Assessment of aeration control strategies for biofilm-based partial nitritation/anammox systems

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ABSTRACT

The objective of this work was to compare the nitrogen removal in mainstream, biofilm-based partial nitritation anammox (PN/A) systems employing (1) constant setpoint dissolved oxygen (DO) control, (2) intermittent aeration, and (3) ammonia-based aeration control (ABAC). A detailed water resource recovery facility (WRRF) model was used to study the dynamic performance of these aeration control strategies with respect to treatment performance and energy consumption. The results show that constant setpoint DO control cannot meet typical regulatory limits for total ammonia nitrogen (NH_x-N). Intermittent aeration shows improvement but requires optimisation of the aeration cycle. ABAC shows the best treatment performance with the advantages of continuous operation and over 20% lower average energy consumption as compared to intermittent aeration.

Key words | aeration, ammonia-based aeration control, biofilm reactor, deammonification, partial nitritation/anammox, process modelling

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INTRODUCTION

The partial nitritation/anammox (PN/A) process consists of the partial oxidation of ammonium to nitrite followed by the anaerobic reaction of ammonium and nitrite to form dinitrogen gas. This process is of great interest because of its potential for much lower oxygen consumption than traditional nitrification/denitrification processes with no supplemental carbon requirement.

The process can be implemented in a two-reactor configuration where partial nitritation occurs in the first aerobic reactor and the anammox reaction occurs in the second anoxic reactor, or in a one-reactor configuration where both reactions occur simultaneously in an aerated reactor (Van der Star *et al.* 2007). The current focus is on one-reactor configurations that use biofilm, granular sludge, or sequencing batch reactors (Lackner *et al.* 2014). To date, PN/A has been primarily used to treat high nitrogen loads found in the centrate from anaerobically digested solids (Lackner *et al.* 2014; Regmi *et al.* 2015). A more recent application is for mainstream nitrogen removal in water resource recovery facilities (WRRFs). Mainstream PN/A is more challenging than sidestream PN/A because of the lower nitrogen loading and lower wastewater temperature.

Regmi *et al.* (2014, 2015) studied different control strategies at pilot-scale for supressing nitrite-oxidising bacteria (NOB) in mainstream PN/A systems including ammonia vs. nitrate and nitrite (NO_x) control (AvN). In the Regmi *et al.* (2015) study, nitritation was accomplished in a conventional activated sludge process that followed a high-rate A-stage reactor for carbon removal. An anammox moving-bed biofilm reactor (MBBR) was placed downstream of the B-stage. Al-Omari *et al.* (2015) used process modelling to compare AvN and ammonia-based control (ABAC; Rieger *et al.* 2014) in mainstream suspended growth deammonification reactors and found that AvN provided higher nitrogen removal. Corbalá-Robles *et al.* (2016) performed a model-based study of granular sludge PN/A systems and found that continuous aeration provided higher nitrogen removal in a sequencing batch reactor than with intermittent aeration due to its higher maximum dissolved oxygen (DO) concentrations. Klaus *et al.* (2017) developed a PN/A

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aeration control strategy for single reactor PN/A MBBRs, treating equalised sidestreams, that was based on either pH, conductivity, or total ammonia nitrogen (NH_x-N).

In the current study, the focus is to assess ABAC of mainstream single reactor biofilm-based PN/A systems faced with typical diurnal nitrogen loads. This application presents a unique challenge because of the low nitrogen concentrations, low temperature, and the need for precise DO control. Studies by Brockmann & Morgenroth (2010), Pérez *et al.* (2014), Isanta *et al.* (2015), Laureni *et al.* (2016) and Rosenthal *et al.* (2018) found that DO concentrations below 0.5 mg/L are required for ammonia-oxidising bacteria (AOB) to out-compete NOB (to prevent full nitrification) and to allow anammox growth in a biofilm reactor. This is especially important in mainstream systems where effluent limits on NH_x-N and total nitrogen (TN) must be met. McQuarrie *et al.* (2015) indicate that three DO control approaches have been used in commercial biofilm-based PN/A reactors: (1) traditional DO control with a setpoint between 0.5 and 1.5 mg/L, (2) intermittent aeration, and (3) a strategy where the DO setpoint is varied depending on the level of ammonia removal and the ratio of nitrate produced to ammonia removed. Intermittent aeration is thought to promote NOB out-selection because of an observed NOB lag in adapting to aerobic conditions after a period of anoxia as compared to AOB (Regmi *et al.* 2014).

The objective of this work is to assess the nitrogen removal performance of mainstream, single reactor biofilm-based PN/A systems employing constant setpoint DO control and intermittent aeration, and then to demonstrate the potential advantages of using ABAC. Ammonia-based aeration control has a high control authority in biofilm-based PN/A systems because of the long solids retention time (SRT) and diffusion-controlled reaction rates. A process model is developed to compare the control strategies and provide a proof of concept.

METHODS

The aeration control methods are studied using a representative WRRF performing mainstream PN/A that has been modelled in SIMBA# 3.2 (ifak 2019). The WRRF model (Figure 1) includes diurnal influent flow and chemical oxygen demand (COD), NH_x-N, and soluble phosphorus (SP) concentration patterns, primary clarifiers, a carbon removal moving-bed biofilm reactor (MBBR), mainstream PN/A in an MBBR, solids separation (e.g. secondary clarifiers, DAF, etc.), anaerobic digestion, and sidestream PN/A treatment using an MBBR.

The primary clarifiers and the carbon removal MBBR are used to reduce the readily biodegradable COD concentration before the mainstream PN/A reactors. The sidestream PN/A reactor effluent is recycled back to the mainstream PN/A reactor to seed ammonia-oxidising and anammox bacteria. Raw wastewater characteristics are given in Table 1 and the facility design characteristics are provided in Table 2.

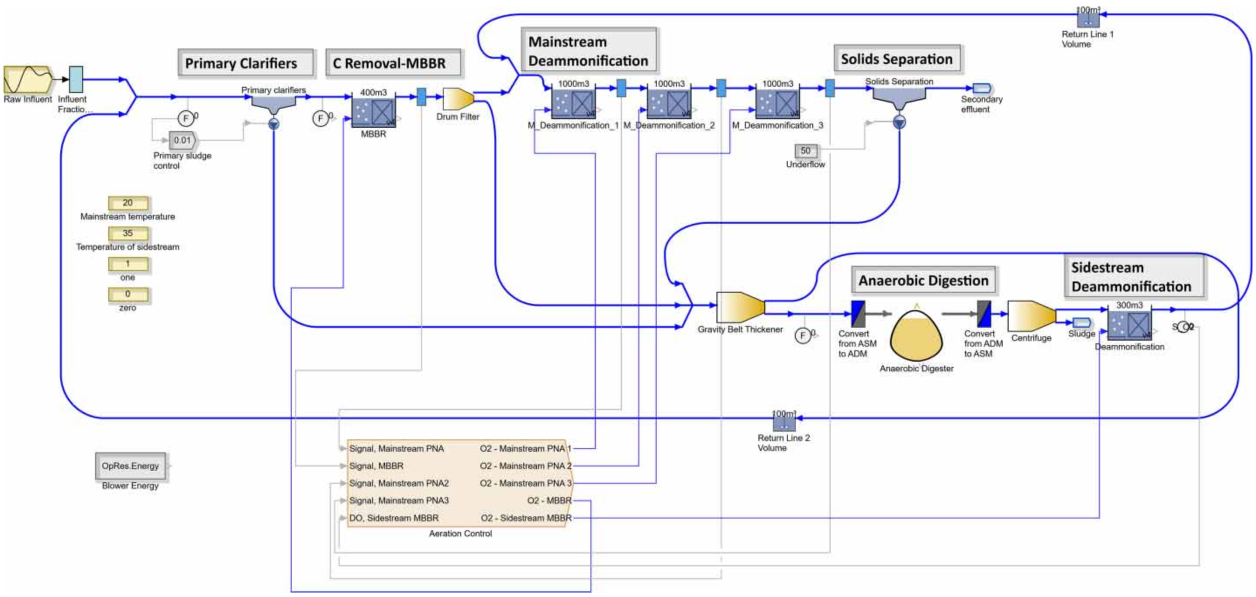

Figure 1 | Example WRRF used to study mainstream PN/A aeration control strategies for biofilm reactors. The WRRF uses a sidestream PN/A MBBR to seed the mainstream PN/A MBBRs.

Table 1 | Influent characteristics for modelled WRRF

Parameter	Value	Unit
Raw influent		
Flow rate	15,000	m^3/d
Total COD	460	mg/L
TKN	41.6	mgN/L
NH_4-N	26.2	mgN/L
TP	7.3	mgP/L
PO_4-P	2.5	mgP/L
Readily biodegradable fraction of total COD	0.2	gCOD/gCOD
Soluble inert fraction of total COD	0.05	gCOD/gCOD
Particulate inert fraction of total COD	0.13	gCOD/gCOD
OHO fraction of total COD	0.1	gCOD/gCOD
Colloidal fraction of total COD	0.15	gCOD/gCOD
Temperature	20	°C

Table 2 | Physical data for modelled WRRF

Parameter	Value	Unit
Primary clarifiers		
TSS removal efficiency	50	%
Primary sludge flowrate as % of influent	1	%
Carbon Removal MBBR		
Volume	400	m^3
Depth	4	m
DO controller setpoint	2	mg/L
Carrier specific surface area	500	m^2/m^3
Carrier fill fraction	60	%
Water volume displaced per carrier volume	0.18	m^3/m^3
Mainstream Deammonification MBBRs		
Volume per reactor (3 in series)	1,000	m^3
Depth	4	m
Carrier specific surface area	800	m^2/m^3
Carrier fill fraction	50	%
Water volume displaced per carrier volume	0.18	m^3/m^3
Sidestream Deammonification MBBR		
Volume	300	m^3
Depth	4	m
Carrier specific surface area	500	m^2/m^3
Carrier fill fraction	50	%
Water volume displaced per carrier volume	0.18	m^3/m^3
Temperature	35	°C
Secondary clarifiers		
Effluent TSS	10	mg/L
Underflow rate	50	m^3/d
Gravity belt thickener		
TS concentration of dewatered sludge	4	%
TSS removal efficiency	95	%
Centrifuge		
TS concentration of dewatered sludge	25	%
TSS removal efficiency	95	%
Anaerobic digesters		
Liquid volume	1,800	m^3
Headspace volume	200	m^3
Temperature	35	°C

The WRRF model uses the inCTRL-ASM biokinetic model, which includes two-step nitrification and the growth of anammox bacteria (AMX), in addition to hydrolysis, adsorption, fermentation, and the growth of ordinary heterotrophic organisms (OHO), phosphorus accumulating organisms (PAO), and methylotrophs. The anammox biokinetic sub-model is based on the model of Koch *et al.* (2000). The value of the half-saturation coefficient for oxygen was determined based on data reported by Strous *et al.* (1997) and was set to 0.035 mg/L. The proportional-integral (PI) controller block in SIMBA# is used for feedback control of DO and ammonia. The upper and lower DO setpoint limits for the ammonia controller are 3 and 0.1 mg/L, respectively. The upper DO limit was selected to ensure that excessively high DO values are not used which would reduce the potential energy savings. A temperature of 20 °C is used in the mainstream MBBR and 35 °C is used in the sidestream MBBR. The mainstream MBBR has a hydraulic retention time of 5.4 h. The raw influent TKN loading rate per carrier surface area is 0.52 $gN/d/m^2$.

RESULTS AND DISCUSSION

Dynamic simulations were used to evaluate the different aeration control strategies and their impact on nitrogen removal. Initially, traditional DO control was studied using steady-state simulations and it was found that using a three reactor in series configuration for the mainstream PN/A MBBR was helpful in encouraging anammox growth. Using reactors in series is known to increase the extent of chemical and biochemical reactions (Fogler 1986). Table 3 compares the steady-state simulation results for a single reactor, two reactors in series, and three reactors in series over a range of DO

Table 3 | Sensitivity study of the effect of the DO setpoints and the number of mainstream PN/A MBBRs used on the nitrogen concentrations in the effluent of the last mainstream MBBR at a wastewater temperature of 20 °C using steady-state simulations

	Effluent nitrogen concentration (after last MBBR)				
Scenario	**NH_x-N [mgN/L]**	**NO_2-N [mgN/L]**	**NO_3-N [mgN/L]**	**TN [mgN/L]**	**N_2-N [mgN/L]**
1 MBBR: Volume = 3,000 m^3 **Constant Setpoint DO Control**					
DO setpoint = 1.5 mg/L	0.342	0.0397	27.0	28.9	6.27
DO setpoint = 1 mg/L	0.39	0.044	26.4	28.3	6.86
DO setpoint = 0.5 mg/L	1.20	0.102	18.7	21.4	13.7
DO setpoint = 0.3 mg/L	4.53	0.195	2.63	8.82	26.3
2 MBBRs: Volume = 1,500 m^3 each **Constant Setpoint DO Control, Same DO setpoint in each MBBR**					
DO setpoint = 0.5 mg/L in both MBBRs	0.366	0.0498	11.3	13.0	22.2
DO setpoint = 0.3 mg/L in both MBBRs	5.17	0.24	4.68	11.3	23.8
2 MBBRs: Volume = 1,500 m^3 each **Constant Setpoint DO Control, Same DO setpoint in each MBBR**					
DO setpoints of 0.5, 0.3 in the 2 MBBRs	0.816	0.0893	9.34	11.5	23.6
3 MBBRs: Volume = 1,000 m^3 each **Constant Setpoint DO Control, Same DO setpoint in each MBBR**					
DO setpoint = 1 mg/L in all 3 reactors	0.0474	0.00826	17.5	18.9	16.2
DO setpoint = 0.5 mg/L in all 3 reactors	0.192	0.0320	10.4	11.8	23.4
DO setpoint = 0.3 mg/L in all 3 reactors	3.41	0.212	5.07	9.83	25.3
3 MBBRs: Volume = 1,000 m^3 each **Constant Setpoint DO Control, Different DO setpoint in each MBBR**					
DO setpoints of 1, 0.5, 0.3 in the 3 MBBRs	0.0664	0.0127	17.4	18.7	16.4
DO setpoints of 0.5, 0.3, 0.2 in the 3 MBBRs	0.792	0.115	3.55	5.69	29.4
DO setpoints of 0.3, 0.2, 0.1 in the 3 MBBRs	13	0.115	0.135	14.5	20.7

concentrations and demonstrates the improved nitrogen removal when using three reactors as compared to one or two reactors. As most of the organic carbon is removed in the carbon removal MBBR, the presence of dinitrogen (N_2) gas provides an indication of anammox activity. Figures S1 to S6 in the Supplementary Material show the concentrations of AOB, NOB, Anammox bacteria and DO in the biofilm layers in the single reactor with a DO concentration of 0.3 mg/L and the three reactors in series at steady-state conditions with DO concentrations of 0.5, 0.3, and 0.2 mg/L respectively.

In order to achieve significant PN/A activity and low effluent NH_x-N, the DO setpoints were 0.5 mg/L in the sidestream MBBR and 0.5 mg/L in the 3 mainstream MBBRs. It was found that the effluent TN was almost 12 mgN/L in this case (Table 3), which would be too high in areas with strict nitrogen limits. Lowering the DO to 0.3 mg/L in all three reactors lowers the effluent TN but increases the effluent NH_x-N to over 3 mgN/L. In order to encourage more anammox activity in the last two reactors, DO setpoint tapering was tested (Table 3). It was found that using DO setpoints of 0.5, 0.3, and 0.2 mg/L in the three mainstream MBBRs reduces the effluent TN to 5.69 mgN/L and still maintains an effluent NH_x-N below 1 mg N/L (Table 3).

In order to study the dynamic behaviour of the system, diurnal flow and pollutant concentration patterns were created using the influent generation tool developed by the HSG group (Langergraber *et al.* 2008, 2009). Three scenarios were studied as shown in Table 4.

In each scenario, the simulation was initialised at steady-state conditions, and a dynamic simulation with a diurnal influent was run until it reached a cyclic steady-state. From there, a three-day dynamic simulation was conducted. In each scenario the biofilm thickness was allowed to reach its own equilibrium thickness and was found to be 0.11 mm in the mainstream PN/A reactors and 0.37 mm in the sidestream PN/A reactor.

Figure 2 shows the results for Scenario 1 with constant DO setpoints of 0.5, 0.3, and 0.2 mg/L, respectively.

Table 4 | Control strategies studied using dynamic simulations with a diurnal influent

Scenario	DO control	Type of aeration	NH_x-N control
1	DO setpoints of 0.5, 0.3, and 0.2 mg/L	Continuous	Not used
2	DO setpoint of 2 mg/L during aerated part of cycle	Intermittent cycle; 0.5 hr aeration followed by 0.5 hr of no aeration	Not used
3	DO setpoints provided by NH_x-N controller	Continuous	• NHx-N setpoints of 15, 4 and 1 mgN/L • DO setpoint bounded between 0 and 3 mg/L

As shown, the NH_x-N concentration averages around 3.8 mgN/L with peaks of almost 10 mgN/L and the nitrate concentration averages around 3.5 mgN/L with peaks of 4.4 mgN/L. Clearly, the constant DO control strategy would require further effluent polishing to meet typical NH_x-N limits. Using a DO setpoint of 1 mg/L in the first mainstream PN/A reactor reduces the NH_x-N peaks to below 1 mgN/L but increases the nitrate concentration to 10 mgN/L.

In Scenario 2, intermittent aeration is used with a cycle consisting of 30 min of aeration with a DO setpoint of 2 mg/L followed by 30 min without aeration. This cycle was determined by running simulations over a range of aeration phase lengths and comparing the effluent nitrogen concentrations to determine the most suitable aeration phase length (Table S1 in the Supplementary Material). Using this cycle, the effluent NH_x-N peaks at 4 mgN/L and the nitrate peaks are 14 mgN/L (Figure 3). This is an improvement as compared to DO control with constant DO setpoints but would require optimisation of the aeration cycle if the TN needs to be less than 10 mgN/L or a higher-level ammonia controller that determines the length of the aeration phase.

In Scenario 3, ABAC is implemented with a separate ammonia controller providing a DO setpoint to each mainstream PN/A DO controller. With NH_x-N setpoints of 15, 4, and 1 mgN/L, respectively, the effluent NH_x-N is kept around 1 mgN/L and the nitrate peaks are 2.8 mgN/L (Figure 4). The NH_x-N setpoints were selected based on

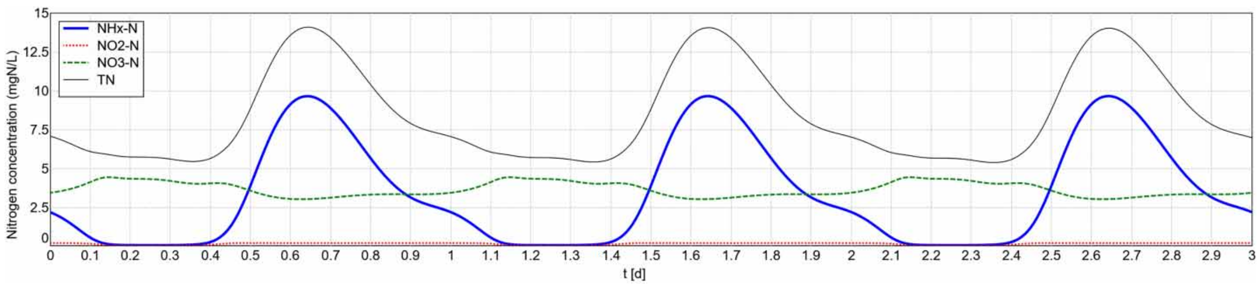

Figure 2 | Scenario 1 effluent nitrogen species concentrations with constant DO setpoints of 0.5, 0.3, and 0.2 mg/L in the 3 mainstream PN/A reactors at 20 °C.

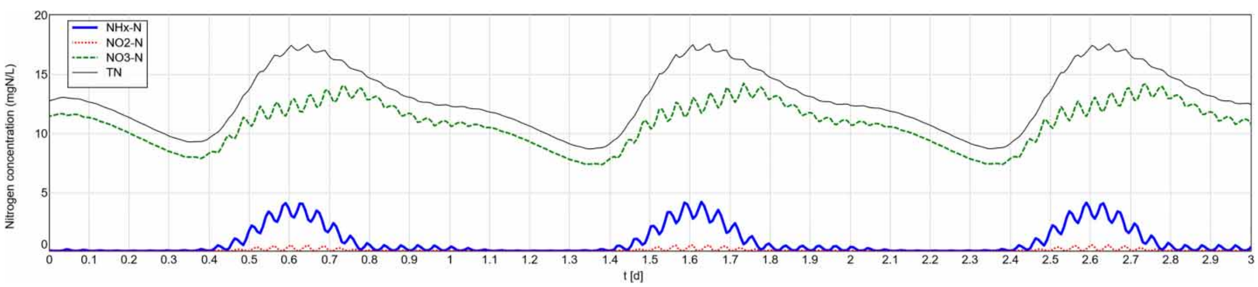

Figure 3 | Scenario 2 effluent nitrogen species concentrations with intermittent aeration in the mainstream PN/A reactors, with a cycle of 0.5 h of aeration followed by 0.5 h of no aeration and a DO setpoint of 2 mg/L during the aerated phase of the cycle at 20 °C.

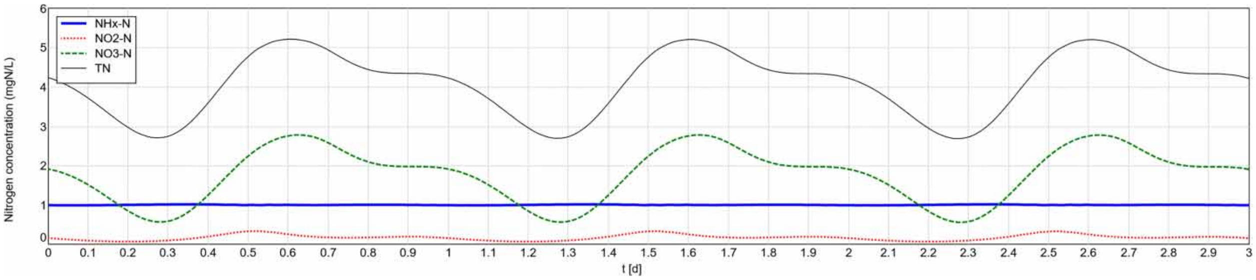

Figure 4 | Scenario 3 effluent nitrogen species concentrations with ABAC and ammonia setpoints of 15, 4, and 1 mgN/L in the three mainstream PN/A reactors respectively at 20 °C.

the NHx-N concentrations in the reactors at steady-state in Scenario 1. The ideal setpoints will depend on the temperature and nitrogen loading. Three separate ABAC controllers were used, as a single controller in any one of the reactors did not provide the same level of nitrogen removal (even when the DO concentrations in the other two reactors were proportional to the DO in the controlled reactor). To demonstrate, Figure 5 is provided to show the effluent nitrogen concentrations when a single ammonia controller is used in the second MBBR with an NHx-N setpoint of 4 mgN/L. The DO setpoints in the first and third MBBRs are calculated by multiplying the DO setpoint in the second MBBR by 1.7 and 0.7, respectively (i.e. the ratios between DO setpoints used in Scenario 1). As shown, using three controllers gives better performance than one ammonia controller but using one controller has better performance than using constant DO setpoints (Figure 2).

A comparison of the microorganism concentrations in the biofilm for the three scenarios is given in the Supplementary Material (Figures S7 to S15). It is found that Scenario 3 with ABAC has the largest AOB population, the lowest NOB population, and the highest anammox population.

The ammonia controller is able to tightly maintain the NH_x-N at the setpoints (Figure 6) in a biofilm system because of the high SRT and the diffusion-controlled reaction rates, which are very sensitive to changes in bulk liquid DO concentrations. In addition, the ABAC and DO controllers are not limited by constraints such as minimum airflow. It is assumed that mechanical mixers are used for carrier suspension so that a minimum airflow for mixing is not required. In practice, process disturbances, measurement noise, sensor and actuator response times, and process response lags would degrade the performance of ABAC so that there would be more variability in the effluent NHx-N concentration. Because the goal of this study is to provide a proof of concept of the ABAC control strategy, an ideal model is used as it is easier to explain and to compare the results between scenarios.

As shown in Figure 7, the ammonia controller in the first MBBR increases the DO setpoint to near 1 mg/L during peak loading, which improves system performance considerably. This suggests that ABAC is the better alternative to intermittent aeration for PN/A aeration control and can help eliminate the need for further effluent polishing after mainstream PN/A reactors. ABAC has the advantage of continuous operation. Intermittent aeration is typically accomplished by cycling air between parallel aeration tanks to avoid turning blowers on and off numerous times per day and this limits the flexibility in adjusting the length of the aerated and unaerated phases.

To ensure that ABAC can handle different influent TKN loads and wastewater temperatures in the mainstream PN/A

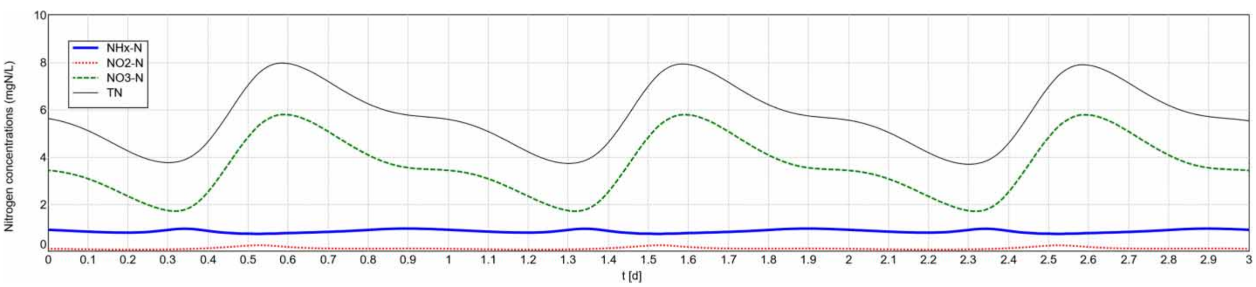

Figure 5 | Effluent nitrogen species concentrations with ABAC using a single ammonia controller in the second MBBR with an ammonia setpoint of 4 mgN/L and the DO setpoints in the first and third MBBRs calculated as ratios of the DO setpoint in the second MBBR at 20 °C.

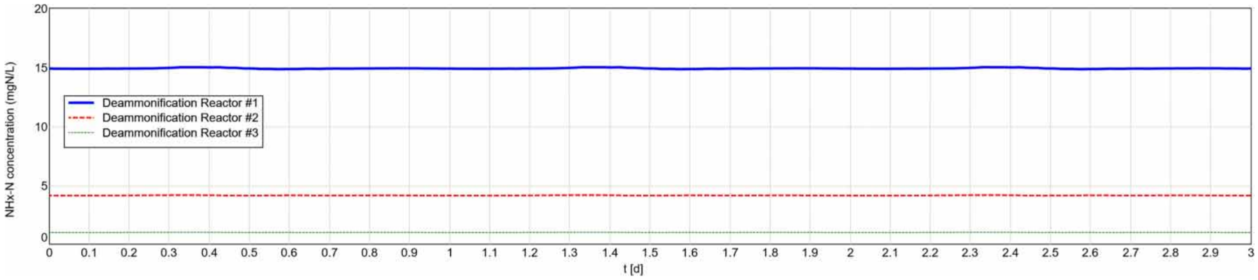

Figure 6 | Scenario 3 controlled NH_x-N concentrations with ABAC and ammonia setpoints of 15, 5.4, and 1.3 mgN/L in the 3 mainstream PN/A reactors respectively at 20 °C.

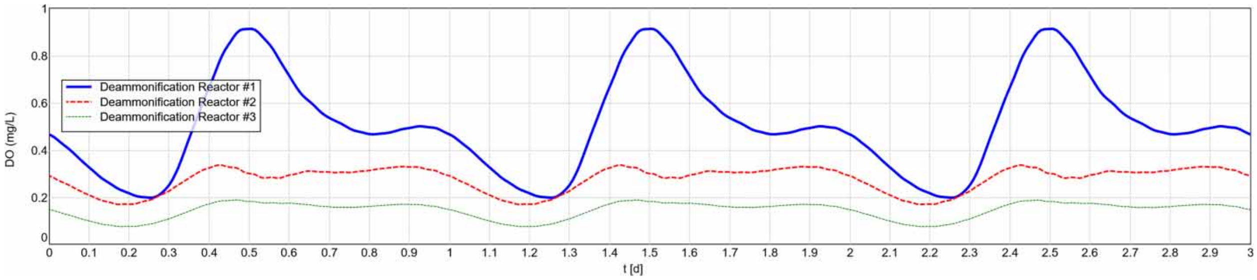

Figure 7 | Scenario 3 mainstream PN/A reactor DO concentrations with ABAC at 20 °C.

Table 5 | Comparison of aeration energy consumption and nitrogen removal performance in the PN/A aeration control scenarios studied

	Energy consumption (kWh/d)		Effluent NH_x-N (mgN/L)		Effluent TN (mgN/L)	
Scenario	**Average**	**Peak**	**Average**	**Peak**	**Average**	**Peak**
1: DO control	843	877	3.8	9.6	8.8	14
2: Intermittent aeration	1,120	2,960	0.93	4.1	12.3	17.5
3: ABAC	843	1,140	1.0	1.0	4.2	5.2

reactors, simulations were conducted at two additional temperatures (15 °C and 10 °C) and two additional influent TKN loads (0.62 gN/d/m^2 and 0.75 gN/d/m^2). See Figures S16 to S19 in the Supplementary Material for plots of the simulation results. It is found that ABAC can handle higher influent loads than 0.52 gN/d/m^2 and lower temperatures than 20 °C, but the effluent TN will be higher than 10 mgN/L. Lowering the effluent TN would require additional reactor volume and carrier media. This highlights that there is a loading limit for the reactors and that it will be difficult to meet stringent TN limits at mainstream temperatures below 20 °C at an influent TKN loading of 0.52 gN/d/m^2 or greater.

The aeration energy consumption and effluent NH_x-N and TN are shown in Table 5 for each of the scenarios detailed in Table 4. Scenario 1 with constant setpoint DO control has the lowest average and peak energy consumption but has the poorest effluent quality. Scenario 2 with intermittent aeration has the highest peak energy consumption but has improved effluent quality as compared to Scenario 1. Scenario 3 with ABAC has the same average energy consumption as Scenario 1 while providing the highest level of NH_x-N and TN removal. In addition, Scenario 3 has over 20% lower energy consumption on average than Scenario 2 with intermittent aeration. Scenario 3 with ABAC provides the best compromise between removing nitrogen and minimising energy consumption. Ammonia-based aeration control does not reduce the energy consumption as compared to DO control in Scenario 1 because low DO setpoints are already being used. In this application of ABAC, it is being used to improve treatment performance by increasing DO concentrations, if required.

CONCLUSIONS

This study has demonstrated that mainstream PN/A biofilm reactors operated using DO controllers with constant setpoints may not meet typical effluent NH_x-N and TN limits. Intermittent aeration improves nitrogen removal but requires optimisation of the aeration cycle, which is often limited by the need to cycle between parallel aeration tanks to avoid turning blowers on and off during each cycle. ABAC provides nitrogen removal through PN/A that is comparable or better than with intermittent aeration and has the advantage of continuous operation and much lower energy consumption. ABAC has the same average energy consumption as with DO control with constant setpoints but with improved PN/A performance. This study suggests that ABAC is a very promising control strategy for mainstream PN/A systems. Tapering of the NHx-N setpoints from one MBBR to the next was helpful in maximising PN/A activity. ABAC effectively controls NOB washout and has a high control authority because of the long SRT and diffusion-controlled reaction rates. One aspect that requires further study is the selection of the NH_x-N setpoints. This was done manually in this study but could be performed automatically using a supervisory controller as shown by Schraa *et al.* (2019) in the context of optimal SRT control.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at https://dx.doi.org/10.2166/wst.2020.174.

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