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. However, implementation of anammox in the liquid mainstream of WWTPs remains limited. For sidestream treatment applications, a robust ammonium and nitrite supply enable anammox bacteria to produce di-nitrogen gas. However, in the mainstream, nitrite oxidizing bacteria (NOB) are better competitors than anammox for the nitrite produced by ammonium oxidizing bacteria (AOB). These technical limitations have caused mainstream lab and pilot scale anammox systems to fail due to an inadequate nitrite supply to annamox. A relatively novel pathway for nitrite production involves Nitrate-Dependent Anaerobic Methane Oxidizing archaea(n-damo), which 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. The methane supply for n-damo could originate from a sludge anaerobic digester onsite, from off-site sources, or an already methane rich wastewater stream if an anaerobic membrane bioreactor (AnMBR) is employed, 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 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 operationally control 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

Wastewater treatment accounts for 2% of energy used 0.5% of green house gas (GHG) emissions in the U.S, primarily in the form of methane [1][2]. Methane is a potent greenhouse gas with approximately 35 CO2 equivalents over a 100 year time horizon, so even small quantities can greatly impact atmospheric quality [3]. Given this, reducing emissions and energy used by wastewater treatment plants (WWTPs) while improving effluent conditions will be imperative to ensure long term water and energy security.

Typically, half energy consumption in WWTPs is due to aeration, and most methane is produced during the digestion of anaerobic sludge. Therefore, much effort has been put into the development of technologies that both reduce sludge production and aeration demands. In biological nitrogen removal, anaerobic ammonium oxidizing bacteria (anammox) have has spurred development of such technologies. Anammox are able to anerobically oxidize ammonium to dinitrogen gas utilizing nitrite as an electron acceptor. The overall catabolism on anammox is shown in rxn 1.

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| NH4+ + 1.3 NO2- 🡪 N2 + 0.3 NO3-[4] | rxn |

Biological nitrogen removal (BNR) with anammox drastically reduces aeration demands by 60% and sludge production by 75%[5]. NO2- is supplied to anammox by feeding half of the influent to an aerobic reactor where ammonium oxidizing bacteria (AOB) will oxidize NH4+ to NO2-. Rather than nitrite oxidizing bacteria (NOB) further oxidizing the the NO2- to NO3-, the NO2- is supplied to the anammox as an electron acceptor along with the untouched ammonium. In traditional BNR, all influent is completely nitrified before being denitrified. Because the anammox requires only half of the influent to undergo only nitritation, as opposed to full denitrification, oxgen demands, and therefore aeration demands, are significantly reduced. Anammox BNR removal also produces significantly less sludge, because no biomass is produced from NOB, biomass from AOB is halved, and anammox have a much lower biomass yield when compared to denitrifying heterotrophs, (0.13 and 1.29 gVSS/gN respectively)[6]. However, anammox has not yet been successfully impletmented in mainstream WWT as it is very difficult to limit the activity of NOB in these systems.

Recently, an organism has been discovered that could obviate the need for anammox to outcompete NOB for nitrite while simultaneously reduce the production of methane in WWT[7]. Nitrate-driven anaerobic methane oxidizers (n-damo), named *Ca. Methanoperedens nitroreducens*, use methane as an electron acceptor to reduce nitrate to nitrite in the stoichiometry provided in rxn 2.

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| CH4 + NO3-  🡪 CO2 + NO2- [8] | rxn |

N-damo have been successfully shown to grow with anammox in multiple bioreactors [8]–[12]. The n-damo bacteria (nitrite-driven denitrifying bacteria) that would compete with anammox for nitrite would have been shown to be outcompeted by anammox under a nitrate/ammonium feeding regime[11]. This is supported by the calculated kinetic affinities of anammox, n-damo bacteria for nitrite, 0.0024[13] and 0.04[9], [14] respectively. However, these organisms require a source of dissolved methane.

This study supposes that a source of methane could be conveniently provided by a relatively new COD removal technology, mainstream Anaerobic Membrane Bioreactors (AnMBRs). These systems have been gaining attention in WWT because of the high-quality effluent they generated at low temperatures and low sludge production rates[15]–[18]. In these systems, COD is directly fermented to biogas for energy generation. However, recent life cycle analysis research on these systems reveal that one of the major disadvantages to this technology is the potential for downstream GHG emissions due to the high concentrations of dissolved methane in the system’s effluent[15]. Because n-damo require a source of dissolved methane, they could serve as the ideal methane sink to bring this efficient technology to the forefront of WWT and nutrient removal.

# Materials & Methods

Scenarios modeled are pictured in figure 1. Influent concentration of nitrogen was varied between 0-50 mgN/L as ammonium. Influent concentration of COD was varied between 0-300 mgCOD/L. Resulting oxygen demands, sludge, production rates, and methane production rates were compared to the base case. 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:Downloads:NDAMO Feasibility Fig 1.png |
| Figure . The four scenarios modeled are pictured here. |

## Scenario A: Classic Nitrification/Denitrification

This base case scenario represents a classical Modified Ludzak-Ettinger (MLE) BNR system. 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. The volume of landfilled sludge is reduced by the methanogens in the digester. Methane is respired as biogas, which can be burned for energy recovery.

## Scenario B: CANON Anammox

The anammox system is based on the Complete Autotrophic Nitrogen Removal Over Nitrite (CANON) system. Unlike MLE, the CANON system does not remove COD. Influent COD must be removed before entering the CANON reactor to avoid competition between denitrifiers and anammox. Consequently, an aerobic high-rate BOD removal system was added to the front-end of this scenario whereby COD is respired to CO2 by heterotrophs that use oxygen as an electron acceptor. The clarifier and anaerobic digester are assumed to operate identically to the system in scenario A.

In practice, operating a CANON system requires stringent dissolved oxygen control, and converting enough ammonium to nitrite to supply to anammox has proven impractical for mainstream wastewater treatment [19]. In opposition to current literature, it was assumed that anammox were able to outcompete NOB for nitrite in this system and anammox have enough nitrite to convert 100% of influent nitrogen.

## Scenario C: Anammox + n-damo

Similar to scenario B, this scenario also uses high rate BOD removal and a clarifier/anaerobic sludge digester. However, it differs in that anaerobic n-damo archaea are assumed to be able to thrive with anammox in an anaerobic reactor. In scenario B, it is assumed that there are no NOB present whereas in this scenario, it is assumed that approximately half of the influent nitrogen is fully oxidized to nitrate by NOB. This nitrate is reduced by n-damo archaea back to nitrite for use by the anammox as an electron acceptor. Because ndamo archaea can supply a consistent nitrite flux, this scenario obviates the need to tightly control the dissolved oxygen as in scenario B, and will in practice yield a higher nitrogen removal.

Methane for the n-damo is supplied to the reactor from the biogas produced in the anaerobic sludge digester. In the range of influent concentrations considered here, more methane is produced than is consumed by the NDAMO. The rest of the biogas is then available for energy recovery at the WWTP.

## Scenario D: Anammox + n-damo + AnMBR

A fourth scenario D was also considered in which COD is removed anaerobically via a mainstream anaerobic membrane bioreactor (AnMBR). The purpose of mainstream anaerobic treatment is not only for the reduction of COD, but also to supply a stream that is 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 the nitrification reactor configuration is such that dissolved methane is not stripped during aeration and all dissolved methane is available to n-damo. At high nitrogen levels, additional methane is supplied to the reactor from the AnMBR. If the influent C/N ratio is too low to supply n-damo with enough methane, methane must be purchased from an external supply at a cost to the WWTP. The required methane addition was quantified and shown in figure xxx….

# Results & Discussion

## Sludge Handling

In the EU and UK, sludge handling accounts for approximately half of the cost of WWTP operation[20]. By decreasing the volume of sludge produced WWTP operation costs can be decreased substantially. Sludge production rates for scenarios B, C, and D, are compared to sludge production rates in base case scenario A in figure 2. Increased sludge production is shown in red, whereas decreased sludge production is shown in blue.

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| Macintosh HD:Users:kathryncogert:Reference:ndamo-econ:NDAMO_Feasibility:Images:sludge.png |
| Figure . 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 high nitrogen/low COD concentrations because the denitrifiers required in scenario A 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 in scenario A (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 |
| Figure . 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 (figure 2 middle) is slightly higher at all concentrations because it additionally includes NOB and n-damo biomasses.

Scenario D (Figure 2 right) appears highly favorable at most concentrations. The organisms in the AnMBR have a much lower biomass yield compared to the heterotrophs in high rate BOD removal or denitrification, so sludge production at high influent COD levels is greatly reduced when compared to the other scenarios simulated.

## 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 in blue.

The three scenarios compared in figure 4 reveal the impact that anammox can have on methane production. In scenario B (figure 4 left), less methane is produced as nitrogen levels in the influent increase. This is because anammox have a lower biomass yield than heterotrophic denitrifiers, and thus produce less sludge. Less sludge means less methane fermented by the anaerobic methanogens in the anaerobic digester. In scenario C (figure 4 middle), this effect is compounded as some methane produced is then consumed by the n-damo. In scenario D (figure 4 right), there is no sludge digester and methane is produced from the AnMBR only, so much less methane is produced. As low COD in the influent even less methane is produced from the AnMBR. At high nitrogen in the influent, more methane is consumed by the n-damo and methane produced decreases even more.

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

## Oxygen Demand

By reducing oxygen demand, less aeration is required. Since aeration typically makes up about half of energy consumption by WWTPs, a dramatic impact can be had on operational costs by reducing the oxygen demand. In figure 5, blue represents a lower oxygen demand as compared to scenario A and red represents an increase in oxygen demand. At high nitrogen, scenario B (figure 5 left) and scenario C (figure 5 middle) require much less oxygen. Because anammox can convert ammonium directly to di-nitrogen gas with nitrite as an electron donor, only half of the nitrogen present must be oxidized whereas all of the nitrogen present must be oxidized in an MLE system. However, as carbon in influent increases, aeration required in the anammox systems for high rate BOD removal increases and the oxygen demands become similar to that of an MLE system. Scenario C has slightly higher oxygen demands than scenario B because more oxygen is required for the complete nitrification of ammonia to nitrite whereas in scenario B it is assumed that the system can be successfully controlled such that only AOB are present, and ammonia oxidation stops at nitrite.

Scenario D (figure 5 right) again reveals the powerful synergy that could exist between an n-damo + anammox system and an AnMBR as oxygen demand is reduced at all concentrations simulated. 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 it is removed by anaerobic organisms in the AnMBR. 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:o2.png |
| Figure . 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….