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

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Concern

Reject water from anaerobic digestion contains $\text{NH}_4^+$ and $\text{CH}_4$

$\text{NH}_4^+$
- Eutrophication
- Toxic for living organisms

$\text{CH}_4$
- Greenhouse gas (34 $\text{CO}_2$ equivalent)
- High impact on global warming
Removal of CH₄ and NH₄⁺

Nitrite-dependent anaerobic methane oxidation (N-damo)

\[ 3\text{CH}_4 + 8\text{NO}_2^- \rightarrow 3\text{CO}_2 + 4\text{N}_2 \]

could be combined with

Anaerobic ammonium oxidation (anammox)

\[ \text{NH}_4^+ + 1.3\text{NO}_2^- \rightarrow \text{N}_2 + 0.3\text{NO}_3^- \]

N-damo vs. anammox bacteria

<table>
<thead>
<tr>
<th></th>
<th>N-damo</th>
<th>anammox</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slower growth rate of N-damo - ( \mu_{\text{max}} ) [d⁻¹]</td>
<td>0.0495</td>
<td>0.052</td>
</tr>
<tr>
<td>≈ biomass yield (autotrophic growth) – Y [gCOD.g⁻¹N*]</td>
<td>0.16</td>
<td>0.17</td>
</tr>
<tr>
<td>Lower nitrite affinity of N-damo - ( K_{\text{NO}_2} ) [gN.m⁻³]</td>
<td>0.6</td>
<td>0.005</td>
</tr>
<tr>
<td>More sensitive to nitrite inhibition - ( K_{i_{\text{NO}_2}} ) [gN.m⁻³]</td>
<td>40</td>
<td>400</td>
</tr>
</tbody>
</table>

* N-NH₄⁺ for anammox bacteria and N-NO₂⁻ for N-damo bacteria
Could we combine N-damo and anammox in NON-AERATED granular sludge reactors to simultaneously remove \( \text{CH}_4 \) and \( \text{NH}_4^+ \)?

Granular sludge reactors

- Low footprint
- High SRT
- Different microbial communities
Could we combine N-damo and anammox in NON-AERATED granular sludge reactors to simultaneously remove CH$_4$ and NH$_4$$^+$?

Yes, we can!

IF

- influent CH$_4$:NH$_4$$^+$:NO$_2^-$ ratio close to stoichiometric
- biomass loading rate sufficiently low
- preferably small granules

Winkler et al., Water Research, 2015

Modelling simultaneous anaerobic methane and ammonium removal in a granular sludge reactor

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Could we combine **N-damo** and **partial nitritation-anammox** in AEROBIC granular sludge reactors to simultaneously remove **CH\(_4\)** and **NH\(_4^+\)** from reject water?
Mathematical model

One dimensional mathematical model – Aquasim
Assessment of bacterial competition in aerobic granules

<table>
<thead>
<tr>
<th></th>
<th>$O_2$</th>
<th>$NH_4^+$</th>
<th>$NO_2^-$</th>
<th>$CH_4$</th>
<th>$NO_3^-$</th>
<th>$N_2$</th>
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<tbody>
<tr>
<td>Anammox bacteria</td>
<td><img src="image" alt="Consumed" /></td>
<td><img src="image" alt="Consumed" /></td>
<td><img src="image" alt="Consumed" /></td>
<td><img src="image" alt="Produced" /></td>
<td><img src="image" alt="Produced" /></td>
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<tr>
<td>N-damo bacteria</td>
<td><img src="image" alt="Consumed" /></td>
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<td><img src="image" alt="Produced" /></td>
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<tr>
<td>Anaerobic Heterot.</td>
<td><img src="image" alt="Consumed" /></td>
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<td><img src="image" alt="Consumed" /></td>
<td><img src="image" alt="Produced" /></td>
<td><img src="image" alt="Produced" /></td>
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<tr>
<td>AOB</td>
<td><img src="image" alt="Consumed" /></td>
<td><img src="image" alt="Consumed" /></td>
<td><img src="image" alt="Consumed" /></td>
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<td>NOB</td>
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Could we combine N-damo and partial nitritation-anammox in AEROBIC granular sludge reactors to simultaneously remove CH$_4$ and NH$_4^+$ from reject water?

Scenario analysis

- Effect of O$_2$ concentration in the bulk liquid
- Effect of influent NH$_4^+$ concentration
- Biomass distribution in the granules

Most optimistic scenario: CH$_4$ stripping not considered
Effect of $O_2$ concentration in the bulk liquid

$NH_4^+ = 300 \text{ g N.m}^{-3}$
$CH_4 = 100 \text{ g COD.m}^{-3}$
Granule size = 0.75 mm
$O_2 = 0.1-1.5 \text{ gO}_2.\text{m}^{-3}$

Optimum at limited $O_2$ concentrations:

$0.2 – 0.3 \text{ gO}_2/\text{m}^3$

- If higher, anammox and N-damo bacteria inhibited
- If lower, not enough conversion to NO$_2^-$
Effect of $O_2$ concentration in the bulk liquid

$NH_4^+ = 300 \text{ g N.m}^{-3}$

$CH_4 = 100 \text{ g COD.m}^{-3}$

Granule size = 0.75 mm

$O_2 = 0.1-1.5 \text{ gO}_2\text{.m}^{-3}$

Optimum at limited $O_2$ concentrations:

$0.2 - 0.3 \text{ gO}_2\text{/m}^3$

99% $CH_4$ removal achieved

95% N removal achieved
**Effect of influent NH$_4^+$ concentration**

\[
\text{NH}_4^+ = 100\text{-}2000 \text{ gN.m}^{-3}
\]
\[
\text{CH}_4 = 100 \text{ gCOD.m}^{-3}
\]
Granule size = 0.75 mm
\[
O_2 = 0.2 \text{ gO}_2\text{.m}^{-3}
\]

Coexistence of anammox and N-damo:

- **Influent NH$_4^+$**
  - 300 – 500 gN/m$^3$

- If higher, anammox bacteria outcompete N-damo bacteria
- If lower, not enough substrate (NH$_4^+$ and NO$_2^-$)
Biomass distribution in the granules

\[ \text{NH}_4^+ = 300 \text{ g N/m}^3 \]
\[ \text{O}_2 = 0.2 \text{ g O}_2/\text{m}^3 \]
\[ \text{CH}_4 = 100 \text{ g COD/m}^3 \]
Granule size = 0.75 mm

- Anammox bacteria located closer to the surface area compared to N-damo bacteria
- AOB dominate the outer oxic part
- no MOB – no aerobic methane oxidation
Conclusions

• Simultaneous NH$_4^+$ and CH$_4$ removal feasible in aerated granular sludge reactors, neglecting CH$_4$ stripping

• Careful control of bulk oxygen concentration required
  - high enough for NH$_4^+$ conversion to NO$_2^-$
  - low enough to prevent inhibition of N-damo and anammox

• Influent ammonium concentration
  - high enough for NO$_2^-$ production
  - low enough to prevent outcompetition of N-damo
Thank you for your attention
Questions?

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