Techno-Economic Analysis of Simultaneous Anaerobic Methane and Ammonium Removal in Wastewater Treatment

# Authors

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# Abstract

In wastewater treatment plants (WWTPs), side stream biological nitrogen removal (BNR) via anaerobic ammonium oxidizing bacteria (anammox) has been shown to be more energy efficient and cost effective than conventional nitrification-denitrification systems, but mainstream implementation of anammox remains limited. Under sidestream conditions, a robust ammonium and nitrite supply enable anammox bacteria to produce di-nitrogen gas. However, in the mainstream, nitrate oxidizing bacteria (NOB) are better competitors than anammox for the nitrite produced by ammonium oxidizing bacteria (AOB). These technical limitations have cause all lab and pilot scale anammox systems to fail. Nitrate Dependent Anaerobic Methane Oxidizing archaea(n-damo) use nitrate and methane producing nitrite and carbon dioxide. It has been previously proposed that the nitrite supply challenge posed by mainstream anammox implementation could be solved by utilizing a microbial community of AOB, NOB, n-damo, and anammox, In this study, a mathematical model was constructed to compare the major cost factors of a traditional BNR system, an anammox system, and an Anammox/n-damo system, with and without mainstream anaerobic membrane digester (AnMBR). These simulations show that while an anammox system remains the more efficient option to treat low carbon high nitrogen influent, the anammox/n-damo system would be theoretically easier to control operationally at an only slightly higher cost. An AnMBR mainstream anaerobic digester would provide an ideal synergy with an anammox/n-damo reactor, with substantially lower aeration and sludge handling demands across a wide range of influent carbon and nitrogen concentrations if compared to conventional treatment solution.

# Introduction

Nitrate is produced in the nitrification reactor via AOB and NOB. Nitritation occurs when ammonium is oxidized to nitrite by the chemotrophic AOB (rxn 2). Nitratation occurs when nitrite is then oxidized by the chemotrophic NOB to nitrate (rxn 2).

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| Nitritation by AOB: NH4+ + 1.5O2 🡪 NO2- +2H+ + H2O [cite] | (rxn 1) |
| Nitratation by NOB: NO2- + 0.5O2 🡪 NO3-[cite] | (rxn 2) |

Approximately half of influent is fed to an aerobic nitritation reactor dominated by AOB where ammonium is converted to nitrite. Subsequently, nitrite and residual ammonium are anaerobically converted to di-nitrogen gas and a small amount of nitrate (rxn 4) by anammox.

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| Anammox: NH4+ + 1.3 NO2- 🡪 N2 + 0.3 NO3-[2] | (rxn 4) |

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| n-damo: CH4 + NO3-  🡪 CO2 + NO2- [3] | (rxn 5) |

NDAMO archaea are unique in their ability to reduce nitrate back to nitrite by using methane as an electron acceptor (rxn 5).

Sludge handling makes up a significant portion of operational costs incurred. Commonly, sludge is disposed of when it is transported from the WWTP to a landfill. In the US this can cost anywhere from $20-185/ton of sludge produced depending on the distance to the landfill. Furthermore, many plants are experiencing significant cost increases as permitting this disposal becomes more challenging with previously used local landfills. [Cite]

Aeration costs typically makes up half of energy costs accrued by WWTPs. By reducing oxygen demand, less aeration is required[cite]. Therefore, a dramatic impact can be had on operational costs by reducing the oxygen demand.

Anammox SHARON reactors are currently in use in over 75 full scale wastewater treatment plants to treatment high temperature, low carbon, high nitrogen anaerobic digester centrate which makes up only 1% of the mainstream flow.[cite]

Anammox remains unused in mainstream wastewater treatment because mainstream conditions are unfavorable to the anammox process. In this process, ammonium is oxidized to nitrite first by AOB. NOB and anammox then must compete for the resulting nitrite. If NOB activity is high, nitrate will accumulate and nitrogen removal will be insufficient. Currently, there are two control schemes implemented to limit NOB activity.

The first requires a high temperature influent stream (>25°C). At these higher temperatures, AOB have a higher growth rate than NOB and the reactor sludge retention time (SRT) can be controlled such that the NOB will be washed out before the AOB, and AOB will dominate[cite]. Because mainstream temperatures are typically cooler, this control scheme will not work for mainstream treatment.

The second takes advantage of the difference in oxygen affinity between AOB and NOB. AOB have a higher affinity for oxygen than NOB, with the affinity of AOB typically around 0.5 mg/L and the affinity of NOB typically around 0.9 mg/L [cite]. Given this, if dissolved oxygen levels are controlled between these two affinities, AOB will outcompete NOB for oxygen, and AOB will dominate. However, when attempting this control scheme, it was found that AOB activity was inhibited and were unable to supply sufficient nitrite to the anammox. This resulted in high ammonium levels in the effluent.[cite] These high levels are acceptable for sidestream centrate treatment, where the resulting stream only makes up 1% of total effluent from the plant, however this is not acceptable in mainstream treatment.

# Materials & Methods

Scenarios modeled are pictured in figure 1. All scenarios were simulated using R, and detailed calculations for all scenarios can be found in supplemental material.

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| Macintosh HD:Users:kathryncogert:Google Drive:Lucidchart:NDAMO Feasibility Fig 1.png |
| Fig 1. The four scenarios modeled are pictured here. |

## Scenario A: Classic Nitrification/Denitrification

This scenario represents a classical Modified Ludzak-Ettinger (MLE) biological nitrogen removal (BNR) system. This is the base case against which all other cases are compared in the results.

Influent is first fed into an anoxic denitrification reactor. If the COD/N ratio in the influent is too low to remove all nitrate from the nitrification reactor, supplemental COD must be added at a cost to the WWTP, this was quantified during the simulations and can be seen in figure 3.

Effluent from the nitrification tank removal system is then fed into a clarifier. Treated effluent is decanted while the sludge is fed to an anaerobic digester where the volume of sludge to be handled is reduced by methane respiration to biogas which can be burned for energy recovery.

## Scenario B: SHARON Anammox

The anammox system in this study is based on the granular sludge Single reactor system for High Activity ammonium Removal Over Nitrite (SHARON). The clarifier and anaerobic digester are assumed to operate identical to the system in scenario A.

In this scenario, influent COD must be removed before BNR with anammox to avoid competition between denitrifiers and anammox in the anaerobic reactor. Consequently, an aerobic high-rate BOD removal system was added whereby COD is respired to CO2 by heterotrophs that use oxygen as an electron acceptor.

In practice, operating a nitritation reactor and keeping nitrate levels low while converting enough ammonium to nitrite to supply to anammox has proven impractical for mainstream wastewater treatment. In opposition to current literature [cite] it was assumed that anammox were able to outcompete NOB for nitrite in this system.

## Scenario C: SHARON Anammox + n-damo

Similar to scenario B, this scenario also uses high rate BOD removal for COD removal and a clarifier/anaerobic digester for methane production for energy recovery and sludge volume reduction. However, it differs in that the anaerobic n-damo archaea are included in the anaerobic anammox reactor.

In this scenario half of the influent is fully nitrified in order to supply n-damo with nitrate in the second reactor. The second reactor receives a blend of nitrate and ammonium in approximate molar ratios. Methane is supplied to the reactor from the biogas produced in the anaerobic digester. The nitrate will be converted to nitrite by n-damo archaea, delivering the necessary electron acceptor to anammox in order to anaerobically oxidize the remaining ammonium by anammox bacteria. In the range of influent concentrations considered here, more methane is produced then is consumed by the NDAMO. The rest of the biogas is then available for energy recovery.

Because anammox then has a consistent nitrite supply, this obviates the need to tightly control the previous aerobic reactor (scenario C step 2) for only nitritation, so the aerobic reactor (scenario C step 2) is a nitrification reactor, with partial conversion of influent ammonia to nitrate via AOB and NOB.

## Scenario D: SHARON Anammox + n-damo + Mainstream Anaerobic Digesters

A fourth scenario D was also considered in which COD is removed anaerobically via a mainstream anaerobic membrane digester (AnMBR). The purpose of mainstream digesters is not only the reduction of COD, but also to supply a stream high in dissolved methane to the NDAMO archaea. Approximately half of the influent is nitrified in the first compartment. The other half is fed directly into the n-damo – anammox reactor. It is assumed that all dissolved methane is stripped from the nitrified stream whereas methane stays dissolved in the un-nitrified stream. At high nitrogen levels, additional methane is supplied to the reactor from the AnMBR.

# Results & Discussion

## Sludge Handling

By decreasing the volume of sludge produced, WWTP operation costs can be decreased substantially, so sludge production rates for scenarios B, C, and D, are compared to sludge production rates in base case scenario A in figure 2.

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| Macintosh HD:Users:kathryncogert:Reference:ndamo-econ:NDAMO_Feasibility:Images:sludge.png |
| Fig 2. The percent difference in sludge produced in Scenarios B (left), C (middle), and D (right) vs. sludge produced in scenario A. Blue represents a reduction in sludge production as compared to an MLE process and red represents in increase in sludge production. |

Scenario B, (figure 2 left) is highly favorable at higher nitrogen/low COD concentrations because the denitrifiers required in scenario have a much higher biomass yield than anammox in scenarios B, C and D and n-damo is scenarios C and D. Furthermore, supplemental COD addition (quantified in figure 3). dramatically increases sludge production as it means more substrate for the heterotrophic denitrifiers. The anammox in scenarios B, C, and D are autotrophic and thus do not require supplemental COD. Therefore, at low COD concentrations significantly less sludge is produced.

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| Macintosh HD:Users:kathryncogert:Reference:ndamo-econ:NDAMO_Feasibility:Images:COD.png |
| Fig 3. COD addition in scenario A. As nitrogen loading increases, external COD must be added for the denitrifiers. |

In contrast to scenario B, sludge production in scenario C is slightly higher at all concentrations because it includes NOB and n-damo biomass as well.

Scenario D appears highly favorable at all concentrations. As anaerobic fermenters grow slowly, digesters have a much lower biomass yield compared to the heterotrophs in high rate BOD removal or denitrification.

## Methane Production

Methane produced by WWTPs is a potent greenhouse gas, but if used for energy recovery it can be a fiscal boon in WWT operational costs. In figure 4, higher methane production than the base case scenario A is shown in red and lower methane production is shown by

In scenario B (figure 4 left), less methane is produced at higher N as slow growing anammox produce less sludge then heterotrophic denitrifiers. Less sludge means less methane fermented by the anaerobic methanogens in the anaerobic digester.

This effect is compounded in scenario C (figure 4 middle) as not only are slow growing organisms supplying less sludge to the anaerobic digester, but some methane produced is then consumed by the NDAMO.

Conversely in scenario D (figure 4 right), a lot of methane is produced at high carbon as not only is the COD fermented to methane, but the sludge produced in the AnMBR is eventually converted to methane in the anaerobic digester. This effect drops off as less COD is in the influent and is available to the AnMBR. This is compounded at high nitrogen concentrations. At these concentrations, the demand from NDAMO on methane increases beyond the dissolved methane concentrations and some of the gaseous methane produced from the AnMBR is consumed.

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| Macintosh HD:Users:kathryncogert:Reference:ndamo-econ:NDAMO_Feasibility:Images:methane.png |
| Fig 4. The percent difference in methane produced in Scenarios B (left), C (middle), and D (right) vs. methane produced in scenario A. |

## Oxygen Demand

In figure 5, blue represent a lower oxygen demand as compared to scenario A and red represents an increase in oxygen demand.

Scenario B (figure 5 left) is favorable at high nitrogen and low carbon concentrations but as carbon in influent increases, aeration required for high rate BOD removal increases and the system becomes unfavorable.

Scenario C (figure 5 middle) is very similar to scenario B, but even more unfavorable at high carbon in influent as more oxygen is required for nitrification of ammonia to nitrate as compared to the nitritation of ammonia to only nitrite.

Scenario D (figure 5 right) is drastically more favorable across all concentrations because not only is less oxygen required at high nitrogen concentrations (as with scenarios B & C), but at high COD concentrations less oxygen is required as well. In scenario A, if not enough nitrate is available to remove all of the COD, additional oxygen is supplied to the denitrification reactor. Conversely, scenario D removes all COD anaerobically, so no additional oxygen is required to ensure that all COD is removed.

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| Macintosh HD:Users:kathryncogert:Reference:ndamo-econ:NDAMO_Feasibility:Images:sludge.png |
| Fig 5. The percent difference in oxygen demand in Scenarios B (left), C (middle), and D (right) vs. sludge produced in scenario A. |

When compared to traditional MLE, the scenarios simulated here suggest that low COD high nitrogen concentration influent treated by an n-damo anammox system would provide significant savings to WWTP operational costs as compared to traditional MLE systems.

When compared side by side to the anammox only system, the simple addition of n-damo to the SHARON anammox reactor seems to increase the demands on aeration and sludge production only slightly. Therefore, The cost of an n-damo anammox system would only be slightly higher than that of an anammox system and would be much easier to control.

The simulations also highlight that an AnMBR system plus a SHARON anammox and n-damo system would present a powerful treatment scheme for a wide range of influent concentrations.

Something about greenhouse gases when I get that part done….