The granular system of Paques includes a lamella separator

Table 2 – Overview of the biofilm (MBBR and granular) and two-stage plants surveyed for this study.

	Malmö	Olburgen	Lichtenvoorde	Landshut	Rotterdam	Bergen op Zoom
	ANITAMox™	ANAMMOX®	CIRCOX®/ ANAMMOX®	Terrana®	(SHARON®) ANAMMOX®	NAS®
Source	Centrate	Potato UASB effluent + centrate	Tannery	Centrate	Centrate	Potato UASB effluent
Volume reactor(s) [$m^{c}{}_3$]	4 × 50	600	150 + 75	288 + 495	1800 + 70	7920 (2370, 1650, 1600, 2300)
TSS [$g\ l^{-1}$]	16[a)]	25[b)]	25[b)]	10–12, 5–6	0.27, 7–10[c)]	0.3, 5, 5, 5 (2–7.6)
HRT [h]	24	5	8	25, 42	36, 6	80 (total)
Vol. loading operation [$kg_N\ m^{-3}\ d^{-1}$]	1.0–1.2	1.0–2.33	0,89–1 0.78	1.11, 0.65	0.27, 7.03	0.1 (average)
Sludge loading design/	64	80	62	110, 118	260	26 (average)
operation [$g_N\ kg_{TSS}^{-1}\ d^{-1}$]	64	93	71	101, 108	238	18 (average)
Energy demand [$kWh\ kg_N^{-1}$]	1.05 1.45–1.75[d)]	1.86	–	–	4.17 (including the SHARON®)	–

[a] estimated based on pilot data from Lackner and Horn (2012).
[b] estimations based on the information from Rotterdam as similar reactor type (concentrations provided are at the low end).
[c] assuming a TSS/VSS ratio of 75% (value given 20 g l^{-1} VSS).
[d] Christensson et al. (2013).

Table 3 – Influent and effluent comparison of all surveyed plants. In case of 2-stage systems effluent concentrations of both stages are provided (-: not available).

Plant	Influent composition			Effluent composition				
	NH_4^+–N [mg l^{-1}]	COD/NH_4^+ –N	PO_4^{3-}–P [mg l^{-1}]	NH_4^+–N [mg l^{-1}]	NO_3^-–N [mg l^{-1}]	NO_2^-–N [mg l^{-1}]	COD [mg l^{-1}]	PO_4^{3-}–P [mg l^{-1}]
Olburgen	<500	1.1	<20	<25	<25	<25	<200	<15
Bergen op Zoom	<500	3.7	≈50	<5	<10	–	–	–
Lichtenvoorde	≈500	2	<5	≈25	≈25	<10	<250	<5
Zürich	700	0.9	<50	<50	<20	<1	–	–
Balingen	>500	1.6	–	<100	<50	<1	–	–
Plettenberg	>500	–	–	<100	<50	<5	–	–
Amersfort	>500	–	–	≈150	<25	<5	–	–
Heidelberg	≈1000	–	–	<50	≈50	<5	–	–
Malmö	≈1000	0.7	–	<100	<100	<5	–	–
Ingolstadt	≈1000	0.7	–	≈150	<100	<1	≈250	<25
Nieuwegein	≈1000	0.6	≈200	≈200	<100	<20	–	–
Rotterdam	≈1000	15	<50	≈500/<50	–/<100	≈500/< 5	–	–
Apeldoorn	>1000	1.8	≈200	≈100	≈50	<5	<1000	≈150
Landshut	>1500	0.3	<20	≈750/≈100	≈10/≈ 50	>500/<1	–	–

for granule retention, while the IFAS system of Veolia retains the fine particulate sludge containing ammonium oxidizing bacteria with a settler.

Volumetric loading rates under operating conditions vary significantly from as low as 0.04–0.65 kg-N m^{-3} d^{-1} for the survey SBR systems (Table 1). The correlation between operation strategy and performance is not evident from the selection of plants in Table 1. Some of the low volumetric loading rates result from operation way below the design capacity or may also be the result of a retrofit of an SBR plant into a too large volume for the actual loading. A high variability is also observed in the total suspended solids (TSS) content in the SBRs, ranging from <1 g l^{-1} up to more than 4.5 g l^{-1}. Hydraulic retention times vary between 1 and 5 days. The observed operational sludge loading rates in all of the 8 surveyed SBRs range from 71 g-N kg-TSS^{-1} d^{-1} up to 155 g-N kg-TSS^{-1} d^{-1}. For autotrophic systems with high sludge ages such as these PN/A systems the inert fraction can vary significantly depending on local conditions which also influences a TSS based specific sludge activity. In comparison, sludge loading rates for nitrification stages in classical activated sludge systems are around 50–100 g-N kg-TSS^{-1} d^{-1} (ATV, 1997).

The energy demand of the SBR – PN/A side-stream treatment systems ranged from as low as 0.8 kWh kg-N^{-1} to around 2 kWh kg-N^{-1}. Similar values of 1.2 kWh kg-N^{-1} have been reported previously by Wett et al. (2010). Compared to a conventional N/DN side-stream treatment (as also installed and running at the WWTP Ingolstadt parallel to the SBR-PN/A) with an energy demand of approximately 4.0 kWh kg-N^{-1} (only accounting for electricity consumption in the side stream) the savings of PN/A SBR systems are at least 50%, and depend largely on the oxygen transfer efficiency, and hence the type of bubble aeration.

Table 2 summarizes the data of the remaining 6 surveyed installations including biofilm based and 2-stage systems. The biofilm systems (1- and 2-stage) show higher volumetric loading rates starting with 1.0 kg-N m^{-3} d^{-1} and reaching values of up to 7.0 kg-N m^{-3} d^{-1} in the anammox stage of a 2-stage systems such as in Rotterdam. These high rates can be explained by the much higher biomass concentrations in those systems with 15–20 g l^{-1} in carrier based biofilm systems and 25–35 g l^{-1} in granular systems. The 2-stage system in Landshut is a suspended sludge system with bentonite functioning as carrier material and pH stabilizer (TERRANA®). This system reaches solids concentrations of 5–12 g l^{-1}. This also results in much lower sludge loading rates <100 kg-N g-TSS^{-1} d^{-1} for the biofilm systems (except the Rotterdam plant which shows higher values of >200 kg-N g-TSS^{-1} d^{-1}. HRT was also significantly lower, mostly <24 h. These values probably explain the more robust behavior of biofilm/granular based systems compared to SBR.

Energy demands seem slightly higher for the latter systems compared to the SBR (most of these reactors are also the respective prototypes or retrofitted versions of the applied technology and might not exactly represent future designs yet).

3.2. *Process parameters: control and strategies*

3.2.1. *Online monitoring*

Online monitoring and control are important aspects in the operation of any type of PN/A system. The aim of process control is to provide the operator with a stable, reliable and robust strategy to run the PN/A system with as little manual manipulation as possible. Table 4 summarizes the sensors that are used in the surveyed PN/A plants, indicating whether the signal is used for monitoring or control purposes. Due to the rather complex combination of microbial processes compared to conventional N/DN processes, there is a high demand on online sensors for process control. Even though most of the PN/A plants use a large number of online sensors (including online measurements of ammonium and nitrate in most, and nitrite in some cases), the most common measurements are pH and the DO concentration. Relying only on DO can however be misleading because the concentration alone might not always provide a good correlation with substrate depletion or biomass activity. Therefore, monitoring the air flow rate in combination with the nitrogen species seems more accurate (Joss et al., 2011), especially in cases where nitrate accumulation is already problematic.

Table 4 – Online sensor equipment and labor effort, as provided by the operators; X: measurement; O: also for control; -: no online sensor/no data available.

Plant	pH	DO	NH_4–N	NO_3–N	NO_2–N	Cond.	ORP	Foam	T	TS	MP[a] [h/d]
Amersfoort	O	O	X	X	O	–	–	–	X	X	–
Apeldoorn	O	O	X	X	–	–	–	–	X	–	1
Balingen	O	O	–	–	–	–	X	–	X	–	2–4
Heidelberg	O	O	X	X	–	X	X	–	X	–	2–3
Ingolstadt	X	O	X	X	–	X	X	–	X	X[b]	3
Nieuwegein	O	O	X	X	X	–	–	–	X	X	1
Plettenberg	O	O	–	–	–	–	–	–	X	–	–
Zürich	X	X[c]	O	X	–	X	X	O	X	–	3 (11)[e]
Malmö	O	O	X	X	–	–	–	–	X	–	1
Olburgen	O	–	X	–	X	–	–	–	X	–	2
Landshut	O	X	X	X	O	X	–	–	X	–	<1
Lichtenvoorde	–	O	O	–	X	–	–	–	–	–	2
Rotterdam[d]	–	X	–	–	X–O	X	–	O	X	–	1–2
Bergen op Zoom	O	X	–	–	–	–	X	–	X	–	–

[a] MP – manpower.
[b] in the influent line.
[c] max. DO level controlled (off).
[d] data for the ANAMMOX® reactor only.
[e] value for severe malfunctioning (a few days per year maximum).

Depending on the local conditions, the required manpower to run and maintain PN/A systems is estimated between 1 and 4 h/d for normal operation. This value can be higher for short times when extraordinary circumstances occur.

3.2.2. *Set-points*

As already seen from Table 4, controlling the DO level and the pH online are the most implemented strategies on the surveyed PN/A plants. Table 5 gives the applied set-points for DO and pH (where provided). The DEMON® type SBR systems have mean DO values of 0.2–0.3 mg l^{-1}. These settings are very consistent between the different plants. However, the time based on/off control of the aeration varies among the DEMON® systems from around 8–12 min *on* and 2–20 min *off*. The SBR in Zürich follows a simple continuous aeration pattern with a target DO of <0.05 mg l^{-1}. Other SBRs, e.g. Gütersloh (see Table SI 6), operate at higher DO set-points of 0.5 mg l^{-1} but also continuous aeration. In Ingolstadt operation is based on strict intermittent aeration with a 6 min *on* and 9 min *off* pattern and DO limits of 0.8–1.0 mg l^{-1}. The biofilm bases systems employ slightly higher DO concentrations with values up to 1.5 mg l^{-1}. From the data collected pH control is only implemented in the DEMON® SBR and in one of the granular based biofilm systems. The pH control of the DEMON®, however, rather functions to avoid NH_4^+ depletion and to control the feed. It is not meant to avoid CO_2 limitation. Most concepts rely on the fact that the centrate provides enough alkalinity/buffer capacity to keep a stable pH and

Table 5 – Set-points and concentration ranges for online DO and pH values from all systems as given by the operators.

Plant	pH [-]		DO [mg l^{-1}]		Aeration [min]	
	Min	Max	Min	Max	On	Off
Amersfort	–	–	–	0.3	–	–
Apeldoorn	6.785	6.815	–	0.3	12	12
Balingen	7.0	7.1	–	0.3	8	2
Heidelberg	6.9	7.1	–	0.35	10	15
Ingolstadt	–	–	0.8	1.0	6	9
Nieuwegein	±0.02		–	0.2	Intermittent	
Plettenberg	6.9	7.1	–	0.25	12–15	20
Zürich	–	–	–	0.05	Continuous	
Malmö	–	–	0.5	1.5	Continuous	
Olburgen	7.5	8.0	–	–	–	–
Landshut[a]	–	–	1.2	1.5	Continuous	
Lichtenvoorde	–	–		Based on NH_4^+/NO_2^- ratio		
Rotterdam	–	–	–	–	–	–
Bergen op Zoom[b]	–	–	0.3	0.9	–	–

[a] data for nitritation reactor.
[b] data from NAS 1 (partial nitritation reactor).

Table 6 – Number of plants (in percentage of total number, $n = 14$) having experienced these factors with a rating of the impact on process performance.

Incident	Impact on the process performance			
	Not reported	Low	Medium	High
pH shock	55%	0%	15%	30%
Temperature variation	45%	35%	20%	0%
Influent solids concentration	30%	20%	30%	20%
Blower failure	65%	10%	15%	10%
Mixing problems	80%	10%	10%	0%
Influent pump failure	70%	10%	10%	10%
Other[a]	60%	10%	10%	20%

[a] failure of oxygen sensor or related.

avoid CO_2 limitations of the biomass. However ammonium concentrations of >2–3 g-N l^{-1} will most likely require additional pH control.

3.3. *Troubleshooting*

3.3.1. *Process perturbations*

P/NA is a rather well established process with currently almost 100 full-scale installations in operation or under construction/planning worldwide. However, the complex microbial community dynamics and the necessity to establish the required short-cut in nitrification, that leads to the energy savings, are still not always under control. Little is reported in literature about full-scale operational difficulties/problems, their origin and troubleshooting.

Table 6 gives an overview of the most critical or relevant problems the surveyed PN/A plants have or had to face and their impact on process performance. Rather few plants had to face technical difficulties with only 20–35% of the questioned operators reported impacts of aggregate failures on process performance (e.g. blowers, mixing units, pumps). As seen before, the DO concentration is the most used and incorporated parameter, and failure in the DO signal can lead to severe consequences in process performance. Several plants reported a high impact of DO sensor problems. Too high aeration intensity that was not detected immediately, e.g. led to an increase in nitrate production from 10 to 40% (Hennerkes, 2012). A measurement of the air flow rate instead of DO concentrations, as also shown by Joss et al. (2011) might therefore be a better and more reliable control parameter esp. when such very low DO concentrations are required.

Temperature variations had very little effect on process performance and only high variations in temperature within a short time frame (8 °C within one week) resulted in a significant influence on process performance (in one case). Fluctuations or shocks in pH only occurred in half of the surveyed plants, however with severe effects. Too high pH values (>8.0) resulted for instance in loss of anammox activity and subsequent nitrite increase, whereas a too low pH (<6.8) caused limitations of the ammonium oxidizing bacteria. Therefore, pH control is recommended in cases where such fluctuations in pH might be expected.

The highest impact on the PN/A performance among the given possibilities falls on the influent solids concentration. 70% of the plants reported high impact or operational problems with high or varying influent solids concentrations. DEMON® SBRs that experienced too high influent TSS loads showed an increase in nitrate production and then required an extra excess sludge withdrawal which reduced the active biomass in the reactor. Unfavorable tank geometries led to very large flocs (in the cm size range) due to an overly well-functioning cyclone and inability to keep the sludge afloat. Inhibitory effects are also related to incoming solids. Observations of black centrate (presumably high in sulfide) which led to a loss/reduction in performance have been observed at three installations. Countermeasures included increased sludge withdrawal or simply waiting for recovery.

Intake of solids and polymer via the influent (from a belt filter press) increased the reactor TSS (inert fraction) in one plant requiring an increase in sludge wastage and thereby a loss of active biomass which ultimately led to a drop in activity by 40% (i.e. reduction of N removal from 80% down to 40%).

Further inhibitory substances have also been suspected in certain types of centrate where turnover rates were rather unstable and activity losses increased the DO level in the reactor to 0.5 mg l^{-1} (at low blower frequency) indicating inhibition of ammonium oxidizing bacteria (performance dropped within 2 days down to 25%). Such inhibition incidents lasted several weeks, however, it was not possible to identify specific inhibitors (Hennerkes, 2012; Joss et al., 2011). A change in aeration pattern to 9 min *on* and 18 min *off* with DO concentrations of up to 1 mg l^{-1} was successful to restore activity in one SBR, whereas long stirring times, and low aeration and loading had to be employed at another site.

3.3.2. *Accumulation of N species*

To facilitate good performance and high turnover rates accumulation of ammonium, nitrite and nitrate should be avoided in PN/A plants. Especially ammonium (and, dependent on pH and temperature, the free ammonia) and nitrite concentrations have to be limited due to potentially inhibitory effects. Table 7 summarizes the information provided by the operators about their experiences on related operational upsets. 30% of the surveyed plants experienced ammonium accumulation lasting from a few days up to three weeks. One SBR installation even had continuously high ammonium levels due to lack of alkalinity in the centrate. Previously mentioned blower malfunctioning also caused ammonium increase over short time periods (2 days). Loss of (anammox) biomass due to failure of the settler was also mentioned as the cause of a 1–3 weeks lasting incident (of ammonium accumulation). Two plants report possible effects of toxic compounds in the centrate, too little biomass in the system or oxygen limitation as causes for ammonium built-up. Ammonium built-up only becomes critical at concentrations >200 mg l^{-1} which, at unfavorable pH (>7.6) and temperature (>35 °C) conditions, can result in inhibitory free ammonia concentrations. Long term effects as reported by Fernández et al. (2012) have not been reported for full scale installations.

Nitrite and nitrate accumulation are usually more critical. 50% of all surveyed installations reported their build-up with

Table 7 – Typical process stability issues faced during full scale operation.

Issue	Impact in % of plants duration	Countermeasures
NH_4^+ build-up	30% 2–21 days	• Increase aeration if sustainable (NOB growth) • Reduce feeding • Reduce excess sludge removal
NO_3^- build-up	50% few days – several weeks	• Aeration: lower DO set-point, lower blower Hz, • Increase removal of floccular sludge fraction via cyclone or shorter settling times SBR) • Increase excess sludge removal (granular) if sufficient anammox activity is present • Increase length of anoxic periods or intermittent aeration is often done, but might rather remove the symptoms (lower NO_3^-) than solve the problem (NOB growth)
NO_2^- build-up	50% 1–7 days	• Aeration: reduce aeration/air flow, switch to intermittent aeration, stop aeration • Decrease feed
Foaming	30% 1–5 days	• Dosage of anti-foaming agent • Sprinkling with treated effluent
Scaling	35% 1–14 days	• Regular cleaning; cleaning blowers via flushing with air must be handled carefully, since air pulses may favor NOB growth • Decrease pH, tap the grid material from the reactor
Sludge retention/settling /solids separation	45% up to 21 days	• Temporary addition of flocculation agents • Proper design of effluent drawing unit (regular removal of filamentous sludge) • Avoid residual NO_2^- during the settling phase (obligate stirring phase without aeration prior to settling)

nitrate generally lasting up to several weeks, whereas nitrite accumulation mostly only occurs over several days (up to 7 days reported). Nitrite build-up is usually caused by a disturbance of the anammox population or an overcapacity in aerobic ammonium oxidation. Especially during start-up nitrite has to be watched carefully as ammonium oxidizing bacteria grow faster than anammox bacteria potentially leading to high and inhibitory NO_2^- concentrations. Inhibition of the ammonium oxidizing bacteria and subsequent increase in reactor DO has been reported to cause subsequent inhibition of anammox bacteria (Joss et al., 2011) and thereby higher nitrite levels. Countermeasures that have proven successful include decrease or, depending on the extent, complete stop of aeration, biomass removal and a decrease in loading (influent flow rate). A complete stop (only mixing) of the reactor to remove nitrite (or for an extended period of time) might also be necessary in certain cases. The pH and nitrite concentration range present in the surveyed PN/A plants makes inhibition by free nitrous acid rather unlikely.

Nitrate build-up is not crucial in terms of inhibition; however, an increase in nitrate signals that the microbial community is unbalanced and too many nitrite oxidizing bacteria have accumulated. This has been reported in 50% of the questioned plants and throughout all technologies (SBR, granular and biofilm systems). The main reason for accumulation of nitrite oxidizing bacteria and therefore nitrate, is a too high oxygen supply to the reactor which however, is not necessarily detected as an increase in DO concentration. SBR plants also report nitrate build-up at higher TSS concentrations. Reduction of the air flow rate, the DO set-point, blower frequency or runtime (increased anoxic phases) and intermittent aeration (changes in on/off times) are most often applied to counteract nitrate accumulation events. In SBRs, removal of floccular sludge, either by a hydrocyclone or reduced settling times, is the other main factor to control nitrate build-up.

3.3.3. *Further operational aspects/problems*

Aside from mechanical failures and accumulation of nitrogen species, three other issues/problems have been identified by the survey: foaming, scaling, and solids retention, settling and separation (see also Table 7). From the plants presented here 30% had or have occasional foaming incidents. The impact on reactor performance is not very critical and dosage of antifoam agents or water sprinkling has proven sufficient to handle foam. Reasons might be found in over-dosage of polymer in the dewatering unit (one report from a belt-filter press). Recovery is usually fast (1–5 days).

Scaling has been reported in 35% of the plants. Even though no direct impact on performance was reported, scaling in pipes, pumps and aeration units can cause severe operational problems due to persistent depositions. Also sensor equipment can be affected. Especially certain types of centrate or wastewater with high ammonium and phosphate (e.g. bio-P sludge digestate) require more attention and regular cleaning, which might not always be successful. Two plants reported that their scaling problems are still not resolved and that the durability of sensors and pumps are negatively affected. Additionally, biofilm systems or systems relying on density separation (hydrocylone) can be negatively affected by scaling directly on biofilm or granular surfaces.

A more serious issue is the sludge retention, settling, and solids separation. With 45% a significant amount of plants reported problems with handling their solids regime. As already discussed previously, regularly occurring high solids content in the influent can cause problems in operation. Accumulation of too many inactive dry solids can cause decrease in activity. Especially settling problems in buffer tanks, and sudden TSS deposition into the main reactor can cause a severe performance perturbation. Also bad settling in the reactor (for SBR) which ultimately leads to high biomass loss has been reported (e.g. filamentous sludge). This has to be faced by change in settling phase length or even repeated settling phases of 30–60 min (four times before discharge). Also dosage of flocculant, e.g. Nanofloc, has been used, but not always successfully. Too high SRT during start-up has also caused setbacks in performance in one of the surveyed SBR, nonetheless starting sludge withdrawal significantly improved the performance.

Settling problems occurred in SBRs as well as granular systems (failure of the settler). In one SBR there was the opposite problem of too large flocs and a too high degree of agglomeration of the sludge cause by bad mixing and cyclone operation – sludge removal became difficult due to bad mixing – suspension.

This work shows that many different technologies have been successfully implemented and operated for the treatment of centrates but also of industrial wastewaters with high ammonium concentrations and low C:N ratios. All these technologies can meet target nitrogen removal efficiencies and achieve comparable conversion rates, however, none is without problems. The consideration of site-specific issues can be crucial. Future work should focus on optimizing operational conditions and solving the remaining obstacles, especially regarding the solids regime and further process automation. Little is known still about the effect of certain influent components influencing reactor performance, i.e. inhibitory effects or nutrient limitations. Nitrous oxide emissions from PN/A systems will also have to be considered for their potentially negative impact on the carbon footprint of the technology.

Despite some remaining issues in daily practice, mostly inherent to any type of biological wastewater treatment, PN/A has become a well-established technology. Reaching more than 100 operational installations worldwide within the next 1–2 years shows the importance and acceptance of the PN/A process for biological nitrogen removal. The proposed and proven energy savings have and will reward all the efforts that have been put into implementing this technology.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.watres.2014.02.032.

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