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## Nitrous Oxide Production in a Granule-based Partial Nitrification Reactor: A Model-based Evaluation

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Sustainable wastewater treatment has been attracting increasing attentions over the past decades. However, the production of nitrous oxide ( $N_2O$ ), a potent GHG, from the energy-efficient granule-based autotrophic nitrogen removal is largely unknown. This study applied a previously established  $N_2O$  model, which incorporated two  $N_2O$  production pathways by ammonia-oxidizing bacteria (AOB) (AOB denitrification and the hydroxylamine ( $NH_2OH$ ) oxidation). The two-pathway model was used to describe  $N_2O$  production from a granule-based partial nitrification (PN) reactor and provide insights into the  $N_2O$  distribution inside granules. The model was evaluated by comparing simulation results with  $N_2O$  monitoring profiles as well as isotopic measurement data from the PN reactor. The model demonstrated its good predictive ability against  $N_2O$  dynamics and provided useful information about the shift of  $N_2O$  production pathways inside granules for the first time. The simulation results indicated that the increase of oxygen concentration and granule size would significantly enhance  $N_2O$  production. The results further revealed a linear relationship between  $N_2O$  production and ammonia oxidation rate (AOR) ( $R^2 = 0.99$ ) under the conditions of varying oxygen levels and granule diameters, suggesting that bulk oxygen and granule size may exert an indirect effect on  $N_2O$  production by causing a change in AOR.

Nitrous oxide ( $N_2O$ ) is of significant environmental concern since it is not only a potent greenhouse gas (approximately 265-fold stronger global warming potential than carbon dioxide), but also responsible for stratospheric ozone depletion<sup>1,2</sup>.  $N_2O$  can be produced during wastewater treatment, especially from biological nitrogen removal (BNR). Ammonia oxidizing bacteria (AOB) have been considered as the main contributor to  $N_2O$  production via two pathways: (i) the sequential reductions from nitrite ( $NO_2^-$ ) to nitric oxide (NO) and to  $N_2O$  as the end product, termed as AOB denitrification<sup>3–5</sup>; (ii)  $N_2O$  as a side product during incomplete oxidation of hydroxylamine ( $NH_2OH$ ) to  $NO_2^-$ <sup>6,7</sup>.  $N_2O$  production by AOB was demonstrated to be related to dissolved oxygen (DO), nitrite, pH, ammonia loading, alkalinity, etc<sup>3,4,8–12</sup>. The site preference (SP), a promising isotopic technique for source identification of  $N_2O$  production, was calculated as the difference between alpha and beta isotopomer signatures. SP has a major advantage of being independent of the precursors<sup>13</sup>. DO and nitrite played important roles in shifting the contribution of AOB denitrification pathway and  $NH_2OH$  oxidation pathway<sup>13–15</sup>.

During past years, an innovative technology based on shortcut nitrification (partial nitrification, PN) and anaerobic ammonium oxidation (anammox) offers a superior alternative to conventional processes in WWTPs (i.e. nitrification-denitrification), saving 30–40% of the overall costs due to a significantly lower oxygen ( $O_2$ ) demand, minimized external carbon requirements and sludge yield<sup>16</sup>. Granule-based reactors have been widely used for PN processes owing to high specific nitrification rate, good settling velocity and efficient biomass retention<sup>17</sup>. However,  $N_2O$  emissions in the partial nitrification/anammox processes have been demonstrated to be significant, particularly in the partial nitrification process<sup>18–20</sup>. The results from SP analysis in the study of Rathnayake *et al.*<sup>17</sup> revealed that AOB denitrification pathway and  $NH_2OH$  oxidation pathway made comparable contributions to  $N_2O$  production from a lab-scale granule-based PN reactor, which was fed with synthetic wastewater without organic carbon supplement. Higher  $N_2O$  production in autotrophic PN granules was observed at higher bulk

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DO concentration and pH of 7.5, which was mostly contributed by *Nitrosomonas europaea* in oxic layer<sup>21</sup>. Pijuan *et al.*<sup>22</sup> observed a much higher N<sub>2</sub>O emission in sequencing batch mode compared to continuous airlift mode and a increase of N<sub>2</sub>O upon decreasing DO levels in granular bioreactors. Nevertheless, more research needs to be conducted to elucidate the involved mechanisms in such a system, including the source identification of N<sub>2</sub>O production and its correlation to multiple parameters.

Mathematical modeling serves as a powerful tool for design and operation of wastewater treatment systems and provides insights into the biochemical pathways. Mathematical models describing N<sub>2</sub>O production by AOB from single pathways or two pathways have been developed and assessed under varying operational conditions (i.e. DO, nitrite, inorganic carbon, etc.)<sup>23–27</sup>. Peng *et al.*<sup>28</sup> further compared these single-pathway models and two-pathway model to identify the applicable region, defined by varying DO and nitrite levels, for each of the models. Besides the suspended-growth systems, mathematical model was also used to predict N<sub>2</sub>O production from biofilm systems. Peng *et al.*<sup>29</sup> applied a single-pathway model to investigate N<sub>2</sub>O production from biofilm reactor performing partial nitrification and anammox (PNA) and found the optimal conditions at low ammonium concentration (<50 mg N/L), moderate DO level (at around 0.5 mg O<sub>2</sub>/L) and biofilm thickness of 1000 μm. Sabba *et al.*<sup>30</sup> revealed that the diffusion of NH<sub>2</sub>OH to anoxic region of biofilm significantly enhanced N<sub>2</sub>O emission using a two-pathway N<sub>2</sub>O model. These previous work clearly demonstrated the importance of mathematical modeling for improving the understanding of N<sub>2</sub>O production mechanisms<sup>26,27</sup>. However, mathematical modeling of N<sub>2</sub>O production in granule-based PN bioreactor using the two-pathway N<sub>2</sub>O model is currently unavailable. Van Hulle *et al.*<sup>31</sup> performed numerical simulation of N<sub>2</sub>O/NO emissions from single-stage granular PNA. However, only one single N<sub>2</sub>O pathway was applied and no verification was performed with experimental data. Pijuan *et al.*<sup>22</sup> correlated N<sub>2</sub>O production in a continuous granular airlift nitrification reactor to DO levels. And these experimental data was further compared to predictions of a granular N<sub>2</sub>O model under varying DO concentrations<sup>30</sup>. However, the involved mechanism including the substrate conversion (i.e. NH<sub>2</sub>OH, electron, etc.) inside granule and the impact of key parameters on N<sub>2</sub>O production as well as the two pathways are unclear. Therefore, it is of great interest to investigate the N<sub>2</sub>O production and the shift of pathways in granule-based PN reactor as well as inside aerobic granules using the two-pathway N<sub>2</sub>O model.

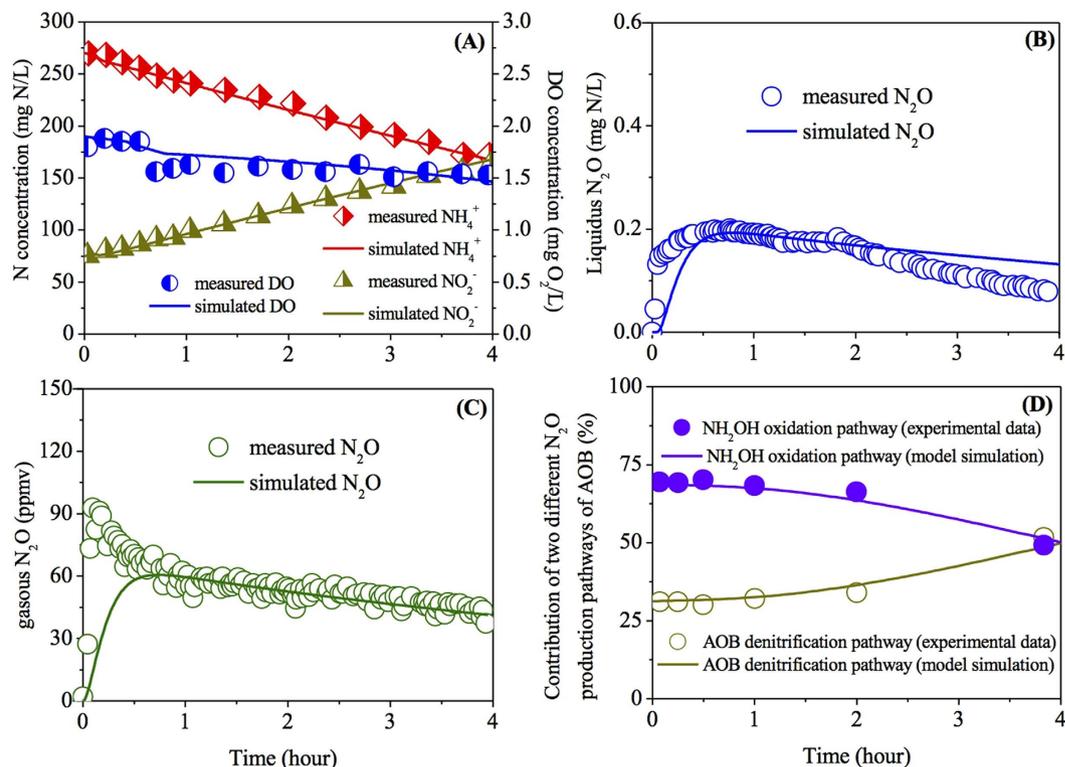
In this work, the previously-established two-pathway N<sub>2</sub>O model incorporating both AOB denitrification and NH<sub>2</sub>OH oxidation pathways<sup>26</sup> was applied to describe the N<sub>2</sub>O production in granule-based PN reactor. The validity and applicability of the N<sub>2</sub>O model were tested by comparing simulations with process data from a lab-scale granular PN sequencing batch reactor (SBR) and isotopic data on pathway contributions. The dependency of N<sub>2</sub>O production on oxygen concentration and granule size as well as the mechanisms involved were evaluated.

## Results and Discussion

**Model evaluation with experimental data.** Model evaluation of this work involved adjusting key parameter values for the nitrogen conversion ( $r_{NH_3,ox}$  and  $K_{O_2,NH_3}$ ) and N<sub>2</sub>O production processes ( $r_{NO_2,red}$ ,  $r_{NO,red}$ ,  $K_{I,1}$  and  $K_{I,2}$ ). The model prediction and experimentally measured data during a typical experimental SBR cycle are shown in Fig. 1, including the nitrogen, DO (Fig. 1A) and dissolved N<sub>2</sub>O in bulk liquid (Fig. 1B), N<sub>2</sub>O emission in the off-gas (Fig. 1C) and the relative contributions of the AOB denitrification pathway and the NH<sub>2</sub>OH oxidation pathway (Fig. 1D). The estimated values of  $r_{NH_3,ox}$ ,  $r_{NO_2,red}$ ,  $r_{NO,red}$  and  $K_{O_2,NH_3}$  are 0.1, 0.077, 0.0059 mg-N/(mg-COD\*h) and 5 mg O<sub>2</sub>/L, respectively. These values are comparable with those reported in the literature, which are 0.15<sup>26</sup>, 0.039<sup>13</sup>, 0.00012<sup>13</sup> mg-N/(mg-COD\*h) and 2.1<sup>11</sup> mg O<sub>2</sub>/L. Figure S1 (in the Supplementary Material) shows the two joint 95% confidence regions for parameter combinations, together with the confidence intervals for all the parameters. Overall, the 95% confidence regions for the two pairs are small, with mean values lying at the center. The 95% confidence intervals for all the single parameters are also small (generally within 10% of the estimated values). These indicate a high-level identifiability and reliability of the estimated values.

Most of oxidized NH<sub>4</sub><sup>+</sup> was converted to NO<sub>2</sub><sup>-</sup> (Fig. 1A) with minimum conversion to NO<sub>3</sub><sup>-</sup> (data not shown). The DO profile displayed a decreasing trend within the range of ~1.5–~1.9 mg O<sub>2</sub>/L. The model simulation results with the calibrated parameters ( $r_{NH_3,ox}$  and  $K_{O_2,NH_3}$ ) applied were in good agreement with the measured N and DO dynamics (Fig. 1A). Both dissolved N<sub>2</sub>O (Fig. 1B) and emitted N<sub>2</sub>O gas (Fig. 1C) increased initially and gradually decreased after reaching peak. The N<sub>2</sub>O emission process was modeled through the N<sub>2</sub>O volumetric transfer coefficient and liquid-phase N<sub>2</sub>O produced by the two pathways. The developed model could generally describe the decreasing trends of both N<sub>2</sub>O profiles. However, the N<sub>2</sub>O peak in gas phase (Fig. 1C) was slightly underestimated by the model, possibly due to the potential gas measurement error considering its inconsistency with the observed liquid phase N<sub>2</sub>O profile, which could not be accurately captured by the model.

Based on analysis of SP measurement, the contributions of each N<sub>2</sub>O pathway were shown in Fig. 1D, where the contribution of NH<sub>2</sub>OH oxidation pathway was initially predominant, but decreased over time and finally was comparable with that of AOB denitrification pathway at the end of cycle. The calibrated N<sub>2</sub>O model properly captured these shifts of N<sub>2</sub>O pathways over time. Based on the predictions by the same N<sub>2</sub>O model, it was seen that AOB denitrification pathway was dominant over NH<sub>2</sub>OH oxidation pathway when nitrite varied between 0 and 700 mg N/L in suspend-growth PN reactor<sup>26</sup>. The inconsistent observations may result from the different operational conditions. For instance, the DO levels in this study (1.5–1.9 mg O<sub>2</sub>/L) are substantially higher than those in Ni *et al.*<sup>26</sup> (~0.55 mg O<sub>2</sub>/L). Higher DO could promote NH<sub>2</sub>OH oxidation pathway, but suppress AOB denitrification pathway<sup>13</sup>. A Haldane-type kinetics ( $S_{NO_2^-}/(K_{NO_2^-} + S_{NO_2^-} + (S_{NO_2^-})^2/K_{I,1})$ ) was applied to describe the NO<sub>2</sub><sup>-</sup> reduction in both studies. However, the obtained value of nitrite inhibition constant for nitrite reduction was 500 mg N/L in this study, while the value of the same parameter was 48 mg N/L in the study conducted by Ni *et al.*<sup>26</sup>, indicating lowered inhibitory effect of nitrite in this study, possibly due to different microbial community involved.

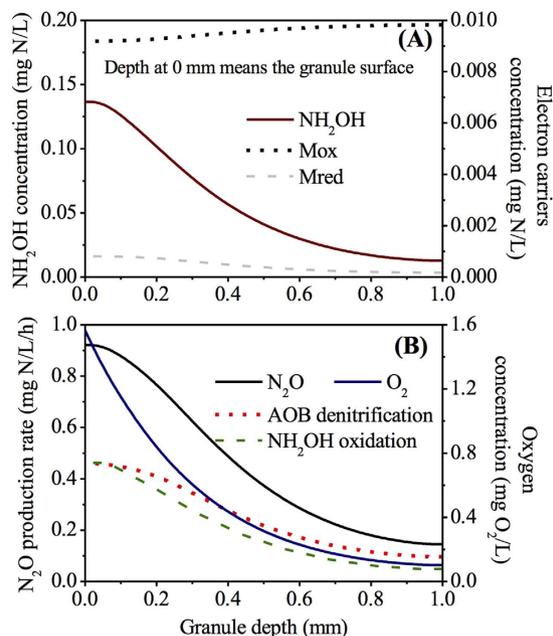


**Figure 1.** Model calibration using experimental data from a partial nitrification granular reactor: (A)  $\text{NH}_4^+$  and  $\text{NO}_2^-$ ; (B) dissolved  $\text{N}_2\text{O}$ ; (C)  $\text{N}_2\text{O}$  emission; and (D) contribution by two  $\text{N}_2\text{O}$  pathways.

Apart from the biological  $\text{N}_2\text{O}$  production pathways, abiotic  $\text{N}_2\text{O}$  generation from the reaction between  $\text{NH}_2\text{OH}$  and free nitrous acid (FNA) could be a recognized resource for  $\text{N}_2\text{O}$  production<sup>32,33</sup>. However, compared to these two studies, the  $\text{NH}_2\text{OH}$  concentration, predicted by the mathematical model, and the FNA, calculated based on pH, temperature and  $\text{NO}_2^-$  were several orders of magnitude lower. Hence, the contribution of the abiotic  $\text{N}_2\text{O}$  production is expected to be minimum.

**$\text{N}_2\text{O}$  production profile inside granule.** In this work, we assume that there is no bacteria growth and AOB is evenly distributed throughout the AOB granule. We admit that this assumption does not necessarily and completely reflect the reality of microbial distribution. We would like to clarify that our model is not meant to describe in full details in AOB granules. Instead, it is meant to be a practically useful tool for predicting  $\text{N}_2\text{O}$  production as well as production pathway under varying conditions in PN-SBR. It is essential that the model component is kept relatively simple. The assumptions are justifiable since heterotrophic bacteria growing cell lysate is very limited due to the lack of organic matter in the influent and AOB are slow growing. The same assumptions have been used in previous study by Sabba *et al.*<sup>30</sup> for description of  $\text{N}_2\text{O}$  production from AOB biofilm and AOB granule. The distribution profiles of  $\text{NH}_2\text{OH}$ , Mox, Mred,  $\text{O}_2$  and  $\text{N}_2\text{O}$  production rates via the two known pathways within the granule at the end of the cycle are presented in Fig. 2. Point 0 on the x-axis indicates the granule surface, while point 1.0 on the x-axis represents the granule center. Along granule depth from surface to inner part,  $\text{NH}_2\text{OH}$  decreased rapidly from  $\sim 0.13$  to  $\sim 0.01$  mg N/L (Fig. 2A). The Mred concentration gradually decreased from 0 to 1 mm and depleted at granule center, whereas the Mox concentration displayed an opposite trend (Fig. 2A). The  $\text{O}_2$  concentration was  $\sim 1.6$  mg  $\text{O}_2$ /L at the granule surface with lower concentration observed at the inner layer (Fig. 2B).

The distribution of  $\text{N}_2\text{O}$  production rate matched the predicted substrate stratification ( $\text{O}_2$ ,  $\text{NH}_2\text{OH}$  and Mred) of the granule (Fig. 2B). From the outer layer to the inner layer,  $\text{N}_2\text{O}$  production rates via both pathways diminished (Fig. 2B), possibly due to the fact that the lower oxygen and  $\text{NH}_2\text{OH}$  levels in the inner layer limited electron supply for both nitrite reduction and NO reduction. Peng *et al.*<sup>13</sup> observed similar correlation between  $\text{N}_2\text{O}$  production rate and DO in an enriched nitrifying culture, which was attributed to the increased electron supplying rate due to the fact that a higher DO increased the ammonia and hence  $\text{NH}_2\text{OH}$  oxidation. However, the model prediction concerning on  $\text{N}_2\text{O}$  production rate displayed a discrepancy against the observation by Rathnayake *et al.*<sup>17</sup>, which was likely due to the different experimental conditions for the PN-SBR and the flow chamber for microsensors measurement. Sampled granules were positioned with five needles in the flow chamber, where DO and pH were roughly constant. The substrate profiles of DO,  $\text{N}_2\text{O}$ ,  $\text{NH}_4^+$ ,  $\text{NO}_2^-$  and  $\text{NO}_3^-$  in the PN granules were measured in a synthetic medium containing 3.5 mg N/L  $\text{NH}_4^+$ , 3.5 mg N/L  $\text{NO}_2^-$  and 0.7 mg N/L  $\text{NO}_3^-$ . In contrast, the SBR was fed with synthetic wastewater containing much higher substrate concentrations

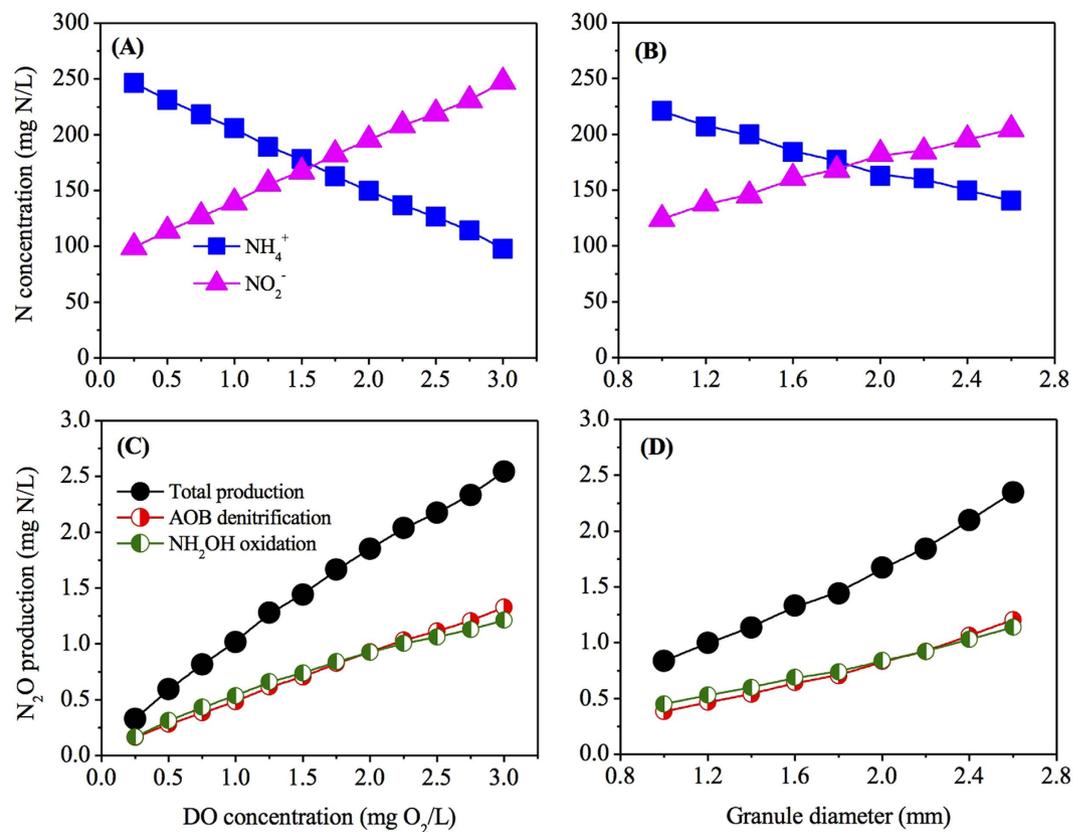


**Figure 2.** Model simulation results of  $\text{NH}_2\text{OH}$  and electron carrier distribution (A) as well as  $\text{N}_2\text{O}$  production and oxygen gradient (B) inside granule.

(210 mg N/L  $\text{NH}_4^+$  and 140 mg N/L  $\text{NO}_2^-$ ). More importantly, the PN-SBR is a complete mixed compartment with higher microbial activity and more dynamic conditions in terms of pH, DO and nitrogen conversion.

Both AOB denitrification and  $\text{NH}_2\text{OH}$  oxidation pathways made comparable contributions at the outer granule layer (0–0.1 mm) with more oxygen. However, from 0.1 to 1.0 mm, the AOB denitrification pathway became the main contributor in the presence of limited oxygen. With the aid of mathematical modeling, the  $\text{N}_2\text{O}$  production via the two known pathways inside PN granule is revealed for the first time in this study. Although there is still a lack of experimental data for validation, the simulation results from granule-based  $\text{N}_2\text{O}$  model were indeed supported by observations from both pure and enriched cultures, where the decrease of oxygen favored  $\text{N}_2\text{O}$  production via AOB denitrification pathway over  $\text{NH}_2\text{OH}$  oxidation pathway<sup>3,13,34</sup>. Anoxic region with the presence of  $\text{NH}_2\text{OH}$  in nitrifying biofilm or granule could further lead to substantially higher  $\text{N}_2\text{O}$  production via AOB denitrification pathway than that in suspended-growth sludge<sup>30</sup>.

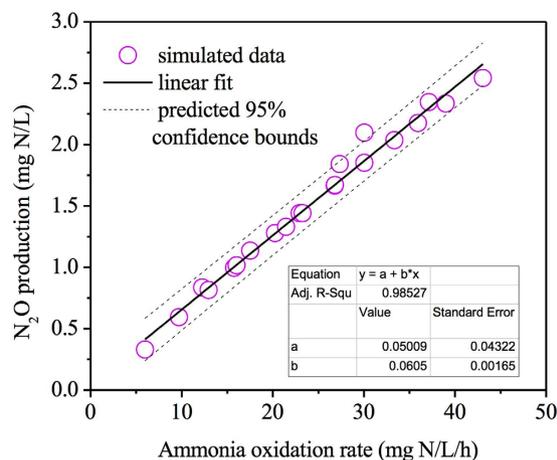
**Effects of bulk oxygen and granule size on  $\text{N}_2\text{O}$  production.** Model simulations for the PN granules with bulk oxygen ranging from 0.25 to 3.0 mg  $\text{O}_2$ /L and diameters in the range from 1.0 to 2.6 mm were conducted to evaluate the effects of DO and granule size on  $\text{N}_2\text{O}$  production from the granular PN system. Figure 3A,C show the simulation results of effluent N and  $\text{N}_2\text{O}$  production at different bulk oxygen concentrations. With the increase of bulk oxygen concentration from 0.25 to 3.0 mg  $\text{O}_2$ /L, the effluent  $\text{NH}_4^+$  concentration decreased from ~250 to ~100 mg N/L, accompanied by corresponding increase of effluent  $\text{NO}_2^-$  (Fig. 3A). Higher  $\text{N}_2\text{O}$  production was observed in PN-SBR with higher bulk oxygen levels (Fig. 3C), provided that both AOB denitrification and  $\text{NH}_2\text{OH}$  oxidation pathways were stimulated by the increased DO concentration. Higher oxygen concentration leads to higher AOR, resulting in a higher electron flow, which would increase  $\text{N}_2\text{O}$  production from both incomplete  $\text{NH}_2\text{OH}$  oxidation and nitrite reduction. At DO level of 2.0 mg  $\text{O}_2$ /L, the contributions of the two pathways were identical. At higher DO levels, AOB denitrification pathway contributed a bit more to  $\text{N}_2\text{O}$  production (~52% at DO of 3.0 mg  $\text{O}_2$ /L), whilst  $\text{NH}_2\text{OH}$  oxidation pathway made more contribution at lower DO levels (~51% at DO of 0.25 mg  $\text{O}_2$ /L). The model prediction with regard to the shift of pathway under varying DO conditions was inconsistent with the observations in previous studies<sup>3,13,34</sup>. It is known that higher DO stimulates  $\text{N}_2\text{O}$  production via affecting ammonia oxidation rate (AOR)<sup>35</sup>. The affinity constant of Mred for NO reduction ( $K_{mred,2} = 1 \times 10^{-5}$  mmol/g-VSS) is much lower than that for nitrite reduction ( $K_{mred,4} = 1.9 \times 10^{-1}$  mmol/g-VSS), indicating a higher competition for electron of the NO reduction process. However, higher bulk DO would also result in higher nitrite accumulation, which in turn exerts an inhibitory effect on  $\text{N}_2\text{O}$  production<sup>36</sup>. It is known that nitrite affects the two  $\text{N}_2\text{O}$  production pathways differently<sup>11,26</sup>. And high nitrite concentration could exert an inhibitory effect on  $\text{N}_2\text{O}$  production in a PN bioreactor<sup>36</sup>, which was consistent with the observations in our study. Furthermore, the inhibition constant for NO reduction ( $K_{i,2} = 60$  mg N/L) is one magnitude lower than that for nitrite reduction ( $K_{i,1} = 500$  mg N/L), suggesting that the inhibition of nitrite accumulation on  $\text{NH}_2\text{OH}$  oxidation pathway is more obvious than the inhibition on AOB denitrification pathway. This was also confirmed by the model simulation in Fig. 1D, where the contribution of  $\text{NH}_2\text{OH}$  oxidation decreased as nitrite concentration increased. The relative contribution of the two known pathways to  $\text{N}_2\text{O}$  production predicted by the granule-based  $\text{N}_2\text{O}$  model in Fig. 3C was a consequence of the combined effect of DO and nitrite.



**Figure 3.** The effect of DO (A,C) and granule size (B,D) on reactor performance and  $N_2O$  production based on the two-pathway  $N_2O$  model.

The simulation results of effluent N and  $N_2O$  production at varying granule diameters are presented in Fig. 3B,D. With the increase of granule diameter from 1.0 to 2.6 mm, the effluent  $NH_4^+$  concentration decreased from ~220 to ~140 mg N/L, accompanied by corresponding increase of effluent  $NO_2^-$  (Fig. 3B). The  $N_2O$  production via two pathways is almost linearly dependent on the granule diameter (Fig. 3D). With the granule number keeping constant, the increase of granule diameter increased the overall granule/liquid interfacial area, thus induced higher reaction rate<sup>37</sup>. However, it should be noted that no biomass growth or decay were considered in this granule-based model for simplification. In reality, the substrate limitation caused by diffusion resistance in the granule would lead to cell decay and leakage of inert cellular products<sup>38</sup>. Consequently, larger granules with higher diffusion resistance contained a higher inert fraction and thereby a decreased volumetric activity<sup>38</sup>. The increase of granule size would result in higher reaction rate, but lower volumetric activity. Stable effluent N would be achieved once they were in equilibrium. In granule diameter range of 1–2.2 mm,  $NH_2OH$  oxidation pathway made more contribution under the simulated conditions (50–54%), while AOB denitrification pathway contributed a bit more to overall  $N_2O$  production in the range of 2.2–2.6 mm (50–51%) (Fig. 3D).

Figure 4 summarizes the  $N_2O$  production at each of the corresponding AOR under various conditions with different DO and granule diameters applied. The  $N_2O$  production increased almost linearly from 0.33 to 2.54 mg N/L as the AOR increased from 6.0 to 43.1 mg N/L/h. By conducting linear regression based on the simulation results, it can be seen that most of the data points stayed within the predicted 95% confidence bounds, indicating good linear relationship between  $N_2O$  concentration and AOR within the tested range. The correlation between  $N_2O$  and AOR identified in this study was consistent with previous studies using PN-SBR systems<sup>9,21</sup>. Law *et al.*<sup>9</sup> observed a linear correlation between  $N_2O$  and AOR within the pH range of 6.0–8.5. pH likely induced a change in the AOR, which may have in turn affected the  $N_2O$  production rate. Rathnayake *et al.*<sup>21</sup> positively correlated  $N_2O$  production rate obtained from batch experiments to the corresponding AOR ( $R^2 = 0.71$ ). Electrons are made available at a higher rate under a higher AOR and diverted to the both nitrite reduction and NO reduction for  $N_2O$  production, since AOB do not possess the capability for  $N_2O$  reduction to  $N_2$ <sup>39</sup>. However, some studies revealed an exponential relationship between  $N_2O$  and AOR, with DO and  $NH_4^+$ <sup>35</sup> or  $IC^{12}$  as the factors to vary AOR. The experimental results were further used to develop a mathematical model considering a non-enzymatic  $N_2O$  production pathway by AOB<sup>35</sup> and an integrated two-pathway model with consideration of catabolic and anabolic processes<sup>25</sup>, respectively. Based on the model predictions, it was seen that higher AOR would cause accumulation of intracellular intermediates such as the unstable nitrosyl radical (NOH), which led to their faster breakdown to form  $N_2O$ . The relationship between  $N_2O$  and AOR relies largely on the involved  $N_2O$  production pathways. The biological pathways (nitrite reduction or NO reduction) result in linear relationship, whereas the chemical pathway (chemical decomposition of NOH) leads to exponential correlation. However, it



**Figure 4.** The correlation between  $N_2O$  production and ammonia oxidation rate under the conditions of different DO levels and granule sizes based on simulation results.

is yet to be fully clarified if NO or NOH are the direct source of  $N_2O$  in  $NH_2OH$  pathway, which require further investigation. This is the first study revealing the linear correlation between  $N_2O$  production and AOR in granular bioreactors with varying DO levels and granule sizes. The model simulations are yet to be verified by experimental data obtained from nitrification granular sludge process.

In summary, a two-pathway  $N_2O$  model incorporating both AOB denitrification and  $NH_2OH$  oxidation pathways was applied to describe a granule-based PN system and provided insights into the  $N_2O$  production mechanisms involved. The main conclusions are listed below:

- The two-pathway  $N_2O$  model could well capture the experimentally measured  $N_2O$  dynamics and pathway distributions in the granule-based PN-SBR.
- The substrate diffusion (i.e.  $NH_2OH$ , oxygen and electron carriers) throughout the granule determined the  $N_2O$  distribution inside the granule. Both pathways made comparable contribution at the granule surface, while AOB denitrification pathway was dominant over  $NH_2OH$  oxidation pathway inside the granule.
- $N_2O$  production via both pathways was positively correlated to both the bulk oxygen and the granule diameter.  $N_2O$  production was linearly dependent on AOR under the conditions of varying bulk oxygen levels and granule diameters.

## Materials and Methods

**Two-pathway  $N_2O$  model.** The two-pathway model for prediction of  $N_2O$  production by AOB was previously established by Ni *et al.*<sup>26</sup>. The  $N_2O$  model integrates both AOB denitrification and  $NH_2OH$  oxidation pathways and synthesizes relevant biochemical reactions in conversion of ammonia ( $NH_3$ ),  $NH_2OH$ ,  $NO_2^-$ , NO,  $N_2O$  and  $O_2$ . The key feature of the two-pathway  $N_2O$  model of AOB is that the model decouples the oxidation and reduction processes through a pool of electron carriers. The electron transfer from oxidation to reduction is modeled by introducing electron mediators (Mred and Mox) as the new state variables. The definition and unit for these substrates are presented in Table S1 in Supplementary Material.

Table S2 summarized the kinetics and stoichiometry of the model. The electrons, generated by incomplete oxidation of  $NH_2OH$  to  $NO_2^-$  via NO (Process 2&3) are donated to the oxidation of  $NH_3$  to  $NH_2OH$  (Process 1),  $O_2$  reduction to  $H_2O$  (Process 5) and the two  $N_2O$  production pathways, including NO reduction to  $N_2O$  ( $NH_2OH$  oxidation pathway, Process 4) and nitrite reduction to  $N_2O$  (AOB denitrification pathway, Process 6). It should be noted that the nitrite reduction (Process 6) is described as a one-step process without NO intermediate to avoid NO and  $NO_2^-$  loop, which is justifiable due to the fact that NO accumulation/emission is rarely observed during denitrification by AOB or heterotrophic denitrifiers<sup>40</sup>. All of the processes above are accompanied by the conversion of Mred to Mox or vice versa. In process 7, an increase of Mred is balanced by a decrease of Mox and vice versa ( $Mred \rightleftharpoons Mox + 2e^- + 2H^+$ ), with the total level of electron carriers ( $C_{tot}$ ) being constant.

**The granule-based reactor model.** The general assumptions made in the granule-based reactor model of this work include: (1) the granules are spherical in shape and uniform in size; (2) the number and size of granules are constant in time; (3) no biomass growth, attachment or detachment and a uniform distribution of AOB throughout the granules for all cases. (4) only radial diffusion transport is considered and is described by Fick's law; and (5) the diffusion coefficient is constant.

Both oxygen and ammonium are supplied into the granules from the bulk liquid. The aerobic granular reactor is modeled through consisting of a completely mixed gas compartment and a biofilm compartment (containing granules and bulk liquid). The gas compartment is linked to the bulk liquid in the biofilm compartment through diffusive links. The oxygen concentration in the gas compartment is dependent on the gas flow rate and the applied gas pressure. The following kinetics (Eq. 1) is used to model the flux of oxygen ( $Flux_{O_2}$ ) from the gas to the biofilm matrix compartment:

$$Flux_{O_2} = k_{O_2} \left( \frac{S_{O_2,g}}{H_{O_2}} - S_{O_2} \right) \quad (1)$$

where  $S_{O_2,g}$  and  $S_{O_2}$  are the concentrations of oxygen in the gas and biofilm matrix compartments ( $\text{g m}^{-3}$ ), respectively,  $k_{O_2}$  is the overall mass transfer coefficient of oxygen ( $0.312 \text{ m d}^{-1}$ )<sup>41</sup> and  $H_{O_2}$  is the Henry coefficient for oxygen ( $\text{mole O}_2 \text{ m}^{-3} \text{ gas/mole O}_2 \text{ m}^{-3} \text{ liquid}$ ).

Parameters with regard to the mass transfer coefficients for the substrates (e.g. ammonium, nitrite, oxygen etc.) are adopted from Hao *et al.*<sup>42</sup>. For the soluble components involved in the biological reactions, the first step is their diffusion into the granules where the reactions take place. Discretization in time of the partial-differential equation describing the reaction-diffusion kinetics in a spherical particle (i.e., granule) is described as the following equation:

$$D_i \left( \frac{d^2 S_i(r)}{dr^2} + \frac{2}{r} \frac{dS_i(r)}{dr} \right) + r_i = 0 \quad (2)$$

with two boundary conditions:

$$\frac{dS_i}{dr} = 0, \text{ at } r = 0$$

$$S_i = S_{i,surface}, \text{ at } r = R$$

where  $S_i$  is the substrate concentration of component  $i$  in the granule,  $S_{i,surface}$  is the substrate concentration of component  $i$  in the granule surface,  $r_i$  is the volumetric substrate conversion rate in the granule,  $D_i$  is the diffusion coefficient of substrate  $i$ ,  $r$  is the distance from the granule center and  $R$  is the granule radius.

It should be noted that no stripping process is considered in the model framework for simplicity as the main objective is to provide insights into involved  $\text{N}_2\text{O}$  production mechanism in granular sludge process rather than to predict the gas phase emissions. Consequently, we use  $\text{N}_2\text{O}$  concentration ( $\text{mg N/L}$ ) in bulk liquid to represent the total  $\text{N}_2\text{O}$  production by the AOB granules under varying operational conditions.

**Experimental data for model testing.** Experimental data for model evaluation were obtained from a lab-scale autotrophic PN-SBR previously reported in Rathnayake *et al.*<sup>17</sup>. The lab-scale PN-SBR had working volumes of 2 L and was operated with a cycle time of 4 hours, consisting of 3 min feeding, 232 min aeration, 3 min settling and 2 min decanting. For each cycle, 1 L synthetic wastewater containing 210 mg N/L  $\text{NH}_4^+$  and 140 mg N/L  $\text{NO}_2^-$  without organic carbon was fed into the SBR, resulting in a hydraulic retention time (HRT) of 8 hours. The incubation temperature was maintained at 35 °C. The influent pH was around 7.7. Airflow rate was fixed at 0.2 L/min at steady state. The nitrogen loading rate was averaged  $43 \pm 2.7 \text{ mg N/L/h}$ . The granules grown in this PN-SBR had an average diameter of 2 mm. After reaching steady state, the  $\text{N}_2\text{O}$  concentrations in the off-gas from the reactor were determined once every minute during one typical 4-h cycle with a 1412 Photo acoustic Field Gas-Monitor (INNOVA, Copenhagen, Denmark). The dissolved  $\text{N}_2\text{O}$  (D- $\text{N}_2\text{O}$ ) concentration in bulk liquid of the reactor was also measured during one typical 4-h cycle with a  $\text{N}_2\text{O}$  microsensor (Unisense, Aarhus, Denmark). Meanwhile, samples were taken during the same cycle and measured on an isotope-ratio monitoring mass spectrometer (MAT 252; Thermo Fisher Scientific K.K, Yoko-hama, Japan) for analysis of isotopomer ratios in  $\text{N}_2\text{O}$  in the off-gas from the SBR.  $^{15}\text{N}$ -site preference as an illustrative parameter of inter-molecular distribution of  $^{15}\text{N}$  was calculated as the difference between alpha and beta isotopomer signatures. Characteristic SP values of 0 per mil and 33 per mil for AOB denitrification pathway and  $\text{NH}_2\text{OH}$  oxidation pathway, respectively, which were estimated in specific pure cultures, were used for estimation of the contribution to each process<sup>43</sup>. Approximate contributions of AOB denitrification pathway and  $\text{NH}_2\text{OH}$  oxidation pathway to  $\text{N}_2\text{O}$  production were estimated by assuming that each process is linearly proportional to the SP value.

**Model-based evaluation.** The two-pathway  $\text{N}_2\text{O}$  model by AOB has been previously evaluated using on-line data from both lab-scale and full-scale bioreactors under different operational conditions<sup>11,13,40</sup>. Unfortunately, a comprehensive dataset including  $\text{NH}_2\text{OH}$  and electron flux directly obtained from granular reactors is not available. Thus, most of the parameter values were adapted directly from literature, as shown in Table S3, which has been validated in different microbial systems. The selection of these parameters for calibration was on the basis of a sensitivity analysis of the parameters in terms of the measured data. In order for accurate predictions of both nitrogen conversion and  $\text{N}_2\text{O}$  production in the granule-based PN reactor, a two-step procedure was applied to calibrate the model with the remaining six key sensitive parameters. Firstly, the ammonium oxidation kinetics (i.e.,  $r_{\text{NH}_3,\text{ox}}$  and  $K_{O_2,\text{NH}_3}$ ) were calibrated using the ammonium, nitrite and DO data. In second phase, two key parameters for  $\text{N}_2\text{O}$  production processes by AOB ( $r_{\text{NO}_2,\text{red}}$  and  $r_{\text{NO},\text{red}}$ ) were further calibrated using the  $\text{N}_2\text{O}$  data in liquid and off gas as well as the results based on SP analysis. The experimental data for model testing displayed a decreasing  $\text{N}_2\text{O}$  production upon nitrite build-up. The inhibitory effect of nitrite on  $\text{N}_2\text{O}$  production in a PN SBR was also reported by Law *et al.*<sup>36</sup>. Thus, inhibition kinetics (refers to Table S3) were applied to describe both NO reduction and nitrite reduction, in which  $K_{i,1}$  (nitrite inhibition constant for nitrite reduction) and  $K_{i,2}$  (nitrite inhibition constant for NO reduction) were also calibrated. Kinetic control of all the enzymatic reaction rates is described by the Michaelis–Menten equation. The rate of each reaction is modeled by an explicit

function of the concentrations of all substrates involved in the reaction. The N<sub>2</sub>O production rates from the two pathways are shown in the following equations, respectively:

$$R_{Deni} = r_{NO_2,red} \frac{S_{NO_2}}{K_{NO_2} + S_{NO_2} + ((S_{NO_2})^2/K_{I,1})} \frac{S_{Mred}}{K_{Mred,4} + S_{Mred}} X_{AOB} \quad (3)$$

where  $R_{Deni}$  represents N<sub>2</sub>O production rate via AOB denitrification pathway;  $r_{NO_2,red}$  is specific maximum nitrite reduction rate;  $K_{NO_2}$  is nitrite affinity constant for nitrite reduction;  $K_{Mred,4}$  is  $S_{Mred}$  affinity constant for nitrite reduction;  $K_{I,1}$  is nitrite inhibition constant for nitrite reduction;  $S_{NO_2}$  and  $S_{Mred}$  are the soluble nitrite concentrations;  $X_{AOB}$  is active biomass concentration of AOB.

$$R_{NH_2OH} = r_{NO,red} \frac{S_{NO}}{K_{NO,red} + S_{NO}} \frac{S_{Mred}}{K_{Mred,2} + S_{Mred}} \frac{K_{I,2}}{K_{I,2} + S_{NO_2}} X_{AOB} \quad (4)$$

where  $R_{NH_2OH}$  represents N<sub>2</sub>O production rate via NH<sub>2</sub>OH oxidation pathway;  $r_{NO,red}$  is specific maximum NO reduction rate;  $K_{NO,red}$  is NO affinity constant for NO reduction;  $K_{Mred,2}$  is  $S_{Mred}$  affinity constant for NO reduction;  $K_{I,2}$  is nitrite inhibition constant for NO reduction;  $S_{NO}$  is the soluble NO concentration.

The initial values, adopted from literature, together with restriction ranges of these six parameters were shown in Table S4. The parameter values were estimated by minimizing the sum of squares of the deviations between the measured data and the model predictions using the secant method embedded in AQUASIM<sup>44</sup>. The secant optimization method is well suited for the minimization of numerically integrated equations using linear approximation of the model functions, which can lead to a much faster end convergence being close to a well-defined minimum. Parameter uncertainty evaluation was done according to Batstone *et al.*<sup>45</sup>. The standard errors and 95% confidence intervals of individual parameter estimates were calculated from the mean square fitting errors and the sensitivity of the model to the parameters. The determined F-values were used for parameter combinations and degrees of freedom in all cases. A modified version of AQUASIM 2.1d was used to determine the parameter surfaces<sup>46</sup>. DO concentration plays a very important role in the PN system performance as well as N<sub>2</sub>O production<sup>35</sup>. The granule diameters also have a significant effect on the simulation results by affecting the overall granule/liquid interfacial area<sup>37</sup>. Hence, Model simulations were then performed under varying conditions (DO in bulk liquid from 0.25–3.0 mg O<sub>2</sub>/L and granule diameters from 1–2.6 mm and) to provide insights into the effects of DO and granule size on N<sub>2</sub>O production from the PN-SBR reactor (Refer to Table S5).

## References

- Ravishankara, A. R., Daniel, J. S. & Portmann, R. W. Nitrous oxide (N<sub>2</sub>O): the dominant ozone-depleting substance emitted in the 21st century. *Science* **326**, 123–125 (2009).
- IPCC. Climate Change, 2013. *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 1535.
- Kampschreur, M. J. *et al.* Effect of dynamic process conditions on nitrogen oxides emission from a nitrifying culture. *Environmental Science & Technology* **42**, 429–435 (2007).
- Kim, S. W., Miyahara, M., Fushinobu, S., Wakagi, T. & Shoun, H. Nitrous oxide emission from nitrifying activated sludge dependent on denitrification by ammonia-oxidizing bacteria. *Bioresour Technol* **101**, 3958–3963 (2010).
- Yu, R., Kampschreur, M. J., Loosdrecht, M. C. M. & Chandran, K. Mechanisms and specific directionality of autotrophic nitrous oxide and nitric oxide generation during transient anoxia. *Environmental Science & Technology* **44**, 1313–1319 (2010).
- Chandran, K., Stein, L. Y., Klotz, M. G. & van Loosdrecht, M. C. M. Nitrous oxide production by lithotrophic ammonia-oxidizing bacteria and implications for engineered nitrogen-removal systems. *Biochemical Society Transactions* **39**, 1832–1837 (2011).
- Stein, L. Y. Surveying N<sub>2</sub>O-producing pathways in bacteria. *Methods in Enzymology* **486**, 131–152 (2011).
- Tallec, G., Garnier, J., Billen, G. & Gossailles, M. Nitrous oxide emissions from secondary activated sludge in nitrifying conditions of urban wastewater treatment plants: Effect of oxygenation level. *Water Research* **40**, 2972–2980 (2006).
- Law, Y., Lant, P. & Yuan, Z. The effect of pH on N<sub>2</sub>O production under aerobic conditions in a partial nitrification system. *Water Research* **45**, 5934–5944 (2011).
- Wunderlin, P., Mohn, J., Joss, A., Emmenegger, L. & Siegrist, H. Mechanisms of N<sub>2</sub>O production in biological wastewater treatment under nitrifying and denitrifying conditions. *Water Research* **46**, 1027–1037 (2012).
- Peng, L., Ni, B. J., Ye, L. & Yuan, Z. The combined effect of dissolved oxygen and nitrite on N<sub>2</sub>O production by ammonia oxidizing bacteria in an enriched nitrifying sludge. *Water Research* **73**, 29–36 (2015).
- Peng, L., Ni, B. J., Ye, L. & Yuan, Z. N<sub>2</sub>O production by ammonia oxidizing bacteria in an enriched nitrifying sludge linearly depends on inorganic carbon concentration. *Water Research* **74**, 58–66 (2015).
- Peng, L., Ni, B. J., Erler, D., Ye, L. & Yuan, Z. The effect of dissolved oxygen on N<sub>2</sub>O production by ammonia-oxidizing bacteria in an enriched nitrifying sludge. *Water Research* **66**, 12–21 (2014).
- Wunderlin, P. *et al.* Isotope signatures of N<sub>2</sub>O in a mixed microbial population system: constraints on N<sub>2</sub>O producing pathways in wastewater treatment. *Environmental Science & Technology* **47**, 1339–1348 (2013).
- Harris, E. *et al.* Isotopic evidence for nitrous oxide production pathways in a partial nitrification-anammox reactor. *Water Research* **83**, 258–270 (2015).
- Vlaeminck, S. E., De Clippeleir, H. & Verstraete, W. Microbial resource management of one-stage partial nitrification/anammox. *Microbial Biotechnology* **5**, 433–448 (2012).
- Rathnayake, R. *et al.* Source identification of nitrous oxide on autotrophic partial nitrification in a granular sludge reactor. *Water Research* **47**, 7078–7086 (2013).
- Desloover, J. *et al.* Floc-based sequential partial nitrification and anammox at full scale with contrasting N<sub>2</sub>O emissions. *Water Research* **45**, 2811–2821 (2011).
- Kampschreur, M. J. *et al.* Dynamics of nitric oxide and nitrous oxide emission during full-scale reject water treatment *Water Research* **42**, 812–826 (2008).
- Okabe, S., Oshiki, M., Takahashi, Y. & Satoh, H. N<sub>2</sub>O emission from a partial nitrification-anammox process and identification of a key biological process of N<sub>2</sub>O emission from anammox granules. *Water Research* **45**, 6461–6470 (2011).
- Rathnayake, R. M. *et al.* Effects of dissolved oxygen and pH on nitrous oxide production rates in autotrophic partial nitrification granules. *Bioresour Technol* **197**, 15–22 (2015).
- Pijuan, M. *et al.* Effect of process parameters and operational mode on nitrous oxide emissions from a nitrification reactor treating reject wastewater. *Water Research* **49**, 23–33 (2014).

23. Pocquet, M., Wu, Z., Queindec, I. & Spérandio, M. A two pathway model for N<sub>2</sub>O emissions by ammonium oxidizing bacteria supported by the NO/N<sub>2</sub>O variation. *Water Research* **88**, 948–959 (2016).
24. Mampaey, K. E. *et al.* Modelling nitrous and nitric oxide emissions by autotrophic ammonia-oxidizing bacteria. *Environmental Technology* **34**, 1555–1566 (2013).
25. Peng, L., Ni, B. J., Law, Y. & Yuan, Z. Modeling N<sub>2</sub>O production by ammonia oxidizing bacteria at varying inorganic carbon concentrations by coupling the catabolic and anabolic processes. *Chemical Engineering Science* **144**, 386–394 (2016).
26. Ni, B. J., Peng, L., Law, Y., Guo, J. & Yuan, Z. Modeling of nitrous oxide production by autotrophic ammonia-oxidizing bacteria with multiple production pathways. *Environmental Science & Technology* **48**, 3916–3924 (2014).
27. Ni, B. J. & Yuan, Z. Recent advances in mathematical modeling of nitrous oxides emissions from wastewater treatment processes. *Water Research* **87**, 336–346 (2015).
28. Peng, L., Ni, B., Ye, L. & Yuan, Z. Selection of mathematical models for N<sub>2</sub>O production by ammonia oxidizing bacteria under varying dissolved oxygen and nitrite concentrations. *Chemical Engineering Journal* **281**, 661–668 (2015).
29. Peng, L., Liu, Y. & Ni, B. J. Nitrous oxide production in completely autotrophic nitrogen removal biofilm process: A simulation study. *Chemical Engineering Journal* **287**, 217–224 (2016).
30. Sabba, F., Picoreanu, C., Pérez, J. & Nerenberg, R. Hydroxylamine diffusion can enhance N<sub>2</sub>O emissions in nitrifying biofilms: a modeling study. *Environmental Science & Technology* **49**, 1486–1494 (2015).
31. Van Hulle, S. W. H., Callens, J., Mampaey, K. E., van Loosdrecht, M. C. M. & Volcke, E. I. P. N<sub>2</sub>O and NO emissions during autotrophic nitrogen removal in a granular sludge reactor—a simulation study. *Environmental Technology* **33**, 2281–2290 (2012).
32. Harper, W. F., Takeuchi, Y., Riya, S., Hosomi, M. & Terada, A. Novel abiotic reactions increase nitrous oxide production during partial nitrification: Modeling and experiments. *Chemical Engineering Journal* **281**, 1017–1023 (2015).
33. Soler-Jofra, A. *et al.* Importance of abiotic hydroxylamine conversion on nitrous oxide emissions during nitrification of reject water. *Chemical Engineering Journal* **287**, 720–726 (2016).
34. Bock, E., Schmidt, L., Stüven, R. & Zart, D. Nitrogen loss caused by denitrifying *Nitrosomonas* cells using ammonium or hydrogen as electron donors and nitrite as electron acceptor. *Archives of Microbiology* **163**, 16–20 (1995).
35. Law, Y., Ni, B. J., Lant, P. & Yuan, Z. N<sub>2</sub>O production rate of an enriched ammonia-oxidising bacteria culture exponentially correlates to its ammonia oxidation rate. *Water Research* **46**, 3409–3419 (2012).
36. Law, Y., Lant, P. & Yuan, Z. The confounding effect of nitrite on N<sub>2</sub>O production by an enriched ammonia-oxidizing culture. *Environmental Science & Technology* **47**, 7186–7194 (2013).
37. de Kreuk, M. K., Picoreanu, C., Hosseini, M., Xavier, J. B. & van Loosdrecht, M. C. Kinetic model of a granular sludge SBR: influences on nutrient removal. *Biotechnology and Bioengineering* **97**, 801–815 (2007).
38. Ni, B. J. *et al.* Modeling a granule-based anaerobic ammonium oxidizing (ANAMMOX) process. *Biotechnology and Bioengineering* **103**, 490–499 (2009).
39. Poth, M. & Focht, D. D. <sup>15</sup>N kinetic analysis of N<sub>2</sub>O production by *Nitrosomonas europaea*: an examination of nitrifier denitrification. *Applied and Environmental Microbiology* **49**, 1134–1141 (1985).
40. Ni, B. J., Pan, Y., van den Akker, B., Ye, L. & Yuan, Z. Full-scale modeling explaining large spatial variations of nitrous oxide fluxes in a step-feed plug-flow wastewater treatment reactor. *Environmental Science & Technology* **49**, 9176–9184 (2015).
41. Terada, A., Lackner, S., Tsuneda, S. & Smets, B. F. Redox-stratification controlled biofilm (ReSCoBi) for completely autotrophic nitrogen removal: the effect of co- versus counter-diffusion on reactor performance. *Biotechnology and Bioengineering* **97**, 40–51 (2007).
42. Hao, X., Heijnen, J. J. & van Loosdrecht, M. C. Sensitivity analysis of a biofilm model describing a one-stage completely autotrophic nitrogen removal (CANON) process. *Biotechnology and Bioengineering* **77**, 266–277 (2002).
43. Sutka, R. L. *et al.* Distinguishing nitrous oxide production from nitrification and denitrification on the basis of isotopomer abundances. *Applied and Environmental Microbiology* **72**, 638–644 (2006).
44. Reichert, P. AQUASIM 2.0—user manual. Swiss Federal Institute for Environmental Science and Technology. Dübendorf, Switzerland (1998).
45. Batstone, D. J., Pind, P. F. & Angelidaki, I. Kinetics of thermophilic, anaerobic oxidation of straight and branched chain butyrate and valerate. *Biotechnology and Bioengineering* **84**, 195–204 (2003).
46. Ge, H., Jensen, P. D. & Batstone, D. J. Pre-treatment mechanisms during thermophilic-mesophilic temperature phased anaerobic digestion of primary sludge. *Water Research* **44**, 123–130 (2010).

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## Author Contributions

L.P., X.D. and B.J.N. wrote the manuscript and developed the methodology; L.P., J.S. and Y.L. performed data analysis and prepared all figures. All authors reviewed the manuscript.

## Additional Information

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