Treatment Intensification for Resource Recovery: Advances in Granules and Membrane Bioreactor Technologies

Wednesday, December 5, 2018

12:00-2:00 pm ET

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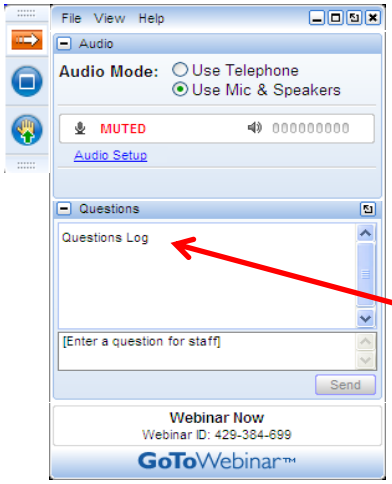
How to Participate Today



- **Audio Modes**
  - Listen using Mic & Speakers
  - Or, select "Use Telephone" and dial the conference (please remember long distance phone charges apply).
- **Submit your questions using the Questions pane.**
- **A recording will be available for replay shortly after this web seminar.**

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Today's Moderator

Christine Radke, PMP
Research Program Director
The Water Research Foundation

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Agenda

Time	Presentation	Speakers
12:00 pm	Welcome and Introductions	Steven Massa, *WEF* Christine Radke, *WRF*
12:05 pm	National Science Foundation's GOALI Projects and MOU with the Water Research Foundation	Karl Rockne, *NSF*
12:15 pm	Bioaugmentation of activated sludge with high activity nitrifying granules/flocs: population selection, survival, biokinetics (TIRR3C15)	David Stensel and Mari Winkler, *University of Washington*
12:45 pm	Advancing the oxygenic photogranule process for energy positive wastewater treatment (TIRR4C15)	Chul Park, *University of Massachusetts-Amherst*
1:15 pm	Biofilm-enhanced anaerobic membrane bioreactor for low temperature domestic wastewater treatment (TIRR5C15)	Steven Skerlos, Lut Raskin, and Tim Fairley, *University of Michigan*
1:45 pm	Q&A	All
2:00 pm	Adjourn	

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National Science Foundation and WRF's Co-Funded Research

Karl Rockne, Ph.D., PE, BCEE
Program Director
Environmental Engineer Program
Division of Chemical, Bioengineering, Environmental and Transport Systems
National Science Foundation

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Bioaugmentation of activated sludge with high activity nitrifying granules/flocs: population selection, survival, biokinetics

H. David Stensel, Ph.D., PE, BCEE, WEF Fellow
Professor Emeritus
Civil & Environmental Engineering
University of Washington

Mari Winkler, Ph.D.
Assistant Professor
Civil & Environmental Engineering
University of Washington

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Bioaugmentation of activated sludge with high activity nitrifying granules/flocs: population selection, survival, biokinetics
WRF TIRR3C15

December 5, 2018
Professor David Stensel
Professor Mari Winkler
University of Washington

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University of Washington Project NSF/WRF GOALI

1. Bioaugment nitrification with nitrifying granules for low SRT continuous flow systems
2. Convert continuous flow systems to granular/floc activated sludge with nitrification, N removal, and possibly EBPR

Professor H David Stensel
Professor Mari Winkler
Professor David Stahl
Maxwell Armenta, MSCE student
Bao Quoc, PhD Student – NSF
Bob Bucher, King County
Pardi Sukapanpotharam, KC

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Agenda

- Granular sludge characteristics and selection
- Bioaugmentation process description
- Project Status
- Sidestream pilot system treatment performance

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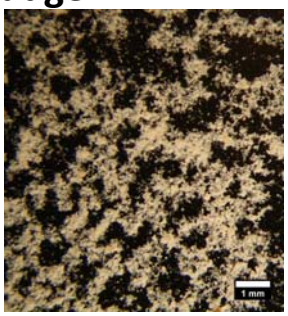
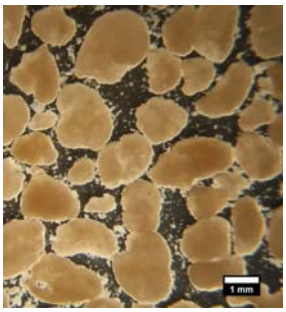
Granular sludge is more compact, settles faster, and thickens better than flocculent sludge





Parameter	Flocs	Granules
Morphology	Loose, irregular	Regular, compact, smooth
Particle size	Small (<400 um)	Large (0.5 - 3 mm typical)
Sludge Vol. Index (SVI)	~120 mL/g	20-50 mL/g
Settling velocity	Slow (~1 m/hr)	Fast (>10 m/hr)
SVI_{5min} / SVI_{30min}	~2.0 (slow thickening)	1.0 - 1.1 (rapid thickening)

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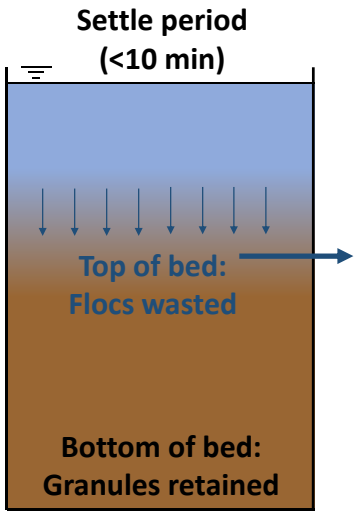
Fundamental selection mechanisms for granules over flocs demonstrated in Nereda® SBR process

- **Hydraulic selection** by short settling times
  - Granules settle faster than floc
  - Upper liquid wasted with slower settling floc
- **Food competition** -Granules get preferential access to food during upflow anaerobic feeding
- **High F/M** feeding provides diffusion gradient to allow substrate uptake deep in the granules



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Advantages of Granular Sludge Biological Nutrient Removal

- High mixed liquor concentration (in range of 8,000 mg/L)
- Less tank volume
- Biological nitrogen and phosphorus removal in simpler flow scheme
- Less energy
- **Increase capacity and/or nutrient removal with less capital cost for retrofits**

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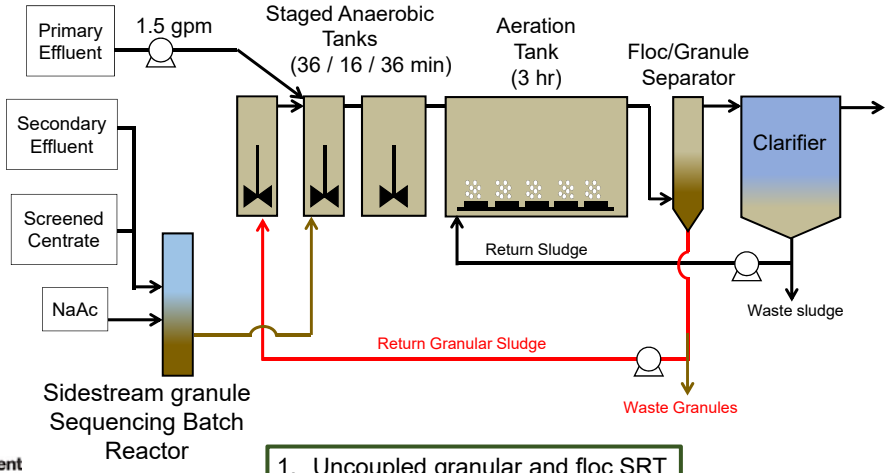
UW Bioaugmentation System with Sidestream Nitrifying Granular Activated Sludge



1. Uncoupled granular and floc SRT
2. Anaerobic/Aerobic with SND

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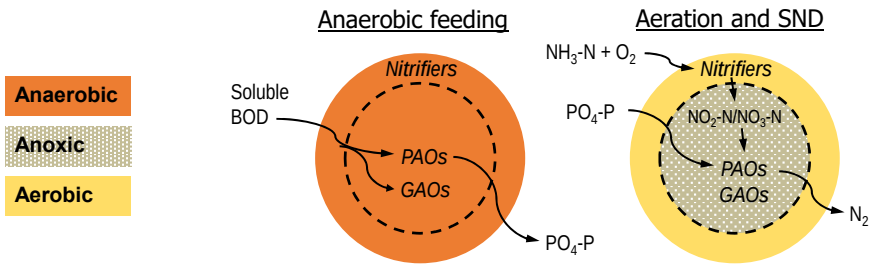
Anaerobic-aerobic operation provides granules with EBPR and simultaneous nitrification/denitrification



PAOs = phosphorus-accumulating organisms
GAOs = glycogen-accumulating organisms

- Same carbon used for PAO/GAO growth and denitrification
- DO controlled to provide simultaneous nitrification/denitrification
- Denitrification provides alkalinity for full nitrification of centrate

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General Aims of Project

I. Demonstrate and evaluate effectiveness of nitrification bioaugmentation by the addition of nitrifying granular activated sludge to mainstream treatment

- Growth of aerobic granules on centrate
- Preferred operating conditions
- Survival and growth of granules in mainstream
- Kinetics and biopopulation characteristics

II. Demonstrate and evaluate the ability to favor AOB over NOB and accomplish short-cut nitrogen removal in sidestream and mainstream

- Operating conditions
- Ability to uncouple granule and flocculent sludge
- Biopopulation characteristics

Test systems and data Collection Design appl.

Dave Stensel

Scientific Advisor Microbial Ecology

Dave Stahl

Microbial and Granule character. Kinetics, models

Mari Winkler

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Project Status

- Start up and successful long-term operation of sidestream reactor
  - Evaluating effects of important sidestream operating factors
    - ✓Feed COD:N
    - ✓SRT
    - ✓Feeding COD gradient (short versus long feed period)
    - ✓DO control
    - ✓Settling time
- Testing granular/floc separator designs
- Mainstream in fabrication and installation by King County
  - Start up planned for first week in January 2019

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Pilot Plant Sidestream Centrate Treatment Granular Growth SBR

1-ft diameter
8-ft liquid depth
50% decant depth
6-hour cycle
fine bubble diffuser

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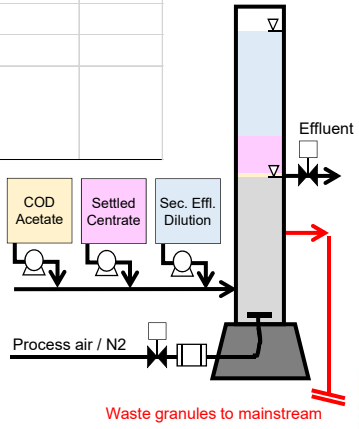
Pilot Sidestream Operation 4 cycles/day 6-hr per cycle

	Anaerobic (min)	Aerobic (hr)	Settle (min)	Decant (min)	Anoxic Idle	Total (hr)
Step Time	55	4.5	7	3	25	6
Premix, N_2	5					
NaAc Feed	10					
Air/Mix		5				
Centrate, Sec. Effl. Feed		15				



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Seeded the sidestream pilot unit with 2.0 ft of 425 um screened King County South Plant mixed liquor

- EBPR anaerobic/aerobic process
- Mixed liquor had about 12% *baby granules* with PAOs

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Start up strategy

- Prevent acetate leakage into the aerobic period
  - Increase acetate load as PAO activity increases
- Promote simultaneous nitrification/denitrification
  - Aeration DO control (~1.8 to 2.2 mg/L)
- Avoid high effluent NO2/NO3
  - Increase proportion of centrate feed as COD load is increased
  - Aim for COD:N feed ratio of 4.0 or less for short cut nitrogen removal
  - Minimize NO3/NO2 remaining at start of acetate feed
- Seed with *baby granules* from King County South Plant
- Gradually decreased settling time

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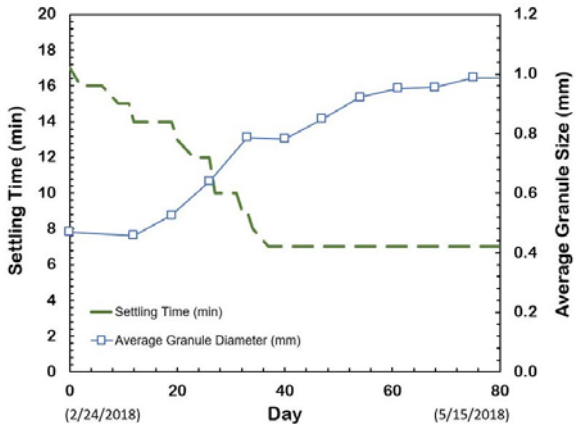
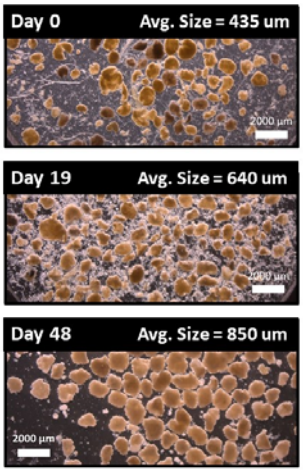
Decreasing settling time after start up increased average granule size (7 min settling time, Solids < 12m/hr settling velocity in effluent)





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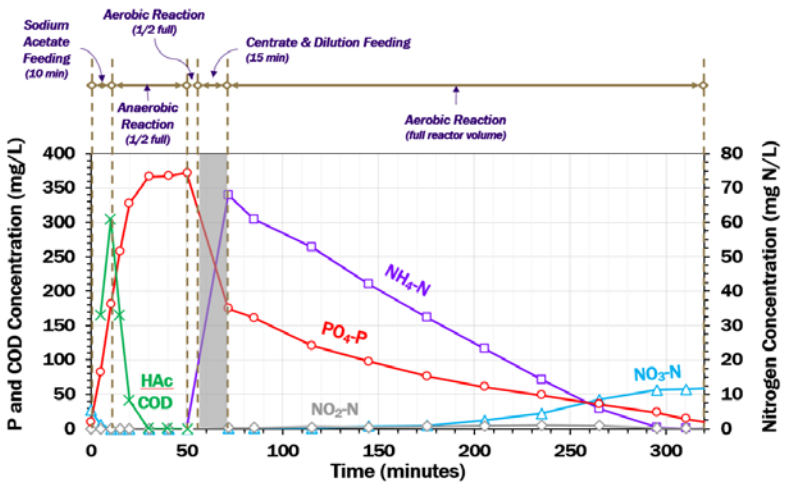
Some Results

Example of weekly profile data

Example of cycle performance (Day 163)



Reactor Parameters

Influent NH3-N
160 mg/L

MLSS
12,300 mg/L

VSS/TSS
73%

P/C Ratio
0.51 mol/mol

Temperature
23°C

SRT
~30 days

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Average Performance (June - September, 2018)

Parameter	Units	June	July	August	Sept
Influent					
NH3-N loading rate	g/L-day	0.46	0.34	0.36	0.38
Feed COD:N ratio	g/g	2.7	3.4	3.5	3.5
Reactor					
SRT, 28-day average	days	86	57	40	41
Average Granule Size	mm	1.24	1.26	1.10	1.16
MLSS	mg/L	14,900	13,600	12,500	12,400
SVI_{30}	mL/g	38	38	31	26
Effluent					
NH3-N	mg/L	51.9	2.4	3.7	5.9
NO2-N	mg/L	11.2	12.1	0.2	0.4
NO3-N	mg/L	0.9	11.2	7.3	10
TSS	mg/L	179	102	72	72

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Nitrogen Removal Performance (June - September, 2018)

Parameter	Units	June	July	Aug.	Sept.
Inorganic N removal	%	71.8	84.2	93.3	90.7
NH3-N Oxidized	%	78.9	98.5	97.9	96.5
SND	%	91.5	85.2	94.4	93.3
COD:N-removed ratio	gCOD/gN	3.5	3.5	3.7	3.7

Assumed 0.024 gN/gCOD for biomass synthesis

Short Cut Nitrogen Removal (NO2 reduction instead of NO3 reduction)
Indicated by low COD:N ratio and low effluent NO3-N.

For acetate:
NO3-N reduction COD:N is 6.0 – 6.5 g/g
NO2-N reduction COD:N is about 3.6 – 3.9 g/g

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Summary

- Centrate sidestream treatment reactor sustained growth of nitrifying granules with 95^{+}% NH3-N removal
- Seeding with harvested granules aided start up
- Decreases in settling time selected for mostly granules
- Granules had settling velocity > 12 m/hr
- Short-cut nitrogen removal observed
- SND efficiencies were 84-94%

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Acknowledgements

King County Dept. of Natural Resources and Parks,
Wastewater Treatment Division / Technology Evaluation Program
Graduate Student Research Fellowship

National Science Foundation

Water Research Foundation
formerly Water Environment & Reuse Foundation,
formerly Water Environment Research Foundation
(project number TIRR3C15)

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GOALI/WERF
BIOAUGMENTATION OF ACTIVATED SLUDGE WITH HIGH ACTIVITY NITRIFYING GRANULES/FLOCS: POPULATION SELECTION, SURVIVAL, BIOKINETICS

PhD student: Bao Nguyen Quoc
University of Washington

Dr. Dave Stensel

Dr. Mari Winkler

Dr. Dave Stahl

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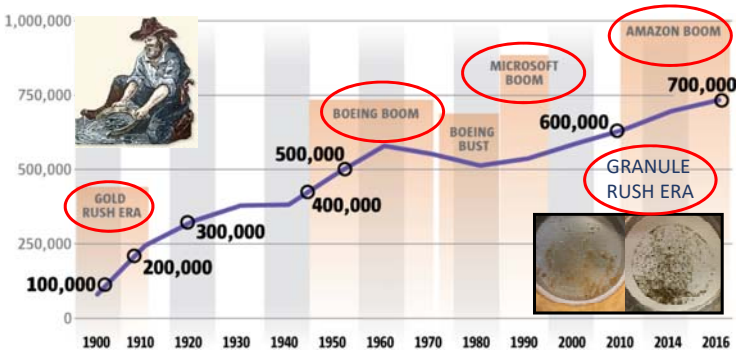
Projected dissolved inorganic nitrogen loads

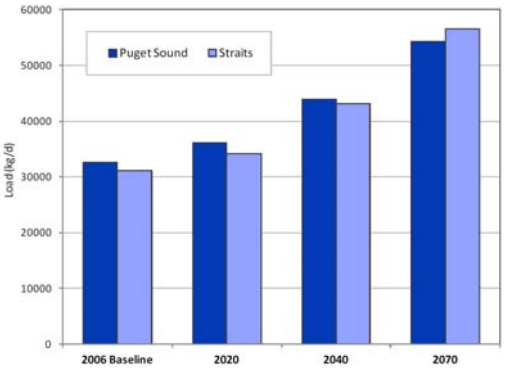
Gene Balk / FYI Guy

Seattle once again nation's fastest-growing big city; population exceeds 700,000

Originally published May 25, 2017 at 6:48 am | Updated May 25, 2017 at 5:55 pm



U.S. Census Bureau, 2016



DoE WA, 2014

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https://www.seattletimes.com/seattle-news/data/seattle-once-again-nations-fastest-growing-big-city-population-exceeds-700000/

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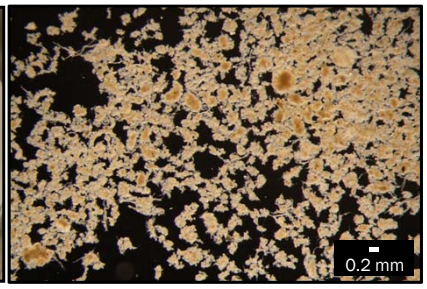
Baby Granules used as seed sludge for pilot

What is a baby granule?

- Shows a granular morphology
- With size > 212 µm

Granules retained on 212 µm sieve Puyallup ML



Microscopic image Puyallup ML

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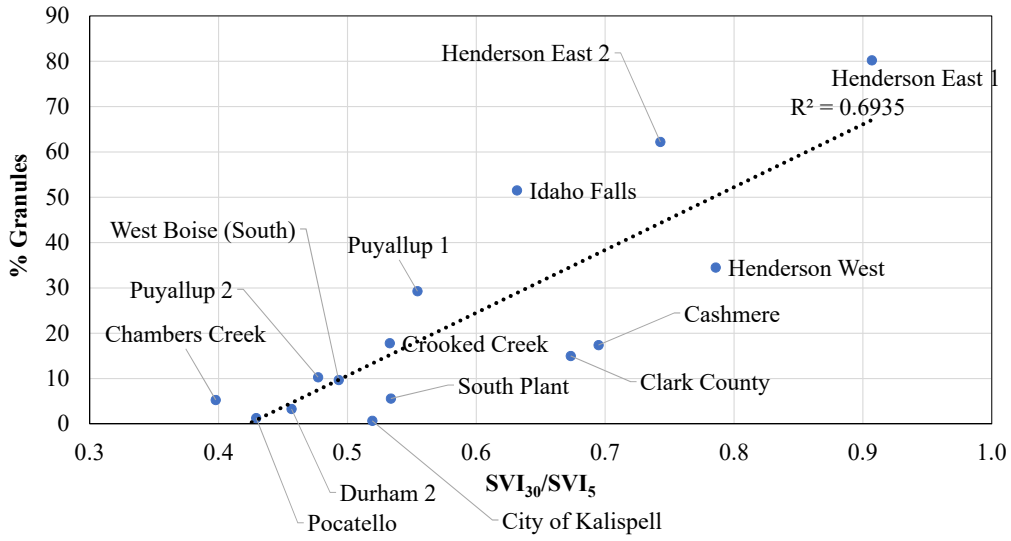
Correlation of % Granules to SVI_{30}/SVI_5



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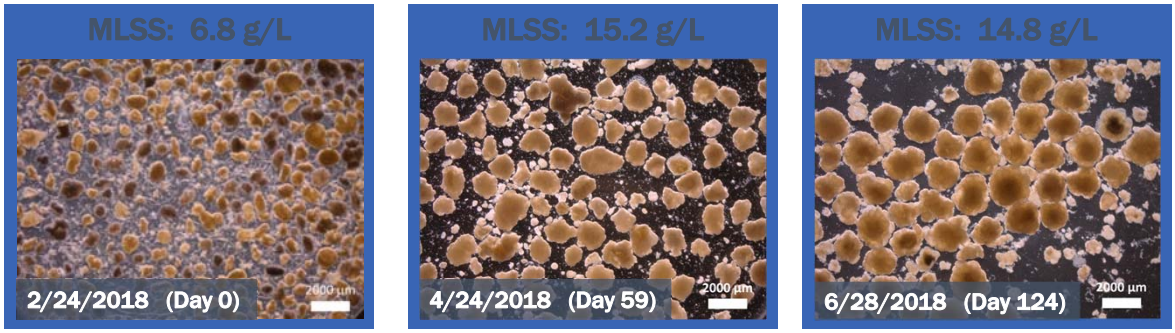
Research on different granules sizes

Why do we need to care about different granule sizes?



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Images from Maxwell Armenta

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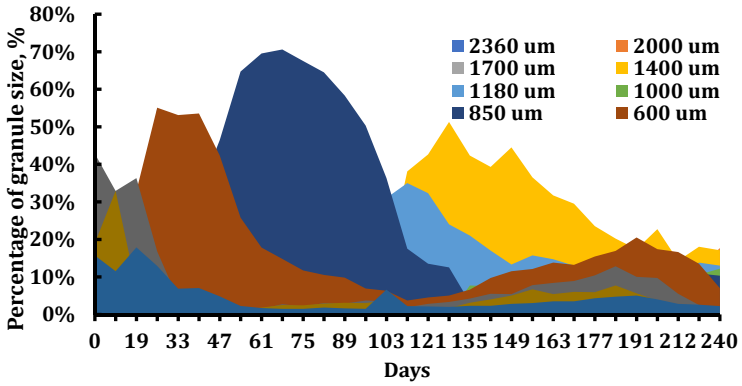
Dynamic granule sizes

- Size not homogenous
- How does microbial activity partitions between granules?
- What is the best granule size?



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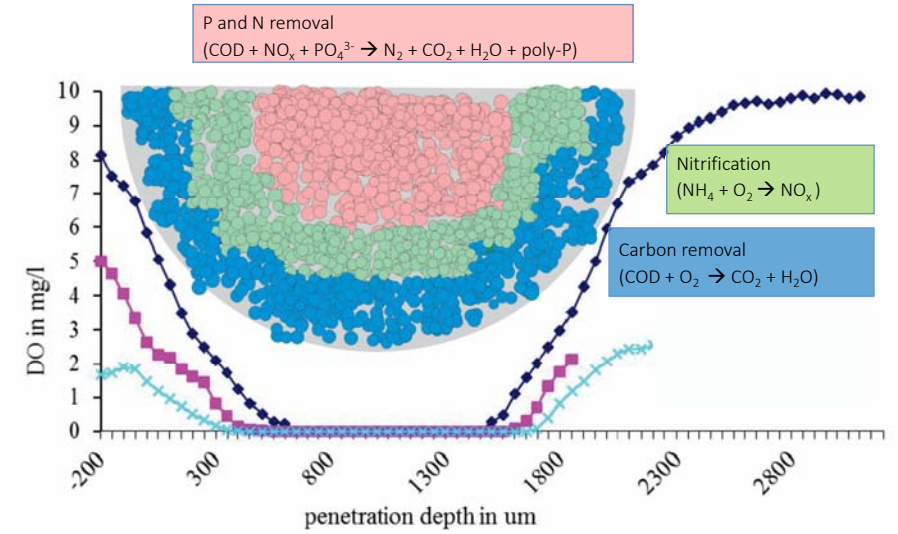
Substrate profile



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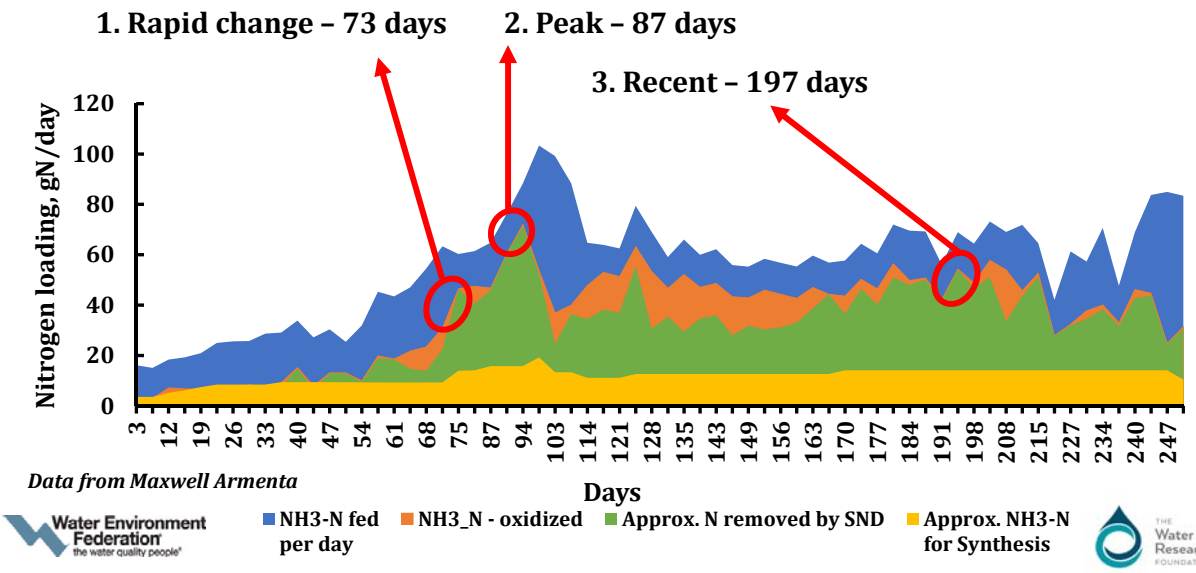
Ammonia loading and removing rate



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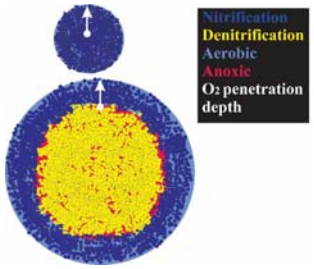
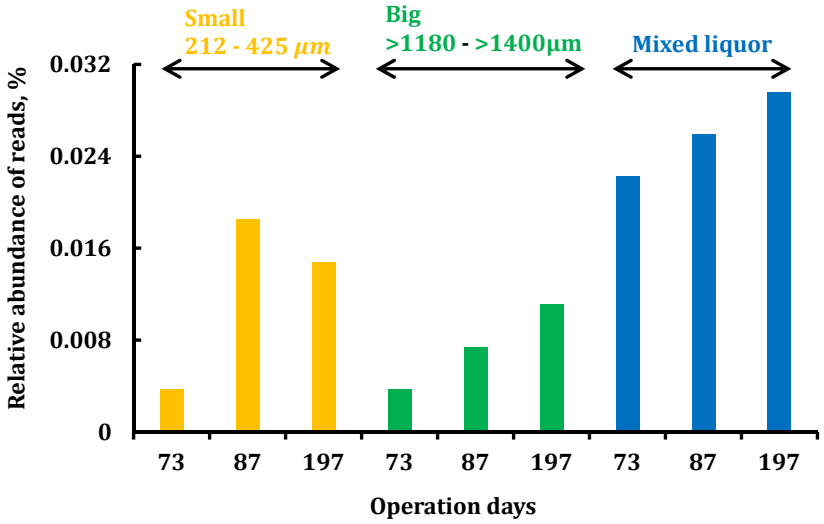
Sequencing: Nitrospira (NOB)

NOB tend to dominate small granules





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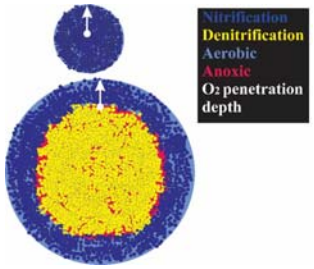
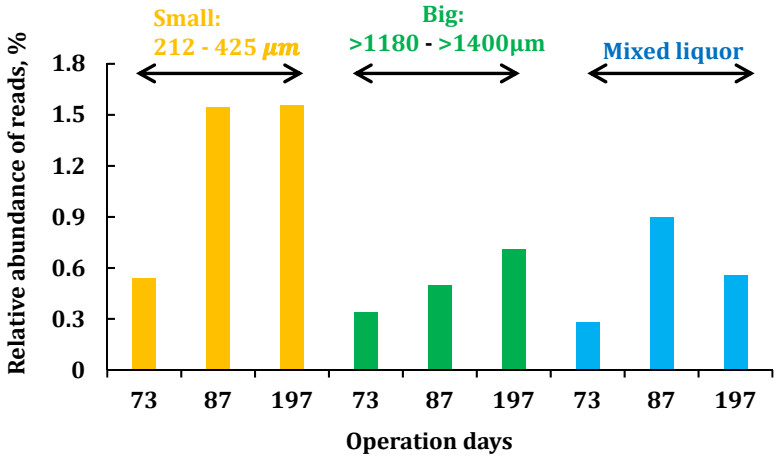
Sequencing: Nitrosomonas (AOB)

AOB tend to dominate small granules





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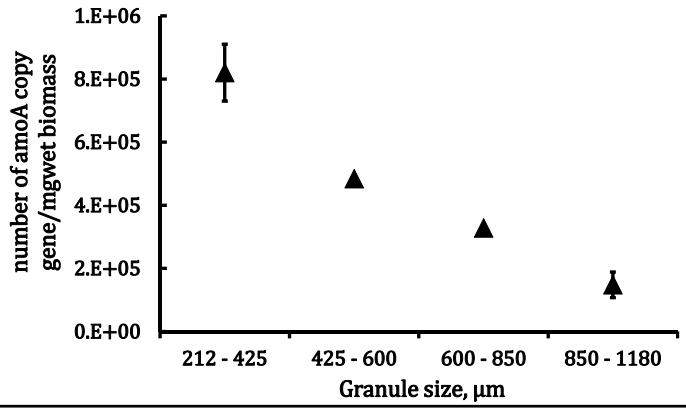
qPCR: amoA genes at different granule sizes

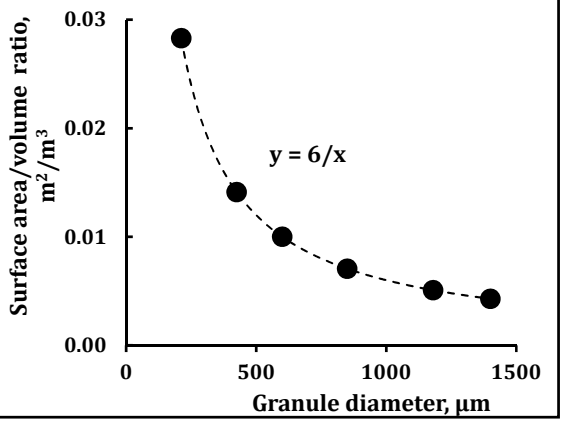
Volume $V = \frac{4}{3}\pi R^3$

Surface area $S = 4\pi R^2$

Surface area/volume ratio $\frac{S}{V} = \frac{6}{D}$

Function $y = \frac{6}{x}$





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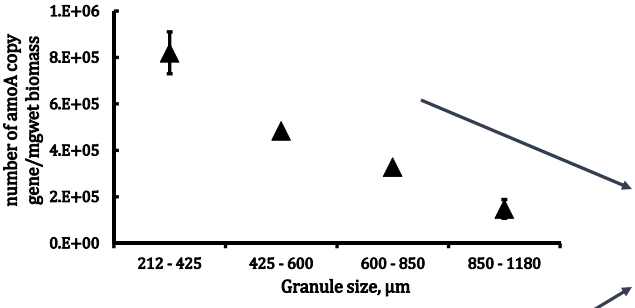
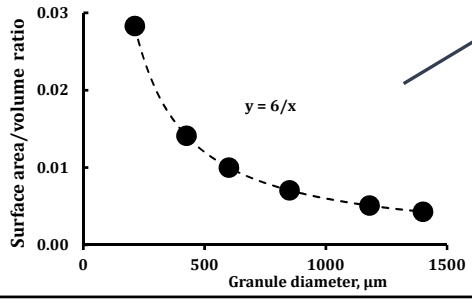
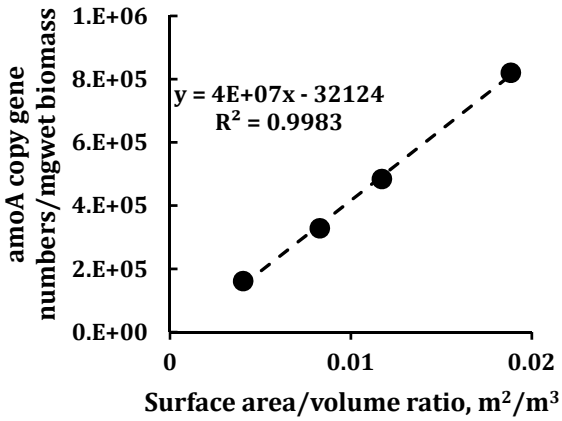
Surface area/volume ratio versus amoA genes







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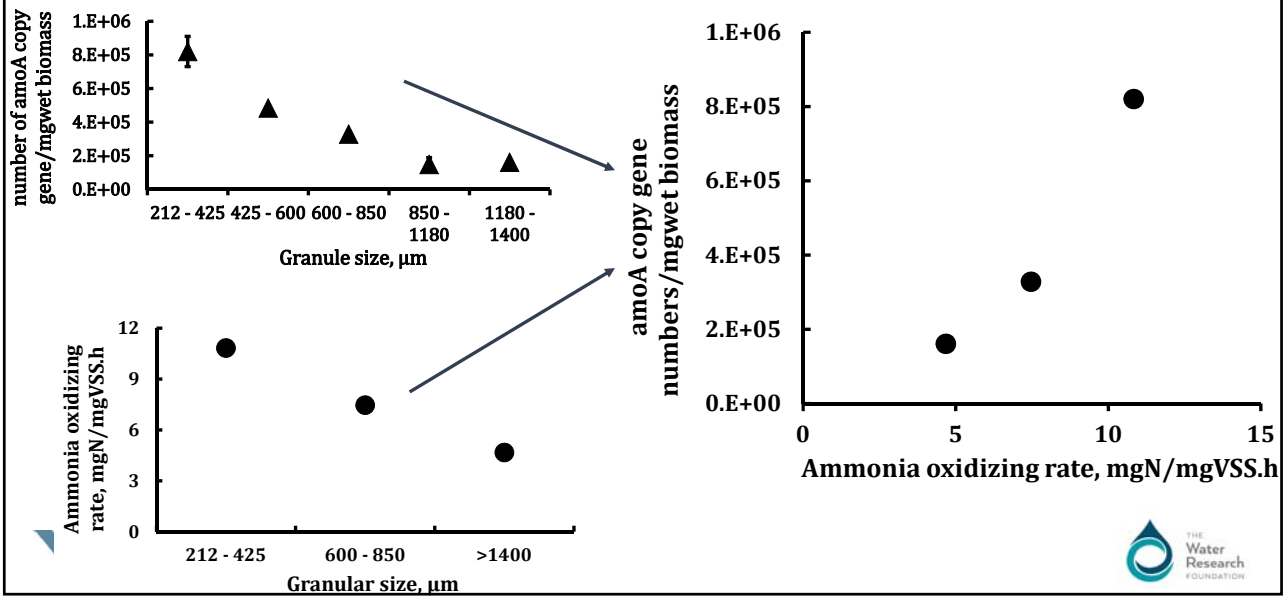
Ammonia oxidization rate versus amoA genes



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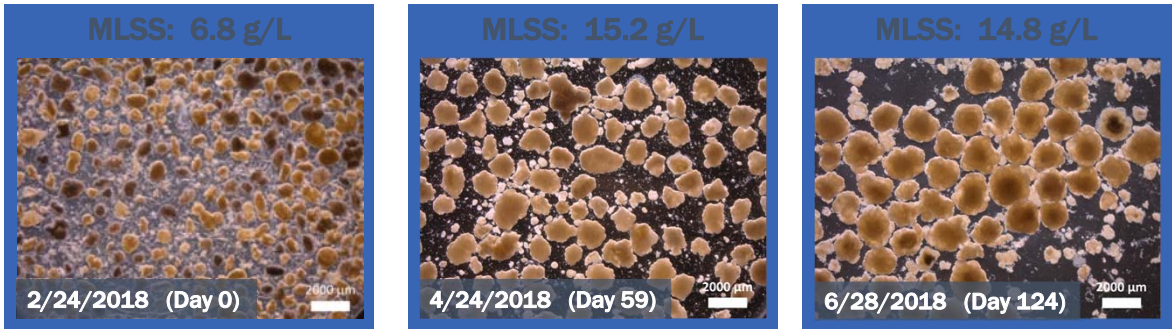
Seed sludge microbial community composition



Images from Maxwell Armenta

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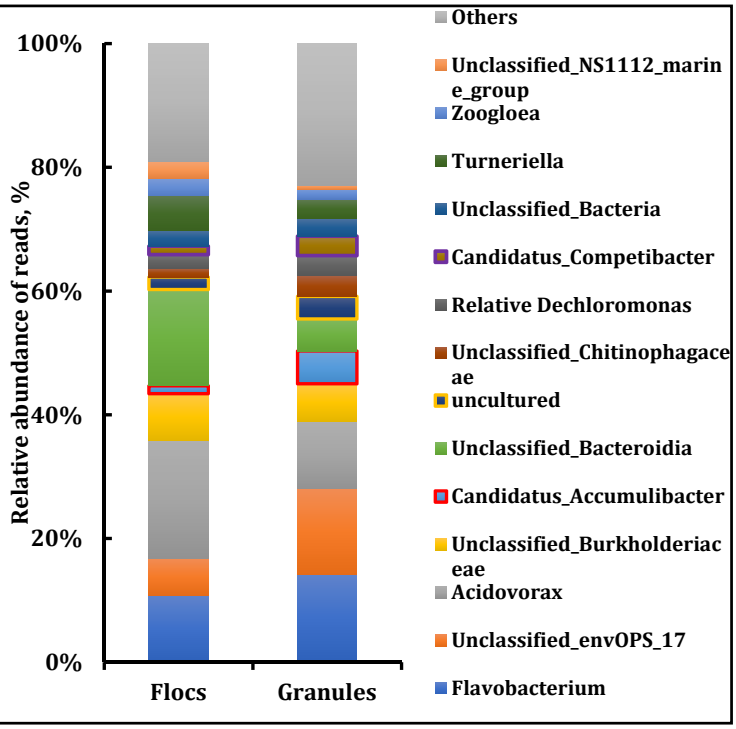
16S rRNA gene sequencing data: South Plant

5.3% of PAO *Accumulibacter*
3.3% of relative *Dechloromonas*
3.1% of GAO *Compactibacter*



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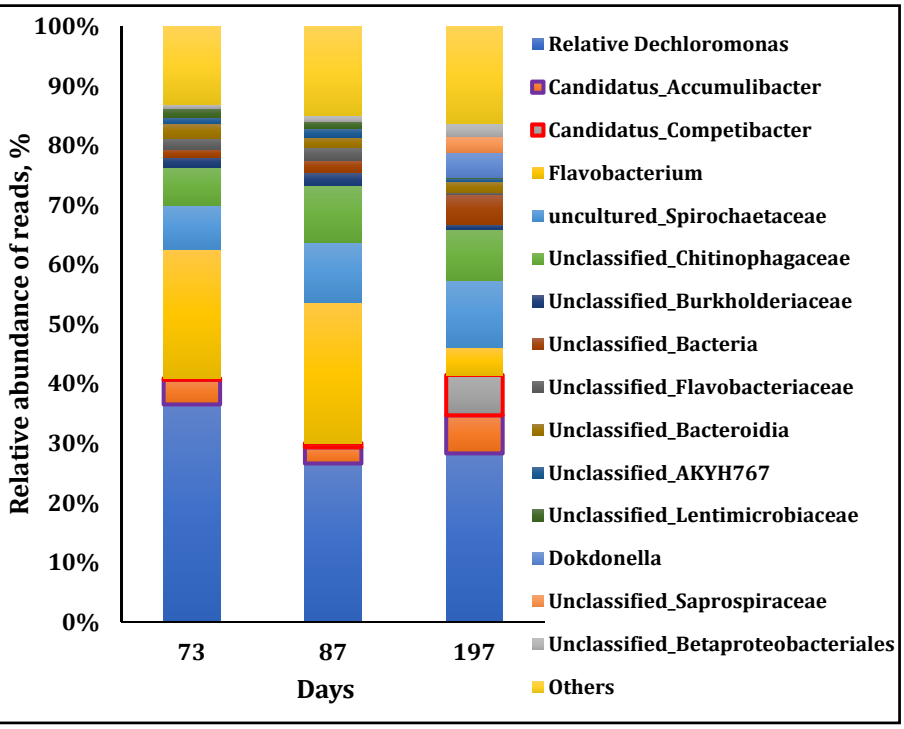
16S rRNA gene sequencing data: Westpoint pilot

5.3% of PAO *Accumulibacter*
3.3% of relative *Dechloromonas*
3.1% of GAO *Compactibacter*

6.4% of PAO *Accumulibacter*
28.3% of relative *Dechloromonas*
6.7% of GAO *Compactibacter*



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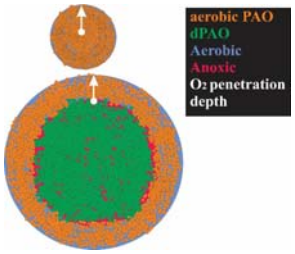
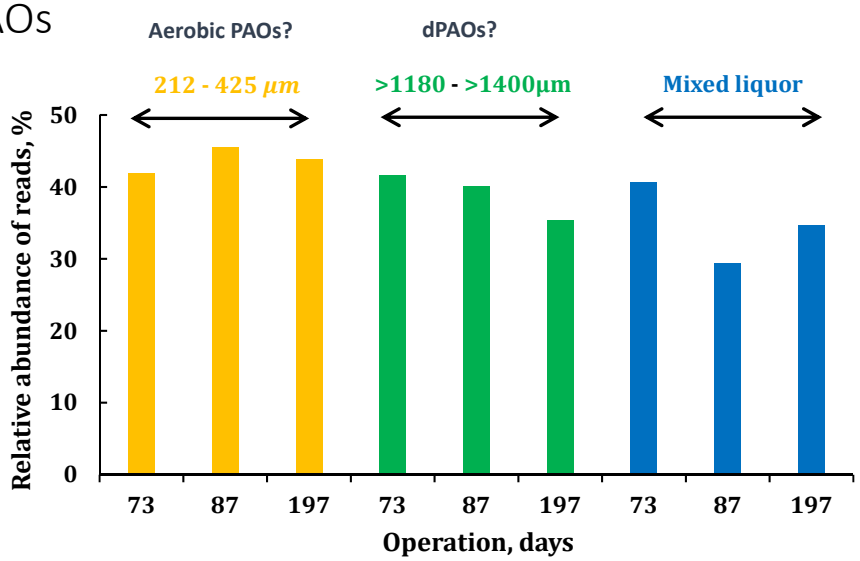
Sequencing: PAOs





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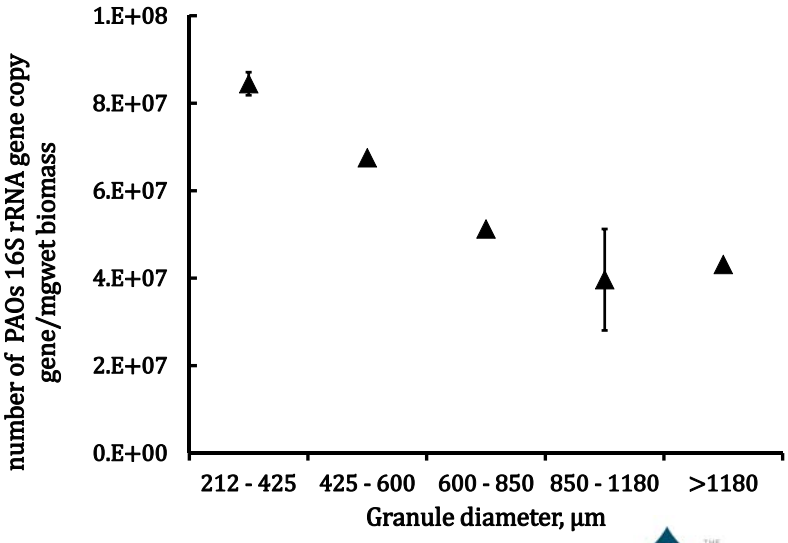
qPCR for *Accumulibacter*

- **Higher PAOs 16S rRNA gene copy number in small granules**
- **Aerobic PAOs?**
- **Acetate and oxygen can penetrate better into small granules -> creating a better environment for PAOs to thrive**



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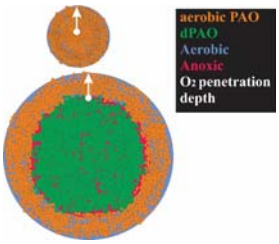
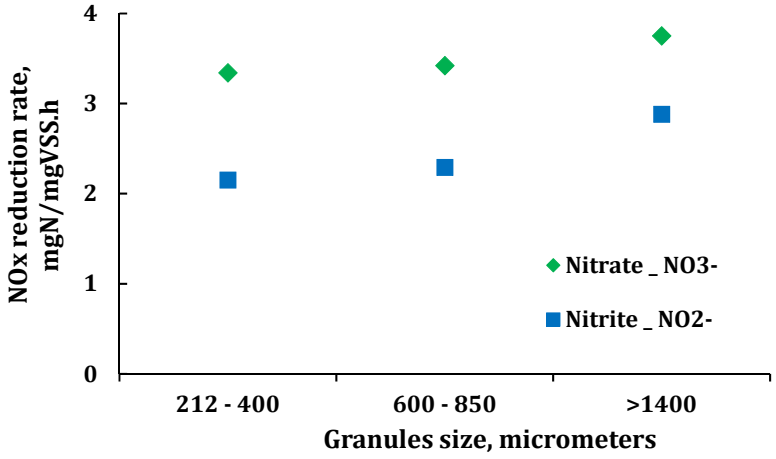
Nitrate & Nitrite reduction rate

Denitrification capacity higher in the big granules

Bigger granules have more anoxic volume fraction => favoring dPAOs

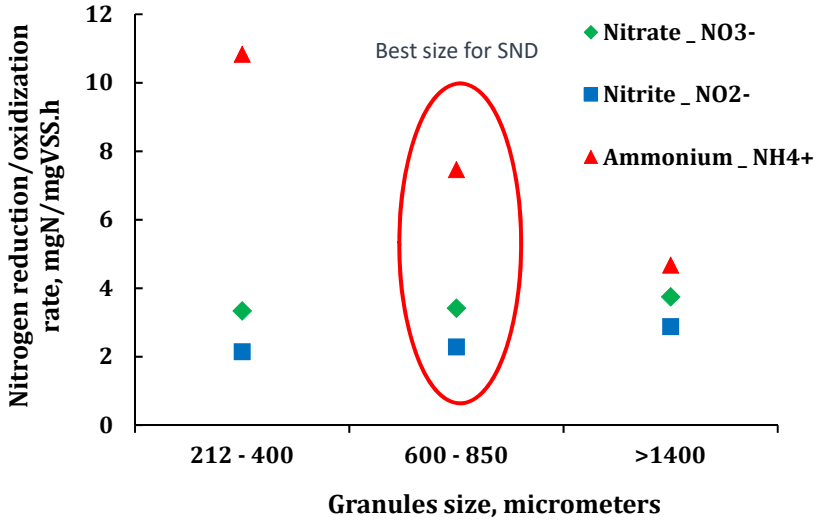




45

What is the optimal granule size?

Ammonia oxidization rate is higher in the smaller granule.
Denitrifying rate is higher in the bigger granules



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Summary

- Higher surface area/volume ratio
  - ⇒ higher amoA copy gene numbers
  - ⇒ higher ammonia oxidizing rate
- AOB and NOB are dominant in the small granules
- *Accumulibacter* tends to be dominant in the small granules (maybe aerobic PAO?)
- Denitrification capacity was higher in the big granules.

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Thank You

King County & University of Washington

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(project number TIRR3C15)

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Advancing the oxygenic photogranule process for energy positive wastewater treatment

Chul Park, Ph.D.
Associate Professor and Graduate Program Director
Department of Civil & Environmental Engineering
University of Massachusetts - Amherst

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Advancing the Oxygenic Photogranule (OPG) Process for Energy Positive Wastewater Treatment

Chul Park, Ph.D.

Department of Civil and Environmental Engineering, University of Massachusetts Amherst

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Acknowledgement

- Dr. Caitlyn Butler @ UMass Amherst
- Dr. Christopher Wilson @ Hampton Roads Sanitation District
- Drs. Kim Milferstedt and Jérôme Hamelin at INRA-LBE
- Dr. Jangkyu Kim and others @ BKT Co., Ltd.
- Graduate students working on OPGs: Adam McNair, Ahmed Abouhend, Abeera Ansari, Camilla Kuo-Dahab, and Joseph Gikonyo

National Science Foundation WHERE DISCOVERIES BEGIN

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UMASS AMHERST

BKT

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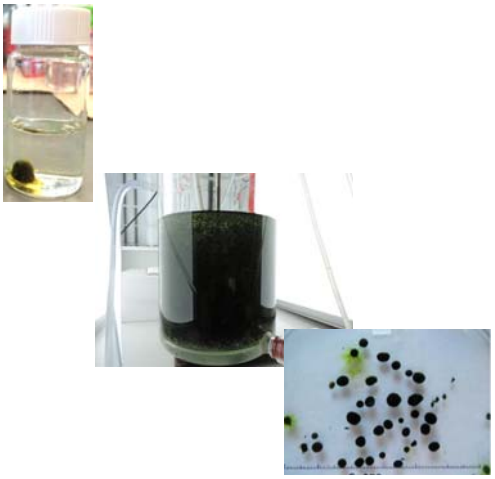
Synopsis

- Phototrophic granules (photogranules) can be generated from transformation of activated sludge under hydrostatic conditions
- Oxygenic photogranules (OPG) can treat wastewater without aeration
- The oxygenic photogranule (OPG) process can recover chemical energy in wastewater
- Need to advance the development of the OPG process for real-world application



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Wastewater Treatment: Energy Opportunities

- Chemical (calorific) energy in wastewater
  - ➢6-8 MJ/m^3 wastewater (2.2 KWh/m^3)

    = (0.5kg COD/m^3) (12-15 MJ/kg COD)

    In the USA alone, 50–100 billion kWh per year, equivalent of energy from burning 30-60 million barrels of oil each year.
  - ➢This is renewable energy!!!

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Wastewater Treatment: Energy Challenges

- *Energy intensive*
  - 0.6 KWh/m^3 wastewater (~2% of national energy)
  - Up to 60% of this is **for aeration**

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Energy Yielding Wastewater Treatment

- Recover chemical energy in wastewater
- Use less energy to treat
- Currently, there is no effective way to achieve these goals
- Wastewater treatment works are currently energy consumers

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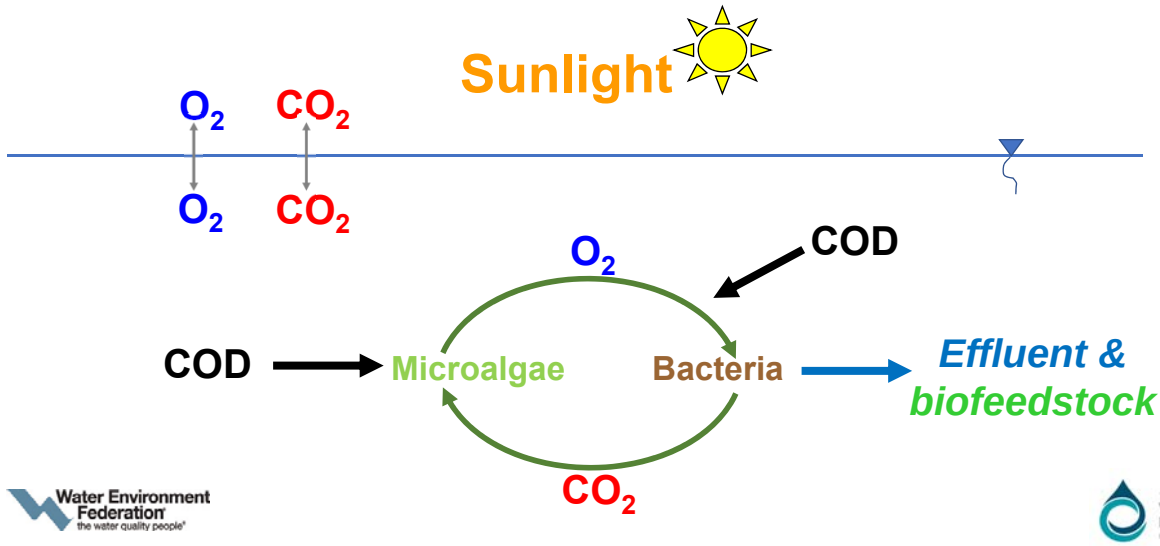
Algae-based Wastewater Treatment



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Algae-based Wastewater Treatment: Challenges

- Algae do not usually aggregate
  - ➢Ineffective separation of algae from water
  - ➢Recycling and harvesting of biomass?
- Suspended growth & need of light!
  - ➢Shallow ponds or lagoons
- Engineering challenges

Source of photo: Algae Biomass Summit 2017

Source of photo: Thief River Falls, MN

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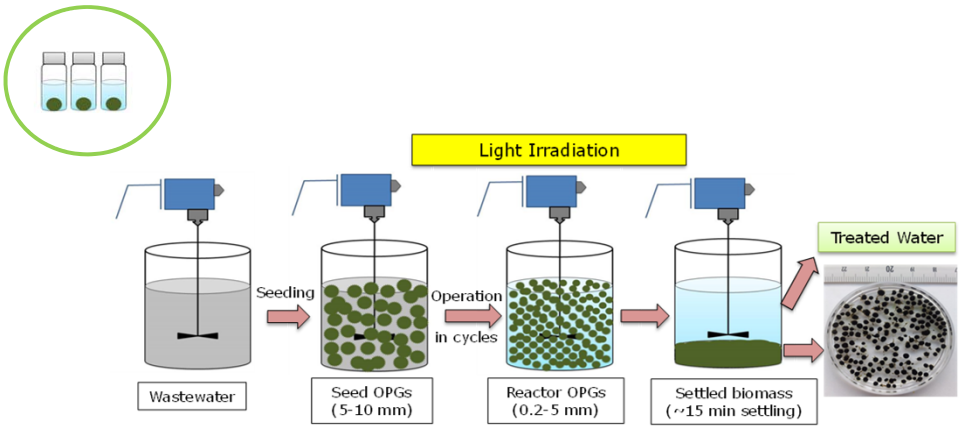
The OPG Process for Aeration-free Wastewater Treatment



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Original Finding of OPGs

Lab windowsill

Milferstedt et al. (2017) *Sci. Rep*

Park & Dolan (2018) U.S. Patent

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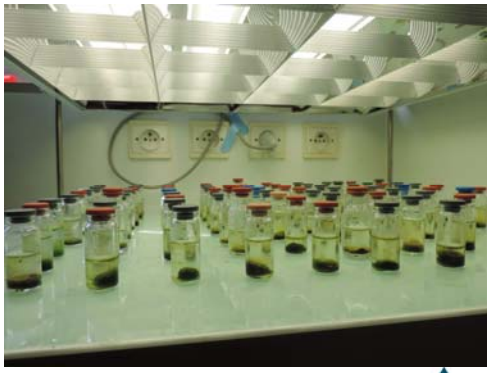
Plant location	Biological Process (CAS* or BNR**)	Aeration basin configuration (covered or open basin)	Solids retention time (SRT)	Incubation start date	First day of compaction & aggregation/ green biomass	First appearance of a biogranule	Mature biogranule
Amherst, MA, USA	BNR, occasionally CAS	Open	10-15 days	11-Dec-14	3/5	10	
Hadley, MA, USA	CAS	Open	10 days	18-Nov-14	2/7	7	
Springfield, MA, USA	BNR	Open	~20 days	6-May-14	2/7	30	
Northampton, MA, USA	BNR	Open	~10 days	6-May-14	2/7	19	
Deer Island-Winthrop, MA, USA	CAS-pure O_2	Covered			3/18	21	
Narbonne, France	BNR	Covered	>20 days	26-Feb-14	2/5	19	
Ornaisons, France	BNR	Open	>30 days	28-Jan-15	5/5	37	
Neuchâtel, Switzerland	BNR	Covered	~5 days	19-May-14	1/7	11	

Milferstedt et al. (2017) *Sci. Rep*



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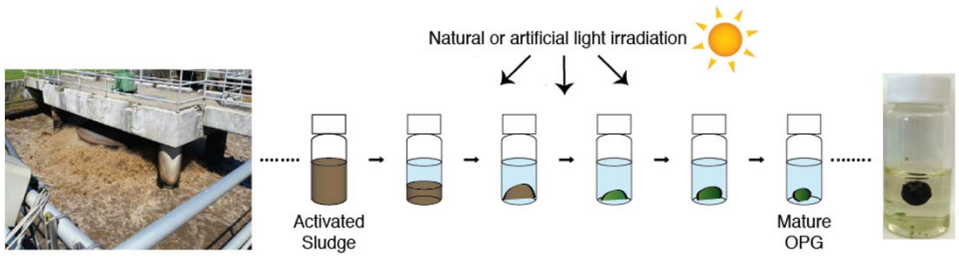
Universal Phenomenon



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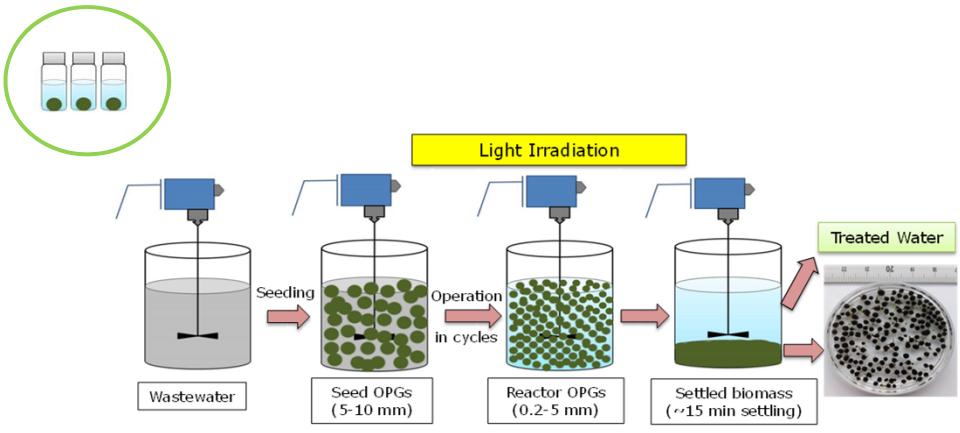
Develop the OPG-based Process for Wastewater Treatment



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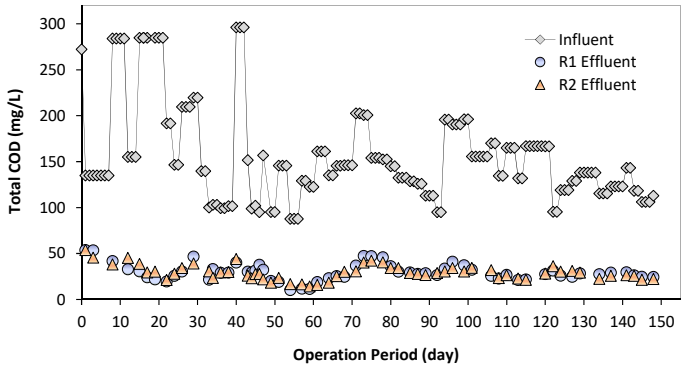
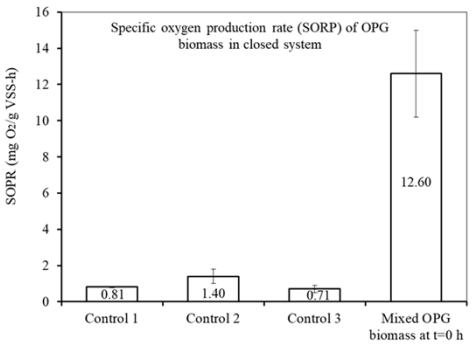
Removal of COD without Aeration





Abouhend et al. (2018) *ES&T*

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NSF GOALI and WRF

	Year 1	Year 2	Year 3
Aim #1. Elucidate the granulation phenomenon in reactor operation	→	→	
Aim #2. Engineer the light pattern to advance the OPG process		→	→
Aim #3. Investigate the feasibility of the OPG process for municipal wastewater treatment		→	→

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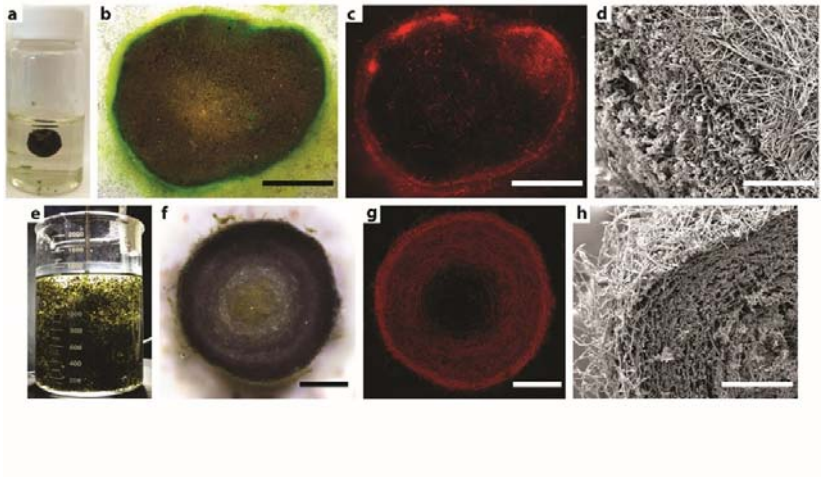
Hydrostatically Formed vs. Reactor OPGs

Hydrostatic

Reactor



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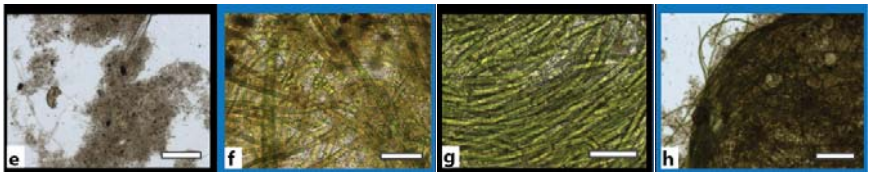
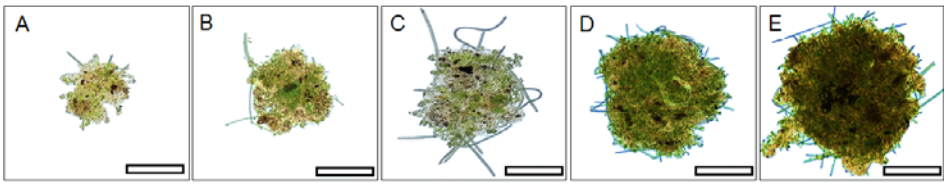
Hydrostatically Formed vs. Reactor OPGs





Panels A to E (during batch): day 0 → day 4

This happens in the presence of mixing!

Abouhend et al. (2018) *ES&T*

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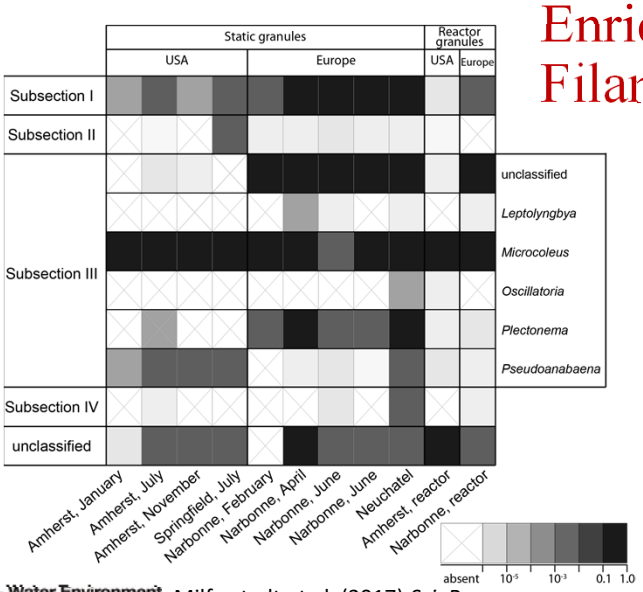
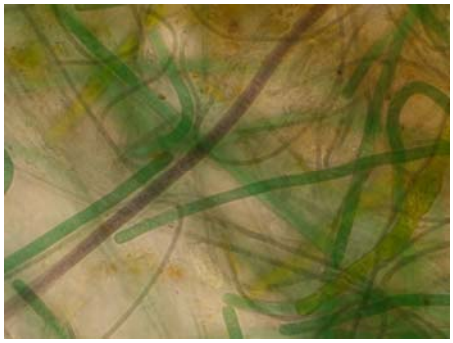
Enrichment of Motile Filamentous Cyanobacteria





Milferstedt et al. (2017) *Sci. Rep*

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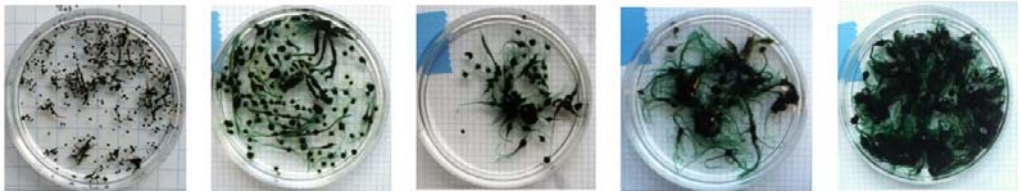
But Filamentous Cyanobacteria Do Not Always Guarantee Photogranules



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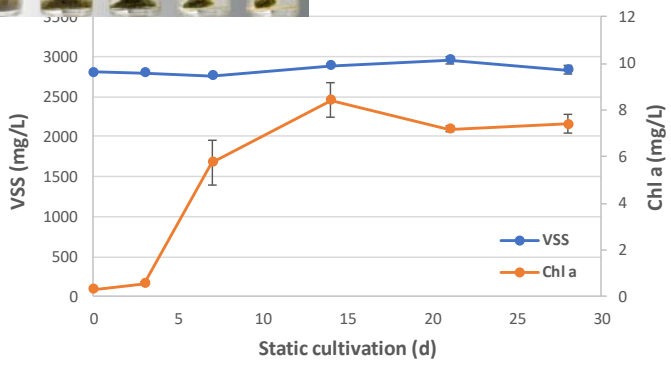
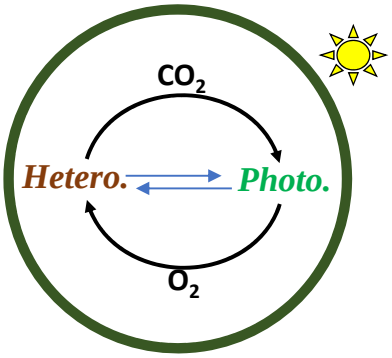
Symbiosis Due to Key and Limited Substrates?





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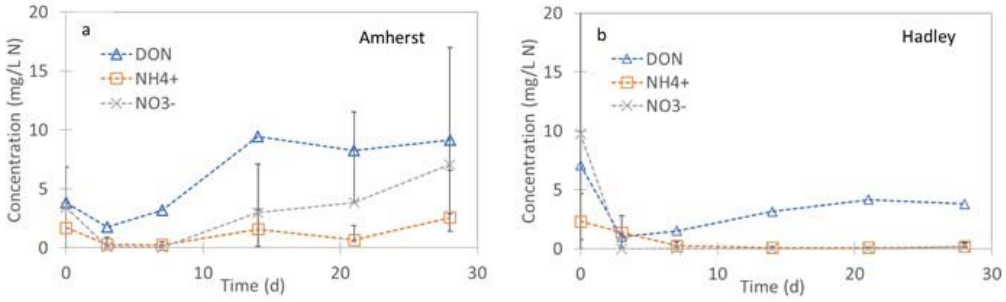
Limitation of Nitrogen



Kuo-Dahab et al. (2017) *ES&T*

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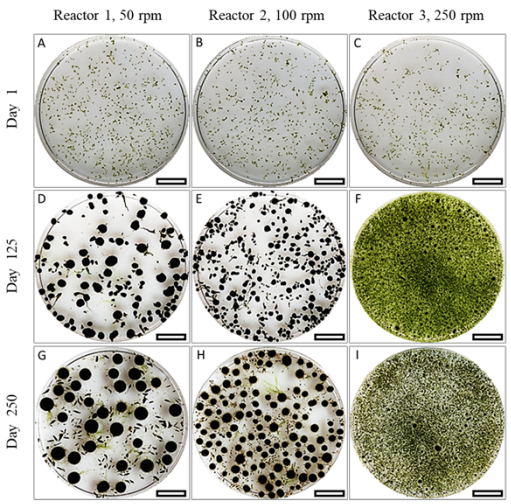
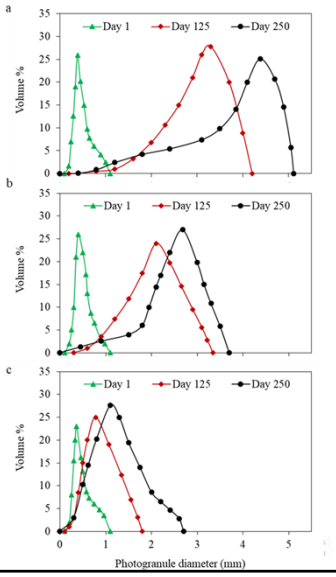
Effect of Shear on Photogranulation

Table 1. Speed of mixing and resulting hydrodynamic conditions used in three SBRs.

N (rpm)	G (s^{-1})	Re ($\times 10^3$)	η (μm)
50	20	2.2	222
100	58	4.4	132
300	299	13.1	58





Abouhend et al. (in preparation)

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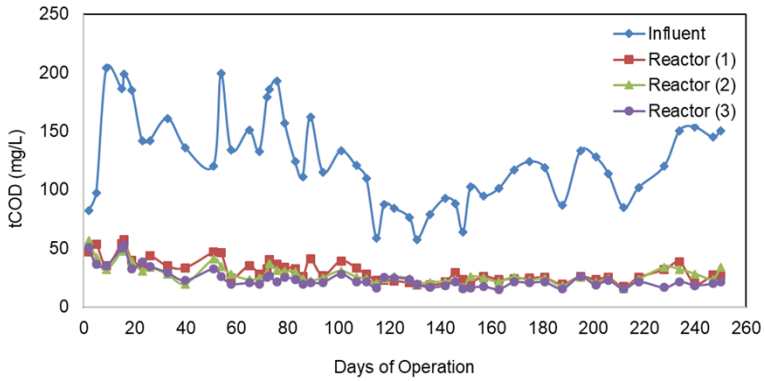
Effect of Shear on COD Removal



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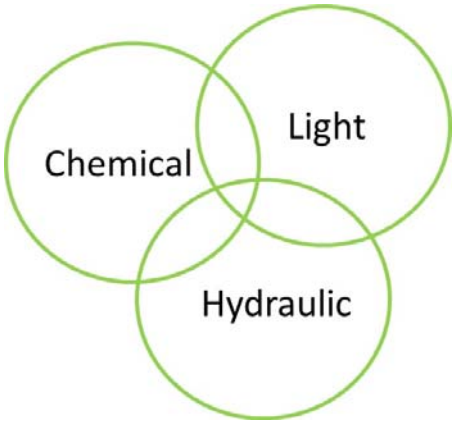
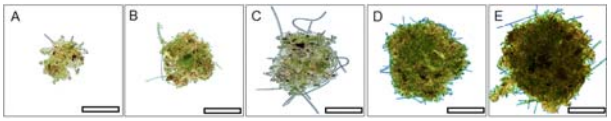
Balance of Energy for Selection Pressures





Gikonyo et al. (in preparation)

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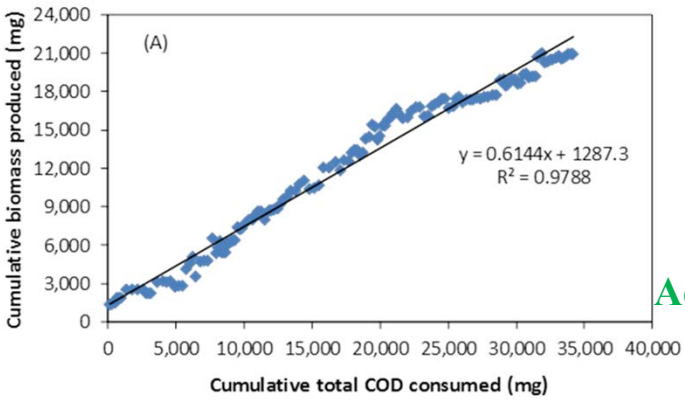
Energy Recovery via OPG Biomass Growth



Biomass yield (**OPG**):

- 0.6-0.7 mg VSS/mg COD
- 1.2-1.3 mg COD/mg COD

Biomass yield (**activated sludge**):

- 0.3-0.6 mg COD/mg COD

Aeration↓ + Recovery of COD

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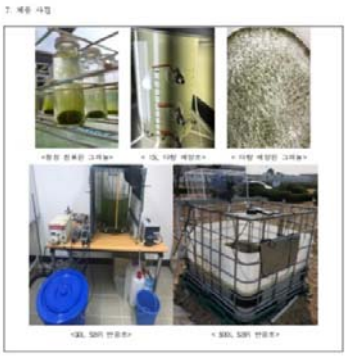
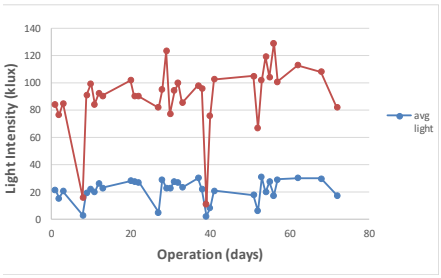
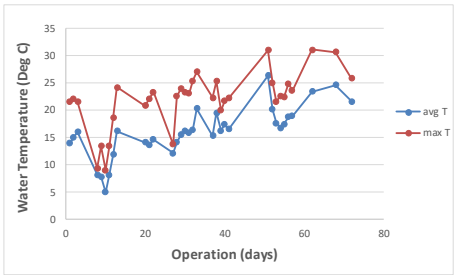
Lessons from the Recent OPG Pilot

- The first 500 L OPG pilot: March 26 till June 4, 2018 (Daejeon, Korea)







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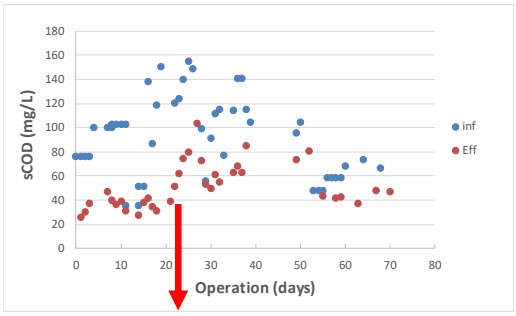

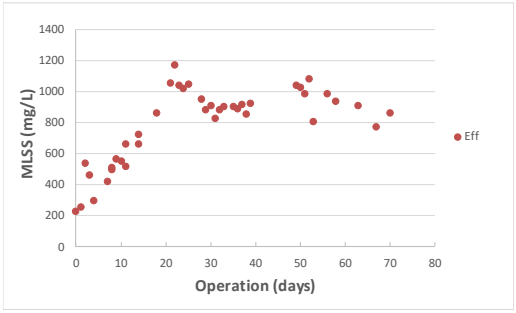

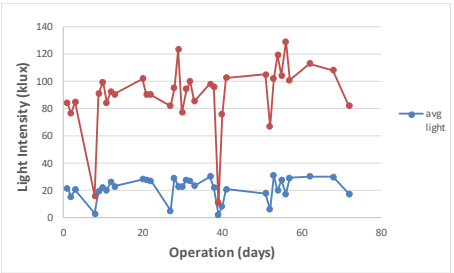

Photoinhibition under Natural Sunlight

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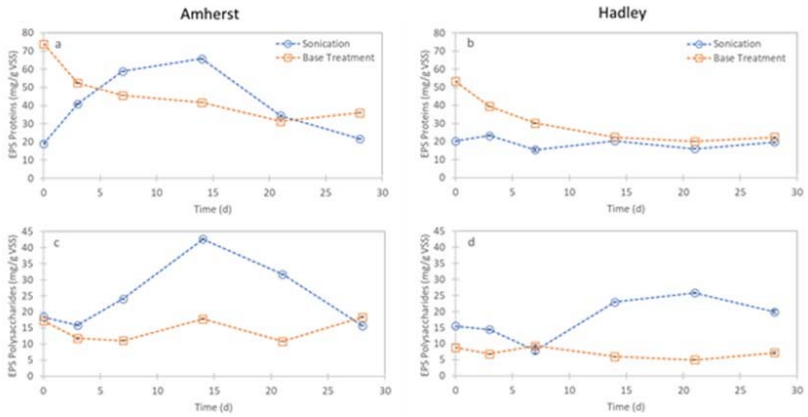
Conclusions

- Formation of granules under conditions that are, based on conventional knowledge, highly unlikely to support granulation
  - ➢Hydrostatic conditions
  - ➢In turbulently mixed bioreactor operations
- Photogranules formed under two different conditions shared similar properties
  - Photogranules were formed by enrichment of motile filamentous cyanobacteria
- Balance of energy: Chemical, Light, and Hydraulic energies

Conclusions

- Achieved the removal of COD and nitrification without aeration!
- The OPG process shows the potential to recover chemical energy in wastewater and solar energy in the form of easily separable biomass
- The first 500 L outdoor pilot taught new lessons
  - ➢Seeding with large dilution works
  - ➢Need to overcome photoinhibition, if sunlight is used

Fate and Dynamics of EPS during Photogranulation



Kuo-Dahab et al. (2017) *ES&T*

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Biofilm-enhanced anaerobic membrane bioreactor for low temperature domestic wastewater treatment

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Professor of Engineering
University of Michigan

Steven Skerlos, Ph.D.
Professor of Engineering
University of Michigan

Timothy Fairley
Graduate Research Assistant
University of Michigan

Biofilm-Enhanced Anaerobic Membrane Bioreactor for Low Temperature Domestic Wastewater Treatment


Lut Raskin
Professor


Steve Skerlos
Professor


Tim Fairley
Environmental Eng.
Graduate Student


Nishant Jalgaonkar
Mechanical Eng.
Graduate Student


Caroline Van Steendam
Environmental Eng.
Graduate Student


Adam Smith
Professor
USC
(Ph.D. UM)

Grants:

WRF – **U2R15** – Next Generation Anaerobic Membrane Bioreactor Development Utilizing 3D-Printing
NSF – **CBET 1604069** – WERF: Biofilm-Enhanced Anaerobic Membrane Bioreactor for Low Temperature Domestic Wastewater Treatment
WE&RF – **TIRR5C15** – Life Cycle Assessment and Analysis of Biofilm Enhanced Anaerobic Membrane Bioreactor
WERF – **ENER4R12** – Low Energy Alternatives for Activated Sludge – Advancing Anaerobic Membrane Bioreactor Research
WRRF – **10-06D** – Anaerobic Membrane Bioreactors as the Core Technology for a Low Energy Treatment Scheme for Water Reuse
NSF – **CBET 1133793** – Low-temperature Anaerobic Membrane Bioreactors for Sustainable Domestic Wastewater Treatment

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December 5, 2018

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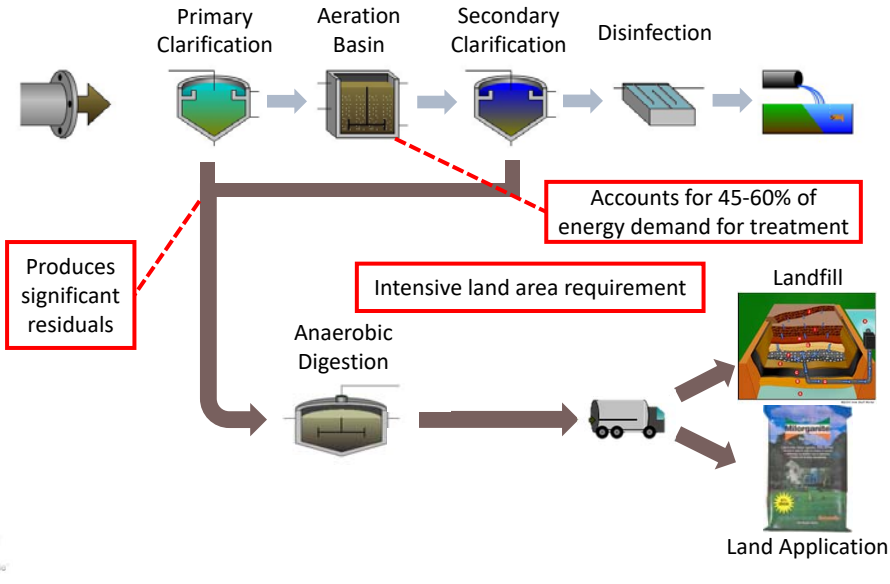
Drawbacks of conventional domestic wastewater treatment



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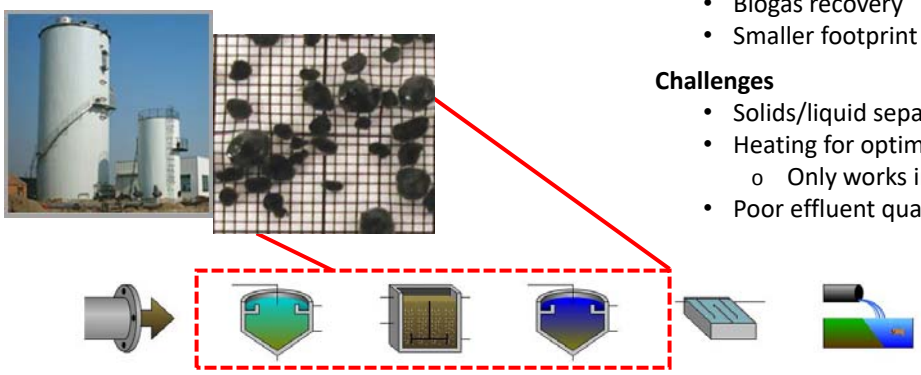
Can anaerobic treatment be implemented in mainstream wastewater treatment?

Upflow Anaerobic Sludge Blanket (UASB)



Benefits

- No aeration required
- Biogas recovery
- Smaller footprint

Challenges

- Solids/liquid separation
- Heating for optimal performance
  - Only works in warm climates
- Poor effluent quality

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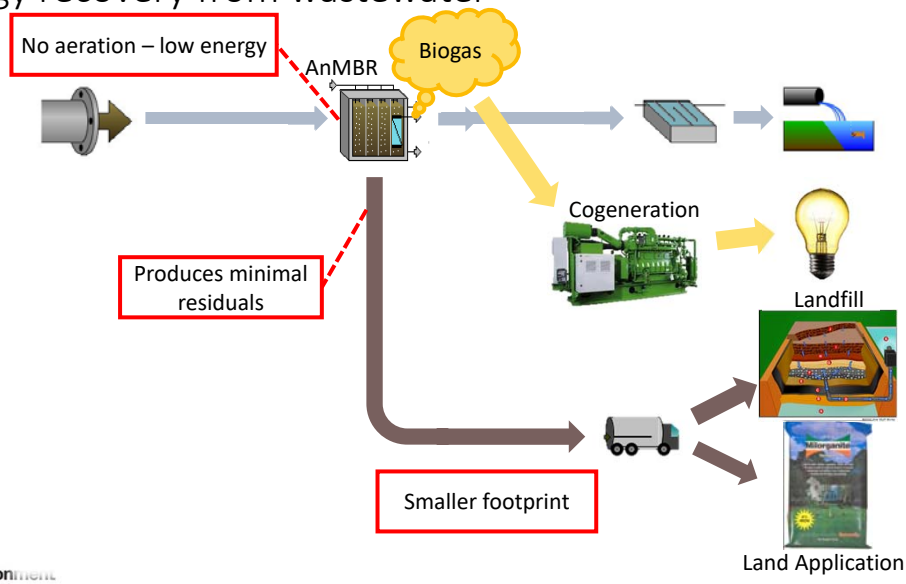
Anaerobic membrane bioreactor (AnMBR) is an emerging approach to energy recovery from wastewater



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Smith, A.L., L. B. Stadler, N.G. Love, S. J. Skerlos, and L. Raskin, 2012, Perspectives on Anaerobic Membrane Bioreactor Treatment of Domestic Wastewater: A Critical Review, *Bioresource Technology*, **122**, 149-159.

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Must answer important questions before AnMBR treatment of domestic wastewater will be implemented

1. Can anaerobic treatment performance be improved, especially at low temperatures?

2. Is AnMBR technology cost and environmentally advantageous to conventional treatment technologies?

85

Must answer important questions before AnMBR treatment of domestic wastewater will be implemented

1. **Can anaerobic treatment performance be improved, especially at low temperatures?**

2. Is AnMBR technology cost and environmentally advantageous to conventional treatment technologies?

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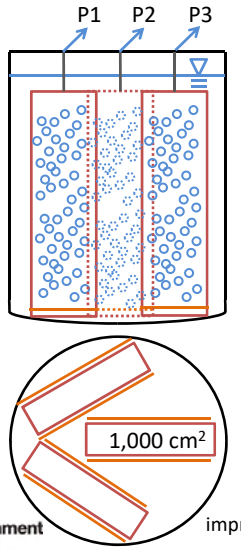
Bench-scale AnMBR study to evaluate question 1



1. Can anaerobic treatment performance be improved, especially at low temperatures?

- Three submerged flat-sheet membranes
- Biogas sparging for fouling control, independently controlled for each membrane
- Psychrophilic temperature (15°C)
- Inoculated with mesophilic sludge only

Smith, A.L., S.J. Skerlos, and L. Raskin, 2015. Membrane biofilm development improves COD removal in anaerobic membrane bioreactor wastewater treatment. *Microbial Biotechnology*, **8**, 883-894.

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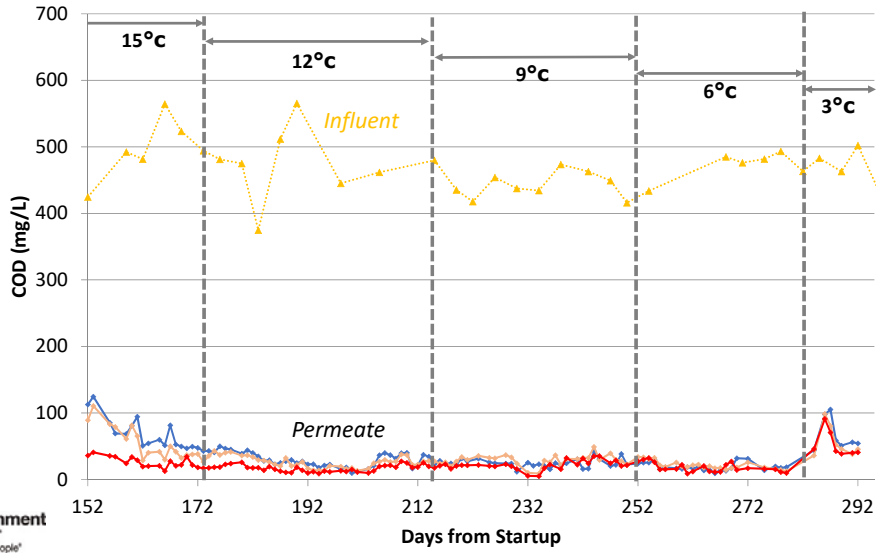
Excellent AnMBR performance maintained down to 6°C



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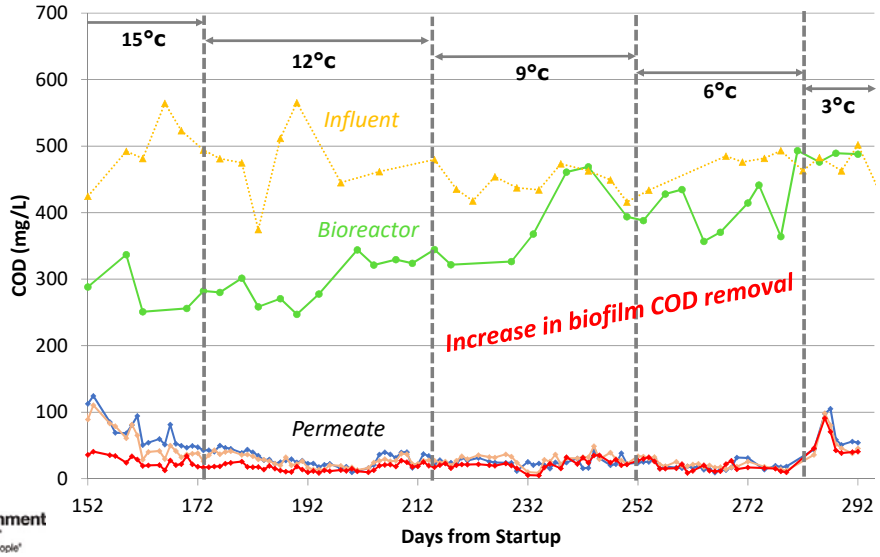
Biofilm's role in treatment becomes more critical as temperature decreases



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However, dissolved methane increasingly a problem with thicker biofilms

Methane oversaturation =
Dissolved methane measured in permeate / calculated equilibrium concentration

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Must answer important questions before AnMBR treatment of domestic wastewater will be implemented

1. Can anaerobic treatment performance be improved, especially at low temperatures?

   Yes: biofilms improve performance but cause unwanted dissolved methane oversaturation in the permeate

2. Is AnMBR technology cost and environmentally advantageous to conventional treatment technologies?

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Must answer important questions before AnMBR treatment of domestic wastewater will be implemented

1. Can anaerobic treatment performance be improved, especially at low temperatures?

   Yes: biofilms improve performance but cause unwanted dissolved methane oversaturation in the permeate

2. **Is AnMBR technology cost and environmentally advantageous to conventional treatment technologies?**

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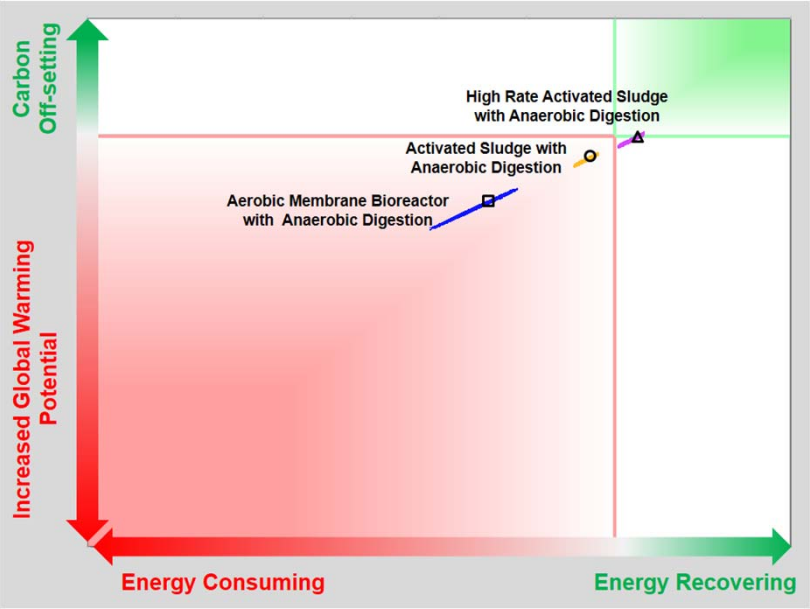
AnMBR has greater net energy demand and global warming impact than competing technologies



AnMBR today:

- Membrane sparging contributes most to energy demand
- Dissolved methane in permeate contributes to 75% of global warming impact

Future AnMBR design requires:

- Reduction in methane oversaturation
- Dissolved methane recovery
- Reduction in energy for fouling mitigation

Smith AL, Stadler LB, Cao L, Love NG, Raskin L, Skerlos SJ, 2014, *ES&T.* **48**(10):5972-81.

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Are AnMBRs for recovery of energy from domestic wastewater a sustainable technology?

- Does the design make significant progress toward an unmet and important environmental or social challenge?
  - **No: the world has plenty of energy and global warming potential not addressed. More work to do.**
- Is there potential for the design to lead to undesirable consequences in its lifecycle that overshadow the environmental/social benefits?
  - **Yes: Excess greenhouse gas (GHG) emissions**
- Is the design likely to be adopted and self-sustaining in the market?
  - **The value proposition right now is mainly smaller size. Net zero energy is possible after more research. The GHG issue is of industry concern and will be a show-stopper for now.**

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New Question

How do we address drawbacks of conventional AnMBRs so that they are cost and environmentally advantageous to existing technologies?

Dynamic Membrane: Filtering biofilm formed on support structure of ~ 10 – 100 microns

- Membrane cleaning is energy intensive (High OPEX)
  - Less Pore Blocking
  - Lower Transmembrane Pressures

- Membrane material cost is expensive (High CAPEX)
  - Cheaper Material (e.g. nylon, polyester, stainless steel mesh)
  - Higher Fluxes – less membrane area required

Must address further hurdles of AnMBRs with novel design decisions

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Modify bioreactor design and operating conditions to improve outcomes

- Harness Maximum Biofilm Treatment
  - → Create large surface area for biofilm formation
  - → Force wastewater through biofilm many times
  - → Utilize conductive surface to promote DIET
- Reduce Dissolved Methane Saturation to Equilibrium in Permeate
  - → Shift methane production away from biofilms on permeating membranes
  - → Incorporate flow pattern that allows for efficient transfer of dCH4 to gas headspace
- Maintain Effective Solids/Liquid Separation with Lower Energy Demand and Cost
  - → Utilize fine meshes instead of MF/UF membranes which allow for low transmembrane pressure
  - → Mesh material (e.g. nylon, polyester, stainless steel) lower capital cost than typical MF/UF membrane
  - → Operate at much higher flux than MF/UF, so less membrane area required

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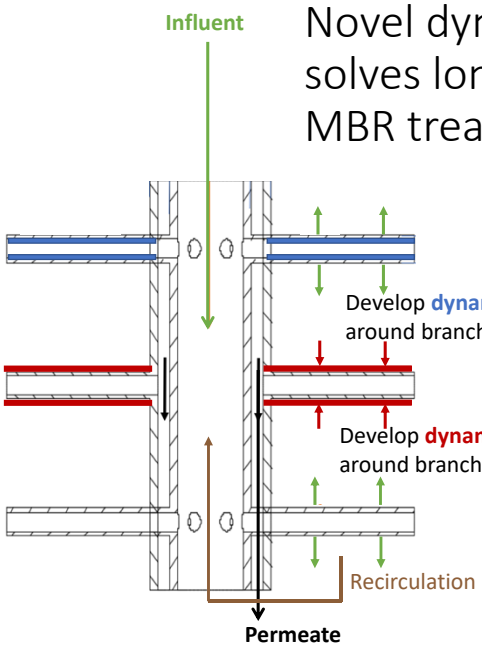
Novel dynamic membrane bioreactor (DMBR) solves longstanding hurdles for conventional MBR treatment of domestic wastewater



- maintain effective solids/liquids separation with lower energy demand?
  - → Utilize fine meshes instead of MF/UF membranes
- harness maximum biofilm treatment?
  - → Force wastewater through biofilm many times
- reduce dissolved methane oversaturation in permeate?
  - → Shift methane production away from biofilms on permeating membranes and allow for dissolved gas transfer to headspace

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MagnaTree

Flow pattern through meshes to develop dynamic membrane achieves desired outcomes

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MagnaTree implementation in a bioreactor analogous to integrated fixed film activated sludge (IFAS) system

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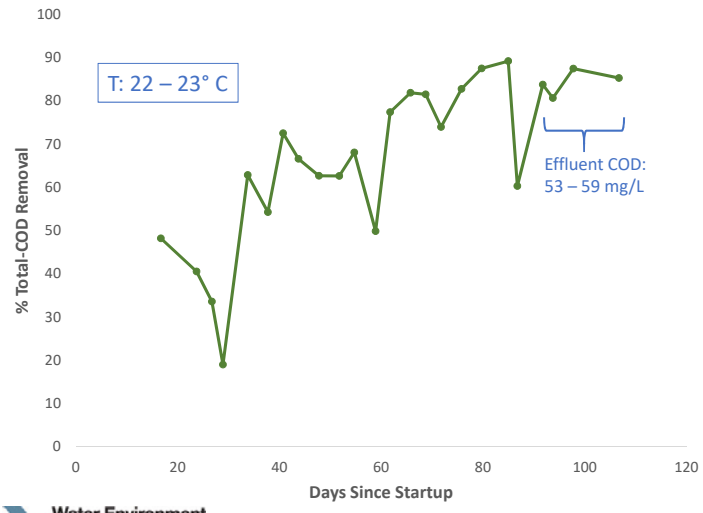
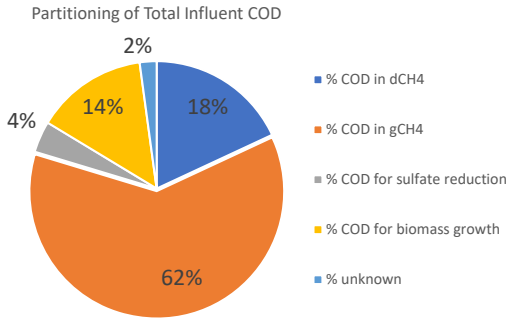
Startup results promising: tCOD removal increased to ~ 90% & large portion (~62%) of tCOD transformed to biogas methane.





- At 15° C, %COD in dCH4 found to be ~31% of total COD

Smith, A.L., S.J. Skerlos, and L. Raskin, 2015. Membrane biofilm development improves COD removal in anaerobic membrane bioreactor wastewater treatment. Microbial Biotechnology, 8(5):883-894.

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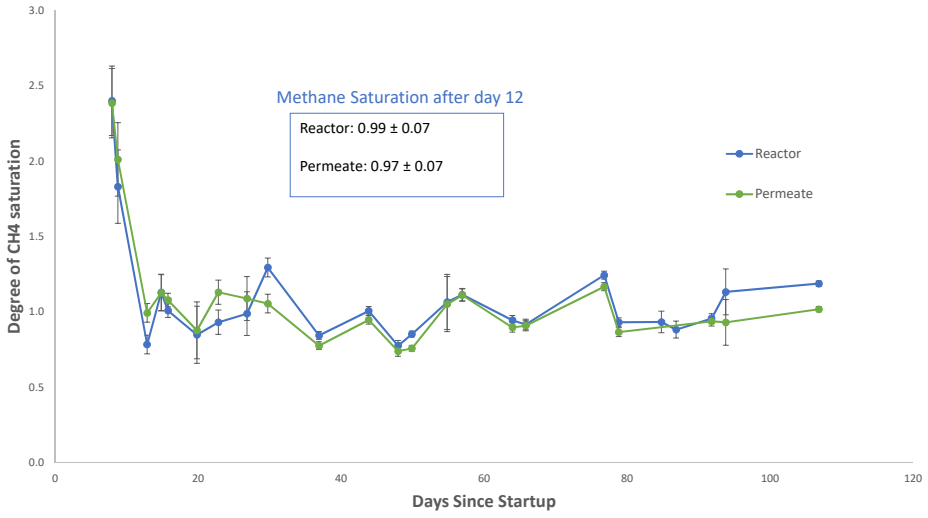
Methane saturation quickly fell to 1 (equilibrium)



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AnMBR Treatment of DWW at Ambient (often low) Temperatures – Early Observations

- Can anaerobic systems adequately treat domestic wastewater, even at low temperatures?
  - Yes, An(D)MBRs can achieve sufficient COD and SS removal while also producing biogas
- How do **conventional AnMBRs** compare to **novel AnDMBRs**?

• High energy demand	• Low energy demand
• High global warming impact	• Low global warming impact
• High capital cost	• Low capital cost
• Complete solids removal	• High solids removal

- Where might we apply novel (An)DMBR (e.g. MagnaTree) technology?
  - Retrofit for existing municipal plants – expand capacity/improve performance
  - Decentralized wastewater treatment, especially in developing countries
  - Industrial applications such as food and beverage wastewater
  - Part of reuse treatment train – reduce fouling to RO/UF membranes

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Acknowledgements

Freddy Ordonez
Environmental Eng.
Graduate Student, UM

Juliana Huizenga
Environmental Eng.
Undergraduate Student, UM

Nigel Beaton
Environmental Eng.
(Previous)
Graduate Student, UM

Ilse Smets
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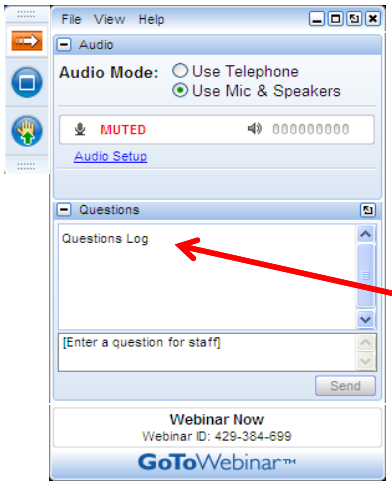
Questions for Our Speakers?



- **Submit your questions using the Questions Pane.**

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Thank You

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