Evaluation of deammonification process performance at different aeration strategies

M. Zubrowska-Sudol, J. Yang, J. Trela and E. Plaza

ABSTRACT

In a deammonification process applied in the moving bed biofilm reactor (MBBR) oxygen is a crucial parameter for the process performance and efficiency. The objective of this study was to investigate different aeration strategies, characterised by the ratio between non-aerated and aerated phase times (R) and dissolved oxygen concentrations (DO). The series of batch tests were conducted with variable DO concentrations (2, 3, 4 mg L^{-1}) and R values (0-continuous aeration; 1/3, 1, 3-intermittent aeration) but with the same initial ammonium concentration, volume of the moving bed and temperature. It was found that the impact of DO on deammonification was dependent on the R value. At R = 0 and R = 1/3, an increase of DO caused a significant increase in nitrogen removal rate, whereas for R = 1 and R = 3 similar rates of the process were observed irrespectively of the DO. The highest nitrogen removal rate of 3.33 g N m^{-2} d^{-1} (efficiency equal to 69.5%) was obtained at R = 1/3 and DO = 4 mg L^{-1}. Significantly lower nitrogen removal rates (1.17–1.58 g N m^{-2} d^{-1}) were observed at R = 1 and R = 3 for each examined DO. It was a consequence reduced aerated phase duration times and lesser amounts of residual nitrite in non-aerated phases as compared to R = 1/3.

Key words | deammonification, dissolved oxygen, intermittent aeration, ratio between non-aerated and aerated phase timings

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INTRODUCTION

Treatment of wastewater rich in ammonium and with low content of easily biodegradable organic carbon in a conventional nitrification – denitrification process requires costly external carbon addition. Much of the research work has been done on innovative sustainable biological nitrogen removal technologies based on an Anammox process (Ganigue *et al.* 2009; van Der Star *et al.* 2009; Vazquez-Padin *et al.* 2009*a*). In such treatment processes, ammonium is partially oxidized to nitrite by ammonium oxidizing bacteria (AOB) and subsequently, Anammox bacteria convert the remaining ammonium to dinitrogen gas using nitrite as an electron acceptor. In this technology oxygen consumption is decreased and no external carbon dosage is needed.

It is known from previous studies (Fux *et al.* 2004; Rosenwinkel *et al.* 2005; Szatkowska *et al.* 2007) that one stage moving bed biofilm reactor (MBBR) with simultaneous nitritation-anammox process is a good option to achieve stable and effective nitrogen removal. In this process, the reactor is operated under such oxygen conditions that allow AOB to have higher growth rate than nitrite oxidizing bacteria (NOB). Therefore, dissolved oxygen is one of the main factors impacting on the nitrogen removal efficiency in the deammonification process. AOB can not produce a sufficient amount of NO_2^--N for Anammox bacteria under too low DO concentrations, which is a rate-limiting step for the process (Szatkowska *et al.* 2007). However, too high DO concentrations in the bulk liquid may cause inhibition effects on the Anammox bacteria (Kartal *et al.* 2007) or increase NOB growth (Wiesmann 1994). Table 1 shows DO concentrations used by different authors during one stage deammonification studies.

Intermittent aeration as an alternative strategy leads to NO_2^--N enrichment if the aerated and non- aerated phase timings are adjusted appropriately. This aeration strategy has

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Table 1 | Comparison of aeration strategies and nitrogen removal in one stage biofilm nitrogen removal systems

Reactor type	Application	DO concentration [mg L^{-1}]	Aeration strategies	N load [N m^{-2} d^{-1}]	N removal efficiency [%]	N removal rate [g N m^{-2} d^{-1}] [kg N m^{-3} d^{-1}]*	References
RBC-full-scale	Landfill leachate	1–3	-	0.5–3.5	30–70	0.4–2.5	Siegrist *et al.* 1998
RBC-lab-scale	Synthetic wastewater	0.57 ± 1.2	-	4.7–8.3	89 ± 5	7.39 ± 0.4	Pynaert *et al.* 2003
RBC-lab-scale	High-salinity wastewater	< 1	-	0.525–1	84	0.35–1	Windey *et al.* 2005
RBC-lab-scale	Landfill leachate	1.8 ± 0.7	-	1–7	56.6	4.5–6.2	Cema *et al.* 2009
MBBR-full-scale	Sludge liquor	0–4	Intermittent aeration	2 (designed)	10–50	0.2–1	Rosenwinkel *et al.* 2005
MBBR-pilot plant	Sludge liquor	1.90	Continuous aeration	1.0–3.5	58.7	0.7–2.7	Szatkowska *et al.* 2007
SNAP biofilm reactor-lab-scale	Synthetic wastewater	2–3	Continuous aeration		60–80	0.48*	Furukawa *et al.* 2006

been applied in the Hattingen WWTP with different DO concentration setpoints between 0–4 mg L^{-1} (Rosenwinkel *et al.* 2005). Himmerfjärden WWTP, Stockholm, also uses intermittent aeration strategy with 30 minute long aerated and 30 minute non-aerated periods in a MBBR reactor and achieves a very high nitrogen removal efficiency. Pulsing aeration has been studied in a SBR due to its lower aeration costs compared to continuous aeration systems and better control of the required low concentrations of dissolved oxygen (Vazquez-Padin *et al.* 2009*b*). Xu *et al.* (2010) successfully studied a SBR with periodic air supply with concentrations of 0–1.5 mg L^{-1} to treat landfill leachate using a combination of partial nitrification, Anammox and denitrification processes.

The aim of this study is to investigate the influence of different aeration strategies (described by both DO concentration and the ratio between non-aerated and aerated phase times-R) on the performance and efficiency of deammonification.

MATERIALS AND METHODS

Laboratory-scale reactor

A laboratory-scale moving bed biofilm deammonification reactor located at Hammarby Sjöstadsverk (Center for innovative municipal wastewater purification, Stockholm) was operated for more than one year. The reactor was filled up to 40% of its total volume (8 L) with Kaldnes biofilm carriers, which have an effective surface area of 500 m^2 m^{-3}. Since November 2009 the operational parameters of the bioreactor have been altered (Table 2) in order to study the influence of different aeration strategies on the efficiency of deammonification. The experiment which outcomes have been presented in this paper has been preceded with a month-long biomass adaptation period to new environmental and operational conditions. The reactor was filled with real supernatant which composition is shown in Table 3.

Batch tests

Three series of batch tests were carried out with different DO concentrations (2, 3 and 4 mg L^{-1}) (Table 4). Four batch

Table 2 | Deammonification laboratory-scale reactor operation parameters

Parameters	Value
Hydraulic retention time [d]	2
N-load [g N m^{-2} d^{-1}]	2.05–2.24
Temperature [°C]	27
pH inside the reactor	6.94–7.98
DO [mg L^{-1}]	0–3.0
R	1 (30 min aeration and 30 min no aeration)

Table 3 | Supernatant characteristics (average value)

Parameters	Value	St. dev.
pH	8.14	0.12
Conductivity [ms cm^{-1}]	6.2	0.88
NO_4^+-N [mg L^{-1}]	852	2.84
NO_2^--N [mg L^{-1}]	0	0
NO_3^--N [mg L^{-1}]	0	0
TN-N [mg L^{-1}]	911	2.06
COD [mg L^{-1}]	376	1.43

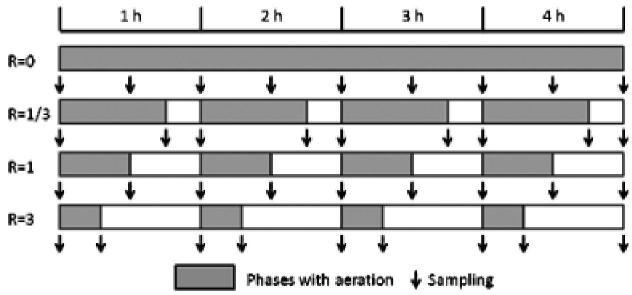

Figure 1 | Different aeration strategies and sampling time at the same DO concentration.

tests have been done for each series of tests with different R values (0, 1/3, 1 and 3). Each batch test was operated in 4 hr cycle with phase arrangement described in Figure 1.

The biomass used in those batch tests was taken from the laboratory scale reactor in the period of its stable operation (determined when similar deammonification efficiencies in consecutive measurements were attained). To avoid the changes in the populations of various groups of microorganisms in the biofilm the experiments were carried out with short time breaks between each individual test. Additionally, after each test the activity of the Anammox bacteria present on the carriers (SAA) have been determined (Table 4).

One litre vessel was used in the batch tests with 40% of the reactor volume filled with Kaldnes carriers. The tests were conducted at 25°C. The feeding medium for the batch tests was a supernatant with NO_4^+-N concentration of 150 mg L^{-1}. Oxygen was fed to the reactor by a laboratory scale aspirator connected to a manometer and distributed inside the reactor by a porous air-stone placed at the bottom of the tank. Additionally a magnetic stirrer was used to assure appropriate mixing of the medium during the test. Under all operational conditions the aspirator was controlled to a constant DO setpoint. Oxygen supply was based on different R values and controlled on-line by a DO meter (Hach Portable 1.5.0.8.3). Liquid samples were taken from the vessel at each end of the aerated or non-aerated phase. In continuous aeration batch tests, samples were taken every 30 minutes (Figure 1).

Analytical methods

In the laboratory reactor, samples of both influent and effluent were collected and analyzed for NO_4^+-N, NO_2^--N, NO_3^--N, COD and alkalinity. Chemical analysis was performed using Dr. Lange cuvette on the samples pre-filtered through a 0.45 μm filter.

Samples taken from batch tests were filtered immediately on 0.45 μm filters and kept in the freezer prior to the analysis.

Table 4 | Batch test; operation parameters

	Parameters	Series I	Series II	Series III
Constant parameters	Temperature [°C]	25	25	25
	Total reactor volume [L]	1	1	1
	Kaldnes carries volume [L]	0.4	0.4	0.4
	Initial ammonium concentration [mg N L^{-1}]	150	150	150
	Test duration [h]	4	4	4
Variable parameters	Dissolve oxygen concentration (DO) during aerated phases [mg L^{-1}]	2	3	4
	Ratio between times of non- aerated and aerated phases (R) [–]	0, 1/3, 1, 3	0, 1/3, 1, 3	0, 1/3, 1, 3
Anammox activity	SAA [g N m^{-2} d^{-1}]	2.50±0.02	2.51±0.02	2.50±0.01

Flow Injection Analysis with AQUATEC-TECATOR 5400 ANALYZER was used to measure NH_4^+-N, NO_2^--N, NO_3^--N concentrations.

Based on nitrogen gas production, specific anammox activity (SAA) was estimated at 25°C (Dapena-Mora *et al.* 2007).

RESULTS AND DISCUSSION

Laboratory-scale deammonification reactor

Figure 2 presents the results from the operation of laboratory-scale deammonification reactor only for the period, when batch tests were carried out. Influent nitrogen load was 2.11 g N m^{-2} d^{-1} as average value.

Nitrogen removal rate was around 2.0 g N m^{-2} d^{-1} during the first 10 days and then decreased to 1.49 g N m^{-2} d^{-1} due to low dissolved oxygen concentration in the reactor (0.7 mg L^{-1} during some days). After one week of operation, nitrogen removal rate achieved again the previous value and nitrogen removal efficiency was equal to 85%. The results presented in Figure 2 also indicate that the problem with aeration caused a decrease of specific anammox biomass activity from 2.5 g N m^{-2} d^{-1} to 1.6 g N m^{-2} d^{-1}. It was probably due to lower nitrite production. After DO was kept again at a level of 3.0 mg L^{-1} SAA achieved the value of 3.0 g N m^{-2} d^{-1}. At the same time, N removal efficiency was higher than 87%. Comparing with SAA results and nitrogen removal rates in the reactor, the process showed a potential ability to work at higher nitrogen influent loads.

Batch tests

Nitrogen conversions at different DO and R

The main purpose of the experiment was to investigate different aeration strategies for the deammonification process in the moving bed biofilm reactor (MBBR). Nitrogen conversions in batch tests performed at one of the tested DO concentrations and at various R values are presented in Figure 3.

In all tests a gradual decrease of ammonium (NO_4^+-N) and inorganic nitrogen ($N_{inorg.}$) concentrations with a simultaneous increase in nitrates (NO_3^--N) were observed. Evolution of nitrite concentrations depended on the chosen aeration strategy. In the tests carried out with continuous aeration, concentrations of NO_2^--N were initially increasing and then quickly reaching a plateau. For the systems with intermittent aeration, step-wise changes in NO_2^--N have been noted: an increase in aerated and decrease in non-aerated phases. An increase in NO_2^--N concentrations was, however, small compared to the elimination of NO_4^+-N and N_{inorg} in all tests. The above results indicate that the actual production of nitrites under aerobic conditions was significantly higher than the observed one and most of the produced nitrites were used as electron acceptors for the oxidation of NO_4^+-N by the Anammox bacteria. Based on these observations it was concluded that two processes: partial nitrification and Anammox were occurring simultaneously in the biofilm. This phenomenon can be explained by the occurrence of aerobic areas in the biofilm where nitritation takes place and anoxic areas, where anaerobic ammonium oxidation occurs (Sliekers *et al.* 2003). In case of intermittently aerated systems, nitrites remaining after aerobic phases were used as electron acceptors for oxidation of ammonium, which led to the observed effect of depletion of inorganic nitrogen forms in the non-aerated phases (Figure 3).

Rate of this process was lower than in the case of aerated phases, which resulted from relatively small amounts of nitrites in the supernatant. Figure 4 shows average values of nitrite concentrations in the reactor in the beginning of non-aerated phases. The obtained results indicate that nitrite concentrations were influenced by the duration times of aerobic phases as well as concentrations of dissolved oxygen. The highest concentration of NO_2^--N of approx.

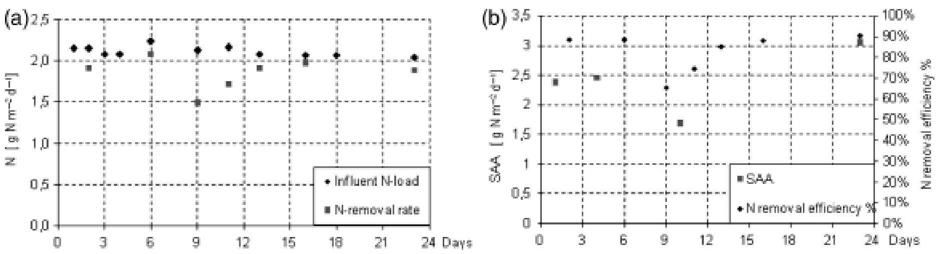

Figure 2 | a) Deammonification laboratory-scale reactor influent nitrogen load and nitrogen removal rate, b) deammonification laboratory-scale reactor specific anammox activity (SAA) and nitrogen removal efficiency.

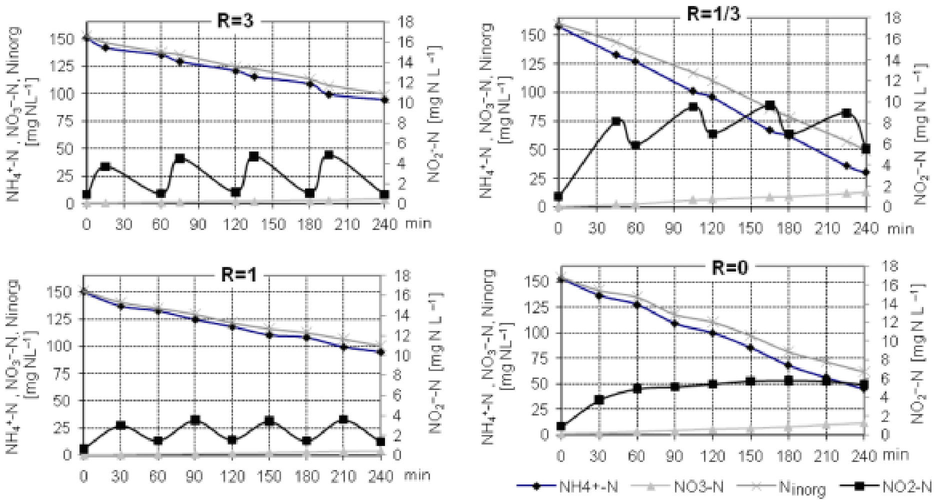

Figure 3 | Nitrogen conversions during batch tests at DO 4 mg L^{-1} and different R.

9 mg NO_2^--N L^{-1} was noted for R = 1/3 and DO = 4 mg L^{-1}. In case of the tests carried out for R = 1 and R = 3 the residual nitrite concentrations after aerated phases were very low (<4.5 mg NO_2^--N L^{-1}) which indicated that only a small amount of nitrogen could be removed during the non-aerated phases. The results presented in Figure 4 also show that for R = 1 and R = 3 the concentrations of NO_2^--N after aerated phases for the same levels of DO were comparable and slightly increasing with DO. Additionally, for all tested DO set-points a decrease in R value to 1/3 resulted in an increase of the remaining NO_2^--N which indicates that duration of aerated phases has a significant influence on NO_2^--N concentrations.

The above described results validate the thesis postulated by Szatkowska *et al.* (2007) and Cema *et al.* (2008) that nitrite production rate is a bottleneck in the overall nitrogen removal in a one stage deammonification process. When selecting an aeration strategy it is therefore important to

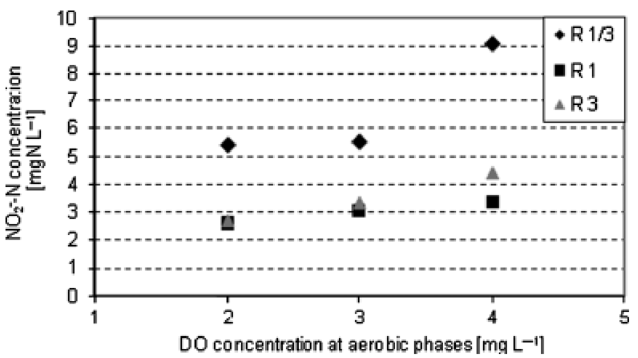

Figure 4 | Average values of NO_2^--N in the beginning of non-aerated phases at different DO concentrations and R.

ensure such environmental conditions which would favour the nitritation process, bearing in mind that too high NO_2^--N concentrations may inhibit the activity of the Anammox bacteria. Van Dongen *et al.* (2001) showed that the Anammox process is irreversibly inhibited by nitrites at concentration exceeding 70 mg NO_2^--N L^{-1} for several days.

Nitrogen removal in aerated and non-aerated phases

To explain and further investigate nitrogen form changes at various aeration strategies, nitrogen balances were calculated. Based on these calculations the amounts of removed ammonium and inorganic nitrogen as well as the amounts of produced nitrates in aerated and non-aerated phases were determined (Table 5). Additionally, the amounts of nitrites consumed in non-aerated phases have been calculated. As all tests were carried out with identical initial ammonium concentrations, volumes of moving bed and temperatures, it was assumed that all observed differences in the changes of various forms of nitrogen and their efficiencies were due to the differences between the chosen aeration strategies. Additionally, to avoid changes in the populations of various groups of microorganisms in the biofilm's biocenosis, the experiments were carried out with short time breaks between each individual experiment.

In the case of tests performed with continuous aeration, a significant increase in N removal was observed after increasing DO concentration from 2 mg L^{-1} to 4 mg L^{-1} (Table 5). The amount of produced NO_3^--N was about 10% of the removed N and was therefore close to the stoichiometric value characteristic for the Anammox process (Strous *et al.* 1998). This significant influence of dissolved concentration

Table 5 | Various nitrogen forms consumption or production at aerated (Aer.) and non - aerated (NoAer.) phases

		Ammonia consumption [mg N L^{-1}]		Nitrite consumption [mg N L^{-1}]	Nitrate production [mg N L^{-1}]		Inorganic nitrogen consumption [mg N L^{-1}]		NO_2^--N/NH_4^+-N
R [–]	DO [mg L^{-1}]	Aer.	NoAer.	NoAer.	Aer.	NoAer.	Aer.	NoAer.	NoAer.
0*)	2	62.7	-	-	3.87	-	56.1	-	-
	3	70.5	-	-	5.83	-	61.8	-	-
	4	108	-	-	11.2	-	92.4	-	-
1/3	2	72.6	11.7	5.80	4.70	2.17	57.5	15.3	0.496
	3	85.2	8.24	7.01	6.01	1.93	68.6	11.0	0.858
	4	106	22.0	10.9	9.68	2.46	80.5	30.5	0.496
1	2	30.4	18.5	5.80	0.52	1.36	23.3	22.9	0.313
	3	42.8	15.4	6.88	1.98	1.20	33.4	21.0	0.448
	4	37.6	17.4	7.69	2.02	1.99	27.1	23.1	0.442
3	2	29.2	10.1	5.80	0.141	0.33	21.5	15.8	0.574
	3	32.1	20.1	10.2	0.556	0.99	25.0	27.0	0.505
	4	29.6	26.5	13.5	0.432	2.96	16.5	37.8	0.511

*These aeration strategies did not include the non - aerated phases.

on deammonification efficiency was proved by Cema *et al.* (2008). The authors showed that the highest nitrogen removal rates were obtained at DOs equal to 3 mg L^{-1} and 4 mg L^{-1}.

Introduction of intermittent aeration at R = 1/3 allowed to increase the amount of nitrogen removed at all investigated DO levels. The achieved results indicate that despite reducing the aeration time by 25%, the amounts of nitrogen removed in aerobic phases were comparable to the ones recorded at a continuous aeration strategy (Table 5). It is probable that in the case of continuously aerated systems, oxygen could diffuse into the deeper layers of the biofilm thus inhibiting some Anammox bacteria. At an intermittent aeration strategy introduction of a 15 minute non-aerated phase allowed a "deoxygenation" of the biofilm and as a result, potentially more Anammox bacteria could be provided with the conditions for anaerobic ammonium oxidation. Results obtained in the tests carried out at R = 1/3 also indicate a similar trend to the tests with continuous aeration, a significant increase in the removal of N occurred after the DO level had been raised from 2 mg L^{-1} to 4 mg L^{-1}. This was attributed to an increase in the extent of N removal in the aerated as well as non-aerated phases which most probably was due to higher nitritation efficiency and subsequently an increased availability of electron acceptors for the Anammox bacteria.

The tests carried out with an intermittent aeration strategy, but for R = 1 and R = 3 have shown that further reduction in aeration phase duration times and at the same time a prolongation of non-aerated phases resulted in a significant decrease of the amount of inorganic N removed. One of the reasons for such a behaviour was a drastic decrease in the amounts of nitrogen removed during the aerated phases (Table 5) due to reduction of their duration times compared to R = 1/3 by, respectively 25% and 50% for R = 1 and R = 3. Additionally, only small amounts of nitrites remained in the treated liquor after the aerated phases (Figure 5), which limited the Anammox process in non-aerated phases (this is supported by the amounts of then removed inorganic nitrogen – Table 5). It can be therefore assumed that removal of nitrogen occurred only during the initial stages of non-aerated phases when nitrites present in the treated supernatant could diffuse into the biofilm where Anammox bacteria were present.

Taking into account the stoichiometry of the Anammox process, it was suspected that during the non-aerated phases, the ratio between removed NO_2^--N to NO_4^+-N would be oscillating close to the value of 1.32 (Strous *et al.* 1998). In reality, much lower values of this ratio were observed (Table 5). Yang *et al.* (2009) explains such behaviour with the possibility of utilising other electron acceptors than nitrites in the anoxic ammonium oxidation process. The authors assumed that such alternative electron acceptors could be sulphates. Sabumon (2009) also indicated the possibility of using other than nitrites inorganic electron acceptors (SO_4^{2-} and NO_3^-) in the process of anoxic ammonium oxidation. It was therefore supposed that a similar situation might have occurred in the tests described in this paper. Another possible explanation of such observations might be a possibility of occurrence of higher nitrite concentrations during non-aerated phases than it was observed after aerated phases. Some NO_2^--N might be produced after turning the aeration off because the biofilm could then still contain some dissolved oxygen. It cannot also be excluded that during non-aerated phases, reactive forms of oxygen could be produced. These forms of oxygen are substrates for producing dissolved oxygen in enzymatic reactions, which could then be used for oxidizing ammonium to nitrites (Sabumon 2009). In order to find a clear-cut answer, profiles of various nitrogen forms through a cross-section of a biofilm should be measured.

Figure 5 shows the relation between aeration time (expressed as percentage of total test duration time) and removed nitrogen in aerated phases (expressed as percentage of total nitrogen removed) for all tested DO concentrations. The presented data indicate that in case of tests carried out with DO of 3 mg L^{-1} and 4 mg L^{-1} the amount of nitrogen removed in aerated phases was directly proportional to oxygen concentration.

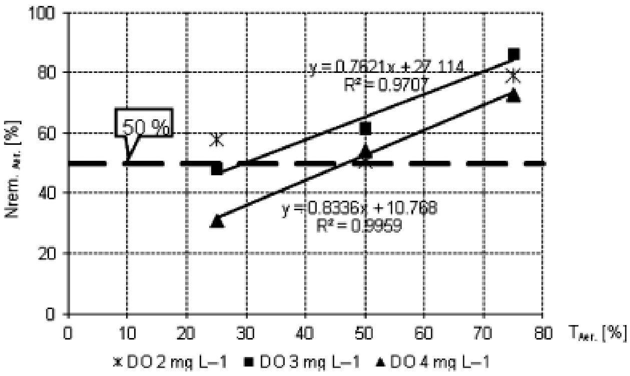

Figure 5 | Relation between aeration times $T_{Aer.}$ (expressed as percentage of total test duration time) and removed nitrogen in aerated phases $Nrem._{Aer}$ (expressed as percentage of total nitrogen removed).

Nitrogen removal rate at different DO and R

To summarise the outcomes of this study, Figure 6 shows the rates and efficiencies of deammonification (estimated from the amounts of inorganic N removed) for different aeration strategies.

Looking at the above results, which have been obtained for constant DO values and variable magnitudes of R, it can be seen that the highest deammonification rates were achieved at R = 1/3. After the comparison of all test results, it was noted that maximum inorganic N removal rate of 3.33 g N m^{-2} d^{-1} was recorded at R = 1/3 and DO = 4 mg L^{-1}. The efficiency of this process for the above operating conditions was 69.5% (Figure 6b). It was therefore only 19.2% lower from the theoretically maximum efficiency for the Anammox process (88.7%) based on stoichiometry (Strous *et al.* 1998).

The obtained results also indicate that the impact of dissolved oxygen on deammonification was dependent on the R value. At R = 0 and R = 1/3, an increase of DO from 3 mg L^{-1} to 4 mg L^{-1} caused a significant increase in nitrogen removal rate respectively from 1.83 g N m^{-2} d^{-1} to 2.77 g N m^{-2} d^{-1} and from 2.43 g N m^{-2} d^{-1} to 3.33 g N m^{-2} d^{-1}. At R = 1 and R = 3 similar rates of the process (1.17–1.58 g N m^{-2} d^{-1}) were however observed irrespectively of the DO.

Taking into account that the costs of aeration are a significant share of the total operational costs of a wastewater treatment plant (Bischof *et al.* 1996), introduction of an appropriately selected intermittent aeration strategy could produce significant savings at no negative impacts on process

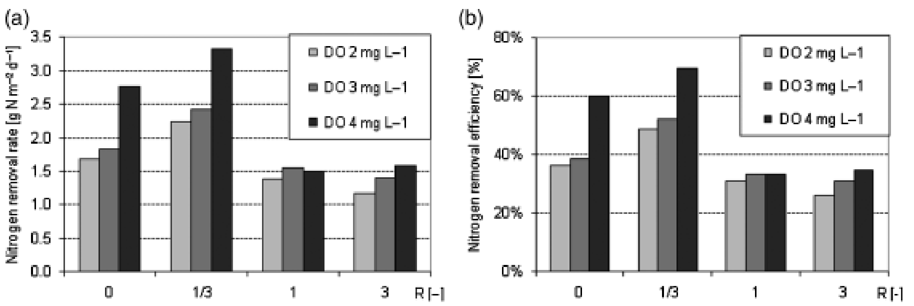

Figure 6 | Nitrogen removal rate (a) and nitrogen removal efficiency (b) in batch tests at different DO concentrations and R.

efficiency. An additional advantage of this aeration strategy is a possibility to reach only the first step of nitrification (Rosenwinkel *et al*. 2005).

Results presented in this paper have been produced in the first stage of experiments aimed to test the impact of different aeration strategies on the efficiency of deammonification in MBBRs. These results indicate that in order to intensify this process it is economically justifiable to search for an optimal aeration strategy, taking into consideration both, DO concentration and the ratio between time of non -aerated and aerated phases. In practical applications a third parameter, namely specific ammonium surface load, should be taken into consideration. According to Hao *et al*. (2002), this parameter affects the optimum DO concentration. The authors showed that higher ammonium surface loads required higher DO levels in the bulk liquid to achieve the maximum nitrogen removal.

Currently, investigations are being carried out in the pilot MBBR equipped with an automatic control system allowing to control DO and R at the same time.

CONCLUSIONS

- The results confirmed that in a deammonification process partial nitrification and Anammox are occurring simultaneously in the biofilm and nitrite production is the bottle neck of the whole process.
- DO concentration together with an R value are two crucial parameters for deammonification process performance and efficiency. Application of an appropriately selected aeration strategy could reduce an energy consumption without any negative impacts on the process.
- The highest nitrogen removal rate and efficiency equal to 3.33 g N m^{-2} d^{-1} and 69.5%, respectively were achieved at $R = 1/3$ and $DO = 4$ mg L^{-1}, although only 75% of energy was used compared with continuous aeration. Operation at an increased R value to 1 and 3 led to a significantly lower nitrogen removal rate due to reduced aerated phase duration time and a lower nitrite production.
- It was found that the impact of DO on deammonification was dependent on the R value. At $R = 0$ and $R = 1/3$, an increase of DO caused a significant increase of the nitrogen removal rate, whereas at $R = 1$ and $R = 3$ similar rates of the process were observed irrespectively of DO.
- The obtained data also indicated a proportional relationship between the amount of nitrogen removed and R when dissolved oxygen were at the levels of 3 mg L^{-1} and 4 mg L^{-1}.

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