Advanced Nitrogen Removal Configuration with MBR Application for Water Reuse

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ABSTRACT

Traditionally there have been two main motivations for utilizing membrane bioreactors (MBRs) in place of gravity settling tanks in municipal wastewater treatment plants. These are to achieve a small plant footprint, or to provide solids-free secondary effluent as a precursor for water reuse. A third reason for incorporating MBRs is emerging in the context of energy-efficient systems involving deammonification; namely, biomass retention. Anaerobic ammonia oxidizers (AAO) are particularly slow-growing organisms with low yield. MBRs offer a means for retaining the slow-growing biomass within the system. Deammonification harnesses the benefits of anaerobic ammonia oxidation to reduce aeration and carbon needs compared to traditional nitrification-denitrification. Initially application was for high-ammonia sidestream treatment at elevated temperatures, but now there is great interest in mainstream deammonification and/or a combination of nitrite shunt and deammonification.

The paper considers three energy-efficient schemes all with a typical municipal wastewater entering a high-rate activated sludge process (HR-ASP with SRT ~ 0.5 – 1 day). HR-ASP surplus activated sludge (with a high content of biodegradable particulate organics) is thickened and directed to anaerobic digestion. Digester centrate is treated in an IFAS-type deammonification or nitritation media reactor (SSMR). Excess sludge from this unit is directed to a mainstream IFAS-type deammonification media reactor (MSMR). Effluent from the HR-ASP settler passes to the MSMR. This stream contains appreciable soluble organics and ammonia. The MSMR output is polished in an aerated MBR.

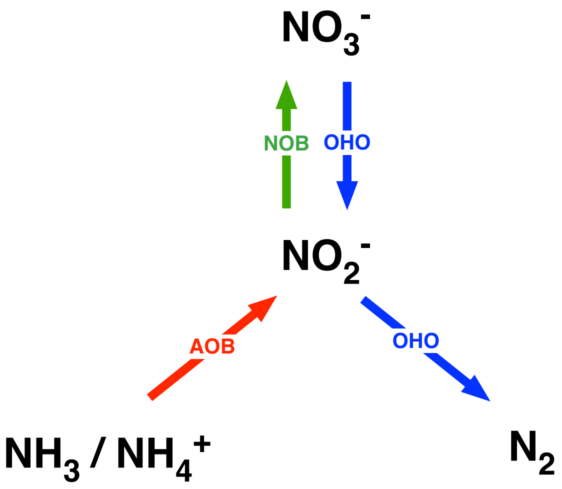
The proposed schemes offer several key benefits: (a) the systems are very compact; (b) process control for the deammonification reactors is very simple (maintaining DO setpoints and hydraulic control of SRTs); (c) heterotrophic denitrification using mainly soluble organics from the HR-ASP can contribute to N removal; (d) biogas generation is maximized; and (e) the low nitrogen content and the solids-free effluent is ideal for water reuse. A potential drawback of the systems without external carbon addition is that oxidized nitrogen is mainly in the form of nitrite rather than nitrate.

1. INTRODUCTION

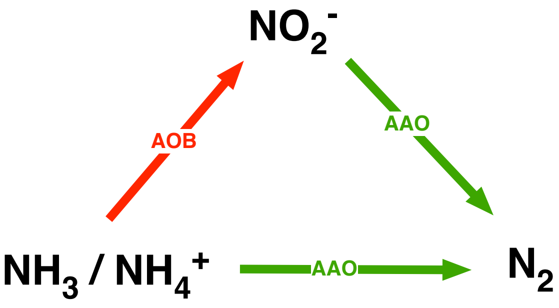
Municipal wastewater can be treated and reused for a variety of purposes such as recreation, groundwater recharge, agriculture, etc. Treatment for water reuse normally demands strict criteria on nutrient (nitrogen and phosphorus) concentrations and suspended solids in the final effluent [1]. If traditional biological nutrient removal processes are utilized to treat the municipal wastewater for water reuse to achieve low levels of nitrogen and phosphorus in the effluent, a long solid retention time (SRT) usually is required. Long SRTs for the suspended growth system imply big reaction tanks and large clarifiers at the wastewater treatment plants [often now referred to as Water Resource Recovery Facilities, WRRFs]. Also, operating costs of these WRRFs may be high due to high aeration requirements for full nitrification and the potential need for external carbon sources for denitrification.

Advanced nitrogen removal technologies are desirable to improve the sustainability and efficiency of WRRFs. Deammonification harnesses the benefits of anaerobic ammonia oxidation to reduce aeration and carbon needs as compared to traditional nitrification-denitrification and has aroused a lot of interest in this regard.

Figure 1 shows different pathways for nitrogen removal by traditional nitrification-denitrification (upper) and by deammonification (lower). In traditional nitrogen removal processes ammonia is oxidized first to nitrite by ammonia oxidizing bacteria (AOB) and the nitrite is further oxidized to nitrate by nitrite oxidizing bacteria (NOB). Nitrate is removed via denitrification by ordinary heterotrophic organisms (OHOs) under anoxic conditions; this requires carbon. Deammonification involves partial nitrification of ammonia (nitritation) to generate nitrite by AOB followed by nitrogen removal mediated by anaerobic ammonia oxidizers (AAOs) [2, 3]. Deammonification requires less aeration and no external carbon addition and therefore implies lower operational cost at WRRFs. Initially application of deammonification was for high-ammonia sidestream treatment at elevated temperatures, but now there is great interest in mainstream deammonification and/or a combination of nitrite shunt and deammonification.



Traditional N removal pathway: nitrification – denitrification



Deammonification pathway: nitritation – anaerobic ammonia oxidation

Figure 1: Traditional N Removal and Deammonification Pathways

There are three important factors to achieve successful deammonification at WRRFs. One of the factors is being able to generate a mixture of ammonia and nitrite in a ratio of 1:1.3, to maximize nitrogen removal mediated by AAOs. The 1:1.3 ratio for the ammonia and nitrite is from the stoichiometric relationship of anaerobic ammonia oxidation [3, 4] shown in Equation (1). This suggests that about 57% of the ammonia in the influent should be oxidized to nitrite.

$$1\ NH_4^+ + 1.32\ NO_2^- + 0.066\ HCO_3^- + 0.13\ H^+ \rightarrow$$

$$1.02\ N_2 + 0.26\ NO_3^- + 0.066\ CH_2O_{0.5}N_{0.15} + 2.03\ H_2O \qquad (1)$$

The second factor is to limit the process of nitrite oxidation to nitrate by NOB; that is, NOB should be repressed or preferably washed out from the system. NOB washout has been studied extensively in sidestream systems. The common strategy for NOB washout from high temperature (30-35°C) sidestream systems is based on control of SRT (1-2 days) and DO concentration (~ 0.5 mg/L) to maintain a situation favouring AOB over NOB. That is, where the $SRT_{AEROBIC}$ satisfies the relationship expressed as the inequality in Equation (2) [f = aerated mass fraction; μ = growth rate; b = decay rate]:

$$\frac{1}{f_A\mu_{NOB} - b_{NOB}} > SRT_{AEROBIC} > \frac{1}{f_A\mu_{AOB} - b_{AOB}} \qquad (2)$$

Many parameters impact the growth rate, μ: DO, temperature, substrate concentration, pH, and inhibition factors (e.g. FA and FNA). In mainstream reactors, NOB washout is difficult because the liquid temperature is relatively low and influent ammonia concentration is only 30 – 60 mgN/L for typical municipal wastewater.

The third factor for successful deammonification is to maintain a good population of AAOs in the system. AAOs are autotrophic organisms utilizing ammonia and nitrite under anaerobic conditions and have an exceptionally slow growth rate and low yield [5, 6]. Extended SRTs are needed to sustain AAOs in the system; this can be facilitated through forming granular sludge or using media for growth in biofilms.

The aims of NOB washout but retaining AAOs are conflicting objectives from the perspective of controlling SRT in the WRRF. One alternative is to achieve deammonification through a two-stage process. Different SRTs can be applied to a nitritation stage and a downstream anaerobic ammonia oxidation stage. However, two separate reactors and two clarifiers are needed and that likely will result in a large WRRF footprint. If deammonification is achieved in a single-stage process, realizing nitritation and anaerobic ammonia oxidation in the same reactor, the footprint of WRRFs can be reduced. However, it is challenging to enrich AOB and AAOs and repress NOB at the same time. Several commercial systems have been developed to facilitate single-stage deammonification. For example, in the DEMON system hydrocyclones are used to enrich the AAO population in sidestream systems, and that approach is also being applied in the mainstream study at Strass [8]; The ANITA Mox system involves AAO growth in biofilms, either in MBBRs or IFAS configurations [9].

Membrane bioreactors (MBRs) have been widely utilized in place of gravity settling tanks in WRRFs for two main reasons. These are to achieve a small plant footprint, or to provide solids-free secondary effluent as a precursor for water reuse. A third reason for incorporating MBRs is suggested in the context of energy-efficient systems involving deammonification; namely, biomass retention. MBRs offer a means for retaining the AAO biomass within the system. This can be implemented for either sidestream or mainstream reactors

The objective of this paper is to suggest an advanced energy-efficient WRRF configuration utilizing deammonification and MBR technology, offering several key benefits: (a) the system is very compact; (b) process control for the deammonification reactors is very simple (maintain a DO setpoint); (c) the system is energy efficient; (d) the low nitrogen content and the solids-free effluent is ideal for water reuse. Key factors affecting the nitrogen removal performance of the WRRFs are analysed through process modelling.

2. METHODOLOGY

Figure 2 below shows the basic scheme of the proposed deammonification-MBR system. The system includes a mainstream organic material removal process (but with limited oxidation of organics), a mainstream nitrogen removal process, sidestream anaerobic digestion, and a centrate treatment process. For the case study, the influent COD load is 12,000 kg/day (flow rate of 24,000 m3/day with an average COD concentration of 500 mg/L) and total nitrogen (TN) load is 960 kg N/day (40 mgN/L).

The high-rate activated sludge process (HR-ASP) is utilized mainly for COD capture rather than oxidation. This maximizes the organic load to anaerobic digester for methane generation. The HR-ASP includes an aerobic activated sludge reactor and a clarifier. The HR-ASP system is operated at very short SRT (~ 0.5 - 1 day), the active biomass concentration is low, and essentially only a portion of the readily biodegradable COD (rbCOD) is oxidized. The overflow of the HR-ASP system will contain mainly ammonia and a limited amount of carbon. This passes to a mainstream media reactor (MSMR) with biofilm growth on suspended media, but with an appreciable MLSS concentration. The MSMR output is polished in an aerated MBR. The coupled MSMR and MBR are operated for nitrogen removal in the mainstream mainly through deammonification.

The surplus waste sludge from the HR-ASP contains a high proportion of particulate biodegradable COD from the influent. This is thickened and then directed to the anaerobic digester for biogas generation with the intention of maximizing the energy recovery. The digester effluent contains a very high concentration of ammonia and very little biodegradable organic carbon. Digester centrate is treated in an IFAS-type sidestream media reactor (SSMR) with biofilm growth on the suspended media. The SSMR could be either a single-stage deammonification reactor to remove nitrogen in the sidestream or a nitritation reactor to convert the high concentration of ammonia to nitrite. Excess sludge from this unit is directed to the MSMR.

If the SSMR is operated as a single stage deammonification reactor, the DO should be controlled in the range of 0.5 to 1 mg/L. Such a DO concentration allows AOB to grow in the bulk mixed liquor and in the out-layer of the biofilm to convert the ammonia to the nitrite. Due to the limited oxygen transfer into the biofilm, the inner layers of the biofilm will be anaerobic, favouring the growth of AAOs to achieve anaerobic ammonia oxidation using nitrite as the electron acceptor. The excess sludge transferred from this unit to the MSMR acts to bioaugment with AOB and possibly AAOs to improve nitrogen removal in the mainstream. In this case, nitrogen is removed by deammonification in the sidestream and the mainstream.

If the SSMR is operated as a partially nitrifying media reactor, bulk mixed liquor SRT can be operated in the range of 3 – 8 days and at a DO of 1.5 – 3 mg/L. This operating mode for the SSMR will allow the growth of AOB but prevents significant growth of NOB (based on the concept of Eq. (2)). Sludge is wasted from the SSMR mainly for the purpose of bulk SRT control. The sidestream output containing a high concentration of nitrite is directed MSMR and mixed with the ammonia-abundant overflow from the HR-ASP to allow deammonification in the MSMR. In this mode, ammonia is oxidized to nitrite in the sidestream and the nitrogen is eventually removed in the mainstream by deammonification.

For the basic scheme of the deammonification-MBR configuration, the volumes of the HR-ASP reactor, HR-ASP clarifier, digester, MSMR, MBR Polish, SSMR and sidestream clarifier are 2500, 4000, 4800, 700, 600, 150, 48 m^3, respectively. The total WRRF tankage volume is 12,800 m^3 for treating the wastewater flow of 24,000 m3/day.

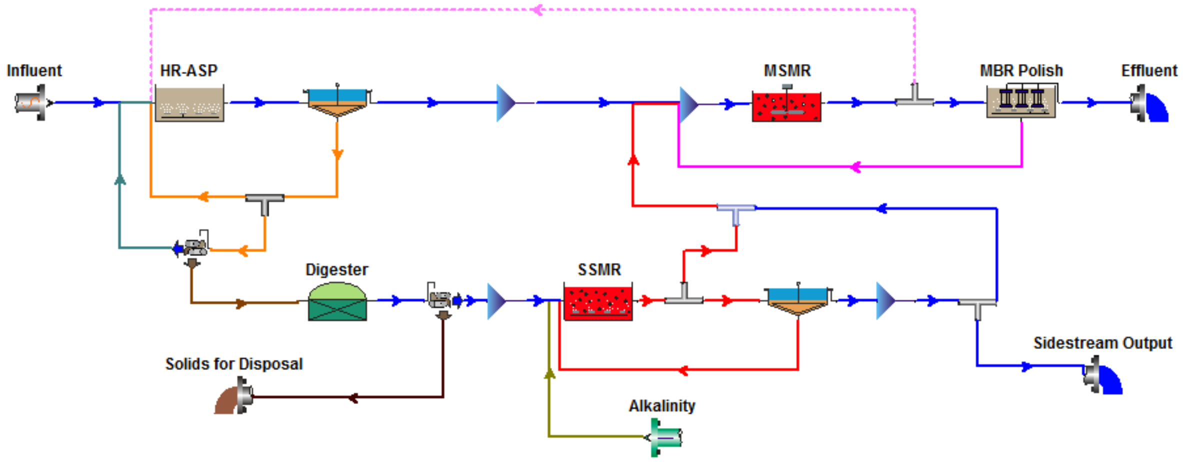


Figure 2 Scheme of Basic Deammonification-MBR System

3. RESULTS AND DISCUSSION

Process modelling was used to assess a range of factors impacting the performance of the systems evaluated in this limited study. The values of several operating parameters were fixed so that the scope did not become too broad. For example, mainstream, digester and sidestream temperatures were fixed at 20°C, 35°C and 32°C, respectively, and the anaerobic digester is operated at an SRT of 20 days. For modelling purposes the biofilms in the attached growth media bioreactors were assumed to consist of three layers.

The analysis was restricted to steady state simulations. This is important to mention because the systems presented below have small reactor volumes, and large diurnal flow and loading variations may impact system performance significantly.

3.1. COD Removal

The goals of operating at a short SRT in the HR-ASP system are (a) to require a small reactor volume and (b) to limit the amount of biological oxidation of organics (and exclude nitrification) so that energy demand for aeration is minimized. This allows ammonia to be carried by the HR-ASP overflow to the MSMR to be removed by the deammonification process (with a low aeration requirement). The sludge going from the HR-ASP to the anaerobic digester contains a high proportion of the influent biodegradable material to maximize biogas generation in the digester. The methane can be used in turn for energy recovery.

The effect of SRT on the portioning of influent COD in the HR-ASP system was evaluated through process modelling. Typical municipal wastewater composition in terms of soluble-particulate and biodegradable *versus* inert fractions were assumed. Table 1 shows the mass rates of COD that are (a) consumed through biological oxidation in the HR-ASP system, (b) that remain in the HR-ASP overflow, and (c) that are directed to the anaerobic digester when SRT was set at 0.5, 0.75, and 1 day, respectively.

Methane production per unit influent COD (volume at 20°C and 1 atm) and the fraction of influent COD that is transformed into methane are also shown in the Table 1. When the SRT of the HR-ASP is increased from 0.5 to 1 day, the COD removed (oxidized) in the activated sludge reactor more than doubles, and the COD carried in the overflow and sludge flow decrease. The volume of methane produced and the fraction of influent COD converted into methane decrease significantly with this increase in SRT. Shortening SRT in the HR-ASP has the double benefit of less COD oxidization in the activated sludge reactor and more methane production in anaerobic digestion; that is, less energy consumption and at the same time more energy recovery with a shorter SRT.

Table 1 Fate of COD Through HR-ASP System

SRT (Day)	COD oxidized in HR-ASP (kg/d)	COD in overflow (kg/d)	COD sent to digester (kg/d)	Methane production (m^3/kg influent COD)	% (COD CH4/ influent COD)
0.50	1,215	2,087	8,699	0.192	49.4%
0.75	2,050	1,439	8,512	0.176	45.3%
1.00	3,030	1,186	7,783	0.143	36.9%

The SRT of the HR-ASP system not only affects the COD removal but also impacts the split of nitrogen between the mainstream and sidestream. With an increase of the SRT from 0.5 to 1 day, the fraction of TN carried in the HR-ASP overflow decreases from 67% to 57% while the fraction of TN in the sludge stream increases. A greater fraction of TN to the sidestream probably is advantageous in terms of N removal because implementing deammonification in the sidestream is simpler than in the mainstream. However, this advantage from increasing SRT for the HR-ASP would be offset by the decreased potential for gas generation. In the scheme proposed in Fig. 2 surplus activated sludge from the second stage of the mainstream (MSMR-MBR) is recycled to the HR-ASP. This provides a small seed of AOB, and a small portion of the NH_3 from the influent may be be oxidized to NO_2 in the HR-ASP.

Table 2 Fate of TN Through HR-ASP System

SRT (Day)	HR-ASP overflow (% of TN)	Stream to digester (% of TN)
0.50	67%	32%
0.75	62%	38%
1.00	57%	41%

3.2. Nitrogen Removal

The nitrogen removal performance of different deammonification-MBR systems was evaluated. An SRT for the HR-ASP of 0.5 day was found to be optimal for nitrogen removal and biogas generation and therefore was applied in evaluating all the deammonification-MBR systems. Better N removal at shorter SRT in the HR-ASP may seem counterintuitive for the reason discussed above (i.e. less TN to the sidestream). However, this was established through simulation, and illustrates the strong interactions between different components of the system [and the benefits from whole plant simulation]. Steady state simulations were conducted to optimize the performance of the two variants of the basic deammonification-MBR system to achieve a TN removal exceeding 70%.

Deammonification in mainstream and sidestream

One variant of the deammonification-MBR scheme is to remove nitrogen in both the mainstream and the sidestream using a deammonification process in both. There are several important factors affecting the system performance; these include: SRT of the mainstream nitrogen removal reactors (MSMR and MBR Polish), SRT of the SSMR, bulk DO concentrations in both MSMR and SSMR, and the seeding flow from SSMR to MSMR. Certain factors are correlated to one another and should not be considered separately for optimizing the nitrogen removal system performance.

The SRT of the SSMR system should be long enough to retain a high population of AAOs in the SSMR for purposes of nitrogen removal in the sidestream. Therefore the waste flow rate should be small. However, the waste flow from the SSMR provides the seeding of AAOs to the MSMR. Simulation indicated that seeding flow to the MSMR is a crucial factor for obtaining the optimal balance for TN removal. The reason for that will be explained later following the discussion around the SRT of the mainstream nitrogen removal reactors.

The MSMR operates at conditions less favourable for AAOs as compared to the SSMR. Firstly, the mainstream temperature typically is lower than the sidestream. As noted, the MSMR was set at 20°C in the simulations. Also, the MSMR receives the HR-ASP effluent where the NH_3 concentration is much less than the NH_3 in the digester centrate. To grow and retain AAOs, a long SRT (> 10 days) is required for the mainstream nitrogen removal reactors. However, the fully-aerobic SRT of the mainstream nitrogen removal reactors should not be too long because long SRTs will promote the growth of NOB that convert NO_2 to NO_3 in the MBR. When a lot of nitrate is generated, the TN removal performance of the system will be reduced because (a) deammonification removes nitrogen through the reaction between NH_3 and NO_2, not NO_3; and (b) a large fraction of biodegradable organic material is sent to the digester for biogas production so there is little carbon remaining for denitrifying NO_3. If NO_3 is generated, it will appear in the effluent. An overall SRT between 10 – 15 days is necessary for the mainstream nitrogen removal reactors; this is based on bulk MLSS as well as biofilm solids. The biofilm solids account for approximately 40% of the solids in both reactors. The SRT portion of the MSMR is between 6 – 9 days. To ensure good deammonification performance in the MSMR under the unfavourable conditions for AAOs and at the SRT of 6 – 9 days, the seeding flow from the SSMR is important. However, as discussed earlier, in the SSMR a longer SRT is favourable (i.e. less wastage and seeding flow). Therefore, an optimal seeding flow rate should be determined for good deammonification performance in both the sidestream and the mainstream.

Steady state simulations were conducted with adjustment of different recycle flows to achieve the minimum TN in the effluent (sum of the TN in the permeate of the MBR and in the sidestream output). This is quite complex because so many different streams can be adjusted with impacts on SRT in different parts of the plant, and different interactive effects. The important streams to consider are the MSMR waste directed to the HR-ASP, MBR recycle to the MSMR, the seeding flow from SSMR to MSMR, and the sidestream clarifier underflow recycle. The optimal flow set-ups were identified and the corresponding flow rate of each recycle stream is labelled in Figure 3. It was also found that the separate discharges of MBR permeate and sidestream output (i.e. the sidestream output was not recycled back to the mainstream in this case) resulted in minimum TN in the combined effluent.

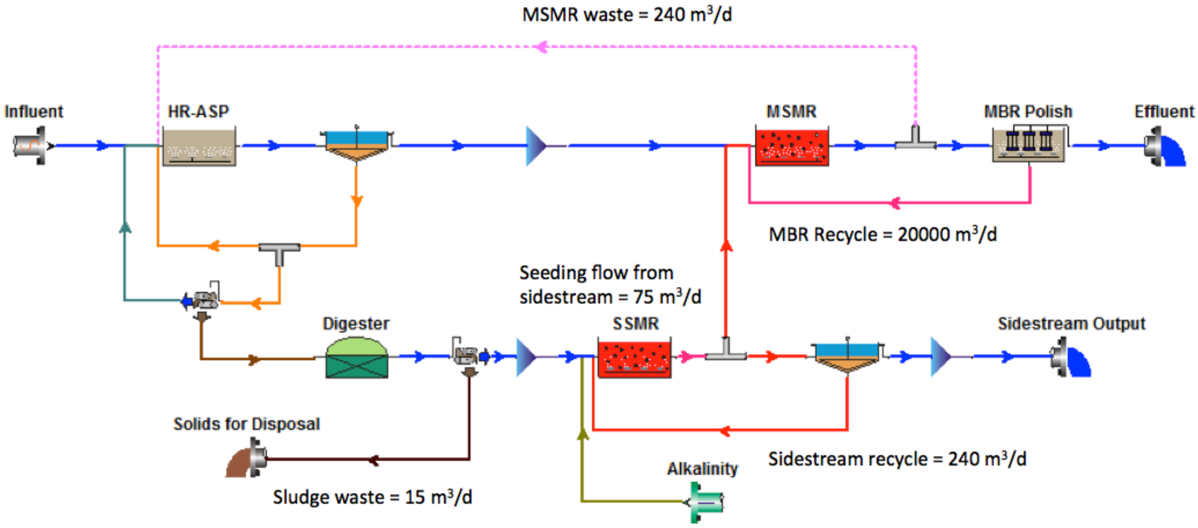


Figure 3 Recycle Flow Rates in the Mainstream and Sidestream Deammonification System

In this mainstream and sidestream deammonification system, the SSMR and MSMR are operated as single-stage deammonification reactors. To facilitate deammonification, air is provided for nitritation but the DO concentrations are controlled at low levels to encourage the growth of AAOs in the inner layers of the biofilms.

In the SSMR the DO is controlled at 0.7 mg/L and it is operated at an SRT of 7.5 days (biomass in the biofilm is included in the SRT calculation). The digester centrate that flows to the SSMR contains 846 mg/L of TN including 816 mgN/L of NH_3 and a small amount of soluble organic nitrogen. The TN of the treated centrate is 67 mgN/L including 8 mgN/L of NH_3, 56 mgN/L of NO_3 and about 1 mgN/L of NO_2. About 92% of the nitrogen in the sidestream is removed. Such a high nitrogen removal is achieved due to the high concentration of ammonia and the high temperature of the digester centrate (32°C) favouring the growth of AAOs. The waste flow from the SSMR (75 m^3/d) provides the seeding flow directed to the mainstream to bioaugment the growth of AOB and AAOs in the MSMR.

The DO of the MSMR is controlled at 0.5 mg/L in the bulk liquid to allow partial nitritation and deammonification in the same reactor. The DO in the MBR is high at 5 mg/L (as a consequence of the high airflow for membrane scouring) and this polishes the effluent of the MSMR by oxidizing the NH_3 residue. The SRT of the mainstream nitrogen removal reactors (MSMR and MBR Polish) is controlled by the flow rates of the MSMR waste stream and MBR recycle. With the recycle set-ups as shown in Figure 3, the SRT of the mainstream nitrogen removal reactors is 13 days. The TN of the HR-ASP effluent is 26 mgN/L including 20 mgN/L of NH_3 and 2.5 mgN/L of NO_2, and some organic nitrogen. The TN concentration of the MBR permeate (final effluent of the mainstream) is 9.2 mgN/L, with NH_3, NO_2, and NO_3 of 0.3, 6.3, and 0.6 mgN/L, respectively. The nitrogen removal for the mainstream through the MSMR and the MBR Polish is about 65%.

The mass rates of nitrogen species in the effluent streams of the deammonification-MBR system at steady state conditions are listed in Table 3. The TN mass rates in the MBR permeate and in the sidestream output are 218 and 10 kgN/d respectively. For the whole system, 76% of the influent nitrogen (960 kgN/d) is converted to nitrogen gas and removed from the liquid phase.

Table 3 Mass Rates of Nitrogen Species in the Effluents Under Optimal Conditions

	Total N (kg N/d)	Ammonia N (kg N/d)	Nitrite N (kg N/d)	Nitrate N (kg N/d)
MBR permeate	218.1	7.6	149.1	15.0
Sidestream Output	10.2	1.2	0.1	8.5

The concentrations of OHOs, AOB, NOB and AAOs in the different layers of the biofilm and in the bulk of SSMR and MSMR are shown in Table 4. In both the SSMR and the MSMR there is significant growth of AOB and AAOs and negligible amounts of NOB. The biomass populations verify that nitrogen removal is achieved mainly through deammonification in both the sidestream and mainstream.

Table 4 Biomass Populations (mgCOD/L) in the SSMR and MSMR

SSMR	OHOs (mg/L)	AOB (mg/L)	NOB (mg/L)	AAOs (mg/L)
Layer 1 (inner)	92	34	0	625
Layer2	441	243	1	1,424
Layer 3 (outer)	1,608	1,895	4	2,877
Bulk	343	84	0	62
MSMR	OHOs (mg/L)	AOB (mg/L)	NOB (mg/L)	AAOs (mg/L)
Layer 1 (inner)	628	125	1	2,727
Layer2	2,027	523	2	3,240
Layer 3 (outer)	7,635	2,479	12	1,421
Bulk	1,106	75	0	21

Sidestream nitritation and mainstream deammonification

The other variant of the deammonification-MBR system is to achieve nitrogen removal through nitritation and anaerobic ammonia oxidation in separate stages. In this scheme nitritation of digester centrate is conducted in the SSMR (without deammonification), and deammonification for N removal occurs in the MSMR. As noted, this appeared counterintuitive. At the outset it was anticipated that the preferred N removal system would involve deammonification in the sidestream because the conditions are very favourable for maintaining good AAO performance. However, simulations indicate that that the reverse provides more stable and slightly better performance; that is, nitration in the sidestream, and directing nitrite to the mainstream for deammonification. This involves operating the SSMR at a higher DO to oxidize the majority of the NH_3 from the digester centrate to NO_2. The HR-ASP effluent that contains NH_3 is mixed with the SSMR effluent containing NO_2 and is directed to the unaerated MSMR for deammonification.

In this configuration, the SSMR waste flow rate is still important in determining the SSMR SRT but does not act as the AAO seeding flow to the MSMR. The MSMR and the SSMR are operated at different conditions to facilitate different biological processes. The operation of the SSMR becomes more critical to the nitrogen removal performance of the whole system since NO_2 required by deammonification is generated in the SSMR. The DO and the SSMR SRT should be adjusted to maximize the oxidation of NH_3 to NO_2 by AOB but to repress NOB growth to avoid production of NO_3.

Steady state simulations were conducted to optimize the nitrogen removal of the overall deammonification-MBR system. The flow rates of different recycle and/or waste streams in the optimized system are labelled in Figure 4.

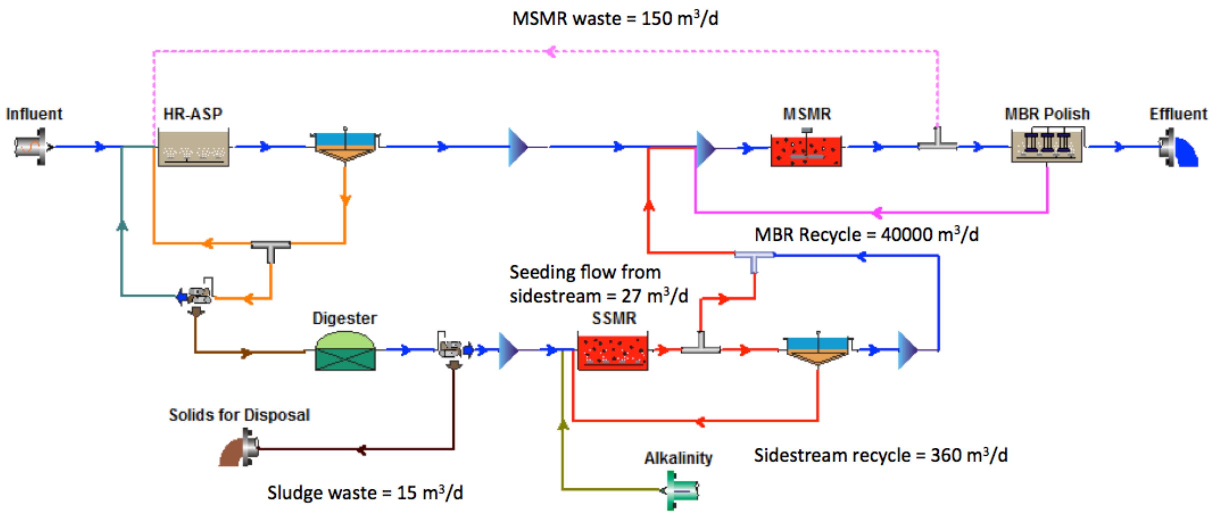


Figure 4 Recycle and/or Waste Flow Rates in the Sidestream Nitritation and Mainstream Deammonification System

The SSMR is operated at a DO of 1.5 mg/L with the SRT at about 8 days. This operating mode stimulates the growth of AOB in the biofilm. Although the inner layers of the biofilm are under anaerobic conditions suitable for the AAOs, the dominant AOB population outcompetes the AAOs for ammonia; and hence the growth of the AAOs is limited by the availability of substrate. The NOB growth rate is also reduced due to unfavourable DO conditions in the biofilm since the NOB have less affinity to oxygen compared to the AOB (*i.e.*, in this modelling, NOB have a higher value for DO half-saturation coefficient in the rate expression). Therefore, in the SSMR, there is only a very small amount of nitrogen removal through anaerobic ammonia oxidation and barely any oxidation of NO_2 to NO_3. Of the NH_3 from the digester centrate, 88% is converted to NO_2 in the SSMR.

In the mainstream, the un-aerated MSMR favours the growth of AAOs. The SRT of the mainstream nitrogen removal reactors (MSMR + MBR) is about 15 days and the SRT of the unaerated MSMR is about 9 days to retain a good AAO population. Ammonia from the HR-ASP effluent and the NO_2 from the sidestream are mixed for the deammonification. The MBR is aerated to remove the residue NH_3 of the MSMR effluent. The recycle from the MBR also returns NO_2 generated in the MBR back to the MSMR for deammonification.

This system only has one effluent stream, the MBR permeate. The TN concentration in the effluent is 8.95 mgN/L with NH_3, NO_2, and NO_3 concentrations of 0.8, 6.26, 0.06 mgN/L, respectively. The mass rates of the nitrogen species in the final effluent are shown in Table 5. The nitrogen removal of this system mainly occurs in the MSMR: approximately 78% of the TN from the influent is removed.

Table 5 Mass Rates of Nitrogen Species in the Effluent under Optimal Conditions

	Total N (kg N/d)	Ammonia N (kg N/d)	Nitrite N (kg N/d)	Nitrate N (kg N/d)
MBR permeate	214.8	19.3	150.1	1.4

The concentrations of OHOs, AOB, NOB and AAOs in the different layers of the biofilm and in the bulk liquid of the SSMR and the MSMR are shown in Table 6. In the SSMR there is almost no growth of AAOs but significant growth of AOB, verifying that the SSMR is mainly for nitritation. In the MSMR, AAOs and OHOs dominate the biofilm to remove nitrogen by deammonification and a small amount of OHO denitrification.

Table 6 Biomass Populations (mgCOD/L) in the SSMR and MSMR

SSMR	OHOs (mg/L)	AOB (mg/L)	NOB (mg/L)	AAOs (mg/L)
Layer 1 (inner)	31	63	0	0
Layer2	197	383	2	0
Layer 3 (outer)	1,345	2,505	14	0
Bulk	732	278	0	0
MSMR	OHOs (mg/L)	AOB (mg/L)	NOB (mg/L)	AAOs (mg/L)
Layer 1 (inner)	698	144	0	1,961
Layer2	2,108	542	2	2,580
Layer 3 (outer)	7,022	2,262	10	2,055
Bulk	1,654	112	0	49

The two basic deammonification-MBR systems presented above have similar setups but are operated in different manners and achieve nitrogen removal in different ways. The first one removes nitrogen by deammonification in both the mainstream and in the sidestream. The second system conducts nitritation in the sidestream and nitrogen removal occurs via deammonification in the mainstream. Both systems have the following advantages in common:

- Excellent TN removal: steady state simulations show that the TN removal exceeds 75% in both systems.
- Very low oxygen consumption (i.e. low energy cost for aeration): oxygen essentially is only required to remove rbCOD, to oxidize 30 – 40% of the influent ammonia to NO_2 (nitritation), and to polish the MSMR effluent in the MBR.
- High biogas production and good potential for energy recovery: a large portion of the influent particulate biodegradable organic material is directed to the anaerobic digester. Almost 50% of the influent COD can be converted to methane when the HR-ASP system is operated at a 0.5 day SRT.
- Simple control strategy: the excellent performance of the system is achieved with a very simple control scheme. Simple DO control in the IFAS-media reactors and hydraulic control of SRTs.

The disadvantage of the two systems is that TN in the effluent mainly consists of nitrite; this would impact downstream disinfection. There are several reasons why the majority of the effluent TN is in the form of nitrite: (a) it is difficult to balance the ratio of NH_3 to NO_2 for deammonification perfectly so there generally is NH_3 residue in the output from the MSMR; and (b) the MBR must be operated at a short SRT allowing oxidation of the NH_3 residue to NO_2 while suppressing the growth of NOB because NO_3 generation implies less TN removal.

The performance of the system may need to be improved to decrease the amount of effluent NO_2 and/or further decrease TN in the effluent. In the next section, modification of the second deammonification-MBR system to improve performance will be discussed.

3.3. Modified deammonification-MBR system

The deammonification-MBR system is now modified to improve the nitrogen removal performance. In the two systems discussed above, nitrogen removal is achieved mainly through deammonification (nitritation and anaerobic ammonia oxidation). To further reduce the effluent TN and to ensure that the effluent consists of NO_3 rather than NO_2, external carbon addition for OHO denitrification may be applied to supplement N removal by deammonification. The external carbon source assumed in this case is a sugar wastewater with a soluble biodegradable COD of 60,000 mg/L. The configuration of the modified system is shown in Figure 5. The modified system was optimized to achieve the maximum TN removal. The recycle flow rates of the optimized system are labelled in Figure 5.

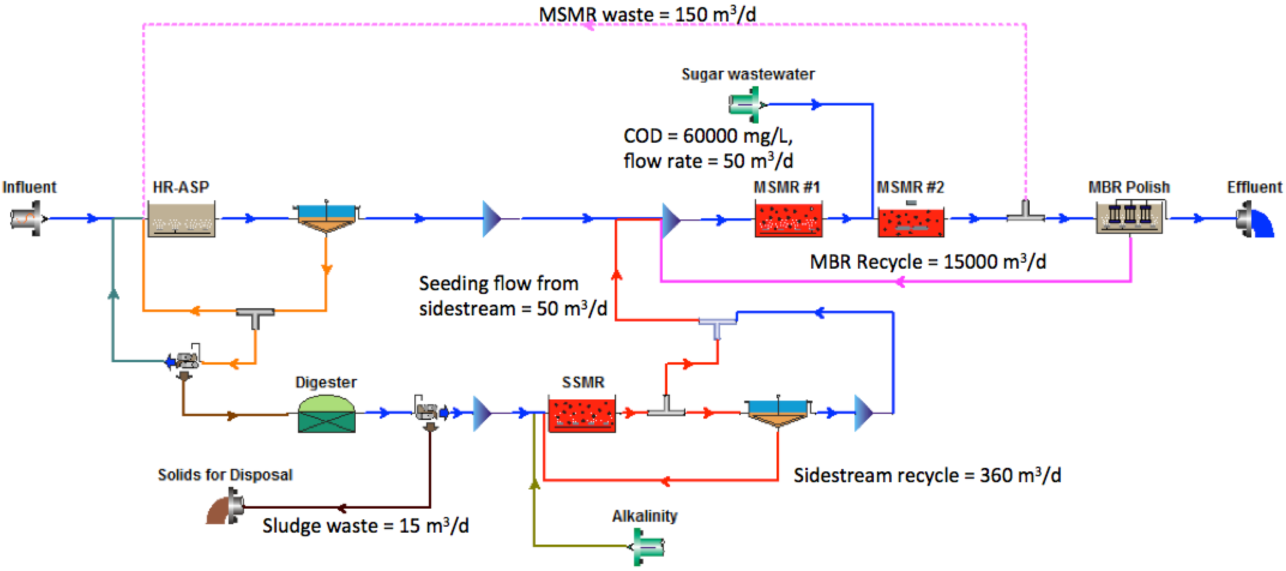


Figure 5 Recycle and/or Waste Flow Rates in the Modified Deammonification-MBR System

In the modified system, the SSMR is operated at a DO of 2.5 mg/L with an SRT of 6.5 days to maximize the oxidation of NH_3 to NO_2. The tank volume of the mainstream nitrogen removal process is increased slightly from 1300 m^3 to 1500 m^3. The MSMR reactor is now divided into two tanks, MSMR #1 and MSMR #2, with equal volumes (500 m^3). MSMR #1 is operated at a DO of 1 mg/L and the MBR Polish tank is operated at the DO of 5 mg/L to oxidize the residue NH_3 or NO_2 in the MSMR effluent to NO_2 or NO_3. MSMR #1 receives a mixture of NH_3, NO_2, and some NO_3. At a DO of 1 mg/L, AOB are able to grow in the bulk and in the out layer of the biofilm to convert the NH_3 to NO_2; AAOs grow in the inner layers of the biofilm and remove nitrogen through deammonification. The unaerated MSMR #2 receives the effluent of the MSMR #1 carrying small amounts of NH_3, NO_2 and NO_3. Sugar water is added to MSMR #2 so that OHOs can remove NO_2 and NO_3 and AAOs in the biofilm remove the NH_3 and NO_2.

Steady state simulations were conducted to evaluate the nitrogen removal performance of the modified deammonification-MBR system. Depending on the amount of sugar water added, the effluent TN can be reduced to less than 5 mgN/L, consisting of 0.2 mgN/L of NH_3, 0.4 mgN/L of NO_2, and 3.1 mgN/L of NO_3. The overall TN removal of the modified system is 87%. The mass rates of nitrogen species in the effluent are shown in Table 7. The NH_3 and NO_2 are removed to extremely low levels and the majority of the TN in the effluent is in the form of NO_3.

Table 7 Mass Rates of Nitrogen Species in the Effluent under Optimal Conditions

	Total N (kg N/d)	Ammonia N (kg N/d)	Nitrite N (kg N/d)	Nitrate N (kg N/d)
MBR permeate	123.7	3.8	9.7	73.4

The concentrations of OHOs, AOB, NOB and AAOs in the different layers of the biofilm and in the bulk liquid of the SSMR and the two MSMRs are shown in Table 8. In the SSMR where nitritation occurs to covert NH_3 to NO_2, the AOB dominate in the biofilm. In the mainstream, 60% of the nitrogen is removed by deammonification in MSMR #1 while 22% of the nitrogen is removed in MSMR #2 by OHO denitritation and/or denitrification. In MSMR #1, both nitrification and deammonification occur (some NO_3 is generated) so AOB, NOB, and AAOs are all growing. In MSMR #2 a small portion of nitrogen is removed by deammonification while most of the nitrogen is removed by denitritation and/or denitrification so OHOs dominate in the biofilm and bulk liquid.

Table 8 Biomass Populations (mgCOD/L) in the SSMR and MSMRs

SSMR	OHOs (mg/L)	AOB (mg/L)	NOB (mg/L)	AAOs (mg/L)
Layer 1 (inner)	95	69	0	0
Layer2	361	419	6	0
Layer 3 (outer)	1,576	2,691	39	0
Bulk	497	171	1	0
MSMR #1	OHOs (mg/L)	AOB (mg/L)	NOB (mg/L)	AAOs (mg/L)
Layer 1 (inner)	855	97	58	2,400
Layer2	2,401	374	224	2,332
Layer 3 (outer)	8,770	1,593	961	266
Bulk	3,030	114	19	8
MSMR #2	OHOs (mg/L)	AOB (mg/L)	NOB (mg/L)	AAOs (mg/L)
Layer 1 (inner)	232	35	22	16
Layer2	1,019	157	96	33
Layer 3 (outer)	8,004	1,378	839	199
Bulk	3,042	114	18	8

The modified deammonification-MBR system has all the advantages of the basic deammonification-MBR systems. However, the modified system further decreases effluent TN from 10 mgN/L to 5 mgN/L by utilizing denitritation and/ or denitrification with the addition of a small stream of the sugar wastewater as the external carbon source. In addition, with the denitrification on top of deammonification to securely control the TN level, the aerobic SRT of the mainstream reactors can be extended slightly to ensure that NH_3 residue is oxidized to NO_3 rather than NO_2.

4. CONCLUSION

This paper demonstrates energy-efficient advanced nitrogen and solids removal deammonification-MBR configurations for municipal wastewater treatment to meet the strict criteria for waste reuse. The configurations use the approach of a HR-ASP to capture a large proportion of the influent wastewater COD to maximize biogas generation in the anaerobic digester. Deammonification is used for nitrogen removal, and incorporating an MBR ensures a solids-free effluent. The deammonification-MBR systems achieve excellent nitrogen removal and at the same time have a small footprint, very low oxygen consumption, and maximized biogas production compared to traditional biological nitrification-denitrification processes. Two variants of the deammonification-MBR configurations were evaluated through process modelling in this study. One utilizes deammonification in both the mainstream and the sidestream, and the other uses nitritation in the sidestream and deammonification in the mainstream. Both configurations can achieve in excess of 75% TN removal and generate effluents with TN ~ 10 mg N/L. Control strategies are simple (maintaining DO setpoints and hydraulic control of SRTs).

One potential concern associated with the deammonification-MBR system is that the effluent TN has a high proportion of nitrite. The presence of NO_2 in the effluent may impact downstream disinfection. A modified deammonification-MBR system was evaluated to address this concern. In addition to deammonification, a small stream of sugar wastewater is added to provide a carbon source for heterotroph denitritation/ denitrification in the system. This reduces the TN level to less than 5 mgN/L in the effluent (as a polish, because over 70% of the removed N is removed by deammonification). The denitritation/ denitrification step ensures the low TN but also allows a slightly prolonged aerobic SRT in the mainstream to oxidize residual NH_3 and/or NO_2 to NO_3.

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