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Modeling Mainstream Nitrogen Removal by Anammox in a Granule-based UASB Reactor

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Summary of key findings

The mainstream anammox process has been widely recognized as the next-generation wastewater management, but mechanisms resulting in stable autotrophic nitrogen removal are not well understood. In this work, a mathematical model was calibrated and validated to evaluate autotrophic nitrogen removal in an anammox granule-based system. The validity of the model was demonstrated using long-term experimental data from a reported UASB reactor treating actual domestic wastewater. The model enabled to describe sufficiently the long-term N-removal performance and provide insights into the dynamics of microbial population in different granule sizes. The influences of granule size distribution, nitritation produced NO_2^-/NH_4^+ ratio, temperature on nitrogen removal performance and microbial community competition are explicitly analysed. Results show that anammox bacteria would dominant in granules despite with granule sizes, while heterotrophic bacteria prefer to grow in the outer layer of a large granule. The obtained results will facilitate stable autotrophic nitrogen removal by granule-based anammox process to treat mainstream wastewater in practice.

Background and relevance

The discovery of the anammox reaction provides a sustainable pathway to treat both domestic and industrial wastewater (Strous et al., 1999). Anammox has been successfully used to treat the ammonium-rich anaerobic sludge digestion liquor (the so-called sidestream autotrophic N removal). Like in the sidestream process, the mainstream autotrophic N removal process involves ammonia-oxidizing bacteria (AOB) converting approximately half the ammonium to nitrite, with the anammox bacteria converting the nitrite formed by AOB and the remaining ammonium to N_2 (and nitrate). This system does not require organic C, produces a negligible amount of sludge and consumes a minimum amount of aeration energy to convert ~50% of the ammonium to nitrite (Kartal et al., 2010).

Various research groups and industry leaders have undertaken many laboratory and pilot plant studies to implement and demonstrate the above process (Kartal et al., 2010; Wett et al., 2013). While showing very promising results, these studies also revealed some bottlenecks the mainstream anammox process is still facing, e.g. how to achieve high nitrogen removal efficiency and rate at lower influent ammonium concentration and operating temperature. In our previous study (Ma et al., 2013), an integrated approach to enhance and maintain high anammox activity and abundance in an upflow anaerobic sludge blanket (UASB) treating low strength wastewater under moderate and low temperatures was successfully developed. Although a nitrogen removal rate of up to 2.28 kg N/m^3/d and nitrogen removal efficiency of 90% was achieved to treat actual wastewater, even at low temperature of 16 °C, mechanisms resulting in stable autotrophic nitrogen removal are not well understood for this anammox granule-based system.

The objective of this work is to develop a model for mainstream nitrogen removal by granule-based anammox reactor, in order to provide knowledge for stable autotrophic nitrogen removal in practice. Furthermore, we apply this mathematical model to investigate the effects of process parameters (granule size distribution, nitritation produced NO_2^-/NH_4^+ ratio, temperature and nitrogen loading rate) on the system performance and microbial structure of the granule-based anammox reactor.

Results

Experimental data from a lab-scale granular sludge anammox reactor (8 L) are used for the model evaluations (Ma et al., 2013). The influent was the actual effluent from a secondary clarifier of a full-scale WWTP. In order to provide the substrate for the growth of anammox bacteria, ammonium chloride (NH_4Cl) and sodium nitrite ($NaNO_2$) were added. The composition of the influent was listed as follows: NH_4^+-N of 16.87 ± 2.09 mg/L, NO_2^--N of 20.57 ± 2.31 mg/L, NO_3^--N of 13.97 ± 3.99 mg/L and soluble COD of 25.54 ± 6.94 mg/L.

A one-dimensional biofilm model was applied to simulate the bioconversion processes and microbial structure in the UASB through employing the software AQUASIM 2.1d. This model synthesizes all relevant reactions involved in the consumption and production of NH_4^+, NO_2^-, NO_3^-, N_2 and COD by anammox bacteria and heterotrophic bacteria. The operational temperature of the UASB in this work varied from 30~16 °C during the long-term operation. Thus, the effect of temperature on a rate constant relative to a standard temperature (293 K) was included in the model, which can be expressed by a modified Arrhenius equation (Hao et al., 2002). The particle size distribution for a lab-scale granular sludge anammox reactor was characterized experimentally by Ma et al. (2013). According to the previous study by Volcke et al. (2012), a total of 4 granule size classes with relative abundance was included in the numerical model, including <0.5 mm (19.0%), 0.5-0.9 mm (44.5%), 0.9-1.5 mm (20.5%), and >2.0 mm (16.1%), respectively. The implementation of the granular sludge reactor model with four granule size classes in AQUASIM was based on the method proposed by Volcke et al. (2012). Sensitivity analysis reveals that the maximum growth rates of heterotrophic bacteria (HB) and anammox bacteria (i.e., μ_{HB} and μ_{AN}) are the key parameters to predict the data sets available.

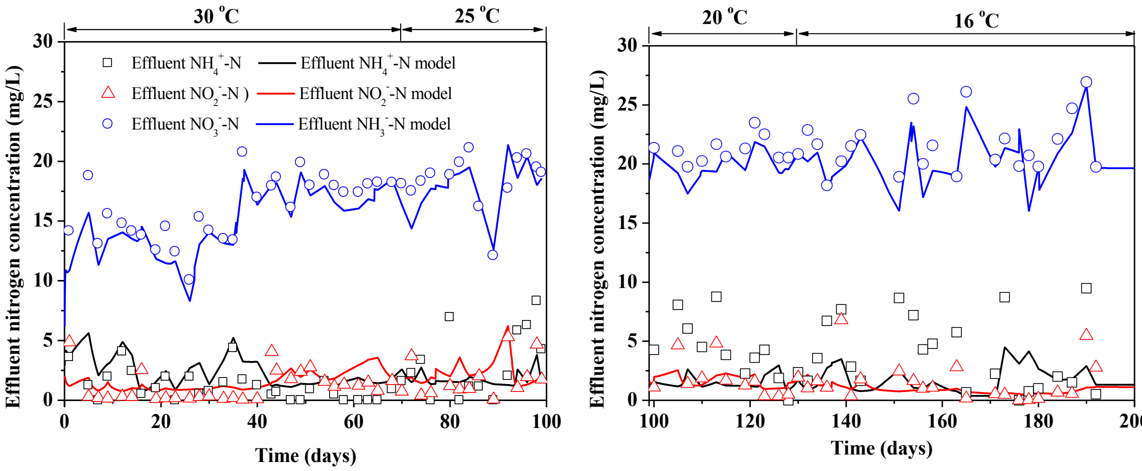

Figure 1 Model calibration using the measured effluent nitrogen concentrations in the initial 99 days of operation under ambient temperature of 30-25 °C (A); Model validation using the measured reactor effluent concentrations between 100 and 200 days operation under low temperature of 20-16 °C (B).

The model calibration was conducted to fit the model simulation results on the measured effluent nitrogen species concentrations during the UASB operating at ambient temperature (25~30 °C). Fig. 1A shows the model simulations matched the measured effluent ammonium and nitrate data well (R^2= 0.95). Nitrite accumulation in the reactor was measured to be very low (average of 1.5 mg N/L) during the whole operation period, which was also well predicted by the model (Fig. 1A). These results supported that the developed model properly captures the relationships among ammonium utilization, nitrite conversion and nitrate production during the operation at ambient temperature. The model verification was based on a check of its capability to predict the effluent components concentrations (S_{NH4}, S_{NO2}, and S_{NO3}) of the anammox reactor operating at low temperature (16~20 °C). The simulation results of the model provide an accurate prediction of S_{NH4} and S_{NO2} consumption in the UASB reactor, as well as the S_{NO3} accumulation (Fig. 1B). The good agreement between the measured and predicted results suggests the validity of the model developed in this work. Thus, the calibrated model could be used to investigate factors influencing operational performance.

Discussion

The effects of granule size distribution on microbial composition in granule are highly assessed (Fig.

2). Different composition profiles are observed for various granule sizes. Overall, insert materials are present in the inner of granules, while anammox bacteria and heterotrophic bacteria prefer to grow the outer layer of granules. With increasing the granule size, the abundance of anammox bacteria would increase, while the fraction of insert materials would decrease. Furthermore, we assessed the influences of granule size distribution, nitritation produced NO_2^-/NH_4^+ ratio, temperature and nitrogen loading rate on operation performance of anammox granule-based reactor. Due to the limitation of the abstract, we will present the data on a full manuscript.

A mathematical model to describe the mainstream anammox process in a granule-based UASB reactor was established in this work. The model was able to simulate the reactor performance well, despite with dynamical influent and temperature conditions. Anammox bacteria would dominant in a smaller granule, while heterotrophic bacteria prefer to grow in the outer layer of a large granule. Our modeling results indicated the essential role of granule size distribution in maintaining the balance among different microbial communities and a high TN removal efficiency in the anammox granule-based system.

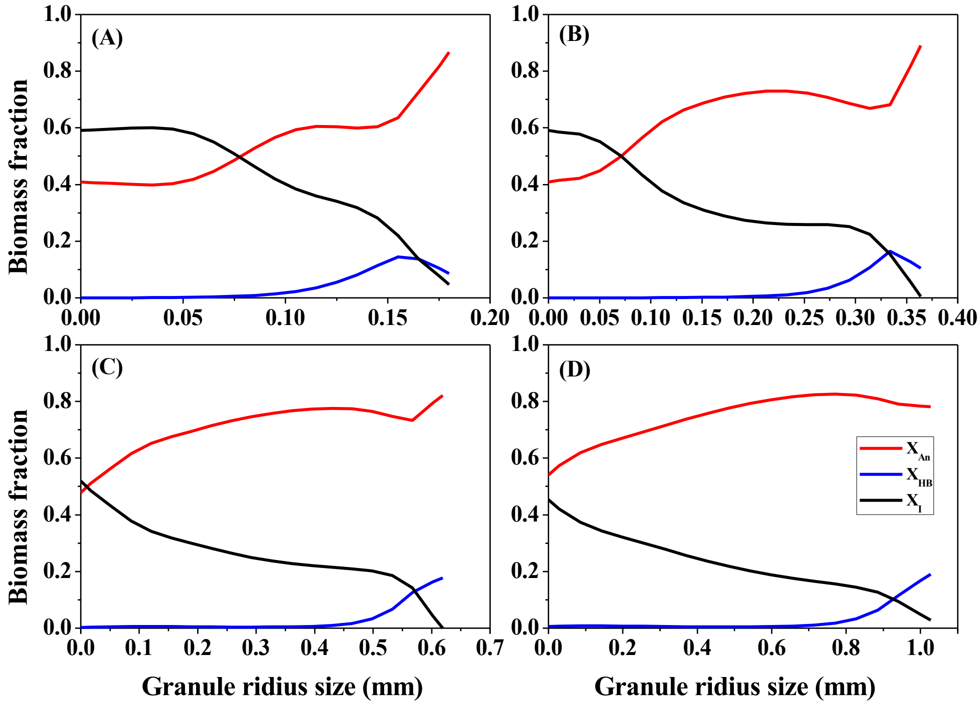

Figure 2 Biomass distribution at various granule sizes (A: granule radius size of 0.18 mm; B: granule radius size of 0.365 mm; C: granule radius size of 0.62 mm; D: granule radius size of 1.185 mm. Note: Radius in the figure is surface area-weighed mean radius.)

References

Hao, X., Heijnen, J.J., Van Loosdrecht, M.C.M., 2002. Model-based evaluation of temperature and inflow variations on a partial nitrification–ANAMMOX biofilm process. *Water Research*, 36 (19), 4839-4849.

Kartal, B., Kuenen, J., Van Loosdrecht, M., 2010. Sewage treatment with anammox. *Science*, 328 (5979), 702-703.

Ma, B., Peng, Y., Zhang, S., Wang, J., Gan, Y., Chang, J., Wang, S., Wang, S., Zhu, G., 2013. Performance of anammox UASB reactor treating low strength wastewater under moderate and low temperatures. *Bioresource Technology*, 129 (0), 606-611.

Strous, M., Fuerst, J.A., Kramer, E.H.M., Logemann, S., Muyzer, G., van de Pas-Schoonen, K.T., Webb, R., Kuenen, J.G., Jetten, M.S.M., 1999. Missing lithotroph identified as new planctomycete. *Nature*, 400 (6743), 446-449.

Volcke, E.I.P., Picioreanu, C., De Baets, B., van Loosdrecht, M.C.M., 2012. The granule size distribution in an anammox-based granular sludge reactor affects the conversion—Implications for modeling. *Biotechnology and Bioengineering*, 109 (7), 1629-1636.

Wett, B., Omari, A., Podmirseg, S.M., Han, M., Akintayo, O., Brandon, M.G., Murthy, S., Bott, C., Hell, M., Takacs, I., Nyhuis, G., O'Shaughnessy, M., 2013. Going for mainstream deammonification from bench to full scale for maximized resource efficiency. *Water Science and Technology*, 68 (2), 283-289.