

Start-up of a full-scale deammonification SBR-treating effluent from digested sludge dewatering

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ABSTRACT

This study shows the start-up and operation of a full-scale sequencing batch reactor (SBR) with a volume of 550 m³ for deammonification of reject water from sludge dewatering over the first 650 days of operation. The SBR was operated with discontinuous aeration and achieved an optimum of around 85% of ammonium removal at a load of 0.17 kg m⁻³ d⁻¹. The application of batch tests for the activity measurement of aerobic ammonium and nitrite oxidizing bacteria and anaerobic ammonium oxidizing bacteria were proven to support the identification of setbacks in reactor operation. Furthermore, the calculation of the oxygen uptake rates from online oxygen measurements helped to explain the overall reactor performance. The aeration regime is a key parameter for stable operation of such an SBR for deammonification. At aeration/non-aeration time ranges from 6–9 min, the best results with respect to turnover rates and low nitrate production were achieved. Compared with the nitrification/denitrification SBR operated in parallel with methanol as the carbon source, a significant reduction in costs for energy and chemicals was achieved. The costs for maintenance slightly increased.

Key words | aeration, anammox, batch activity test, comparison to nitrification/denitrification, partial nitrification, solids regime

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INTRODUCTION

Nitrogen removal is a key process in biological wastewater treatment. In the 1990s, a new group of microorganisms belonging to the phylum of Planctomycetes was discovered. These so-called anammox bacteria are able to use ammonium as the electron donor and nitrite as the electron acceptor under anaerobic conditions in an autotrophic process (Mulder *et al.* 1995; Strous *et al.* 1997).

A combination of this new pathway with partial aerobic ammonium oxidation led to the implementation of single-stage partial nitrification/anammox processes, which is also called deammonification. In particular, deammonification is an energy efficient way to treat high strength ammonium rich wastewaters and has been successfully applied in full scale at municipal wastewater treatment plants for several years. Different reactor configurations have been implemented (Van Hulle *et al.* 2010; Lackner *et al.* 2014), with the sequencing batch reactor (SBR) currently being the most employed technology (>50%) for municipal sludge water treatment. Several reactor configurations and operational regimes have been developed, mainly differing

in their cycle patterns and control strategies (Wett 2007; Joss *et al.* 2009; Schröder 2009; Jeanningros *et al.* 2010; Hennerkes 2012; Vázquez-Padín *et al.* 2014).

Even though full-scale operation of deammonification SBRs has been employed for some years, operators still face unknown and unpredictable obstacles during start-up and operation. Unexpected and sudden loss of microbial activity can be one scenario that has to be dealt with. This study presents detailed information on the start-up and optimization of SBR operation by closely following the microbial activity in a full-scale deammonification plant and discusses measures of the observed instabilities, and potential reasons for them.

MATERIALS AND METHODS

The wastewater treatment plant (WWTP) in Ingolstadt, Germany has a size of 275,000 population equivalents (PE), including 80,000 PE from industrial sites, and operates

on a combination of activated sludge and trickling filters, which are mainly used for nitrification. The WWTP has three anaerobic digesters to treat the primary sludge and all sludges produced in the biological stages. Sludge dewatering is done by thickening and centrifugation. The reject water from this stage has been treated separately by two SBRs with nitrification/denitrification (N/DN) since 2002, which were extended by a third SBR in 2005. In 2011, two of these SBRs (SBR 2 and 3) were insulated and retrofitted to switch operation to deammonification.

The data presented in this study mainly stem from one of the SBRs (SBR 2, deammonification). This SBR reactor, with a volume of 550 m³, was started up with two batches of 20 m³ inoculum sludge from another deammonification SBR in winter 2011. Ammonium influent concentrations were 960 ± 110 mg N l⁻¹ and soluble chemical oxygen demand (COD) concentrations were 320 ± 50 mg l⁻¹. The reactor was operated with four 6-hour cycles per day. The cycle consisted of a 10–14 min filling phase, a 63–72 min aeration phase, 6–27 min stirring, 1–30 min settling (depending on excess sludge removal), and a decanting phase of 7–21 min. Filling and aeration were repeated four times in each cycle as described in Lackner & Horn (2012). The only difference to that operation was that during the assigned aeration phase, intermittent aeration was used for most of the monitored period (see also Table 1).

Batch activity tests applying respirometric measurements with a dissolved oxygen (DO) probe (ammonium and nitrite oxidation rates) and direct anoxic measurements of ammonium, nitrate, and nitrite over time (six time points in 3 hours) were carried out to measure the activities of aerobic ammonium oxidizing bacteria (AOB), nitrite oxidizing bacteria (NOB) and anaerobic ammonium oxidizing bacteria (AnAOB), as further described in Gilbert et al.

(2013). Ammonium, nitrate, nitrite and COD were measured with Lange cuvette tests. Total suspended solids (TSS) and volatile suspended solids (VSS) were determined according to standard methods.

RESULTS AND DISCUSSION

Start-up and reactor operation

The performance of SBR 2 during the first 650 days of operation for ammonium removal and nitrate production is shown in Figure 1(a). During the first 50–75 days, no significant increase in nitrogen removal was achieved. Total nitrogen (TN) turnover remained below 0.05 kg N m⁻³ d⁻¹. Furthermore, ammonium removal decreased from 80% at the start to values below 40% after 50 days of operation. A steady increase in the volumetric removal rate was only observed with the onset of a steady increase in TSS and in particular with the increase in the VSS content (Figure 1(b)). From days 75–150, the TSS concentration more than doubled from 0.5 to almost 2.5 g TSS l⁻¹ with an accompanying increase in the VSS content from 55 to 65%.

Owing to the low initial TSS concentration in the SBR, no sludge was wasted for the first 180 days of operation. The influent TSS concentration was on average 250 ± 68 mg TSS l⁻¹, which partly explains such a rapid increase in reactor TSS as was observed. Estimating a cumulative TSS (influent TSS – effluent TSS) revealed a very close correlation to the TSS development in the reactor, suggesting that the increase in TSS was mostly not caused by biomass growth. Biomass accumulation is only inferred by the increase in VSS.

The development in the first phase led to an increase in TN turnover reaching values of up to 0.12 kg N m⁻³ d⁻¹

Table 1 | Aeration settings over the course of the start-up of SBR 2

Days of operation	Aeration			Oxygen concentration		NH ₄ -N		
	On min	Off min	Time %	Medium mg/l	Max. mg/l	Loading kg N/m ³ /d	Removal %	NO ₃ -N/NH ₄ -N %
61	6	6	43	0.37	0.93	0.13	76	34
237	6	9	36	0.30	0.90	0.17	85	13
36	6	11	35	0.32	1.05	0.15	84	20
37	6	14	29	0.46	1.01	0.12	77	14
18	25	14	64	0.25	0.28	0.12	73	8
27	28	10	71	0.24	0.56	0.09	72	17

Data are sorted by aeration length. Aeration times are related to the respective reaction time of the cycle. NH₄-N loading and removal and nitrate production are average values.

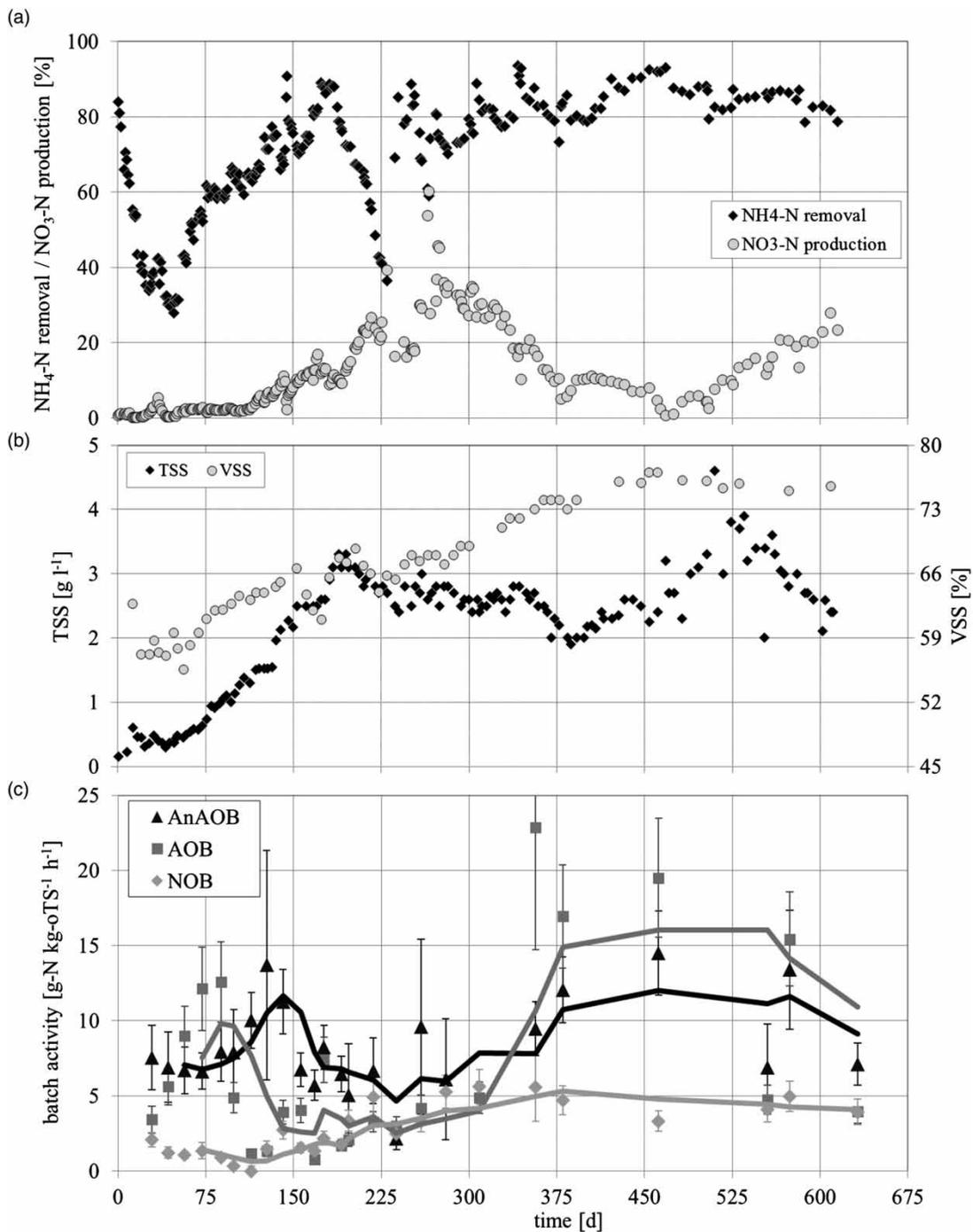


Figure 1 | (a) Reactor operation represented as ammonium ($\text{NH}_4\text{-N}$) removal in percentage and nitrate ($\text{NO}_3\text{-N}$) production in percentage of converted ammonium. (b) Total suspended solids (TSS) and volatile suspended solids (VSS) in the reactor over the course of operation. (c) Results of the *ex situ* batch experiments conducted with biomass from the SBR. AnAOB, anaerobic ammonium oxidizing bacteria; AOB, aerobic ammonium oxidizing bacteria; NOB, nitrite oxidizing bacteria.

after 130 days. Nitrate production as an indicator of deammonification stability stayed well below 15% of the converted ammonium.

Ammonium removal kept increasing until day 185 when it reached 80%, followed by a drastic decrease in the removal

to around 40% within the next 40 days (until day 225). This behavior somewhat correlated with the *ex situ* batch activity measurements conducted every 2–3 weeks over the first 600 days of operation (Figure 1(c)). Batch activity tests were conducted to follow the specific activities of AOB, NOB, and

AnAOB in the SBR. From these batch tests, it became clear that the AOB activity had already faded starting from day 85 onwards and was reduced by half within the following 15–25 days. On day 168, almost no AOB activity remained. This activity loss preceded the drop in reactor performance, which had started to show from day 175 onwards. With a delay of approximately 40 days the AnAOB activity also started to decrease, which was probably caused by the insufficient nitrite production. This decrease in AnAOB activity then directly affected reactor performance, which decreased during the same period. NOB activity was well suppressed until day 125 from when there was a steady increase in NOB activity. This correlated well with the observed increase in the nitrate production, which reached values of more than 25% with maxima of up to 50%.

This sharp drop in activity after 180 days may also have been caused by shock loads of TSS coming with the influent, which might be inferred from large sudden changes in TSS concentration in the reactor (i.e., on days 113, 128, 146, and 175), which coincides with the drop in AOB activity. Such phenomena were also reported by other operators, who observed negative impact on deammonification from solids in the influent (Lackner *et al.* 2014). However, the exact nature of this effect is still unknown. It is speculated that disturbances in the digesters or with the dewatering system cause entry of inhibitory substances to the deammonification reactors.

Owing to the increase in TSS and the operational instabilities, controlled removal of excess sludge via the effluent discharge (decant) was started from day 190 onwards. The TSS in the reactor was then kept at around 2.5 g TSS l⁻¹, by removing sludge via a reduction in settling time, which significantly improved performance. The particle size distribution (data not shown) proved the development of larger flocs over the next 200 days of operation.

The initiation of excess sludge removal helped to restore reactor performance in terms of ammonium removal and led to quite fast recovery of AOB and AnAOB activities. Starting on day 230, ammonium removal stabilized around 80% with maximum removal up to 92%. The decrease in nitrate production, however, took until day 375 when the nitrate percentage fell well below 15% again.

This observation was not evident from the batch activity test for NOB, which remained on the same level (5 g N kg oTS h⁻¹). Therefore, it was assumed that not only the excess sludge removal, which mainly boosted AOB activity, was responsible but also other operational factors (DO as discussed below).

It was also interesting to observe that the VSS kept increasing (even after regular excess sludge removal had

been implemented) from 70% on day 300 to 77% on day 450. Only then did the VSS content remain stable, between 75 and 78% for the rest of the observational period.

The SBR reached a stable volumetric TN removal rate of 0.18 kg N m⁻³ d⁻¹. This value is slightly lower than volumetric turnover rates reported from other SBRs, which generally lie between 0.4 and 0.6 kg N m⁻³ d⁻¹ (Wett 2007; Joss *et al.* 2009; Lackner *et al.* 2014; Vázquez-Padín *et al.* 2014). The sludge loading rates during stable operation were 0.04–0.06 g N g TSS⁻¹ d⁻¹. COD removal was between 35 and 70%, with maximum volumetric loading rates of 0.14 kg COD m⁻³ d⁻¹.

The temperature in the reactor was on average 31 ± 3 °C and reached a minimum of 26 °C for a short time in winter (days 97–106). There was no evident correlation of temperature with the setbacks in TN removal over the experimental period. Nitrite concentrations showed a maximum of 8 mg N l⁻¹ during the first 2 weeks and thereafter stayed well below 0.8–1.0 mg N l⁻¹ for the remaining time.

Aeration regime

The aeration strategy is one of the key operational parameters for deammonification reactors. During the course of this investigation, we tested several settings (see Table 2 and Figure 2(b)). Initially, SBR 2 was operated with long aeration times (25 min) and low oxygen concentrations (<0.3 mg l⁻¹). However, these low oxygen concentrations did not lead to any significant improvement in the turnover. Only an increase in the DO set-point resulted in an increase in nitrate production. Therefore, the aeration pattern was changed to intermittent aeration after 150 days of operation, increasing the maximum DO set-point to 0.6 and later on to 1.0 mg l⁻¹. Aeration intervals of 6 min, with a break of at least 9 min, seemed to achieve optimal operation as the recovery and stabilization of reactor operation coincided well with this increase in maximum oxygen concentration and aerated/non-aerated periods of 6 and 9 min, respectively. The reduction of the

Table 2 | Comparison of the yearly energy, carbon, and labor requirements during operation with N/DN only versus operation with N/DN (SBR 1) and deammonification (SBR 2 and 3)

	N/DN (SBR 1–3)	N/DN (SBR 1) + deammonification (SBR 2,3)	Comparison (%)
Electricity	500,000 kWh	240,000 kWh	– 52
Methanol	290 t	70 t	– 75
Manpower	13 h	20 h	+ 35

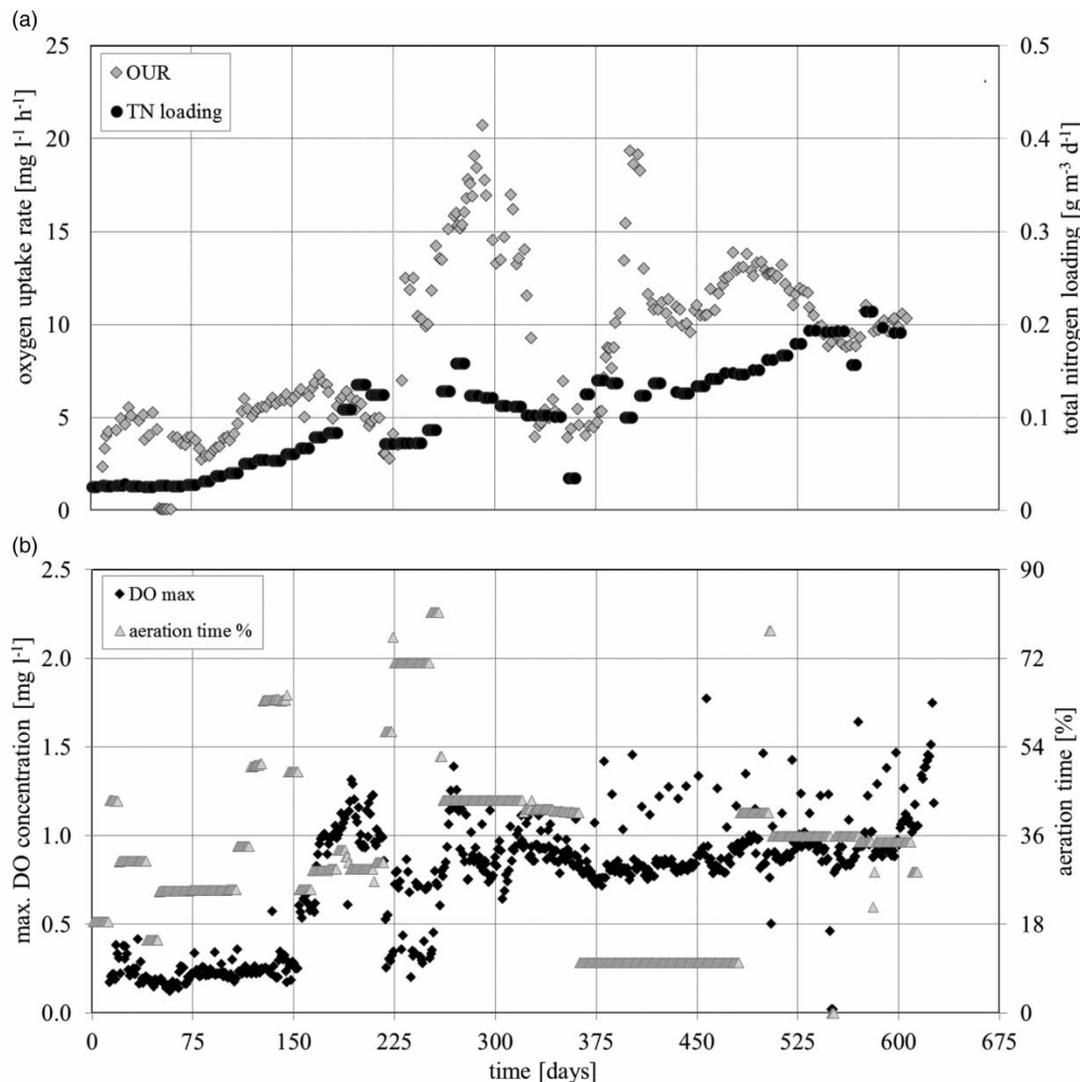


Figure 2 | (a) OUR in comparison to the total nitrogen loading (TN). (b) Maximal DO concentration during the aeration phase and aeration time as a percentage of the reaction time of the SBR.

nitrate production was also favored by this setting, which confirms results from recent literature on a distinct lag-phase of NOB (Gilbert et al. 2014).

Figure 2(a) compares the total volumetric nitrogen loading with the oxygen uptake rate (OUR) calculated from the online data via the depletion of the oxygen concentration during non-aerated phases. Since aerobic ammonium oxidation will be the main oxygen consuming process, the OUR is a genuine parameter to follow AOB activity. Even if all COD removal (on average 50%) was aerobic, it would only account for about 10% of the total oxygen uptake, considering 50% aerobic ammonium oxidation. There was also no correlation between reactor performance (deammonification) and COD removal. The OUR can,

therefore, be considered as a first *in situ* indicator for disturbances in reactor performance. In this study, there was a very clear trend between the decrease in OUR and the setbacks in reactor performance. This indicates that the reduction of biological activity mainly originated from a decrease in AOB activity, as also confirmed by the batch activity tests. For effective reactor control, a combination of OUR measurements and batch activity tests might be necessary to foresee potential reactor failure.

Operational costs

The Ingolstadt WWTP has been operating three SBRs with nitrification/denitrification for the treatment of their reject

water since 2002 (extension by the third SBR in 2005). In 2011, two SBRs were switched to deammonification. This allows a direct comparison (see Table 2) of the operational costs for the conventional nitrification/denitrification process with the newly established deammonification.

The nitrification/denitrification operation required approximately 500,000 kWh/y. External carbon was dosed as methanol (290 t/a) at a cost of €146,000. The labor required to run all three SBRs (including process monitoring, maintenance, and laboratory analysis) amounted to 13 h/week. These expenses resulted in an average 3.40 €/kg N, assuming local energy prices and labor expense.

Beginning in 2011 with the start-up of the deammonification SBRs (data shown here for SBR 2), the operation requirements and expenses could be significantly reduced already only a year after the initial start-up. Even though SBR 1 was still operated as N/DN (still contributing about 30–50% to overall turnover), the energy consumption dropped to 240,000 kWh/a resulting in more than a 50% reduction. In the same period, the methanol dosage was reduced by 75% to a value of 70 t/a. Only the labor required to monitor and maintain the reactors increased by 35%, which was due to the pilot nature of the study. The operation with deammonification at the Ingolstadt WWTP resulted in an overall cost of approximately 1.60 €/kg N, which is about half the costs of the previously used N/DN operation.

The main advantage of deammonification operation lies in the energy savings. To compare the reactor-specific energy consumption of SBR 1 (N/DN) and SBR 2 and 3 (deammonification) during the pilot study, the energy for the stirrers and for aeration was considered in more detail. These two points made up the largest fraction of the specific energy consumption.

Initially, SBR 1 showed higher turnover rates; however, over the course of the start-up of the deammonification SBRs, more and more nitrogen was removed via deammonification. This is also visible in the specific energy consumption. In SBR 1, only 7–11% of the energy is used for stirring whereas SBR 2 and 3 required 25–52% energy. The energy required for aeration was, respectively, less in those reactors and with increasing turnover the stirring fraction will probably decrease further.

Figure 3 compares the specific energy consumption based on the actual nitrogen removal. It is very clear that SBR 1 (N/DN) has a much higher specific energy consumption of around 4 kWh/kg N, whereas both deammonification SBRs (2 and 3) reached values of 1.5–2 kWh/kg N.

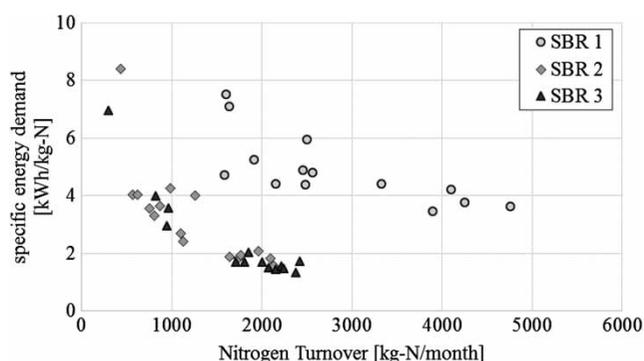


Figure 3 | Specific energy demand for SBR 1 (N/DN) and SBR 2 and 3 (deammonification) relative to their nitrogen turnover (data from Lackner et al. (2013)).

CONCLUSIONS

A deammonification SBR was successfully started and closely monitored during its first years of operation, revealing the importance of batch tests for following microbial activity, the necessity of employing an optimal aeration pattern, and the crucial impact of excess sludge removal for successful reactor performance. Even though reactor performance was not optimal, significant energy (>50%) and cost savings were still obtained compared with conventional nitrification/denitrification.

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