NC AWWA-WEA Annual Conference 2021

Tertiary Partial Denitrification-Anammox (PdNA) Filters for Sustainable Nitrogen Removal

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Hazen and Sawyer

PRESENTATION OVERVIEW

1. Shortcut nitrogen removal?
2. What is PdNA and why is it important?
3. Overview of PdNA filter:
   - Configuration and start-up
4. Results:
   - Start-up
   - Phase 1 operation & results
   - Phase 2 operation & results
   - Molecular analysis
5. Techno economic analysis
6. Conclusions

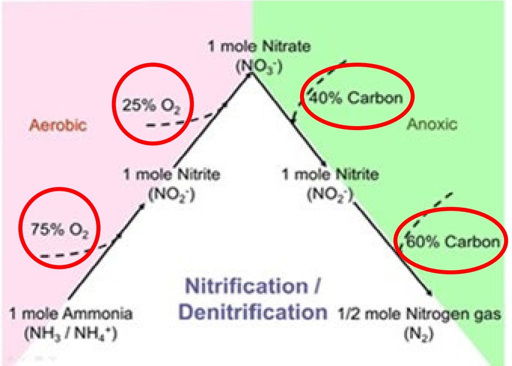
GENERAL

Problem:

1. Concentrated discharges of nitrogen lead to eutrophication
2. Stringent TN discharge limits are being placed on WRFs

Biological Nutrient Removal (BNR):

1. Provides nitrogen and phosphorus removal from wastewater prior to discharge
2. ***Conventionally:*** Two step nitrification/denitrification
3. ***However:*** High aeration, high carbon, and solids generation



Shortcut The Nitrogen Removal Process In Wastewater With UV Sensors (wateronline.com)

SHORTCUT NITROGEN REMOVAL

Capital cost estimates for upgrades to conventional processes have ranged from **125 to 150 million dollars**, in HRSD to meet total nitrogen (TN) limits of 5 mg/L. (Bott n.d.)

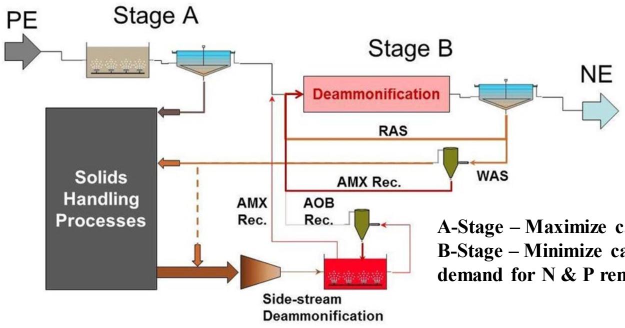
Mainstream Deammonification:

1. Offers potential carbon and energy savings (Reduced oxygen demand)
2. Has been implemented and controlled in industrial and sidestream applications

Relies on Anammox (Anaerobic Ammonia Oxidizing Bacteria)

Mainstream deammonification achieved via two approaches:

1. Partial Nitritation-Anammox
2. **Our Focus:** Partial Denitrification-Anammox (PdNA)



A-Stage – Maximize carbon capture
B-Stage – Minimize carbon & energy demand for N & P removal

Excerpt From WERF Report on Mainstream Deammonification (2015)

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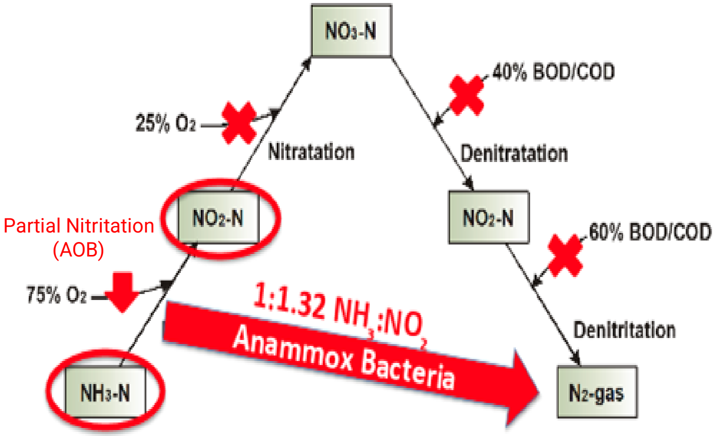
MAINSTREAM DEAMMONIFICATION
PARTIAL NITRITATION/ANAMMOX

Previous Application of Anammox:

Partial Nitritation/Anammox (PN/A)

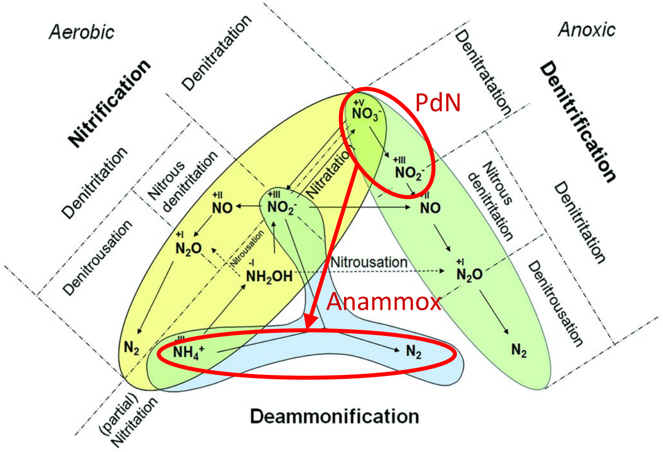


The addition of hydrocyclones for selective anammox bacteria retention (DEMON® process HRSD)

MAINSTREAM DEAMMONIFICATION
PARTIAL DENITRIFICATION/ANAMMOX

Our Application of Anammox:

Partial Denitrification/Anammox (PdNA)



So why PdNA?

1. Obtaining complete out-selection of Nitrite Oxidizing Bacteria (NOB) is difficult in low-strength nitrogen and cold conditions
2. ~38% reduction in O2 demand
3. ~ 50% reduction in supplemental carbon
4. Reductions in excess sludge

Hurdles with PdNA?

1. Inhibition of Anammox at lower temperatures
2. Preventing full denitrification (FdN)

STUDY INTO A SINGLE STAGE PDNA FILTER

Conventionally PdNA:

Research has explored multi-stage processes. Separating the biological processes using SBRs.

Our Idea:

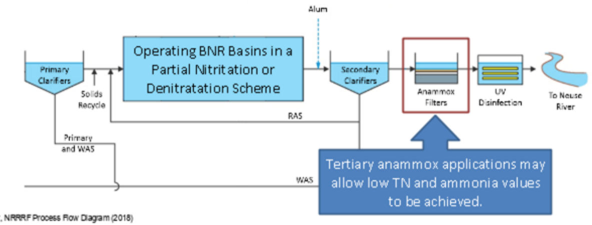
1. Combine processes in filter with a PdN and Anammox phase
2. Biofilm overcomes biomass retention and selection issues
3. Two reactors were utilized to demonstrate the feasibility of PdNA:
    a) **Reactor #1:** PdNA (MicroC 2000 as Carbon Source)
    b) **Reactor #2:** Conventional DF (FdN) (Methanol as Carbon Source)

PILOT-SCALE TERTIARY PDNA FILTERS
RESEARCH OBJECTIVES

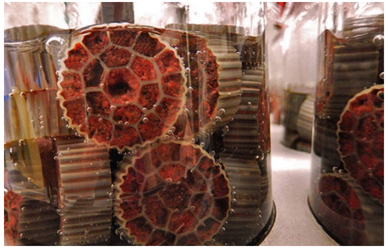
1. Determine the nitrogen removal capability of a PdNA filter, determine whether it can operate at typical filter loading rates, and identify key parameters to ensure performance.

2. Identify the microorganisms present within a PdNA filter and determine the relationship between community structures and nitrogen removal.

3. Compare conventional biological nutrient removal to a PdNA process utilizing techno-economic analysis (OPEX).



Source: Hazen and Sawyer, NRRRF Process Flow Diagram (2018)



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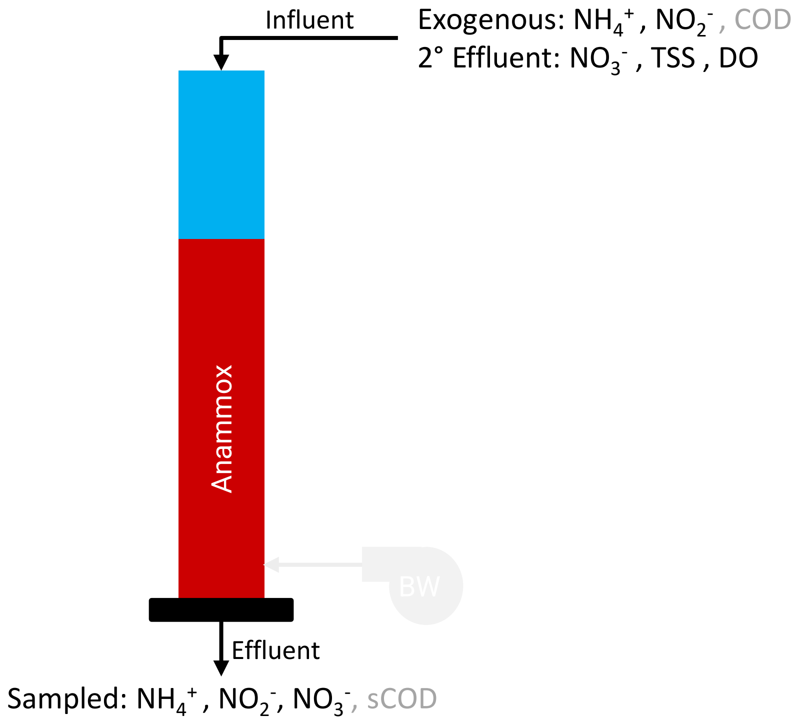
RESEARCH PHASES

1. Start-Up
   a) Anammox Inoculation
2. Phase 1
   a) Supplemental Carbon Feed
3. Phase 2
   a) Feasibility at Typical Filter Loading Rates
   b) Filter Profiles
4. Molecular Analysis
5. Techno-Economic Analysis

Schedule (Days)	Phase	Operation	Reactor in Service
0-15	**Start-Up**	Pre-COVID 19 Anammox Startup	Reactor #1
15-85	**Start-Up**	COVID 19 Shutdown	Reactor #1
(New Day 0)-92	**Start-Up**	Post-COVID 19 Anammox Startup	Reactor #1
92-143	**Phase 1**	Carbon Feed for PdNA & Denitrification Filter Startup	Reactor #1 & #2
143-168	**Phase 1**	Decreased Nitrite Loading to PdNA	Reactor #1 & #2
168-220	**Phase 1**	Programmable Pump	Reactor #1 & #2
220-238	**Phase 2**	Filter Profiles and Reduction to 50 min HRT	Reactor #1 & #2

START-UP CONFIGURATION



START-UP PROCEDURES

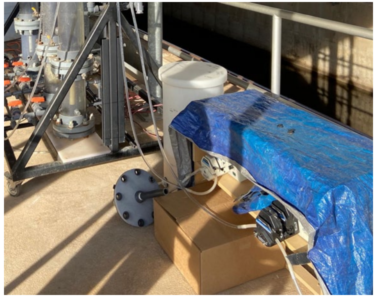
1. **Reactor #1** was loaded with media (Neuse River RRF) and operated at tiered HRTs to ensure establishment of Anammox biomass:
   a) Filter specifications:
      i. Typical deep bed filter configuration (6 ft depth of media/1 ft headwater)
      ii. Diameter = 0.5 ft (Volume= 1.2 ft3)

   b) Media:
      i. Effective Grain Size (d10) = 2.75 mm
      ii. Mixed with 2,800 mL (VSS = 4,070 mg/L) of Anammox Inoculum (HRSD, DEMON)

START-UP PROCEDURES

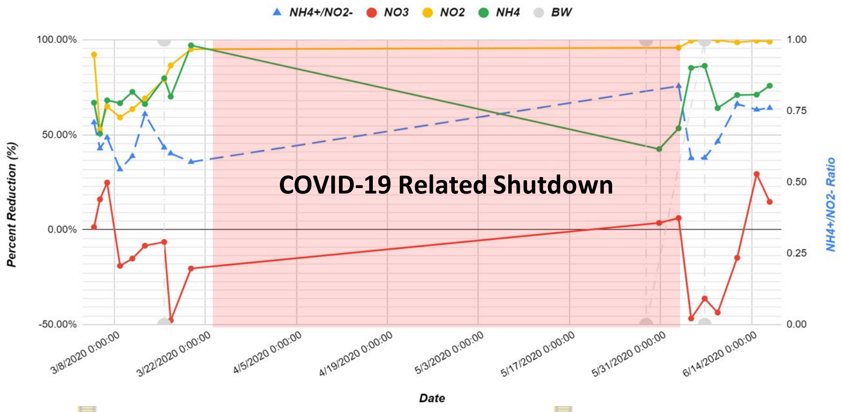
2. **Reactor #1** received secondary clarifier effluent:
   a) Average Influent Characterization:
      - NH_4^+-N (mg/L): 0.25
      - NO_2^--N (mg/L): 0.22
      - NO_3^--N (mg/L): 5.52
      - TSS= 7.36 mg/L
   b) Exogenous nitrite and ammonia inline feed (Previous Research: **NH_4^+ : NO_2^- of 1:1.6**)
   c) Continuous flow into Reactor #1: Progression toward next HRT dependent on achieving 50% influent ammonia and nitrite removal (Anammox Activity):

HRT (min)	Q (L/min)	Filter Loading Rate (gpm/ft^2)
90	0.37	0.50
66.7	0.50	0.67
50	0.67	0.90



START-UP PROCEDURES (COVID-19 SHUTDOWN)

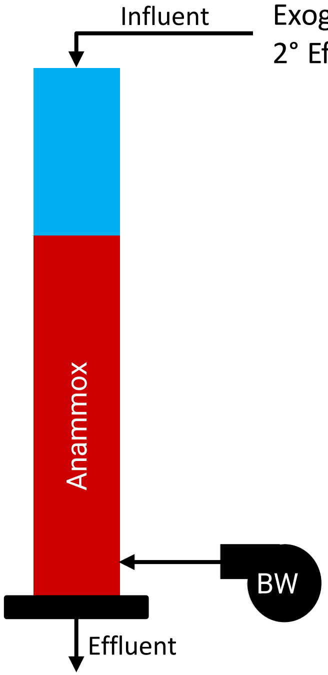
3. Filter start-up proceeded normally until 3/19/2020 (Day 15 of Operation)
   a) Due to COVID-19 filter was shut down until 5/28/2020 (New Day 0 of Operation)
   b) Change in performance noticed between start-up periods
   c) Noticed Nitrite Oxidizing Bacteria (NOB) interference with elevated DO concentrations in influent (Supplemental Carbon = Heterotrophic DO reduction)



START-UP CONFIGURATION (BACKWASHING)

Exogenous: NH_4^+ , NO_2^- , COD

2° Effluent: NO_3^- , TSS , DO



Sampled: NH_4^+ , NO_2^-, NO_3^-, sCOD

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START-UP PROCEDURES (BACKWASHING)

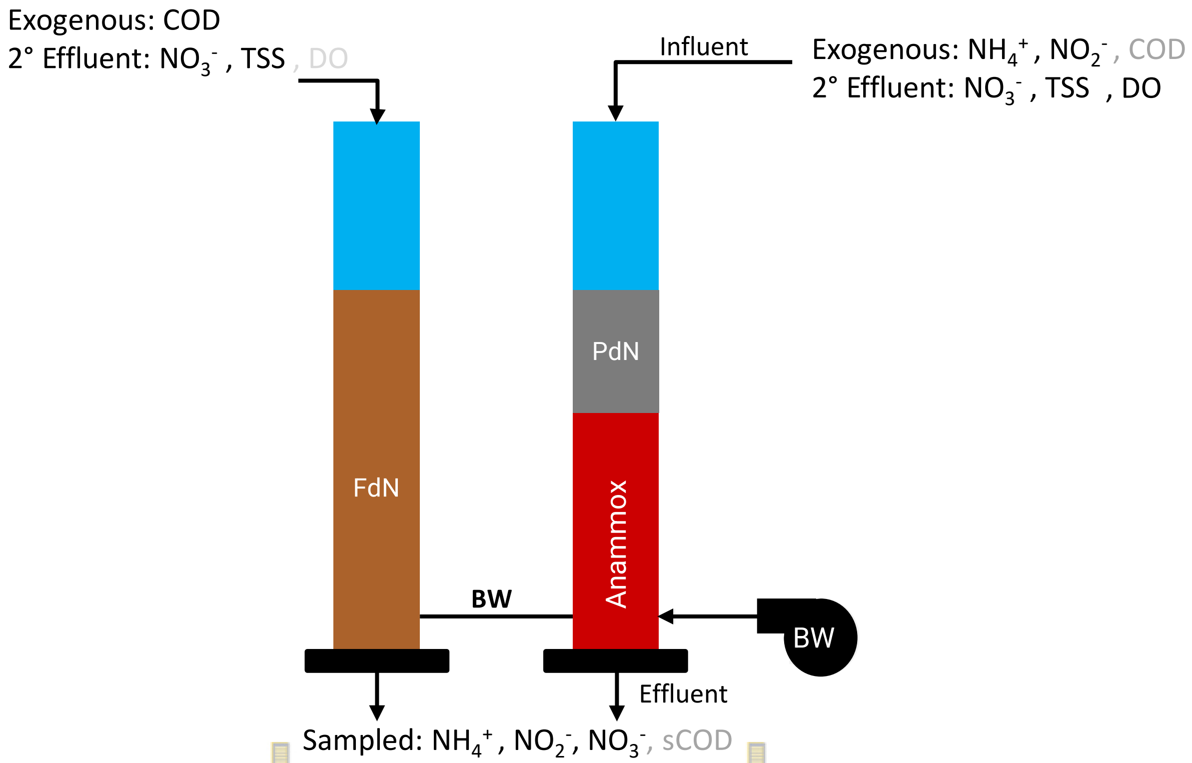
4. Backwashing Requirements:
   a) Backwashing initially performed during startup upon noticeable head loss
   b) Originally, backwashed at 16 gpm for 2 minutes (minimum fluidized bed velocity)

Occurrence	Pre-Backwash Anammox Activity	Post-Backwash Anammox Activity
Full Backwash	97.12%	87.28%
Full Backwash	90.90%	81.95%

   c) Biological filters; so backwashing method adjusted at start of 50 min HRT
      i. Nitrogen Release Cycle: 4 gpm for 2 min every 8 hours
      ii. Backwash Cycle: 4 gpm for 10-15 min every 24 hours

Occurrence	Pre-Backwash Anammox Activity	Post-Backwash Anammox Activity
Alternative Backwash Scheme (Day 67)	82.52% (Day 67)	79.91% (Day 69)
Alternative Backwash Scheme (Day 69)	79.91% (Day 69)	87.77% (Day 71)

START-UP CONFIGURATION (PHASE 1)



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START-UP PROCEDURES (START OF PHASE 1)

5. **At the end of start-up:** PdN & Reactor #2 (FdN) start-up
   a) PdNA (Reactor #1):
      i. Continue NH_4^+ and NO_2^- feed (1:1.6) and begin supplemental carbon
      ii. Reduce NO_2^- feed gradually over time (monitor residual nitrate concentrations) (MicroC 2000) *(Designed for a COD/ NO_3^--N=2.5)*
   b) FdN (Reactor #2):
      i. Started with dirty media from NRRRF tertiary filters (Methylotrophs abundant)
      ii. Utilized existing NO_3^- in SDWRF secondary effluent and began supplemental carbon addition (Methanol) *(Designed for a COD/ NO_3^--N=5.23)*

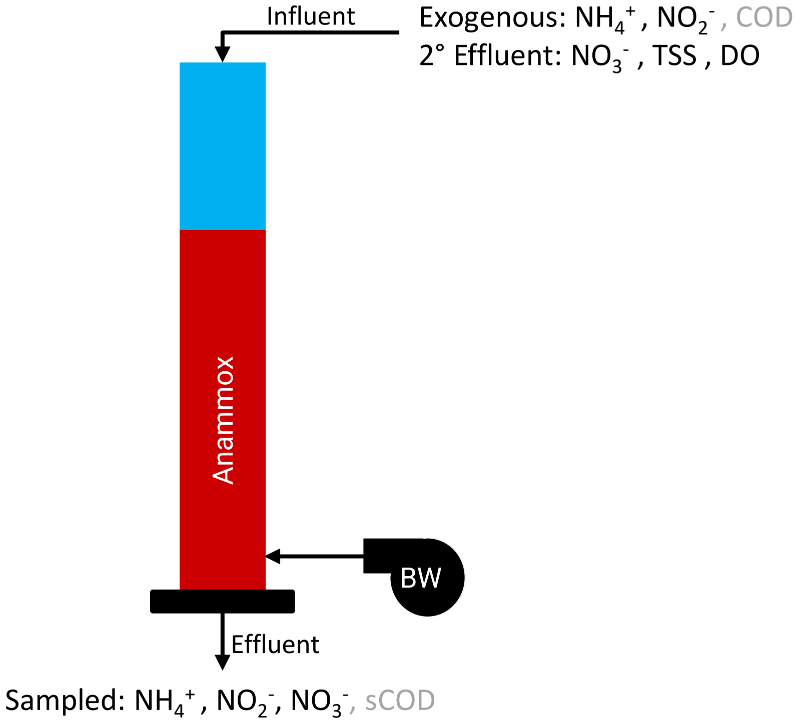
At the end of start-up (Start of Phase 1):

PDN/A: Secondary effluent ($NO_3^- \rightarrow NO_2^-$) + NO_2^- + NH_4^+ + MicroC 2000 (95% glycerin/5% Methanol)

DF: Secondary effluent (NO_3^-) + Methanol (Carbon Source)

OPERATION AND RESULTS

START-UP RESULTS



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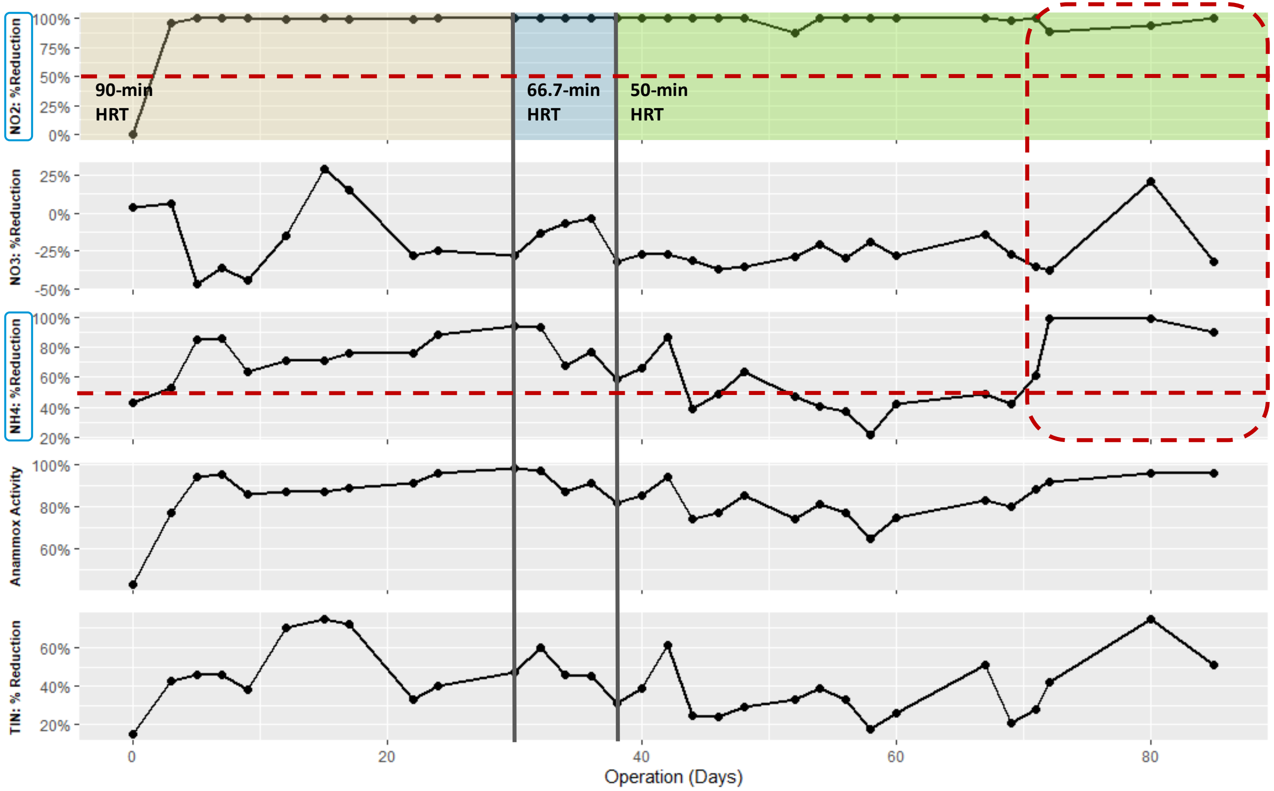
Start-Up Results (Post-COVID-19 Shutdown)

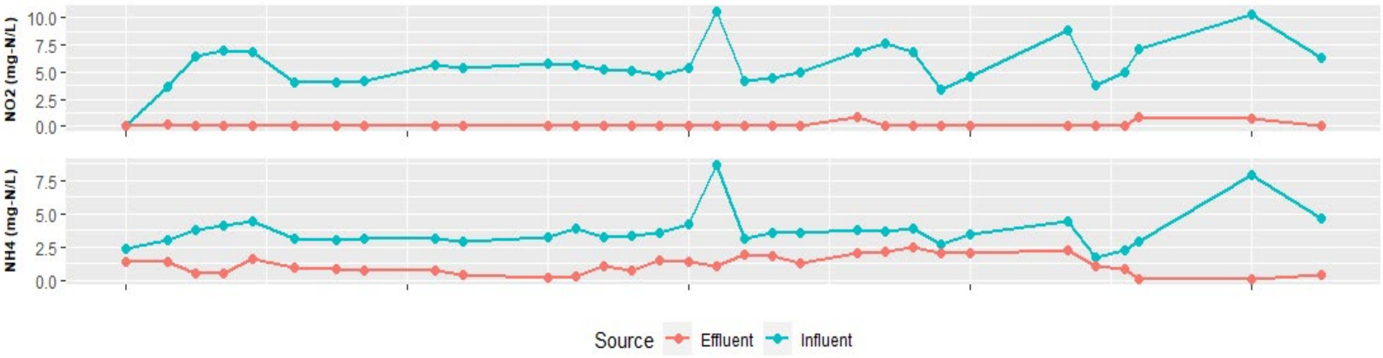


Start-Up Results

1. DO Profile Performed (Top 3-ft):
   a) Assuming 3.51 - 5.0 mg/L of DO removal within the first 1 ft of filter media (nitrification)

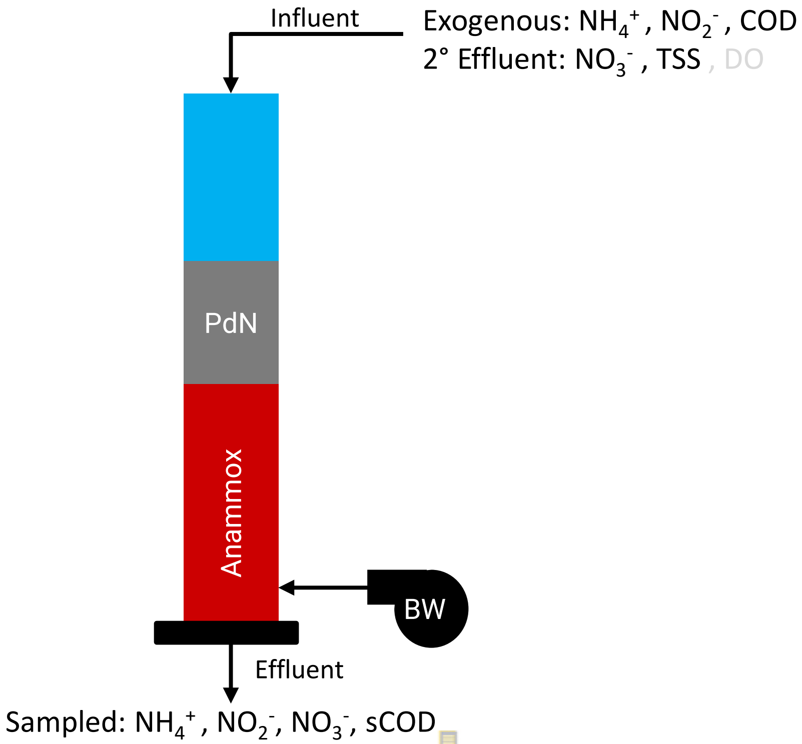
2. Assuming a nitrogenous oxygen demand (NOD) of 4.6 mg O_2 /mg NH_3
   a) 0.76 - 1.09 mg NH_3/L removal could be attributed to nitrification

Sampling Location	DO (mg/L)
Headwater	5.46
Port 1	1.95
Port 2	1.92
Port 3	1.98

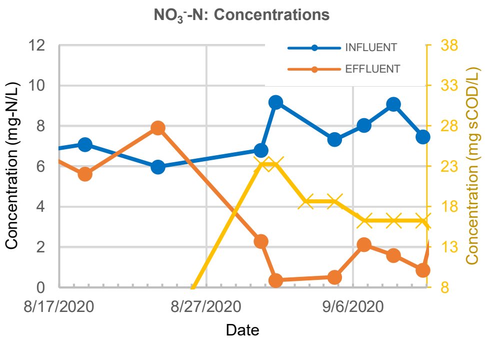


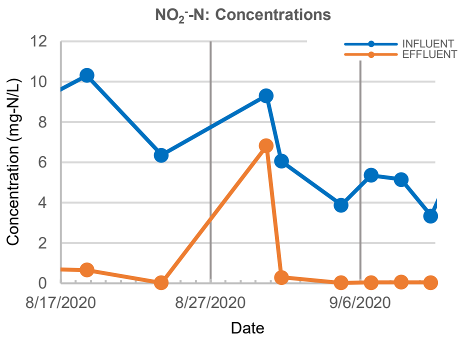
Problem: Multiple biological pathways possible (AOB, NOB, Denitrification, ANMX)

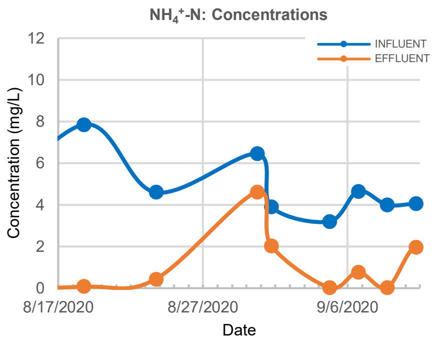
PHASE 1: SUPPLEMENTAL CARBON



Phase 1: Supplemental Carbon







Observations:

1. Sudden fluctuation in nitrite removal attributed to out-selection of NOB:
   a) Clear shift from nitrite oxidation (NO) to Anammox signaled NOB no longer dominating Anammox community

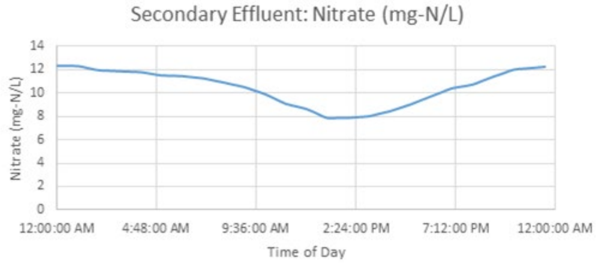
2. Also, spike in nitrite signified initial PdN (NO_3^- to NO_2^-), followed by a drop in to NO_2^- once nitrite reducing bacteria were established (Used residual carbon)

3. The only pathway for ammonia removal within the reactor was through Anammox

PHASE 1: SUPPLEMENTAL CARBON

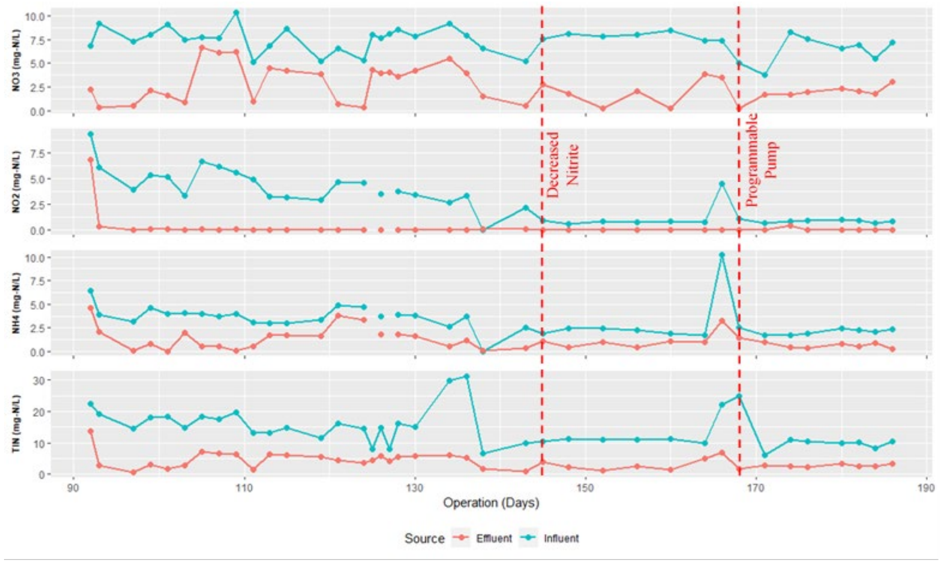
1. **Supplemental carbon** loading:
   a) Target carbon loading relied on maintaining at least 1.5-2.0 mg/L of nitrate residual
   b) Carbon loading designed for heterotrophic DO reduction:
      i. Assuming a Heterotrophic Yield for Substrate = .54 mgCOD/mgCOD
      ii. Avg. DO of Influent = 5.0 mg/L

2. Pilot scale reactors lacked automation & carbon adjustment for diurnal loading conditions:
   a) Ismatec Reglo ICC Digital (pyserial) Peristaltic Pump to match diurnal loading
      i. Improvements were seen in managing nitrate residual

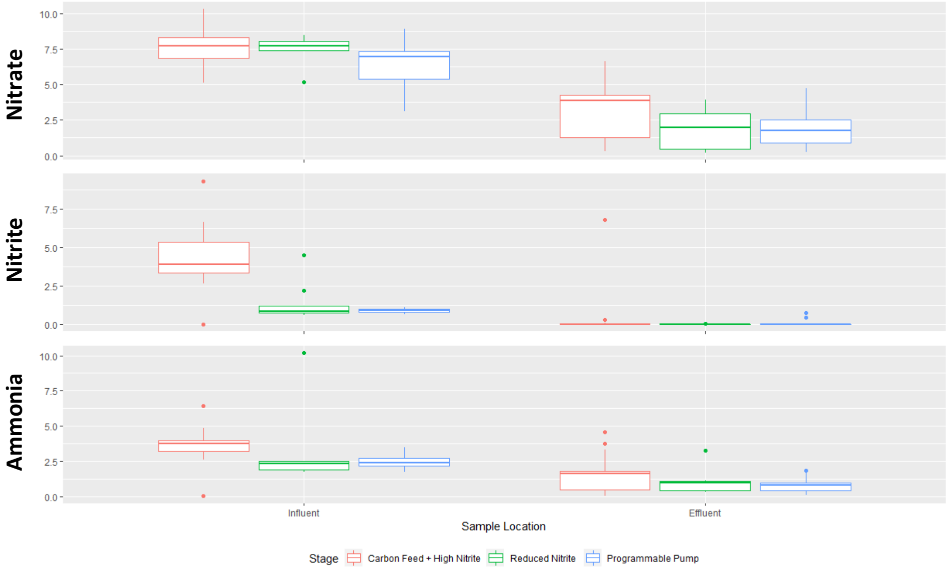


Phase 1: Supplemental Carbon
Operational Conditions

1. Within Phase 1 of experimentation (50 min HRT), study was divided into 3 distinct operational conditions:
    I. Loading a target 1:1.6 (NH_4^+ to NO_2^- ratio) while targeting a nitrate residual of 1.5-2.0 mg-N/L
    II. Decrease in exogenous nitrite
    III. Programmable pump configuration to meet diurnal loading



Phase 1: Supplemental Carbon



Influent			
	High Nitrite Loading	Decreased Nitrite Loading	Programmable Pump
Nitrate (mg-N/L)	7.73	7.69	6.95
Nitrite (mg-N/L)	3.88	0.85	0.90
Ammonia (mg-N/L)	3.78	2.36	2.39

Effluent			
	High Nitrite Loading	Decreased Nitrite Loading	Programmable Pump
Nitrate (mg-N/L)	3.86 (50.0%)	1.97 (74.4%)	1.76 (74.7%)
Nitrite (mg-N/L)	0.0170 (99.6%)	0.0025 (99.7%)	0.0055 (99.4%)
Ammonia (mg-N/L)	1.61 (57.4%)	0.96 (59.3%)	0.802 (66.5%)

Phase 1: Supplemental Carbon

What signified the success of a PdNA filter:

1. Ammonia Removal
2. Nitrite Accumulation

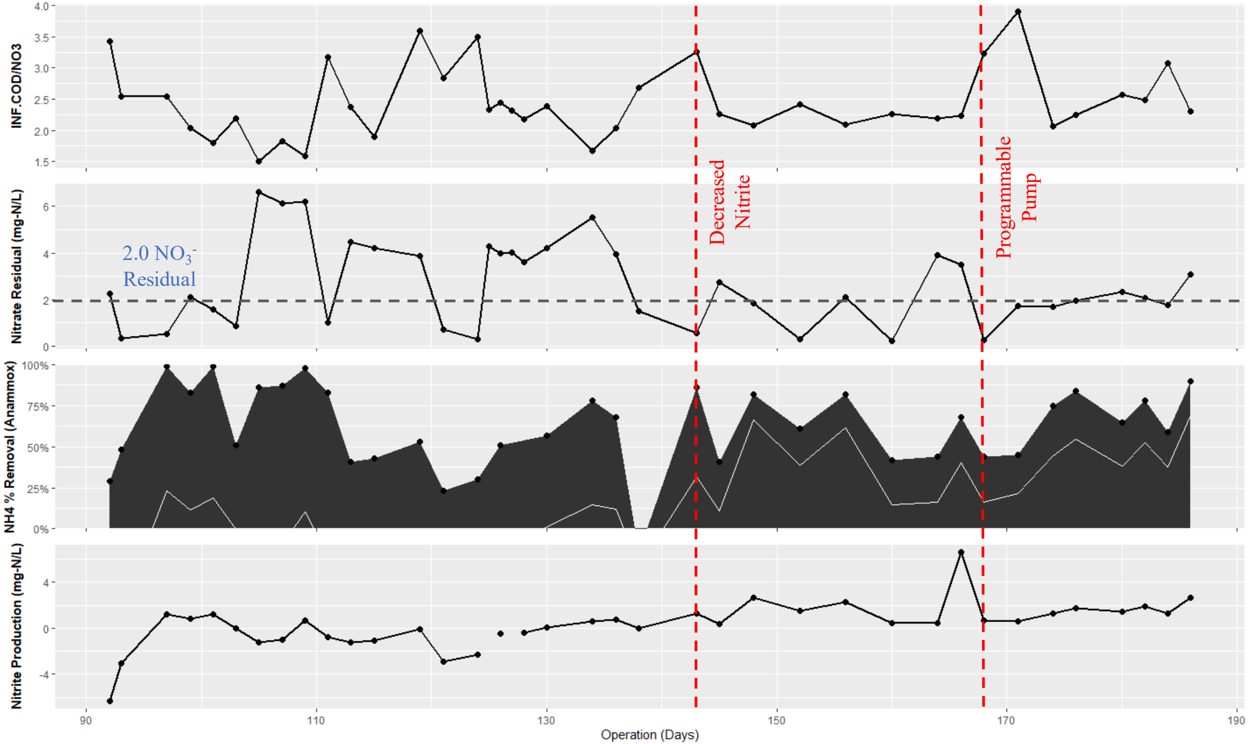
Equations were developed to evaluate the performance of the PdNA filter:

$$\boldsymbol{Nitrite\ Production_{Theoretical\ PdN}}$$
$$= [(INF.NH_4^+ - EFF.NH_4^+) \times 1.6] - INF.NO_2^-$$

$$\boldsymbol{NH_4^+}\ \%\ \boldsymbol{Removal_{(Overall\ Anammox\ Pathway)}} = \frac{INF.NH_4^+ - EFF.NH_4^+}{INF.NH_4^+} \times 100\%$$

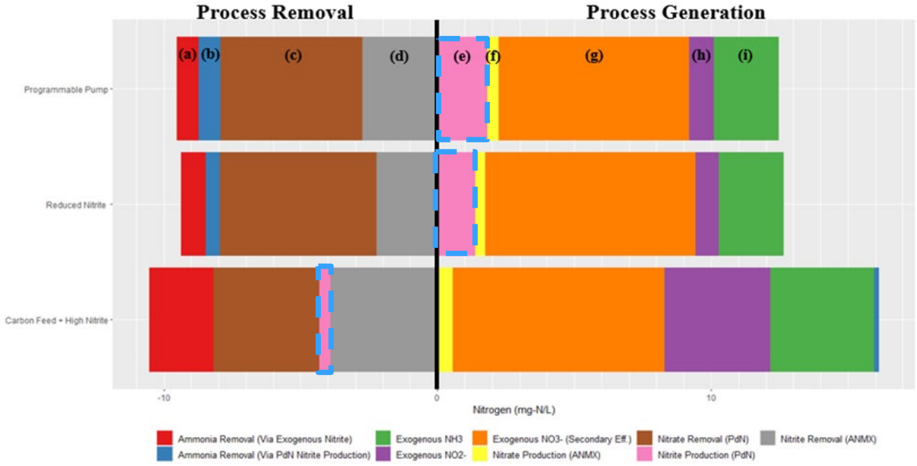
$$\boldsymbol{NH_4^+}\ \%\ \boldsymbol{Removal_{(Normalized)}} = \frac{\left|INF.NH_4^+ - \left(\frac{INF.NO_2^-}{1.6}\right)\right| - Eff.NH_4^+}{INF.NH_4^+} \times 100\%$$

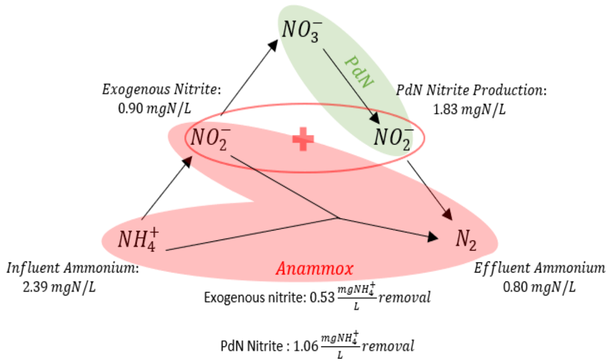
Phase 1: Supplemental Carbon



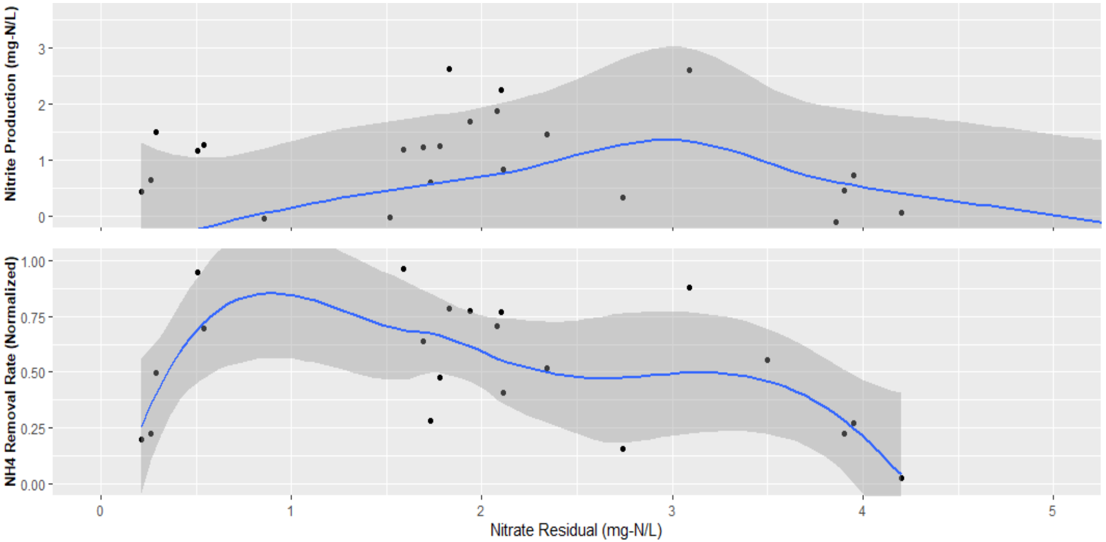
1. 87% ammonia percent reduction
2. >60% ammonia removal attributed to nitrite accumulation via PdN
3. PdN: 2.61 mg-N/L of nitrite accumulation (63% conversion efficiency)

Phase 1: Supplemental Carbon



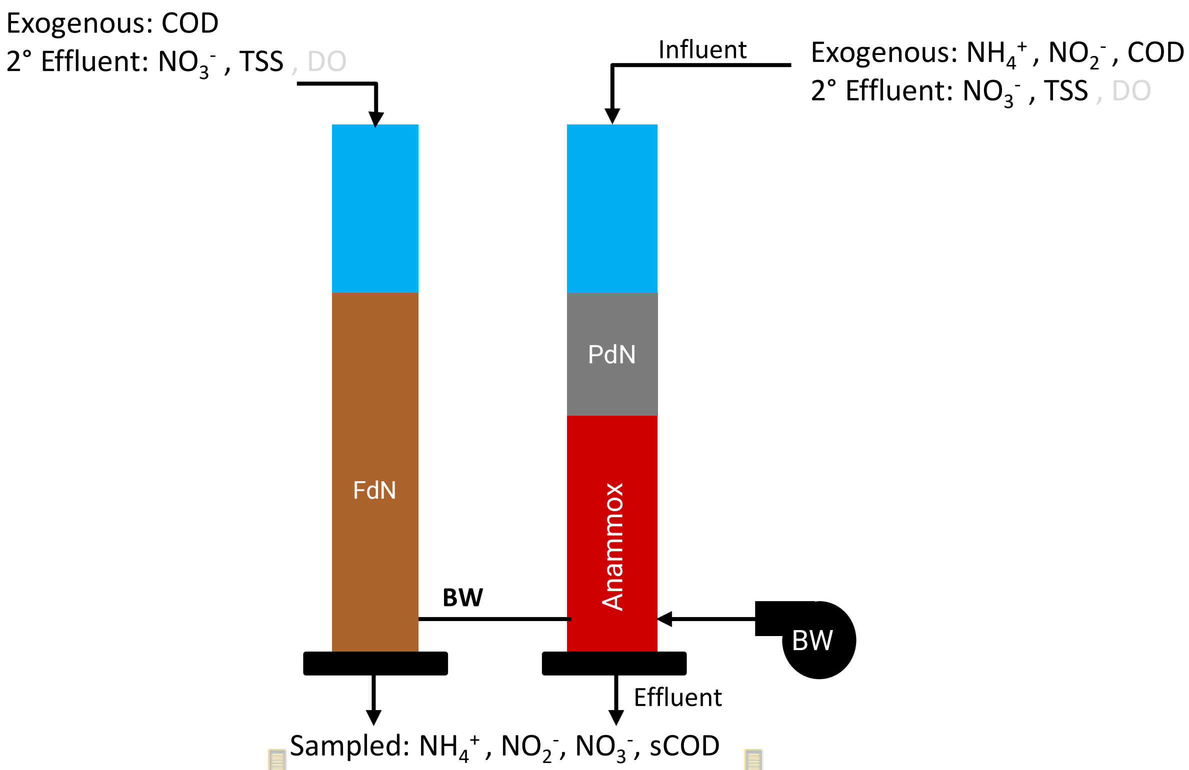


Phase 1: Supplemental Carbon



1. **Operational conditions were compiled**
2. **PdN activity was observed while maintaining >1.5 mg-N/L nitrate residual:**
   a) Nitrite accumulation
   b) Steady ammonia removal

PHASE 1: SUPPLEMENTAL CARBON



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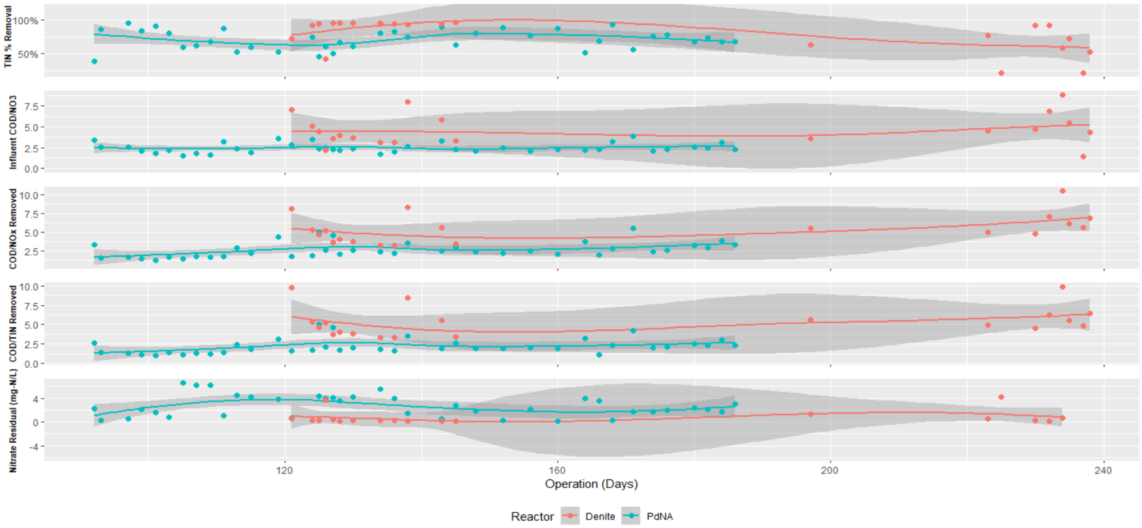
Phase 1: Supplemental Carbon



1. **PdNA vs. FdN C/N ratios demonstrated the viability of the configuration:**
   a) Published methanol FdN ratios of 5.19 gCOD/gTIN (Mokhayeri et al. 2009)
   b) Pilot FdN median C/N ratio of 5.1 gCOD/gTIN
   c) PdNA median C/N ratio of 2.08 gCOD/gTIN; advantageous

2. **PdNA especially advantageous when comparing:**
   a) Theoretical glycerol FdN C/N ratio of 6.35 gCOD/gNO3-N (Bill et al. 2009)
   b) PdNA median C/N ratio of 2.37 gCOD/gNO3-N

PHASE 2: PDNA FEASIBILITY AT TYPICAL FILTER LOADING RATES

1. Pushed past 50 min HRT and planned to follow schedule to reach typical filter loading rate:

Reactor #1 @ Start of Denite Filter	Task 2 Phase 1 (9/24)	Task 2 Phase 2 (10/01)	Task 2 Phase 3 (10/08)	Task 3 Phase 1 (10/15)	Task 3 Phase 2 (10/22)	Task 3 Phase 3 (10/29)	Task 3 Phase 4 (Feasible?)
Secondary Effluent Feed							
HRT (min)	37.50	37.50	37.50	32.00	26.50	21.00	15.50
Sec Eff Q (mL/min)	889.60	889.60	889.60	1042.50	1258.87	1588.57	2152.25
Filter Loading Rate (gpm/sf)	1.20	1.20	1.20	Unachievable			
Note:	COD/N Testing (3.0 COD/N?)	COD/N Testing (2.5 COD/N?)	COD/N Testing (2.0 COD/N?)				

2. Pilot Scale PdNA filters could not reach typical filter loading rates (2.9 gpm/sf):
   a) Cold weather (increased glycerol viscosity)
   b) Small diameter filters
   c) Caking on the surface of filter
3. As a result, filter profiles performed to simulate reduced HRTs and typical filter loading rates

Phase 2: PdNA Feasibility at Typical Filter Loading Rates

Two Specific Filter Profiles:

PdNA (01/08/2021)					
Port	NO_2^-	NH_3	NO_3^-	COD	HRT
Inf	0.07	0.91	5.59	16.90	0
1	0.27	0.02	0.98	0.00	8.3
3	0.14	0.04	0.72	0.00	25.0
5	0.17	0.04	1.12	0.00	41.7

FdN					
Port	NO_2^-	NH_3	NO_3^-	COD	HRT
Inf	0.066	0.908	5.59	25.1	0
1	0.065	0.9	0.5	0	8.3
3	0.055	0.91	0.54	0	25.0
5	0.002	0.923	0.6	0	41.7

Carbon Loading & No Exogenous Nutrients

81% TIN removal (FdN: 78% TIN removal)
98% Ammonia Removal
1.08 mg-N/L Nitrite Accumulation
C/N Ratio: 3.19 gCOD/gTIN (4.92 gCOD/gTIN)

PdNA (01/10/2021)					
Port	NO_2^-	NH_3	NO_3^-	COD	HRT
Inf	1.212	2.76	5.3	0.00	0
1	0.469	1.964	4.66	0.00	8.3
3	0.083	1.58	4.34	0.00	25.0
5	0.009	1.55	4.23	0.00	41.7

FdN					
Port	NO_2^-	NH_3	NO_3^-	COD	HRT
Inf	0.047	0.147	5.30	0.00	0
1	0.012	0.086	5.23	0.00	8.3
3	0.016	0.017	4.68	0.00	25.0
5	0.012	0.039	4.28	0.00	41.7

No Supplemental Carbon (Nutrients added):

33% TIN removal (FdN: 3% TIN removal)
44% Ammonia Removal
Nitrite all consumed by ANMX

Techno-Economic Analysis (OPEX)

Components of Typical Techno-Economic Analysis:

TOTEX (Total Expenditure) = OPEX (Operational Expenditure) + CAPEX (Capital Expenditure)

Our Focus:

OPEX: Over the life of the treatment facility OPEX contributes foremost to TOTEX

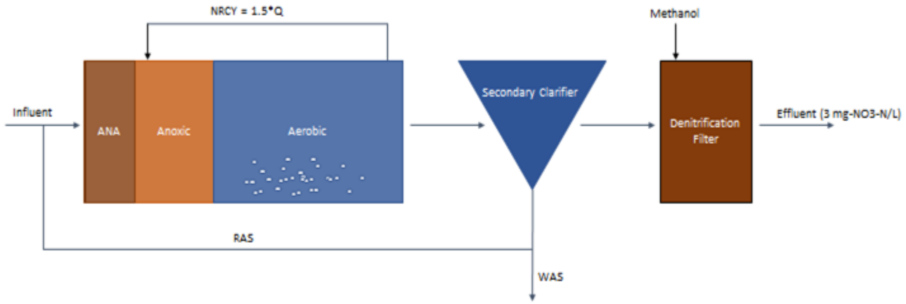
Compared PdNA and conventional configuration, key information regarding plant design and operational conditions were required:

1. The influent and treated wastewater quality (BOD, Ammonia, NOx, and TSS)
2. Energy required for blowers/pumps (Aeration, NRCY, and WAS Pumps)
3. Supplemental carbon loading

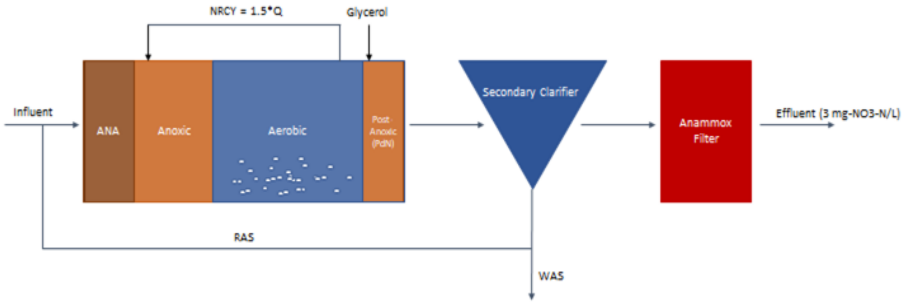
Costs	
Glycerol	2.25 $/gal
Methanol	1.50 $/gal
NC Electricity Rate	.0866 $/kWh

Influent Characteristics	
Flow	16 mgd
cBOD	200 mg/L
TKN	40 mg/L
Ammonia	26 mg/L
Nitrite	0 mg/L
Nitrate	0 mg/L

Techno-Economic Analysis (OPEX):
Configurations



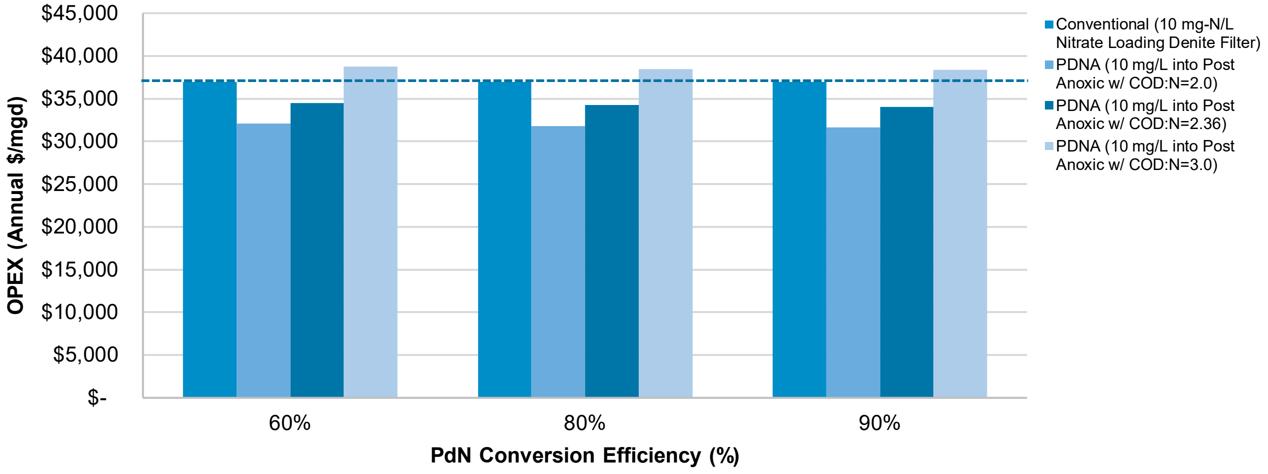
Conventional A²/O + Denitrification Filter Configuration



A²/O (3-Stage MLE + Post-Anoxic PdN) + Anammox Filter Configuration

Techno-Economic Analysis (OPEX):
Findings

OPEX Comparison Plot:



1. **Comparing conventional configuration to the best-case PdNA configuration:**
   a) 14% reduction in OPEX
   b) Annual savings of $5,160 per mgd treated.

2. **With pilot PdNA filter, C/N ratio of 2.36 g COD/g NO_3^-:**
   a) 7% reduction in OPEX
   b) C/N ratio of 2.8 g COD/g NO_3^- is the breakeven

CONCLUSIONS

1. **PdNA works in a Single-Stage Filter:**

    a. Retaining >1.5 mg/L of nitrate residual allows for highest PdN efficiency

    b. > 50% reductions in supplemental carbon

    c. Reduction in supplemental carbon & aeration requirements:
    - PdNA has the potential to reduce OPEX by 14% and provide substantial savings in CAPEX

    d. We have only been able to show that PdNA is feasible at filter loading rates up to around 1.0 gpm/sf. (Profiles did prove feasibility at typ. filter loading rates)

2. It is clear carbon feed control is essential to highly efficient reactors

3. Couldn't answer all our questions due to infrastructure challenges:

    a. Research suggests PdNA is feasible for full scale treatment facilities after additional refinement and process controls!

QUESTIONS?

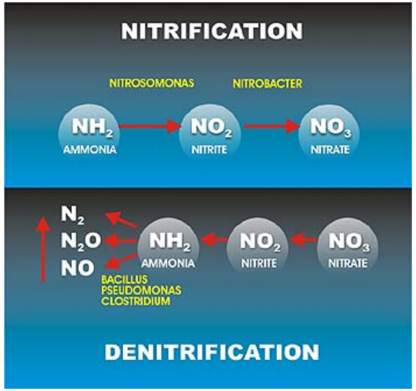
STOICHOMETRIC RELATIONSHIPS

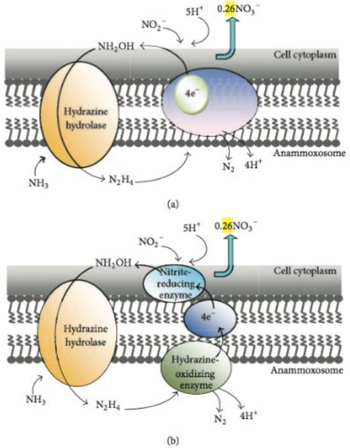
PdN Reaction:

$$C_3H_8O_3 + 5.25\ NO_3^- + 0.13\ H^+ \rightarrow 2.33\ CO_2 + 5.12\ NO_2^- + .13\ C_5H_7O_2N + 3.59\ H_2O$$

Anammox Reaction:

$$NH_4^+ + 1.32\ NO_2^- + 0.066\ HCO_3^- + 0.13\ H^+ \rightarrow 0.26\ NO_3^- + 1.02\ N_2 + 0.066\ CH_2O_{0.5}N_{0.15} + 2.03\ H_2O$$





PHASE 2: PDNA FEASIBILITY AT TYPICAL FILTER LOADING RATES (PROFILE LOADING RATES)

Location	HRT (min)	Q (L/min)	Loading Rate (gpm/ft^2)
Headwater	0.0	0.00	0.00
Port 1	8.3	4.00	5.39
Port 2	16.7	2.00	2.69
Port 3	25.0	1.33	1.80
Port 4	33.3	1.00	1.35
Port 5	41.7	0.80	1.08
Port 6	50.0	0.67	0.90
Effluent	50.0	0.67	0.90