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Modelling simultaneous CH_4 and ammonium removal in a one-stage aerobic granular sludge reactor

Castro-Barros, C.M., Ho, L.T., Winkler, M.-K.H. and Volcke, E.I.P.
Department of Biosystems Engineering, Ghent University, Coupure Links 653, 9000 Gent, Belgium

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Summary of key findings

The feasibility of simultaneous ammonium and CH_4 removal in a one-stage aerobic granular sludge reactor by anaerobic ammonium oxidizing (anammox) bacteria and nitrite-dependent anaerobic methane oxidizing (N-damo) bacteria was assessed based on a one dimensional biofilm model. A simulation study was performed to assess the bacterial competition in the granules, as well as the influence of key variables such as oxygen concentration and ammonium loading rate. Limited oxygen concentration and relatively low ammonium loadings were required for coexistence of anammox and N-damo bacteria in aerobic granules. The results show that simultaneous ammonium and CH_4 removal is feasible in aerobic granules and open the door to future implementations of this technology for more sustainable reject water treatment in an one stage reactor compartment.

Background and relevance

Reject water from anaerobic digestion contains dissolved CH_4 that can potentially escape to the atmosphere during further downstream processing. CH_4 is a strong greenhouse gas (GHG) that accounts for 34 CO_2 equivalents over 100 years horizon (IPCC 2013), meaning that even small emissions of CH_4 have a substantial contribution to the carbon footprint of the wastewater treatment plants (WWTPs). The nitrite-dependent anaerobic CH_4 oxidizing (N-damo) bacteria *Candidatus* Methylomirabilis oxyfera (Raghoebarsing et al., 2006) have the unique capacity to simultaneously oxidize CH_4 to CO_2 and reduce nitrite to dinitrogen gas under anaerobic conditions (Ettwig et al., 2010).

Apart from its dissolved CH_4 content, reject water is characterized by high ammonium concentration and high temperatures and is therefore suitable for the application of anaerobic ammonium oxidation (anammox) technology, resulting in important energy and chemical savings compared to conventional nitrogen removal over nitrate.

The feasibility of the simultaneous CH_4 and ammonium removal by anammox and N-damo bacteria under anaerobic conditions was already studied in lab-scale systems (Luesken et al., 2011; Shi et al., 2013) and by mathematical modelling (Chen et al., 2014; Winkler et al., 2015). In practice, this system needs an additional step performing partial nitrification in order to achieve the CH_4 and ammonium removal. Ammonium can be conveniently removed from reject water with a combined partial nitritation-anammox process (van der Star et al. 2007). However, to avoid problems with CH_4 stripping in the aerated partial nitritation reactor, it is interesting to investigate the possibility of simultaneous CH_4 and ammonium removal in a one-stage system, operated with minimal aeration to avoid stripping effects. A one-stage system could be operated with granular sludge, which allows higher biomass retention time and anoxic and aerobic zones in the same unit. A one-stage configuration would have low footprint, operational and investment costs. The present study is the first to model simultaneous CH_4 and ammonium removal by anammox and N-damo bacteria in single aerobic granular sludge reactor and to assess the feasibility of such a system for reject wastewater treatment.

Results and discussion

Effect of oxygen concentration in the bulk liquid

Oxygen concentrations in the bulk liquid were varied from 0.1 to 1.5 mg O_2 L^{-1} (Figure 1). N-damo and anammox bacteria survived in the system at low oxygen concentrations (0.2-0.3 mg O_2 L^{-1}) (Figure 1A). Higher oxygen concentrations inhibited both bacteria and led in the dominance of ammonium oxidizing bacteria (AOB), nitrite oxidizing bacteria (NOB) and aerobic heterotrophs (HA).

The absence of aerobic methane oxidizing bacteria (MOB) in the granules at high oxygen concentrations was explained due to their detachment from the granule and wash out of the system. Thus, the CH_4 removal efficiency at high oxygen concentrations drops sharply (Figure 1B). The optimal oxygen concentration chosen for all further simulations was 0.2 mg O_2 L^{-1} and corresponded with a nitrogen removal efficiency of 99% (Figure 1B), while did not lower the CH_4 removal efficiency.

Effect of the influent ammonium rate

The influence of ammonium loading rate on the biomass fraction in the granules is shown in Table 1. Anammox bacteria outcompeted N-damo bacteria at high ammonium loading rates, while too low ammonium loading rates did not facilitate their presence, since the formation of nitrite was limited. For the present study, ammonium loading rates of 0.75 and 1.25 kg N d^{-1} m^{-3} (corresponding with a concentration of 300 mg NH_4^+-N L^{-1} and 500 mg NH_4^+-N L^{-1}) enabled the coexistence of N-damo and anammox bacteria in aerobic granules.

Biomass distribution in the granules

Figure 2 shows the biomass distribution inside of a granule. N-damo and Anammox bacteria were both located in anoxic zones of the granules. N-damo bacteria grew in the inner core due to their slower growth rate if compared to N-damo bacteria. AOB dominated the aerobic fraction.

Conclusions

- Simultaneous CH_4 and ammonium removal by N-damo and anammox bacteria in a one-stage aerobic granular sludge reactor was demonstrated feasible by simulation.
- Limited oxygen concentrations and relatively low ammonium loading rates are required for the coexistence of anammox and N-damo in aerobic granules.
- N-damo bacteria grow in inner part of the granules compared to anammox bacteria due to their slower growth rates.

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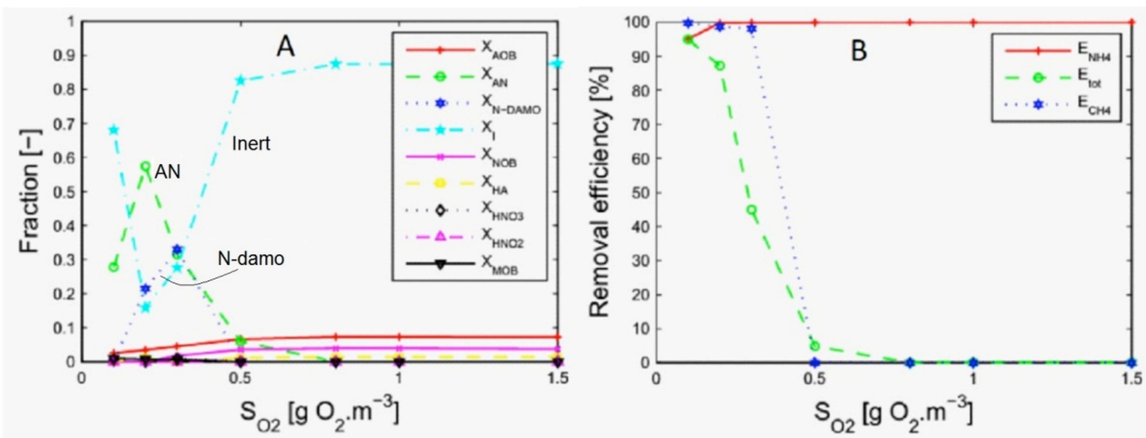

Figure 1 Influence of the bulk oxygen concentration on (A) the biomass fraction in the granules and (B) on the ammonium and CH_4 removal efficiencies. CH_4 = 100 mg COD L^{-1}, granule size = 0.75 mm and influent ammonium concentration = 750 mg N L^{-1}

Table 1 Percentage of biomass in the granules at different influent ammonium loading rates. Grey rows indicate conditions favoring anammox and N-damo bacteria

	Percentage of biomass in the granule						
Ammonium kg N d^{-1} m^{-3}	**N-damo bacteria**	**Anammox bacteria**	**AOB**	**NOB**	**MOB**	**Heter.**	**Inerts**
0.25	0.0	18.0	3.0	0.0	0.3	0.3	78.5
0.75	21.5	57.0	3.5	0.0	1.0	1.0	16.0
1.25	6.0	77.0	3.5	0.0	1.0	1.5	11.0
1.88	0.0	54.0	3.5	0.0	1.0	0.5	41.0
2.50	0.0	54.0	3.5	0.0	1.0	0.5	41.0
3.75	0.0	54.0	3.5	0.0	1.0	0.5	41.0
5.00	0.0	54.0	3.5	0.0	1.0	0.5	41.0

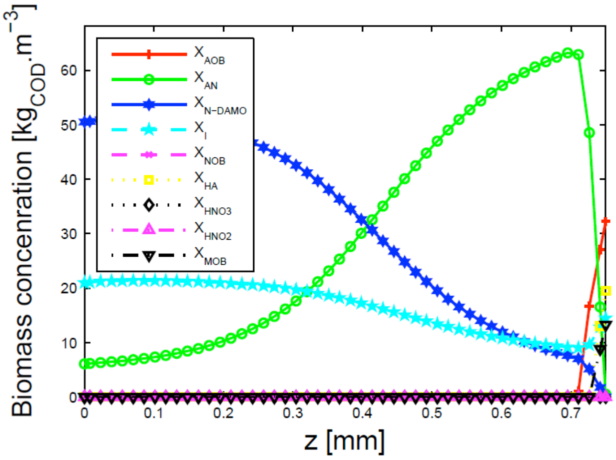

Figure 2 Distribution of the biomass in the granule (bulk oxygen concentration = 0.2 mg O_2 L^{-1}, CH_4 = 100 mg COD L^{-1}, granule size = 0.75 mm, influent ammonium concentration = 300 mg N L^{-1})

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