Would a two-stage N-removal be a suitable technology to implement at full scale the use of anammox for sewage treatment?

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ABSTRACT

Sewage treatment with anammox could be implemented through a two-step reactor system, where the first reactor would be devoted to partial nitritation. A process design was sketched including control loops. The control strategy regulates the flow-rate of the rich ammonium sidestream produced after dewatering the digested sludge, to keep the ammonium concentration at a set point in the partial nitritation reactor by DO sing the Side Stream (DOSIS). A second control loop manages the ammonium concentration set point based on the measurement of the total nitrogen in the partial nitritation reactor. A mathematical model was developed to assess the amount of sidestream required. Even in the case of a strong diurnal variability, simulations show how the control strategy is correctly performing, demonstrating the potential of the proposed technology.

Key words | diurnal variability, dosing sidestream, mainstream, nitrite-oxidizing bacteria (NOB) repression, partial nitritation, reject water

INTRODUCTION

Stable autotrophic nitrogen removal in mainstream conditions is important for the achievement of energy efficient wastewater treatment plants (WWTPs) (Kartal et al. 2010). Two-stage N-removal has been reported in the literature as a possible configuration to face the challenges of such a treatment (Ma et al. 2011; Hendrickx et al. 2012; Torà et al. 2013). Nitrite-oxidizing bacteria (NOB) repression in a two-stage autotrophic configuration would be required in the first stage, i.e., the partial nitritation reactor. NOB repression in biofilm reactors performing partial nitritation of sidestream has been reported as robust (Bartrolí et al. 2010; Torà et al. 2013). The success of such a treatment relies on the use of a control strategy to maintain an adequate ratio between oxygen and ammonium concentrations in the reactor bulk liquid to repress NOB activity in the biofilm (automatic control for partial nitrification to nitrite in biofilm reactors, ANFIBIO) (Bartrolí et al. 2010; Jemaat et al. 2013). A buffer tank receiving the discharge of the centrifuges dewatering the sludge after anaerobic digestion (i.e., sidestream) was used to regulate the flow fed to the partial nitritation reactor (Bartrolí et al. 2010; Torà et al. 2013). NOB repression in the long term has been also proven at laboratory scale with this type of reactor at low temperatures (12.5 °C) treating low strength wastewater (70 gN-NH₄⁺/m³) (Isanta et al. 2015). In addition, an enriched anammox reactor demonstrated the feasibility to treat sewage at low temperatures in a long-term operation (Lotti et al. 2014). They used a granular sludge fluidized bed laboratory-scale reactor continuously fed with real effluent from the A-stage (WWTP, Dokhaven, Rotterdam, The Netherlands). Nitrite was dosed continuously to mimic the oxidation of ammonium to nitrite by ammonia-oxidizing bacteria (AOB), and to allow for anammox activity only. The system was operated for more than ten months at temperatures between 20 and 10 °C. A volumetric N-removal rate higher than 0.4 g N L⁻¹ day⁻¹ was reported at 10 °C (Lotti et al. 2014).

In a two-stage approach for autotrophic N-removal in mainstream conditions, the residual ammonium concentration in the partial nitritation reactor was found to be essential for successful NOB repression in a laboratory-scale reactor (Isanta et al. 2015). The residual ammonium concentration is thought to avoid kinetic limitation of the AOB growth rate, enhancing the possibility of outcompeting NOB (Isanta et al. 2015; Supplementary Table S11, available online at http://www.iwaponline.com/wst/072/281.pdf). If a two-stage approach was implemented in a full-scale installation, the ammonium concentration in the partial nitritation reactor...
would be difficult to control due to the daily fluctuations of the flow rate and, to a minor extent, due to changes in the inflow ammonium concentration. In addition, the variations on both inflow rate and ammonium concentration will be impacted by seasonality (rainy or dry periods). The variations that are known to happen in real installations are standardized by an International Water Association (IWA) task group (Benchmark Simulation Model No. 1 (BSM1)) (Alex et al. 2008). Those standardized variations will be taken into account in the present contribution to assess how a novel control strategy could be used to stably control the residual ammonium concentration in the partial nitritation reactor, with the aim of assuring efficient NOB repression. Moreover, the stability of the ammonium concentration is also important to meet the adequate ammonium/nitrite ratio required to feed the anammox reactor.

Here, we would like to present a procedure to implement the two-stage autotrophic N-removal for sewage treatment, demonstrating its feasibility through a model-based study. The proposed process is presented in Figure 1. A control strategy will regulate the flow-rate of the rich ammonium sidestream produced in the anaerobic digester, to keep the ammonium concentration at a set point in the partial nitritation reactor by DOSing the Side Stream (DOSIS control strategy). A second control loop will manage the ammonium concentration set point based on the measurement of the total nitrogen in the partial nitritation reactor. The main goals of this contribution are: (i) to sketch a procedure to implement a two-stage partial nitritation/anammox N-removal configuration in the mainstream, which will include a sketch of the process diagram and adequate control strategies; and (ii) to assess the performance of the N-removal through modelling, with the main aim to test whether the produced reject water is enough to maintain the desired residual ammonium concentration in the partial nitritation reactor. The residual ammonium concentration in the partial nitration reactor is crucial to assure both efficient NOB repression and a suitable ammonium/nitrite concentration ratio for the anammox reactor.

**MATERIALS AND METHODS**

**Biofilm model, kinetics and parameters**

A one-dimensional biofilm model previously developed (Jemaat et al. 2013) was used to simulate the partial nitritation reactor performance based on Wanner & Reichert (1998) and implemented in the software package AQUASIM (Reichert 1998), v.2.1d. The biomass species described as particulate compounds in the biofilm matrix were four in number in the partial nitritation reactor: AOB, NOB, heterotrophic bacteria and inert biomass. The biofilm area was described as a function of the granule radius, to correctly simulate the biofilm geometry (for further details see Jemaat et al. (2013)). The total biofilm area was defined as a function of granule size and number of granules. A detachment rate was used to keep a constant biofilm thickness in steady state at a predefined value. The attachment of biomass onto the biofilm, or external mass transfer resistance, has been neglected to simplify the model. For the partial nitritation reactor, the microbial kinetics and the stoichiometry used are as in Jemaat et al. (2013) and Isanta et al. (2015), and they are detailed in the supplementary information (section Mathematical modelling, Supplementary Tables S12–S15, available online at http://www.iwaponline.com/wst/072/281.pdf). See also the Mathematical modelling section in the supplementary information for other parameters related to the biofilm. The initial biomass fractions of AOB and NOB in the biofilm were assumed to be 67% and 23%, respectively. The porosity of the biofilm was fixed as 80% and kept constant during all the simulations. For the anammox reactor, the same type of biofilm model was used, the microbial kinetics and the stoichiometry used were as in Volcke et al. (2010), as detailed in the supplementary information (Supplementary Tables S12–S15). The biofilm porosity was also fixed at 80%. Only two particulate compounds were used: anammox and inert material. Initially, no inert material was assumed to be present, i.e., the initial biomass fraction is 100% anammox.
The ability of the model to describe the partial nitration process, and in particular NOB repression, has been proven in previous publications (Jemaat et al. 2013, Isanta et al. 2015). Moreover, the model correctly described under dynamic conditions a period of operation of more than 200 days, with stable partial nitration of a low strength wastewater (70 gN-NH4+/m3) at temperatures decreasing from 30 to 12.5 °C, with satisfactory results (Isanta et al. 2015).

**Modeling strategy and scenarios**

Diurnal variations and seasonality may be challenging for the control strategy. For each particular WWTP under consideration, the magnitude of the variations in the total ammonia nitrogen (TAN) concentration will be mainly affected by the slopes and length of the complete sewer system, linked to the orography of the surrounding area where the wastewater is collected. Therefore, to estimate what amount of sidestream is required to keep the TAN concentration in the partial nitritation reactor at a desired set point through the DOSIS control strategy, two different assessments were carried out: (i) a first indication of the sidestream requirements was determined by keeping constant both the flow-rate and the TAN concentration in the mainstream (i.e., without considering any variability, i.e., steady-state operation); and (ii) a second type of assessment was carried out considering a strong diurnal variability in terms of flow-rate and TAN concentration of the mainstream (influent). A higher amount of sidestream will be required to efficiently control the TAN concentration in the partial nitritation reactor when diurnal variability is taken into consideration. Thus, the first assessment will serve as a baseline, and real needs will be bracketed between these values determined for steady flow-rate and steady TAN concentration of the mainstream, and those obtained for a WWTP presenting strong diurnal variability in both the mainstream flow-rate and TAN concentration.

The diurnal variability pattern used by Alex et al. (2008) for dry weather, and known as BSM1, was used (see Figure 3). This diurnal variability in terms of TAN concentration and flow-rate is used as an example; seasonality or storm events could also be similarly handled by the control strategy. To assess the sidestream requirements under diurnal variability, two different scenarios have been considered.

**Scenario A.** The sidestream has been assumed to be produced with a flow-rate of 2% of the mainstream, meaning ca. 35% of the total nitrogen. This range is likely to occur when a very-high-load activated sludge + settler system to remove chemical oxygen demand (COD) and biogas production is used as in Figure 1.

**Scenario B.** Existing WWTPs conventionally produce a lower amount of N in the sidestream. A potential application of the technology would be the retrofitting of two-stage biological systems (A/B plants). Therefore, in this scenario, a sidestream with a flow-rate of 1% of the mainstream has been considered, meaning 22% of the total nitrogen.

A schematic drawing of the units described by the model for this section is presented in Figure 1. Note how unit 1 (very-high-load activated sludge + settler) is only used to estimate the dumping of the inflow TAN concentration under diurnal variability. To take into account this buffering capacity, a volume of 2,500 m3 was considered. The average flow-rate used in the simulations is ca. 18,500 m3 d−1, with an average biodegradable COD in the influent of 500 g m−3 (ca. 92,000 p.e.). The sidestream has been assumed to have a constant TAN concentration of 1,000 g N m−3. The temperature used for the simulations in all reactors was set to 15 °C and a constant pH of 7.5 was assumed. Further details regarding reactor capacities, and operating conditions can be found in Table 1. The estimation of the sidestream requirements was performed by integrating in time the dynamic flow rate of the sidestream predicted by the model, using as a time basis 1 week.

**RESULTS AND DISCUSSION**

**The novel control strategy applied for the partial nitritation reactor**

Residual ammonium concentration is of key importance for NOB repression in this type of system (Bartrolí et al. 2010; Isanta et al. 2015), but an active control of ammonium

**Table 1** Reactor capacities and operating conditions used for the assessment of the sidestream requirements. The COD removal reactor is only used to dump the ammonium concentration variability, i.e., only a well-mixed tank is used in the simulations, without considering any biological processes

<table>
<thead>
<tr>
<th>Reactor</th>
<th>COD removal</th>
<th>Partial nitritation</th>
<th>Anammmox</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor volume (m3)</td>
<td>2,500</td>
<td>450</td>
<td>2,000</td>
</tr>
<tr>
<td>Biomass concentration (gVSS m−3)</td>
<td>–</td>
<td>4,200</td>
<td>5,000</td>
</tr>
<tr>
<td>Biofilm density (gVSS m−3)</td>
<td>–</td>
<td>40,000</td>
<td>40,000</td>
</tr>
<tr>
<td>Granule size (mm)</td>
<td>–</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>–</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>pH</td>
<td>–</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>DO (g O2 m−3)</td>
<td>–</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

VSS: volatile suspended solids; DO: dissolved oxygen.
concentration in a full-scale installation can be challenging, mainly due to the oscillations in inflow rate and ammonium concentration (daily oscillations, rainy or dry periods, etc.) of the mainstream waterline in a WWTP. The proposed strategy (Figure 1) uses the reject water as a way of dumping those variations, therefore trying to achieve a stable partial nitritation process. The control strategy has two closed loops (as detailed in a conventional block diagram in Figure 2): (i) one to maintain the total ammonia nitrogen (TAN = N-NH\(_4\) + N-NH\(_3\)) concentration in the bulk liquid of the nitritation reactor and (ii) a second one to control the dissolved oxygen (DO) concentration in the bulk liquid.

Note how a buffer tank would be filled with the sidestream produced by the set of centrifuges dewatering the sludge produced in the anaerobic digester (Figure 1). The reject water stored in the buffer tank will be pumped into the partial nitritation reactor on demand, to fulfill the TAN concentration set point, at a flow rate (\(Q_{side}\)) as indicated in Equation (2). ADOSIS control strategy would enable keeping the TAN concentration set point in the partial nitritation reactor to conveniently feed the subsequent anammox reactor (unit 4 in Figure 1). The TAN concentration set point depends on the particular inflow TAN concentration. Therefore, we propose that the set point is calculated in the so-called [TAN]\(_{SP}\) station, by using the online measurement of the NO\(_X^-\) concentration. This is expected to be roughly equivalent to the total nitrite nitrogen (TNN) concentration, since the control strategy will suppress nitrate production by NOB.
The control strategy proposed was also described by the model. The DO control loop was conventionally described in the model as in Jemaat et al. (2013). The TAN control loop is composed of two different parts (see Figure 2): (i) a first basic control loop that keeps a TAN concentration set point by manipulating the sidestream flow rate (stored in the buffer tank) to be dosed into the nitritation reactor; and (ii) the management of the ammonium set point, which is based on online measurements (the NOX analyser). For the TAN control loop, an ad hoc expression was developed, because the control loop has the sidestream flow-rate \( Q_{side} \) as a manipulated variable:

\[
Q_{side} = Q_{side,0} \cdot \left(1 + \frac{[TAN]_{SP} - [TAN]}{[TAN]_{SP}} \cdot a\right) \tag{1}
\]

where \( Q_{side,0} \) is known as the bias of the control action, i.e., the default value of the flow-rate. The controller will always act either by increasing or decreasing \( Q_{side} \) around \( Q_{side,0} \); \([TAN]_{SP}\) is the total TAN concentration in the bulk liquid phase; \([TAN]_{SP}\) is the TAN concentration set point, \(a\) the proportional gain of the controller.

The TAN concentration set point will be varied on demand depending on the concentration of total nitrogen in the reactor. A TNN/TAN concentration ratio between 1.1–1.3 is required to feed the subsequent anammox reactor; TNN being the total nitrite nitrogen (TNN = N-NO\(_2\) + N-HNO\(_2\)). An additional measurement of NO\(_X\) was used to estimate the total nitrogen and to calculate the adequate TAN concentration set point in the so-called \([TAN]_{SP}\) station (see Figure 2).

The \([TAN]_{SP}\) station calculates online the required TAN concentration depending on the measured NO\(_X\) concentration in the reactor bulk liquid phase:

\[
[TAN]_{SP} = \frac{[NO_X^-] + [TAN]}{b + 1} \tag{2}
\]

where \(b\) is the desired ratio between ammonium and nitrite concentration to feed the subsequent anammox reactor, i.e., the TNN/TAN concentration ratio in Figure 3. Since nitrate production will be avoided when using the control strategy, the measured NO\(_X\) concentration will basically be the TNN concentration.

**Model-based assessment of the sidestream requirements**

Sidestream requirements for steady-state operation (i.e., no diurnal variability) have been estimated with the model as presented in Table 2. Effluent from the anammox reactor (unit 4 in Figure 1) containing only 6 mg N L\(^{-1}\) was obtained just by using 30 m\(^3\) day\(^{-1}\) of sidestream. Note how, when no variability is imposed, and therefore both the flow rate and the ammonium concentrations of the raw wastewater are constant (i.e., steady-state case in Table 2), the amount of reject water pumped into the partial nitritation reactor is low (30 m\(^3\) day\(^{-1}\); see Table 2). However when a diurnal variability is imposed (Scenarios A and B), the flow rate of reject water increased to 374 and 196 m\(^3\) day\(^{-1}\), for Scenarios A and B, respectively. The variations in flow rate and ammonium concentration of the raw wastewater (see Figure 3) create disturbances that the control system copes with by adding reject water to the partial nitritation reactor at a higher rate.

Sidestream requirements were much more demanding when a typical diurnal variability of the influent was used. The flow-rate of sidestream required for control purposes was found to increase ca. an order of magnitude (Table 2). For Scenario A, the impact of diurnal variability on the dynamics of the effluent as predicted by the model is shown in Figure 3. The results of the simulations indicate that: (i) the partial nitritation reactor is able to maintain a suitable TNN/TAN ratio for the subsequent anammox reactor in spite of the diurnal variations (Figure 4); and (ii) the total N concentration in the effluent of the anammox reactor is always below the maximum concentration allowed by European legislation (Figure 4). Note how, when the mainstream flow-rate is low, the required flow-rate of the sidestream is very high (Figure 3(a)). The detailed dynamics response for Scenario B, in case of retrofitting existing two-stage biological systems (A/B plants), was very similar to that already discussed for Scenario A (results

**Table 2** Sidestream requirements for steady state and under diurnal variability as predicted by the model

<table>
<thead>
<tr>
<th></th>
<th>Flow-rate sidestream (m(^3) day(^{-1}); %(^a))</th>
<th>Nitrogen as sidestream (%)</th>
<th>Total N in effluent of unit 4 (mg N L(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady state</td>
<td>30 (0.2%)</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Diurnal variability, Scenario A</td>
<td>374 (2%)</td>
<td>35</td>
<td>6(^b)</td>
</tr>
<tr>
<td>Diurnal variability, Scenario B</td>
<td>196 (1%)</td>
<td>22</td>
<td>7(^b)</td>
</tr>
</tbody>
</table>

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\(^a\)As percent of mainstream flow rate.

\(^b\)Averaged value.
not shown). If not enough sidestream would be available, the DO concentration in the partial nitritation reactor (unit 3 in Figure 1) could be manipulated to eventually decrease the conversion of the reactor during low nitrogen-load events. A general approach by which the low nitrogen loading rate (due to diurnal variability) is fully compensated by low DO set points is not advisable, since it would trigger higher N₂O emissions (Pijuan et al. 2014).

**Countermeasures**

In case nitrate is accumulating in the partial nitritation reactor, a higher residual ammonium concentration could be temporarily used by increasing the sidestream dosage rate. Alternatively, a lower DO level could be imposed, thus helping NOB repression. Both countermeasures decrease the DO/TAN concentrations ratio in the bulk liquid, which is known to enhance the stability of nitritation and NOB repression in this type of reactor (Bartrolí et al. 2010; Isanta et al. 2015).

**Suitability of a two-stage autotrophic N-removal system for mainstream treatment**

Operating a reactor to perform a single process is always a clear advantage from the engineering point of view, since process optimization is simpler and higher conversion rates are expected with the two-stage N-removal. The main drawback of the two-stage N-removal is, of course, that it requires higher investment costs because two reactors require more peripheral instrumentation and control elements than one.

The application of autotrophic N-removal in the mainstream implies that the suspended and colloidal material present in the sidestream (reject water) could arrive at the autotrophic stages (partial nitritation plus anammox or CANON/OLAND reactors). This could result in the development of heterotrophic bacteria in those reactors, which would compete with the autotrophic bacteria for oxygen or nitrite (Hendrickx et al. 2012). This problem would be minimized with the DOSIS system proposed in this study, because the buffer tank (Figure 1) will act as a settler for part of the suspended and colloidal material. Finally, the DOSIS system could be limited by the sidestream requirements in case of high demand, which could imply the failure of the control strategy of the partial nitritation reactor because the [TAN]_{SP} could be not maintained. This limitation could be solved by producing more reject water by feeding the anaerobic digester with external wastewater containing COD and N (see, for instance, Abma et al. 2010). In this case, an extra amount of sidestream would be produced, and the results would be equivalent to those presented for the first scenario (Scenario A).

**CONCLUSIONS**

The model-based study shows that the controlled dosage of the sidestream allows implementation of a two-stage N-removal system in the mainstream in spite of a strong diurnal variability of the inflow rate and ammonium concentration in a municipal WWTP.

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