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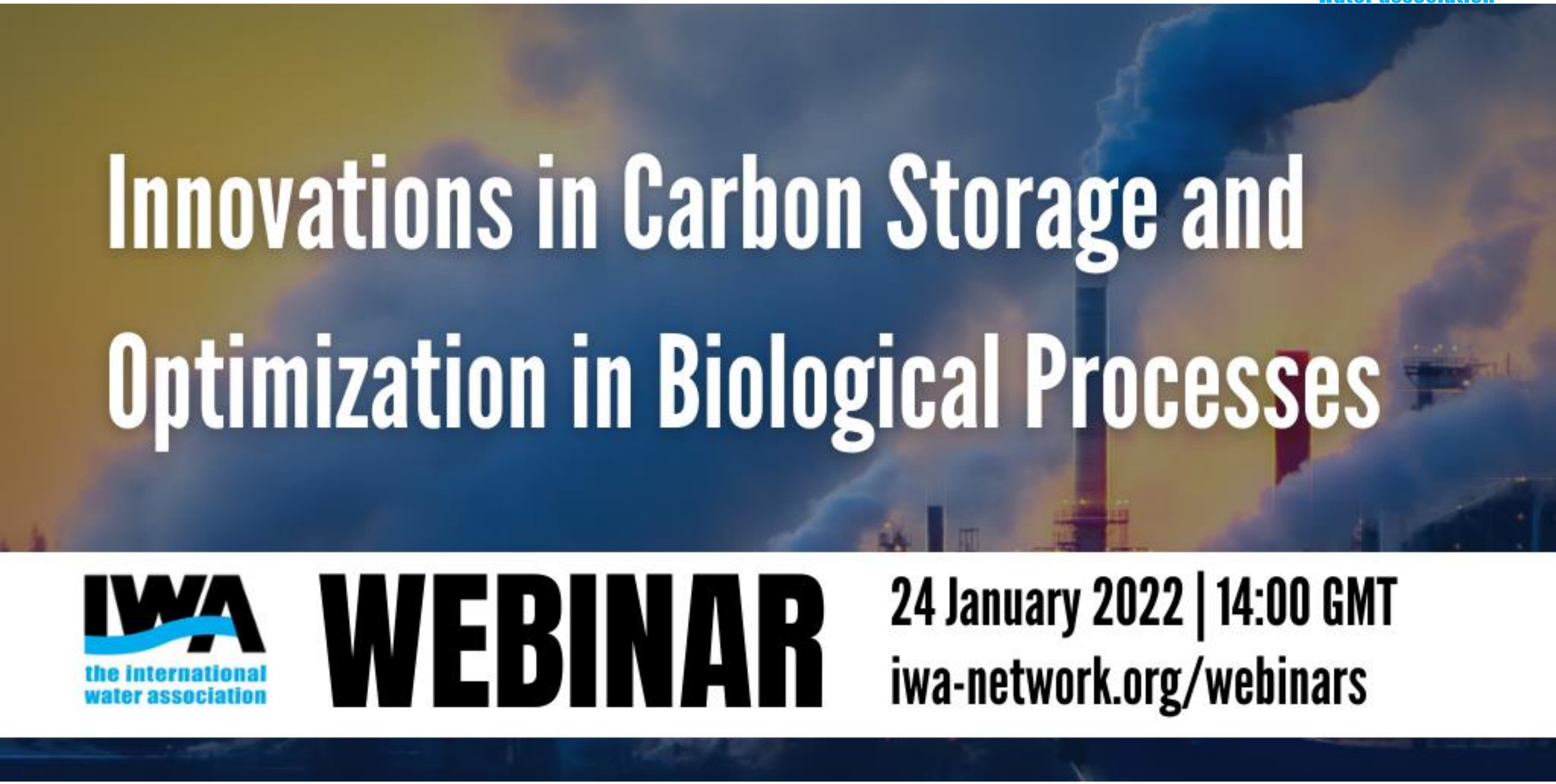

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IWA NUTRIENT REMOVAL AND RECOVERY (NRR) SG

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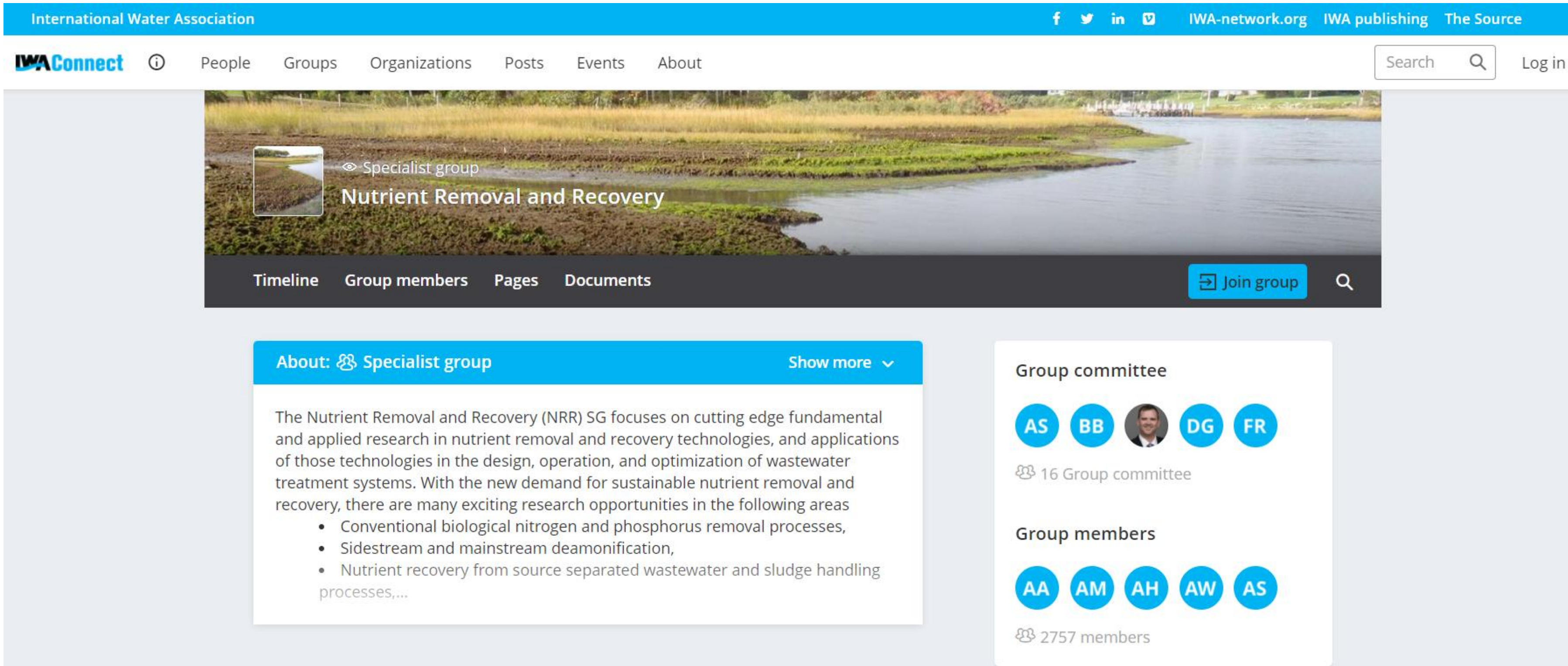

The IWA NRR SC focuses on cutting edge fundamental and applied research in nutrient removal and recovery technologies.

Join the IWA NRR SC on IWA Connect!

https://iwa-connect.org/group/nutrient-removal-and-recovery?searchFor=all

WEBINAR INFORMATION

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- This webinar will be **recorded and made available “on-demand”** on the IWA website.
- Following the webinar, you will be sent a **post-webinar email** with the on-demand recording, presentation slides, and other information.

- **‘Chat’ box**: please use this for general requests and for interactive activities.
- **‘Q&A’ box**: please use this to send questions to the panelists.

  (We will answer these during the discussions)

***Please Note:** Attendees’ microphones are muted. We cannot respond to ‘Raise Hand’.*

AGENDA

- Welcome, introduction & housekeeping rules
  Sudhir Murthy
- Webinar Goals and Objectives
  April Gu
- Tribute to Dr. H. David Stensel
  James Barnard
- Opportunity of DPAOs for optimizing carbon usage for both denitrification and phosphorus removal
  Chris DeBarbadillo, George Wells & Kartik Chandran
- A side-stream process designed for nutrient removal and p recovery from municipal wastewater
  YongMei Li
- EBPR and Mainstream Deammonification – Bringing Two Approaches Together
  Kester McCullough
- Partial Denitrification/Anammox (PdNA) using Internally Stored Carbon
  Stephanie Klaus
- Leveraging internal carbon storage and redirection in new processes for the future
  April Gu
- Facilitated discussion and Q&A
- Final remarks and conclusion

CO-CHAIRS & MODERATOR

April Gu
Cornell University, USA

Sudhir Murthy
NEWhub Corp, USA

James Barnard
Black & Veatch, USA

PANELISTS

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Chris DeBarbadillo
Black & Veatch, USA

George Wells
Northwestern University, USA

Kartik Chandran
Columbia University, USA

Yongmei Li
Tongji University, China

Kester McCullough
HRSD, USA

Stephanie Klaus
HRSD, USA

Bryce Figdore
HDR, USA

BACKGROUND AND GOAL

- This webinar will present new concepts and strategies in developing and implementing nutrient removal processes including enhanced biological phosphorus removal (EBPR) and short-cut nitrogen removal processes, leveraging the internal carbon storage and allow carbon-usage optimization. These innovative processes can overcome some of the main limitations in and enable simultaneous, coupled EBPR and short-cut nitrogen (N) removal.

- In the meantime, nutrient recovery from wastewater is providing a sustainable path. As the paradigm includes circular carbon and nutrient approaches, new research and practice are needed to discover innovative technologies that make up such circular approaches. This webinar will also extend EBPR to P recovery process and attempt to inspire novel ideas for wastewater treatment processes.

- This webinar will be dedicated to Prof. David Stensel (1945-2021), University of Washington, USA, who truly was a fount of knowledge in the field and had a lifelong passion for returning clean water to the environment through biological processes.

LEARNING OBJECTIVES

1. Gain advanced knowledge on the integration of enhanced biological phosphorus removal (EBPR) with short-cut nitrogen removal process

2. Enhance understanding of the role of internal carbon management for carbon-energy-efficient biological nutrient removal (BNR) and recovery systems.

3. Inspire new thinking in carbon re-direction and decarbonization in water cycle.

REMEMBERING DAVID STENSEL (1945-2021)

JAMES BARNARD
BLACK & VEATCH

inspiring change

REMEMBERING DAVID STENSEL (1945-2021)

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With a lifelong passion for returning clean water to the environment through biological processes, Professor David Stensel was truly a fount of knowledge. He made notable research advancements, authored one of the widely used textbook and was recognized with numerous awards.

Ph.D.	Cornell University	1971
M.E.	Cornell University	1968
B.S.C.E.	Union College	1967

Professor Emeritus, CEE, University of Washington, Seattle, WA, 2016-present.

Professor, CEE, University of Washington, Seattle, WA, 1987-2016.

Associate Professor, CEE, University of Utah, Salt Lake City, UT 84112, 1980-1984.

Director of Sanitary Engineering Technology, Envirotech Corporation, Salt lake City, UT, 1976-1980.

Manager, Air Products and Chemicals, Inc., Allentown, PA, 1974-1976.

Senior Research Engineer, Eimco BSP, Salt Lake City, UT 1971-1974.

REMEMBERING DAVID STENSEL (1945-2021)

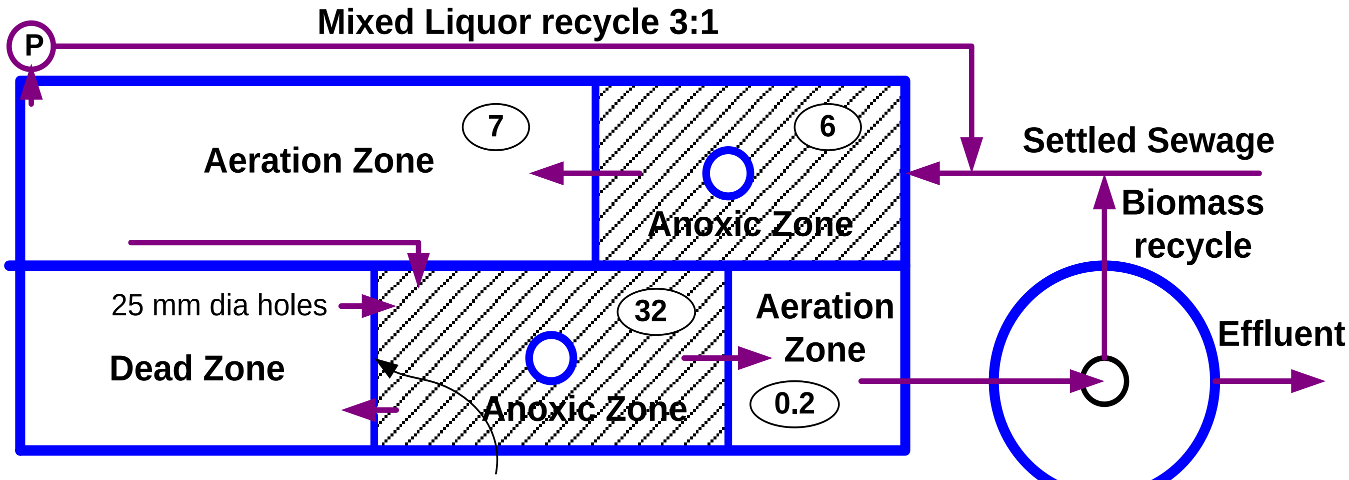
▪ A Colleague & Friend with a Great Sense of Humor

What I so appreciated in Dave Stensel was his sense of humor and his willingness to help. I met Dave in 1972 while visiting a pilot plant at Contra Costa while he was working for Eimco in SLC. Later Eimco decided to take up the Bardenpho patent from the Water Institute in South Africa and I traveled to SLC. Dave picked me up at the airport and took me to his house which set up the pattern for the next 40 years. Later we traveled through the USA to promote the concept and finally we designed the first plant in Palmetto FL. Later, many other opportunities to work together included compiling the first book on BNR design with Dr. Cliff Randall, ten years on NYC Advisory Committee, courses in BNR at Helena MT and St George, UT. Once, we were traveling together and spent a few hours at an airport. Working on a presentation on Trends in Wastewater Treatment I decided to draw a very subjective series of graphs to show the trends. One such trend was independent physical/chemical treatment, and I suggested a short hump in the early seventies. Seriously he suggested a smaller hump in the early eighties. What was that for, I asked, to which he replied, "For all the court cases that resulted from the earlier hump". I miss you buddy.

Dr. James Barnard

REMEMBERING DAVID STENSEL (1945-2021)

- Bardenpho Pilot Plant 1972

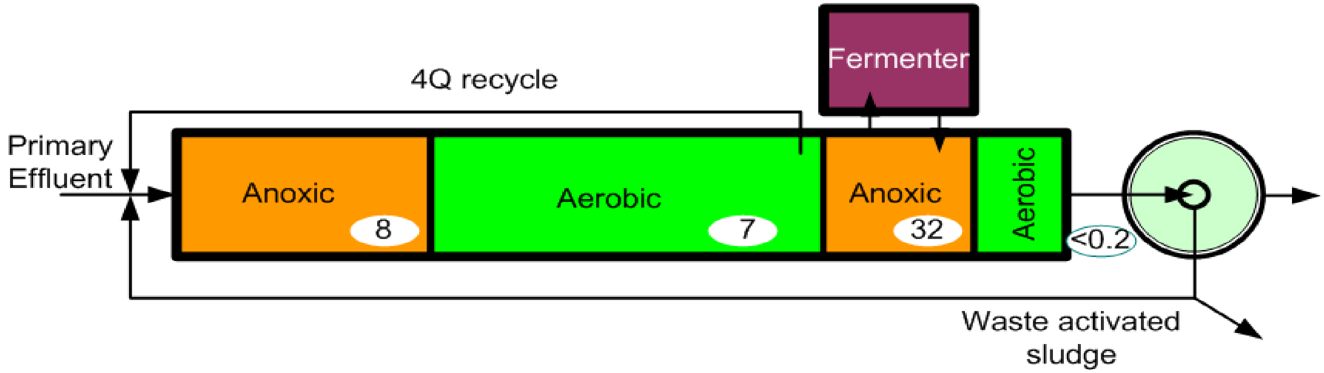


The purpose of the dead zone was to allow relative adjustments to the other zones

REMEMBERING DAVID STENSEL (1945-2021)

- Some early observations…Pilot Plant

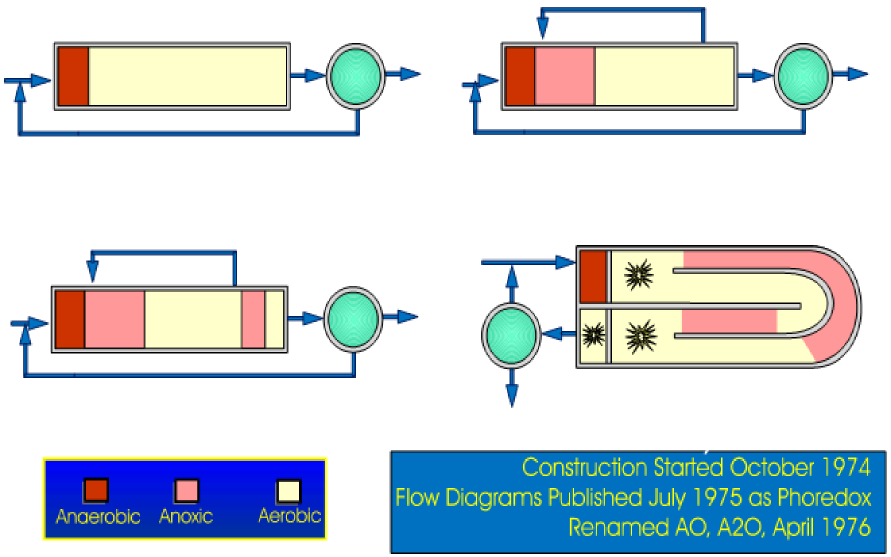
- Fermenter resulted from basin configuration and not deemed important
- Excellent phosphorus removal resulted
- Phosphorus profile shown in ellipses
- Performance could not be replicated in laboratory
- Barnard suggested organisms (PAO) should pass through anaerobic phase with low ORP which triggered EBPR
- Suggested Phoredox process by adding an anaerobic zone up front

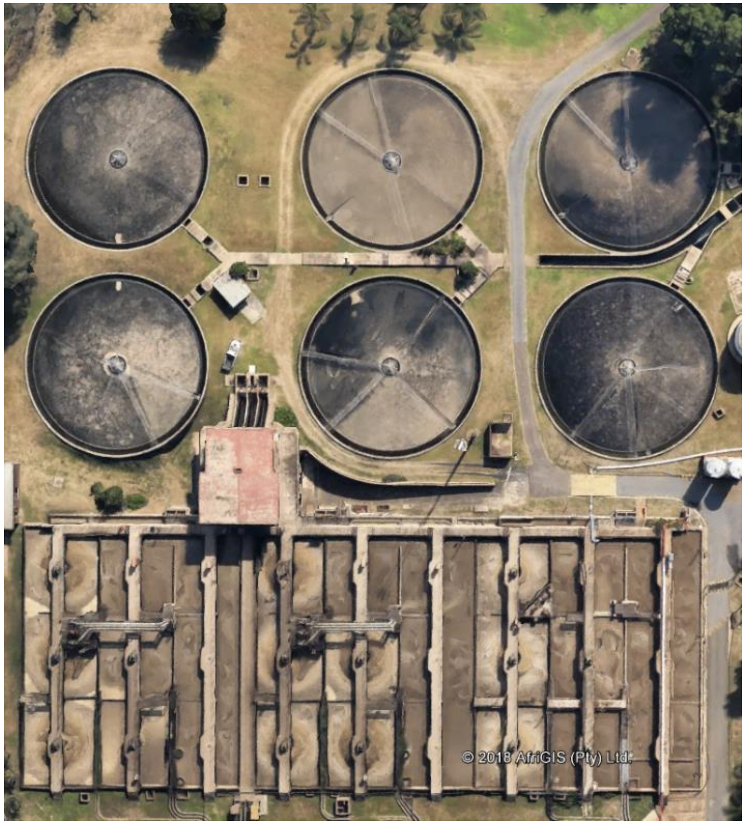


Barnard 100 m^3/d pilot 1972

REMEMBERING DAVID STENSEL (1945-2021)

- Concept of passing all PE through AN Zone Become standard with early designs



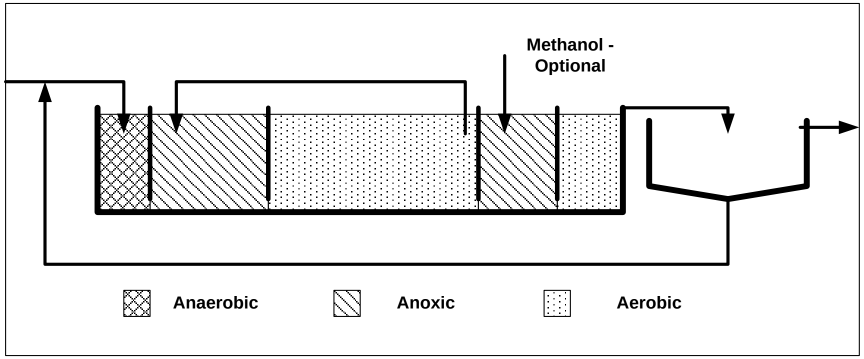


These were followed by others such as UCT, JHB & Westbank

REMEMBERING DAVID STENSEL (1945-2021)

- First BNR Plant Goudkoppies Johannesburg (750,000 PE)

- Design Started 3 months after laboratory experiment. Completed 3 years later



- Reduce N to N_2
- Incorporate P into the surplus sludge
- No need for chemicals
- No threat to salinity
- Clarifiers could be replaced by membranes

REMEMBERING DAVID STENSEL (1945-2021)

- Palmetto FL BNR plant (First in the US)

TN < 3 mg/L

TP < 1 mg/L

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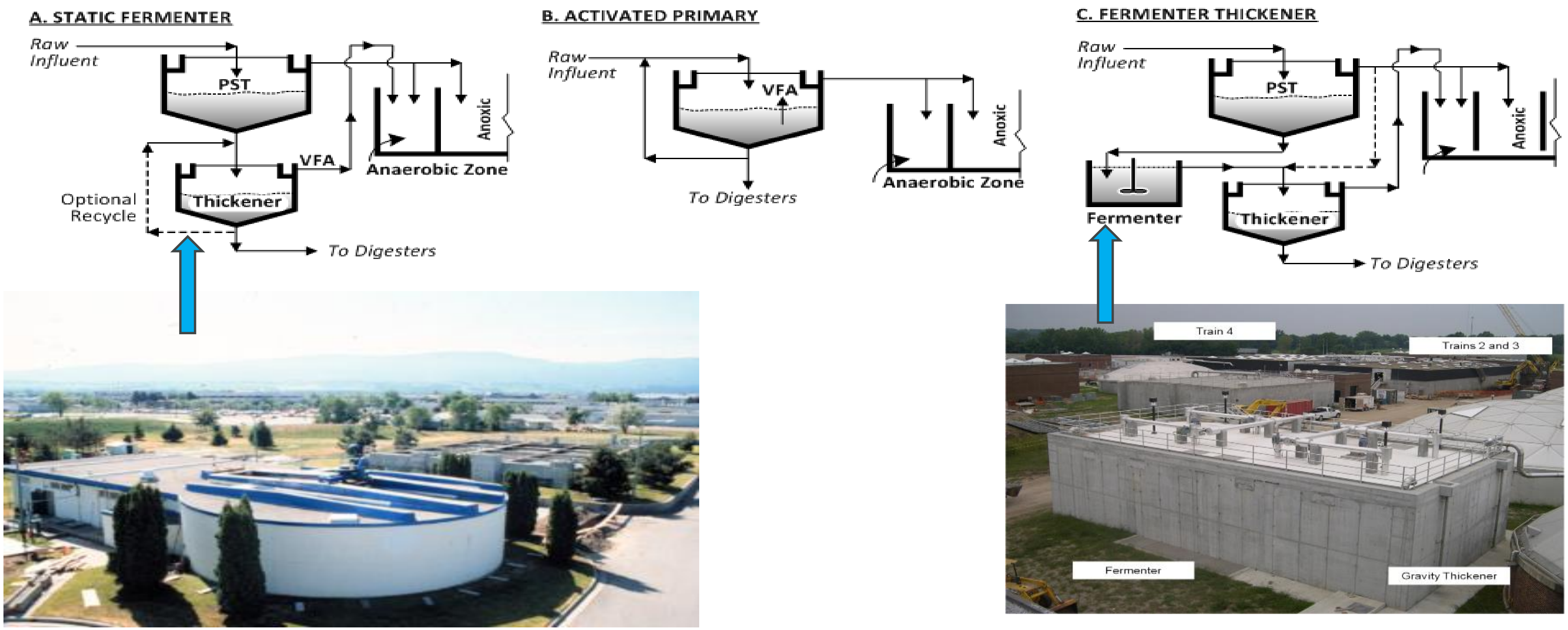
- Bayou Marcus WRF FL. Integrating Carousel with Bardenpho

- Dr. Stensel integrated the Carousel with the Bardenpho process getting increased simultaneous nitrification and denitrification
- This plant produced an average TN of less than 1.7 mg/L over a five-year period
- Became highly successful application at many locations

REMEMBERING DAVID STENSEL (1945-2021)

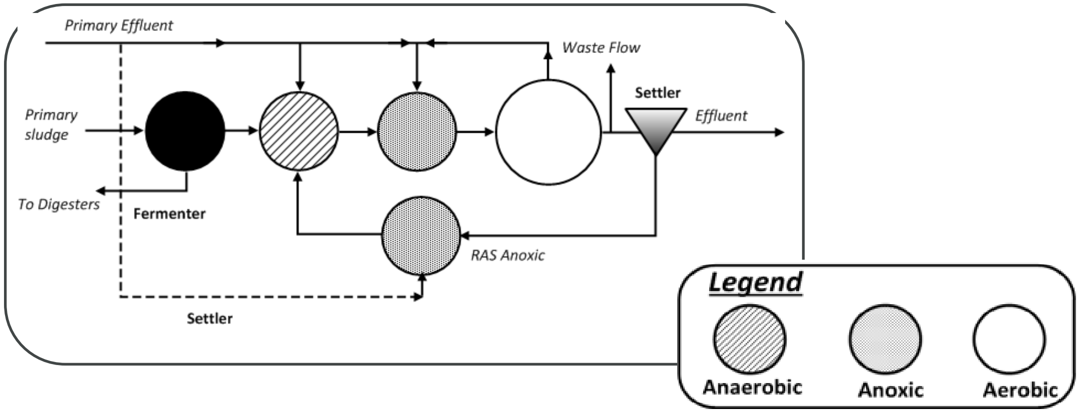
- VFA from Fermenters



- First Acinetobacter and then Accumulibacter identified as PAO

REMEMBERING DAVID STENSEL (1945-2021)

- Westbank Process Incorporated a Fermenter
  - While also allowing for Primary Effluent bypass around the Anaerobic Zone (Knight & Piesold, 1984)



TN	< 6 mg/ℓ
BOD	< 5 mg/ℓ
TSS	< 2 mg/ℓ
TP	< 0.15 mg/ℓ
Mixing energy 0.15 hp/kcf	

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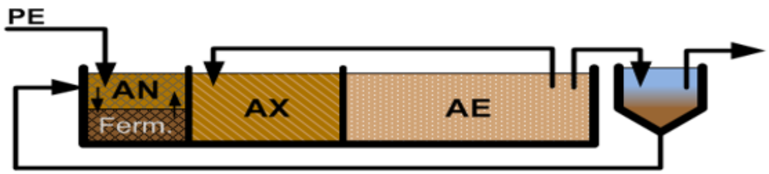
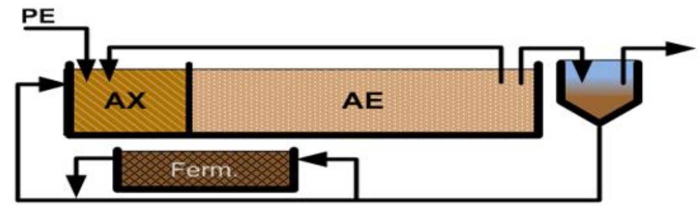
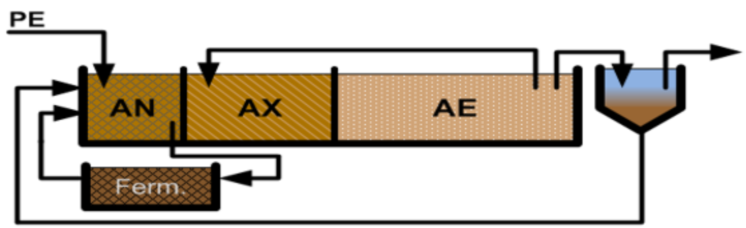
- S2EBPR - A Concept rather than Flowsheet



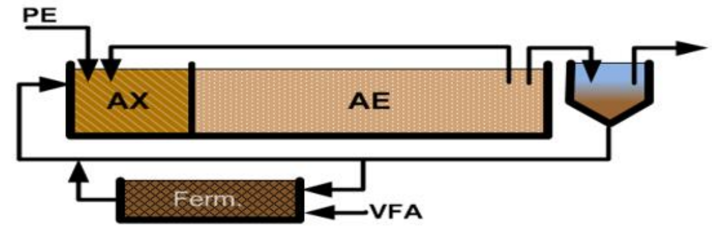
Unmixed In-Line Mixed Liquor Fermentation (UMIF)



Side-Stream RAS Fermentation (SSR)



Side-Stream Mixed Liquor Fermentation (SSM)



Side-Stream RAS Fermentation w/ Additional Carbon (SSRC)

Pass some sludge through deeper anaerobic conditions reflected by ORP < -300 mV

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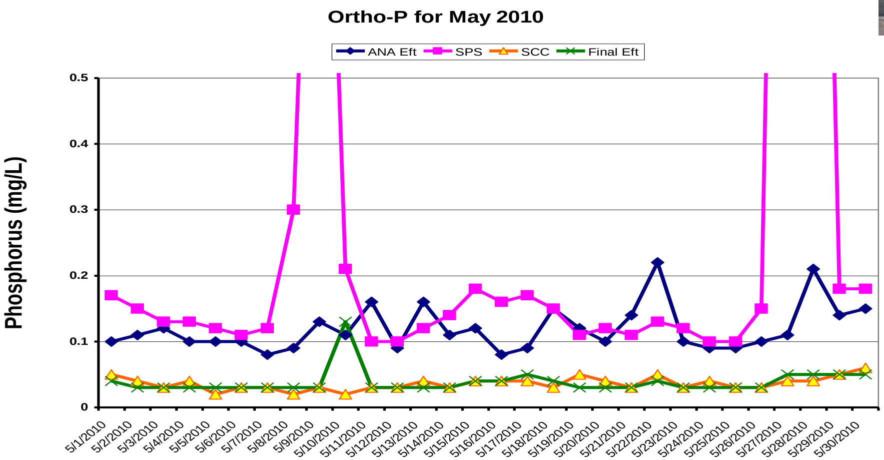
- Carousel Plant Henderson NV 18 mgd – Upgraded to BNR

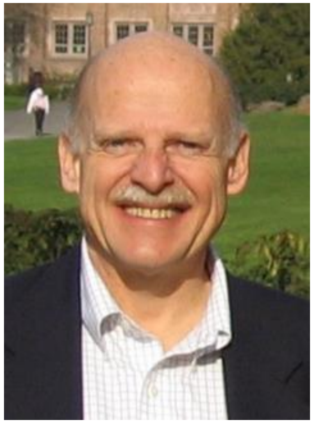
Switching off a mixer in the anaerobic zone resulted in In-plant Fermentation



So far we have seen great improve-ment of SVI when applying S2EBPR

REMEMBERING DAVID STENSEL (1945-2021)

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



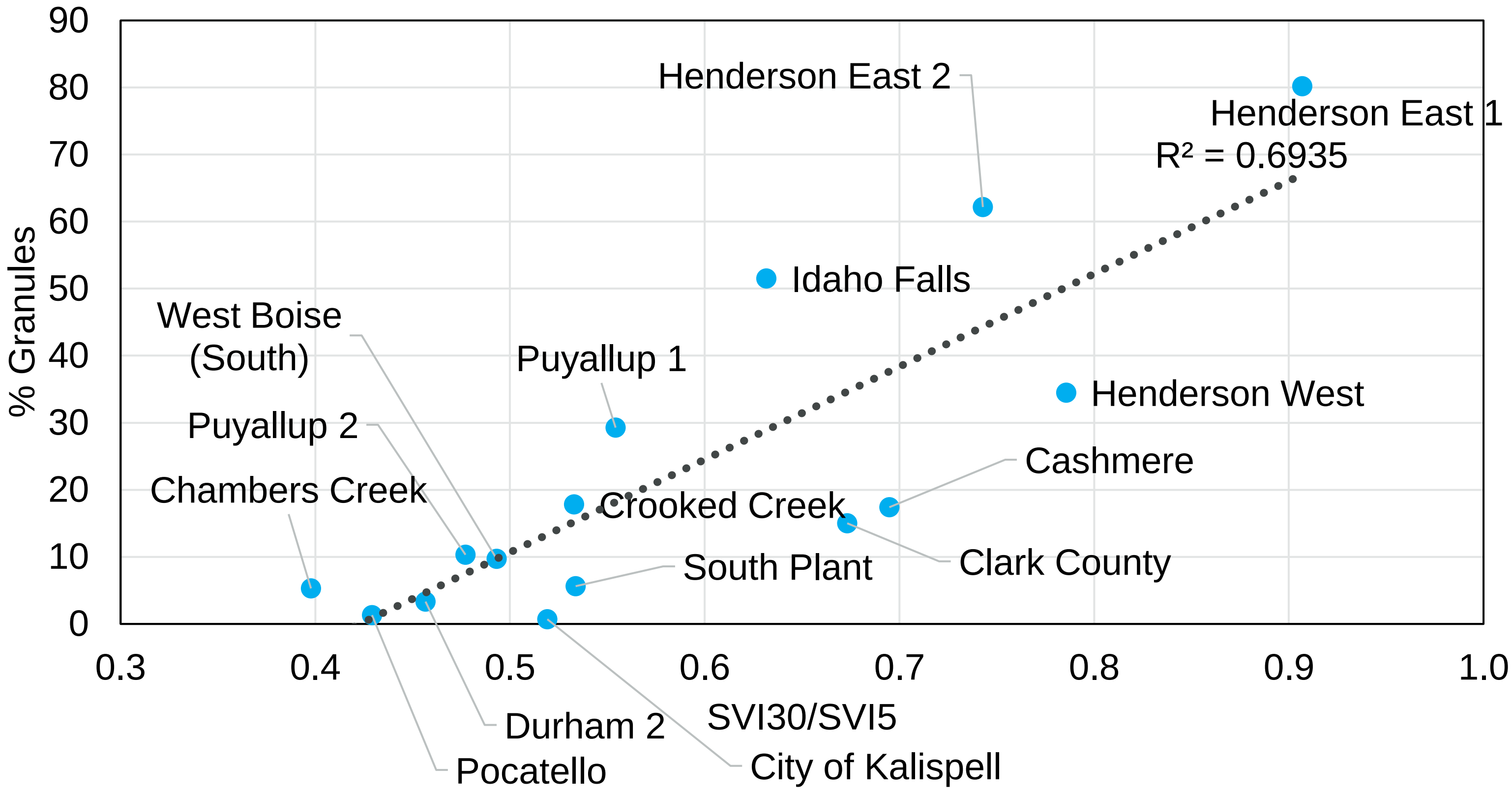
H. David Stensel, Ph.D., PE, BCEE, WEF Fellow
Professor Emeritus, Civil & Environmental Engineering, University of Washington

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

Treatment Intensification for Resource Recovery: Advances in Granules and Membrane Bioreactor Technologies - Webinar December 5, 2018

REMEMBERING DAVID STENSEL (1945-2021)

Correlation of % Granules to SVI_{30}/SVI_5



Treatment Intensification for Resource Recovery: Advances in Granules and Membrane Bioreactor Technologies - Webinar December 5, 2018

REMEMBERING DAVID STENSEL (1945-2021)

- Granule formation in various plants

Figure 3 Selective wasting of mixed liquor Cashmere WA

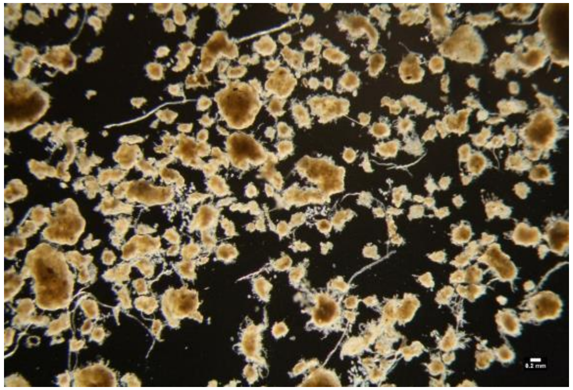


Figure 5 Granular sludge produced in the Henderson NV plant (Supplied by Dave Stensel)

Designed plant for Cashmere WA with Dave S and Tom Coleman with high F/M ratio and selective wastage that produced granular sludge, allowing the plant to operate at near 8000 mg/L MLSS while using only one of two final clarifiers and consistently meet effluent N and P standards. Selective wastage shown in center. Collaborated with DS on granule formation in Henderson NV plant operated with S2EBPR.

REMEMBERING DAVID STENSEL (1945-2021)

- Granule formation at Wakarusa, Lawrence KS

Figure 7 Drone view of Wakarusa KS plant

Figure 8 Surface of aeration basin showing layer of clear liquor on top

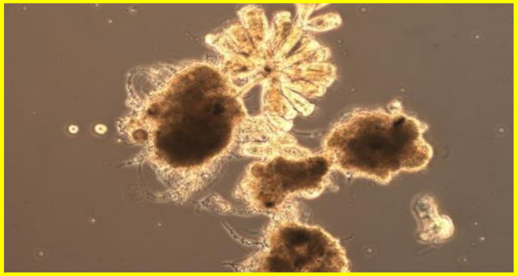
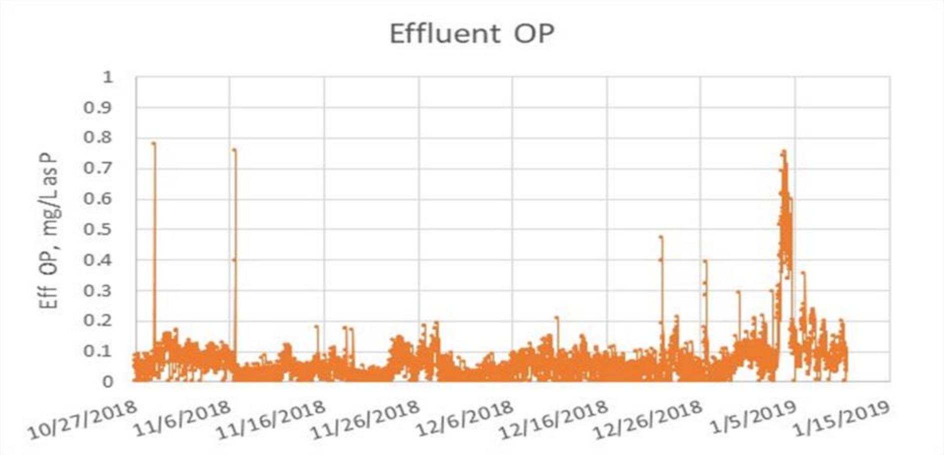


Figure 9 Granules at Wakarusa KS

S2EBPR resulted in only granular sludge with no selective wastage producing very low O-PO_4 concentration and low TN - Was discussing with Dave at time of his death



REMEMBERING DAVID STENSEL (1945-2021)

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- Take home Message

- Dr. Dave Stensel was one of the giants of our time and his work will live on for many generations.

- I was privileged to have known him and worked with him for most of his professional life.

- We had a great exchange of ideas up to the end.

- His latest work on granulation ties in very well with the theme of this Webinar.

OPPORTUNITY OF DPAOS FOR OPTIMIZING CARBON USAGE FOR BOTH DENITRIFICATION AND PHOSPHORUS REMOVAL

CHRIS DEBARBADILLO (BLACK & VEATCH), GEORGE WELLS (NORTHWESTERN UNIVERSITY) & KARTIK CHANDRAN (COLUMBIA UNIVERSITY)



inspiring change

PROJECT BACKGROUND WRF PROJECT NTRY13R16

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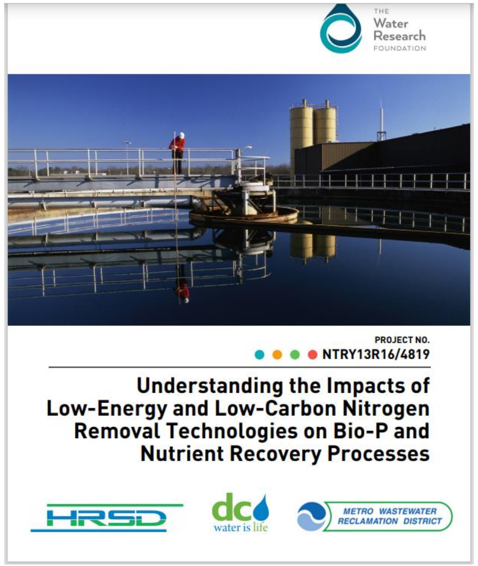
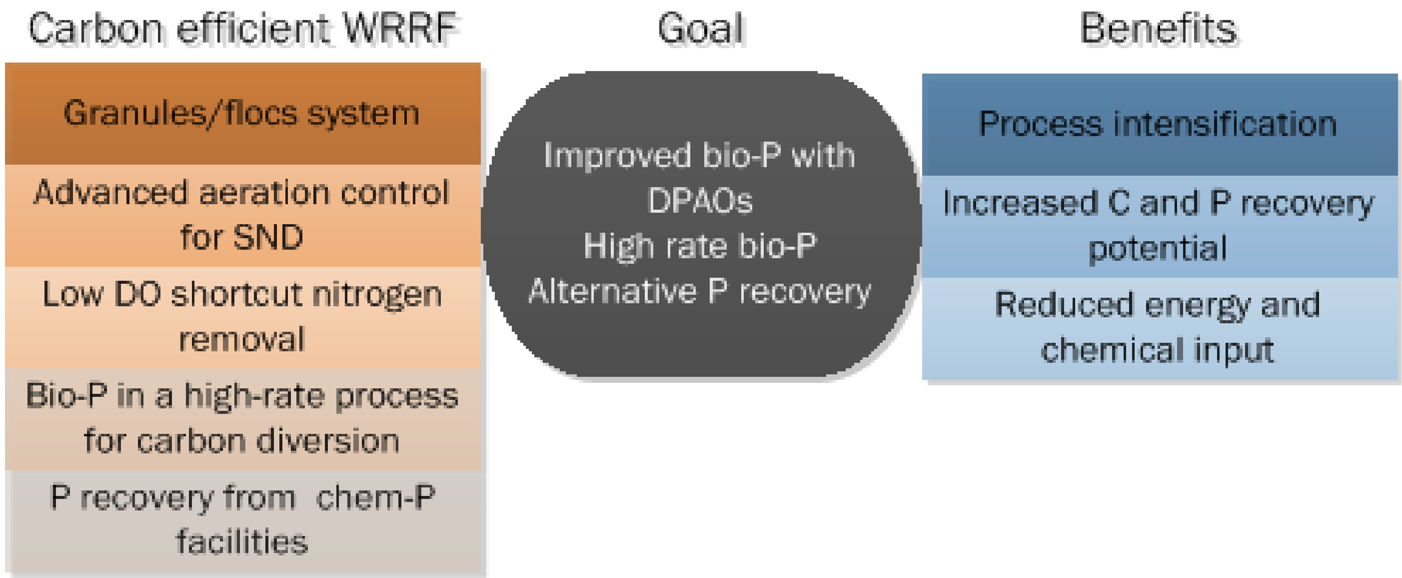
- Understanding the Impacts of Low-Energy and Low-Carbon Nitrogen Removal Technologies on Bio-P and Nutrient Recovery Processes
- Project Partners:
  - Universities – Northwestern University; Columbia University
  - Utilities - Clean Water Services; DC Water; Denver Metro; HRSD; MWRD Greater Chicago; Pueblo, Colorado; VCS, Denmark
  - Consulting Engineers: Brown & Caldwell; Hazen; Jacobs; Primodal
- Three research tracks
  1) Integrate resource efficient N removal processes with bio-P removal through the activity of DPAOs
  2) Test the limits of A-stage high rate bio-P followed by B-stage short-cut N removal.
  3) Implement extractive recovery of P from WRRFs performing both bio-P and chemical P removal



MAIN STUDY OUTCOMES



The primary expected outcome of this project is the successful full-scale implementation of carbon- and energy-efficient N removal with bio-P in WRRFs with stringent N and P criteria across different geographic locations and process configurations

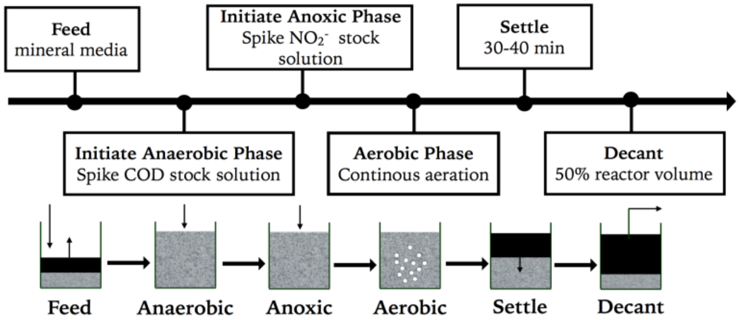
LAB-SCALE DPAO ENRICHMENT REACTOR

Objectives:

1. Quantify kinetics of P and N transformations by denitrifying Accumulibacter clades in the presence of different **electron acceptors** (NO_2^-, NO_3^-, and N_2O) and **electron donors** (acetate and propionate).
2. Assess propensity and mechanism for **N_2O production** by DPAOs
3. Characterize **metabolic pathways and microbial ecology** in a DPAO-enriched consortium

Methodology: 12L SBR (synthetic feed) operated with cyclic anaerobic/ anoxic phases and aerobic polishing step for >1000 days.

- Feed NO_2^- in anoxic phase to simulate upstream nitritation process
- Online monitoring for O_2, N_2O, and pH
- Track community structure and metabolic potential via molecular tools

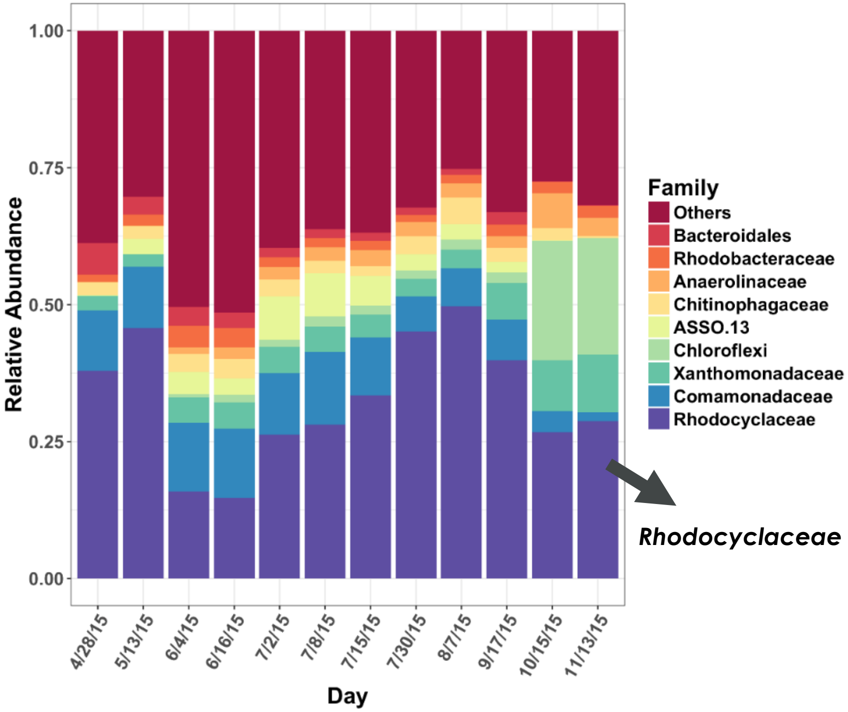


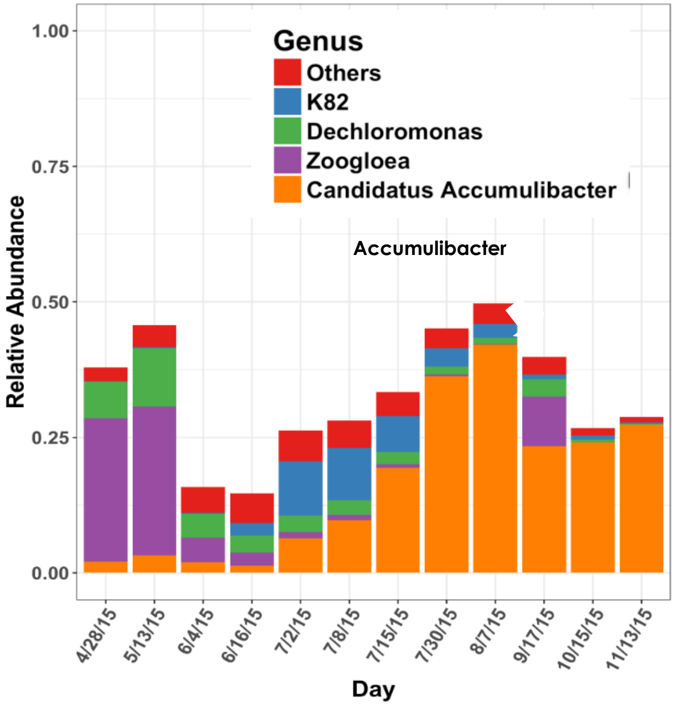
	SBR operation						
	Anaerobic (min)	Anoxic (min)	Aerobic (min)	Total cycle (h)	Initial COD (mg/L)	Initial NO_2^- (mg/L as N)	Initial PO_4^{3-} (mg/L as P)
Phase I (acclimation period, day 0 to 120)	280	300	60	12	<80	<20	25
Phase II (day 121 to 158)	90	120	60	6	45-120	15-45	25
Phase III (day 159 to 181)	90	120	60	6	120-160	35-45	25
Phase IV (day 182 to date)	70	180	60	6	120-160	35-45	15

OVERALL MICROBIAL COMMUNITY STRUCTURE

the international water association

Results from High Throughput 16S rRNA gene sequencing





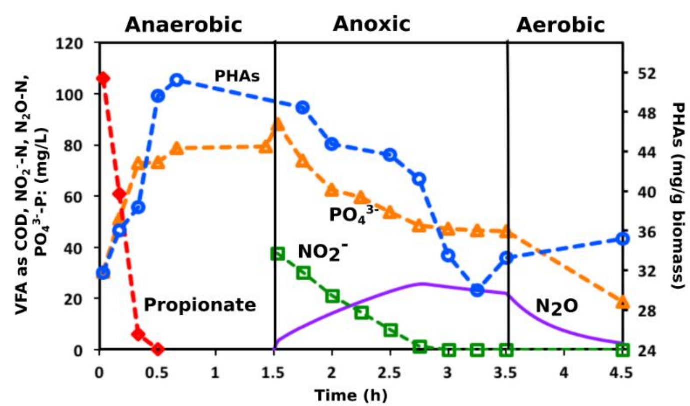
Accumulibacter was enriched from 2% to nearly 50% of the community in 3 months

Gao et al. 2017. *ES&T* 51: 4531-4540

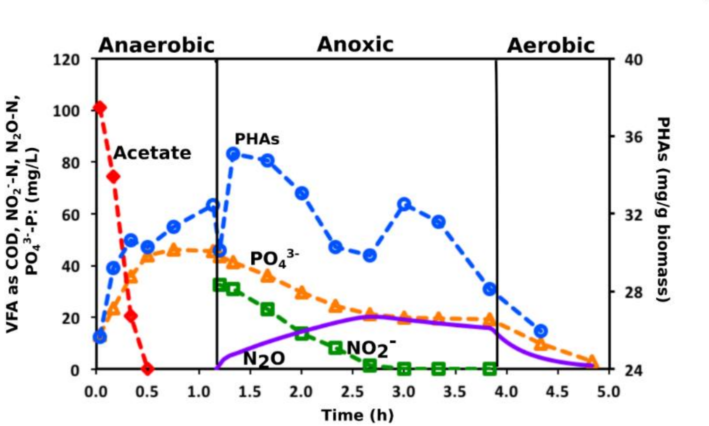
DENITRIFYING PAO ACTIVITY: ROBUST P UPTAKE UNDER ANOXIC CONDITIONS

the international water association

Propionate



Acetate



Comparable anoxic and aerobic P uptake rate

External e$^-$ donors	NO_2^- reduction (mg NO_2^- - N/gVSS/h)	Anoxic P uptake (mg PO_4^{3-}-P/gVSS/h)	Aerobic P uptake (mg PO_4^{3-}-P/gVSS/h)	Anoxic/ Aerobic P uptake rate (%)
Propionate	7.9	**9.0**	**7.2**	**125%**
Acetate	6.2	**4.5**	**4.3**	**~100%**

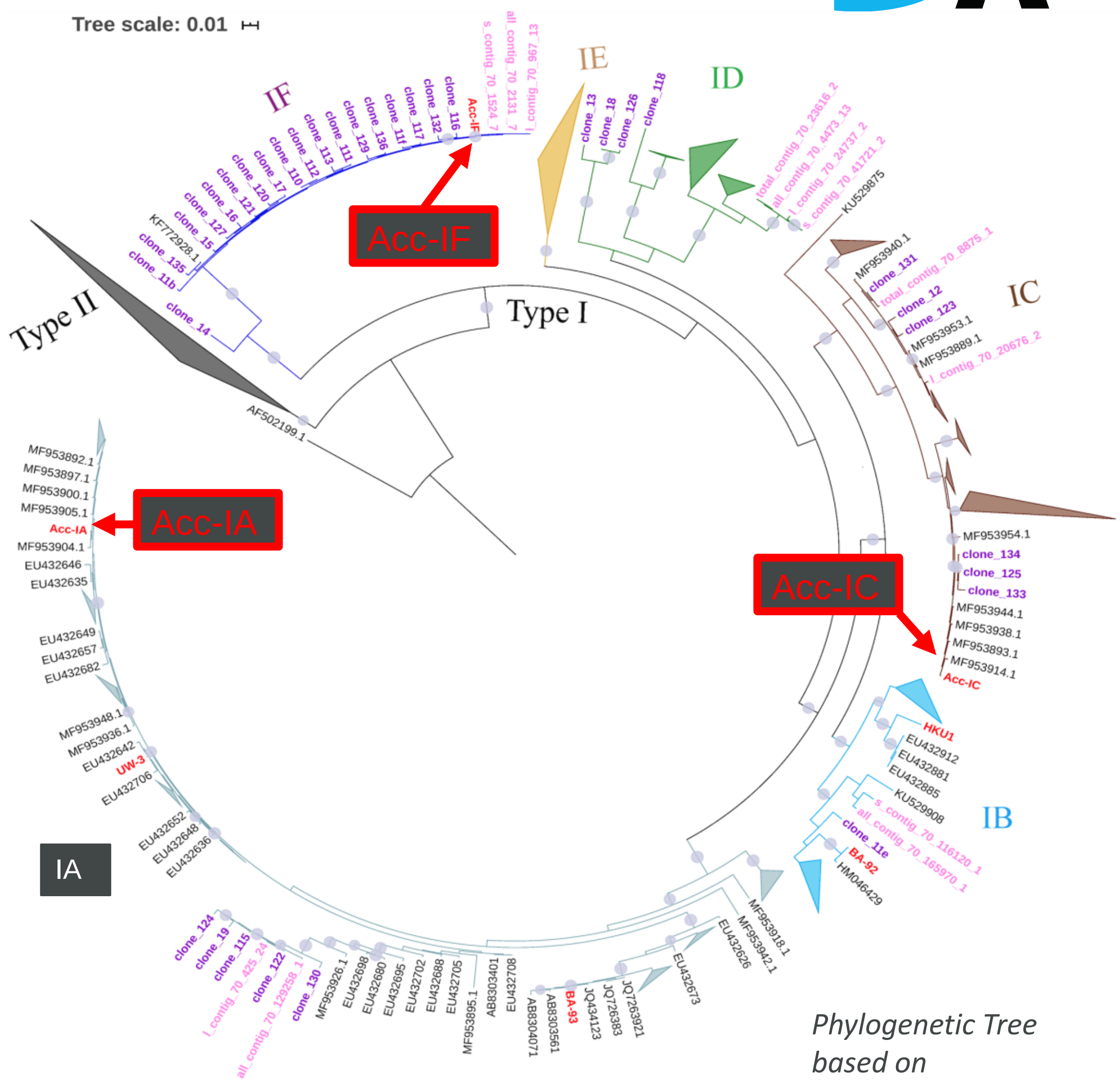
Gao et al. 2017 *ES&T* 51: 4531-4540
Gao et al. 2020 *ES:WR&T* 6: 1028-1043

ACCUMULIBACTER-PAO MICRODIVERSITY

Three Accumulibacter clades co-existed in DPAO-enrichment reactor, based on genome-resolved meta-omic profiling

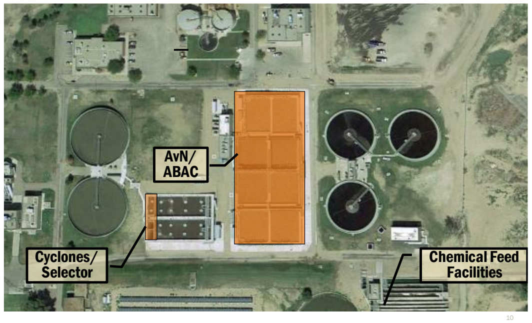
- Type IA
- Type IC (first reported genome)
- A novel Accumulibacter clade (IF), enriched over time and putatively adapted to high rate denitrifying P uptake

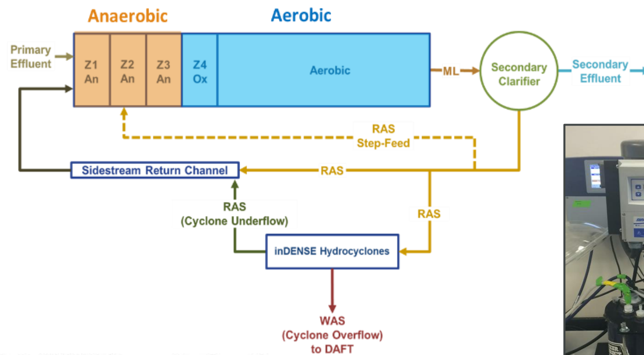
Gao et al. 2019 *Water Research* 155: 276-287
Wang et al. 2021 *Environmental Microbiology 23: 3274-3293*



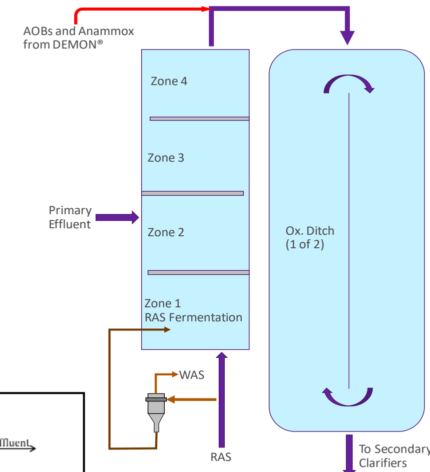
Phylogenetic Tree based on Accumulibacter ppk1 gene sequences

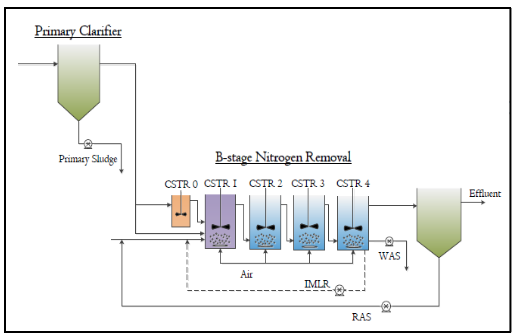
EIGHT PLANTS, TWELVE CONFIGURATIONS TESTED

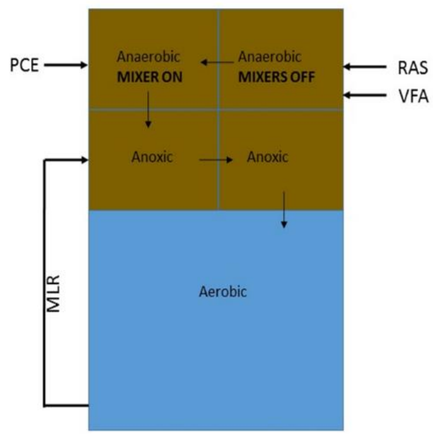


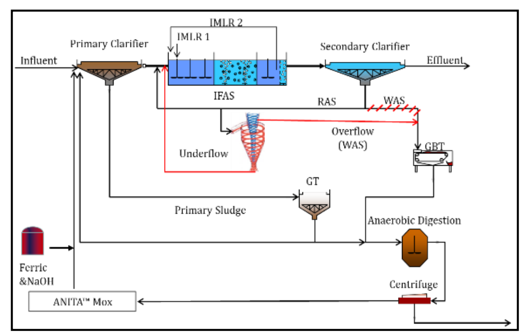


Basin 7 - SSEBPR Process Configuration

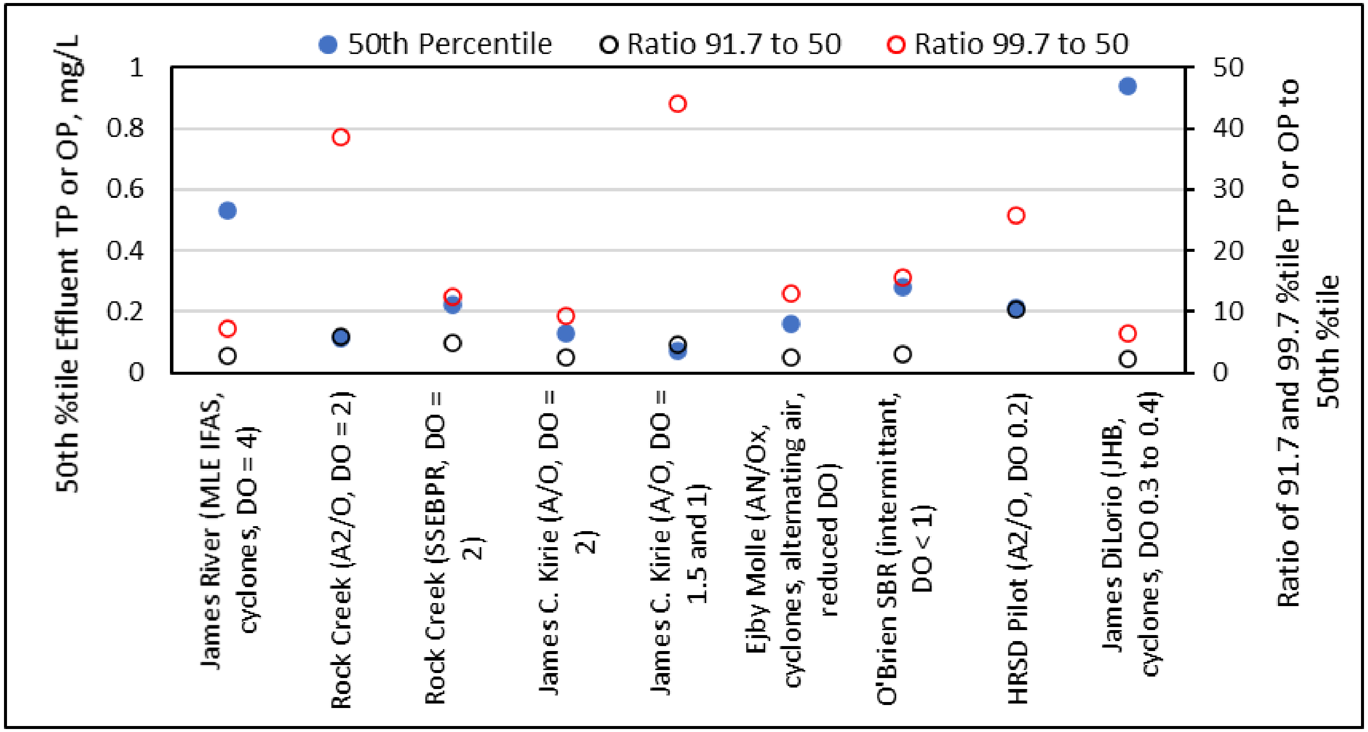








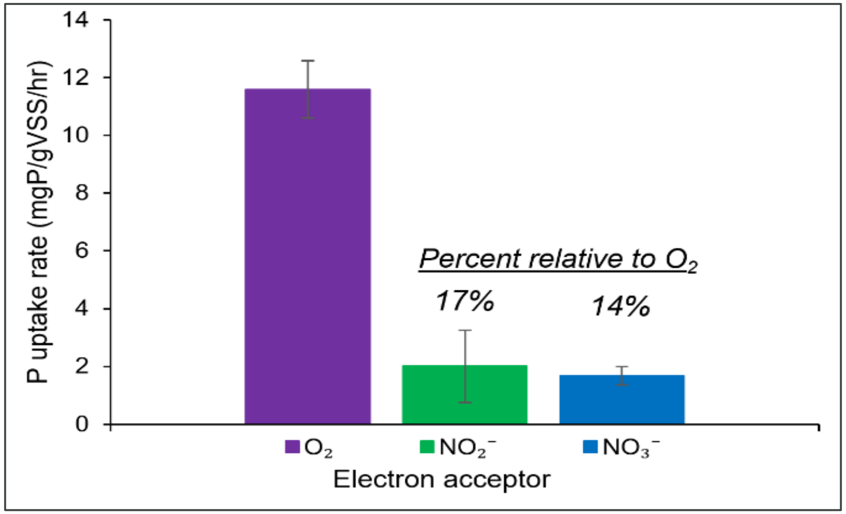
COMPARISON OF EFFLUENT P PERFORMANCE STATISTICS



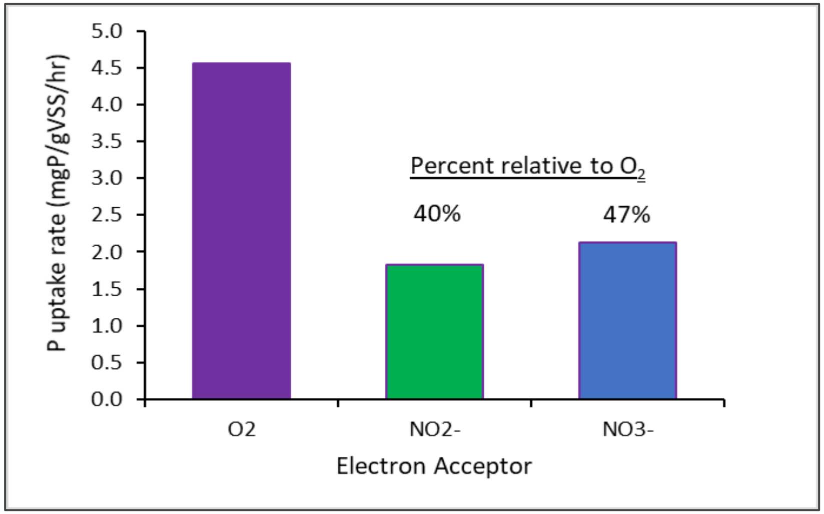
- Achieved good P removal performance (<1 mg/L) at lower DOs
  - Kirie
  - Ejby Molle
  - Obrien SBR
  - HRSD pilot
  - James DiLorio
- Reducing DO at Kirie reduced energy costs, but slightly more variable P
- Rock Creek SSEBPR had less variability in performance than A2/O

P UPTAKE ACTIVITY TESTS – NO_3^- AND NO_2^-

O'Brien SBR Pilot (AN + intermittent aeration)

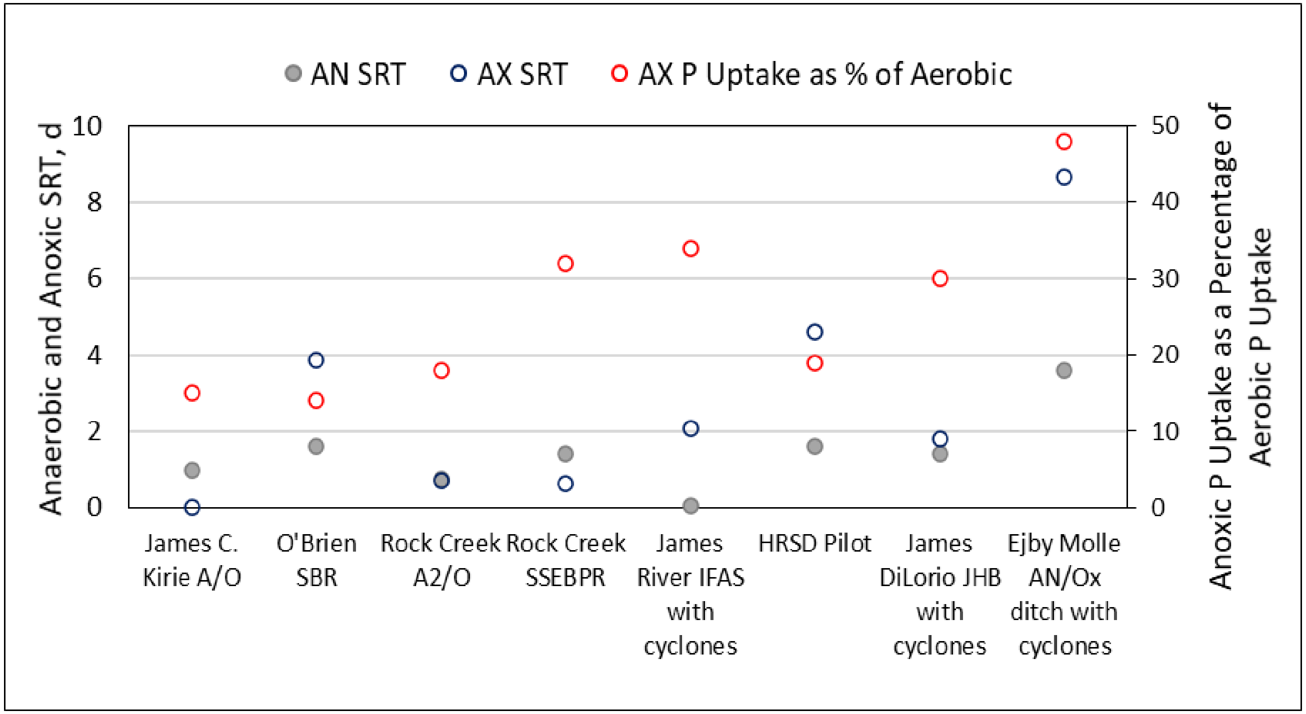


Ejby Molle Full-scale (AN + AX + intermittent/phased aeration, low DO, hydrocyclones)



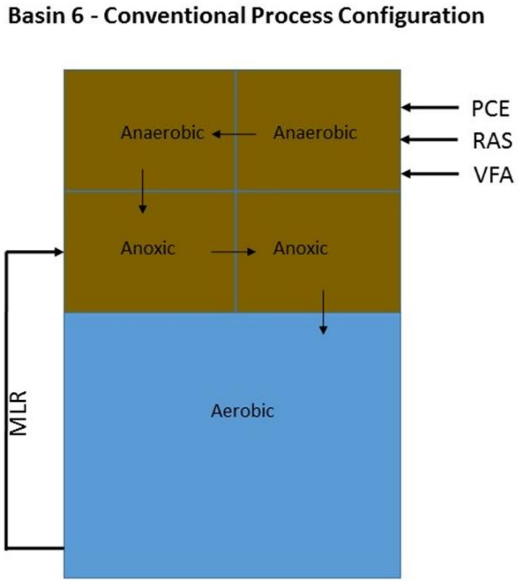
- The two facilities where anoxic P uptake tests were conducted with both NO3- and NO2- did not show major differences in rates between the two electron acceptors
- Very different configurations

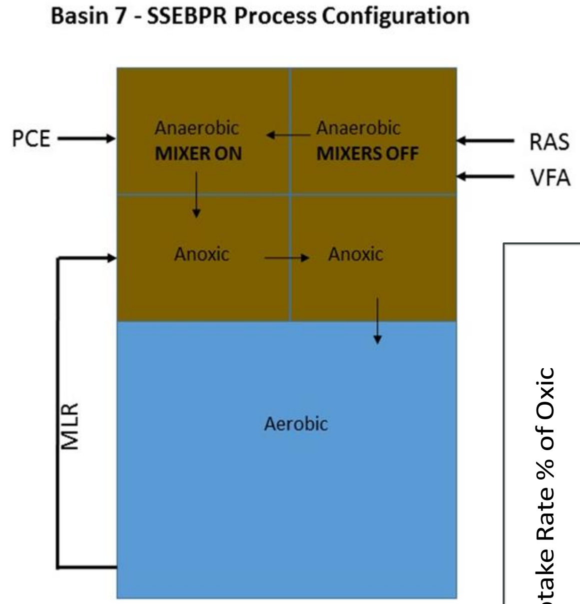
COMPARISON OF ANOXIC P UPTAKE RATES

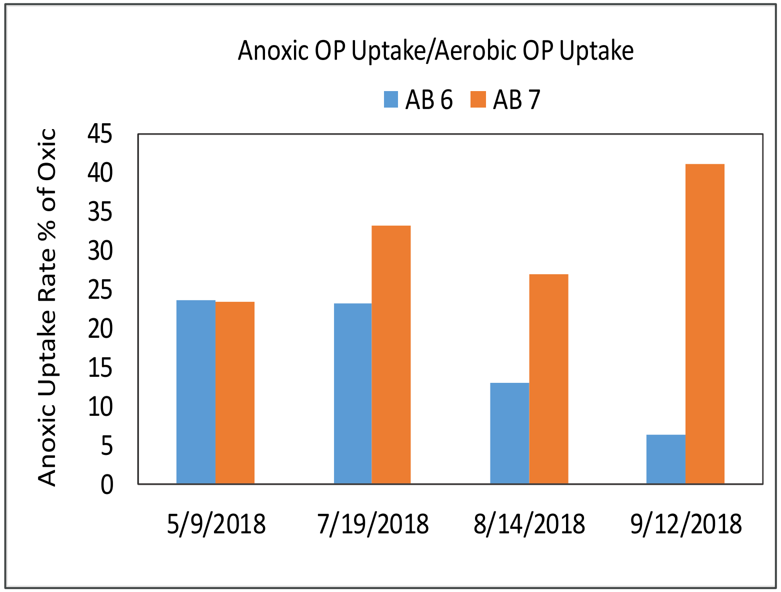


- Higher ratio of AX/OX P uptake seemed to be observed in:
  - Systems with longer AN SRT
  - Systems with hydrocyclones

ROCK CREEK AWTF SIDE-BY-SIDE TESTING OF A2/O AND SSEBPR CONFIGURATIONS





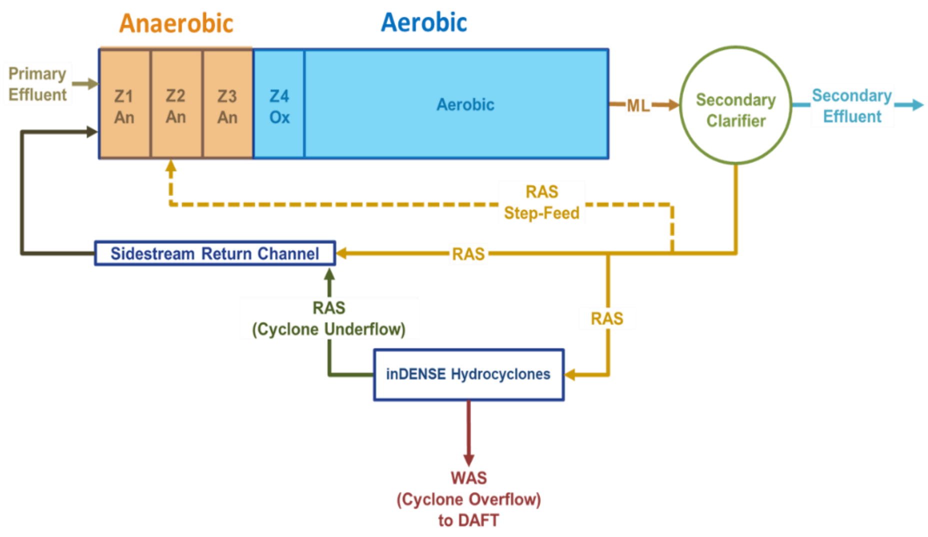


- Same operating parameters
- DPAO activity was higher for SSEBPR than A2/O
- AN/AX/OX volume fractions same, but AN SRT/mass fraction higher for SSEBPR

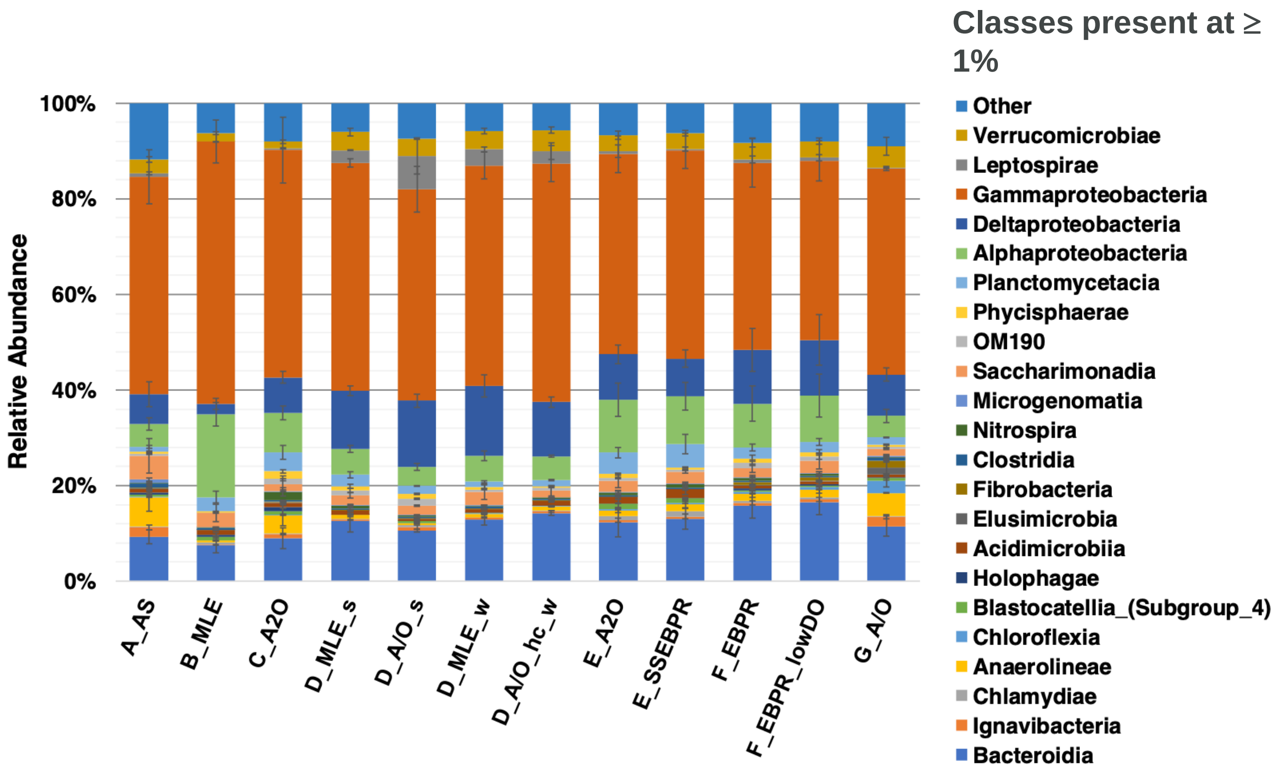
OBSERVATIONS FROM PLANTS OPERATING WITH HYDROCYCLONES

- *Plants with hydrocyclones Seemed to have some of the higher AX P-uptake values*
- James River TP
  - Achieved EBPR w/o almost no AN fraction
  - Highly aerated IFAS system operating at relatively short suspended SRT
- Ejby Molle
  - High AN and AX fractions
  - Alternating aeration
- James DiLorio
  - Low DO/AvN control

- *Operation in A/O with hydrocyclones at the Robert Hite plant showed an increase in PAO relative abundance in 16-S amplicon sequencing compared to A/O*



META-OMICS APPROACHES



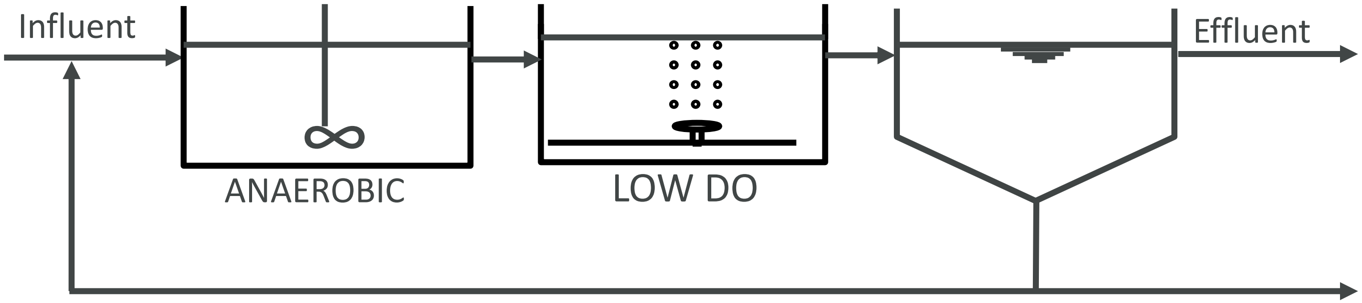
Dominant N- and P-removing genera

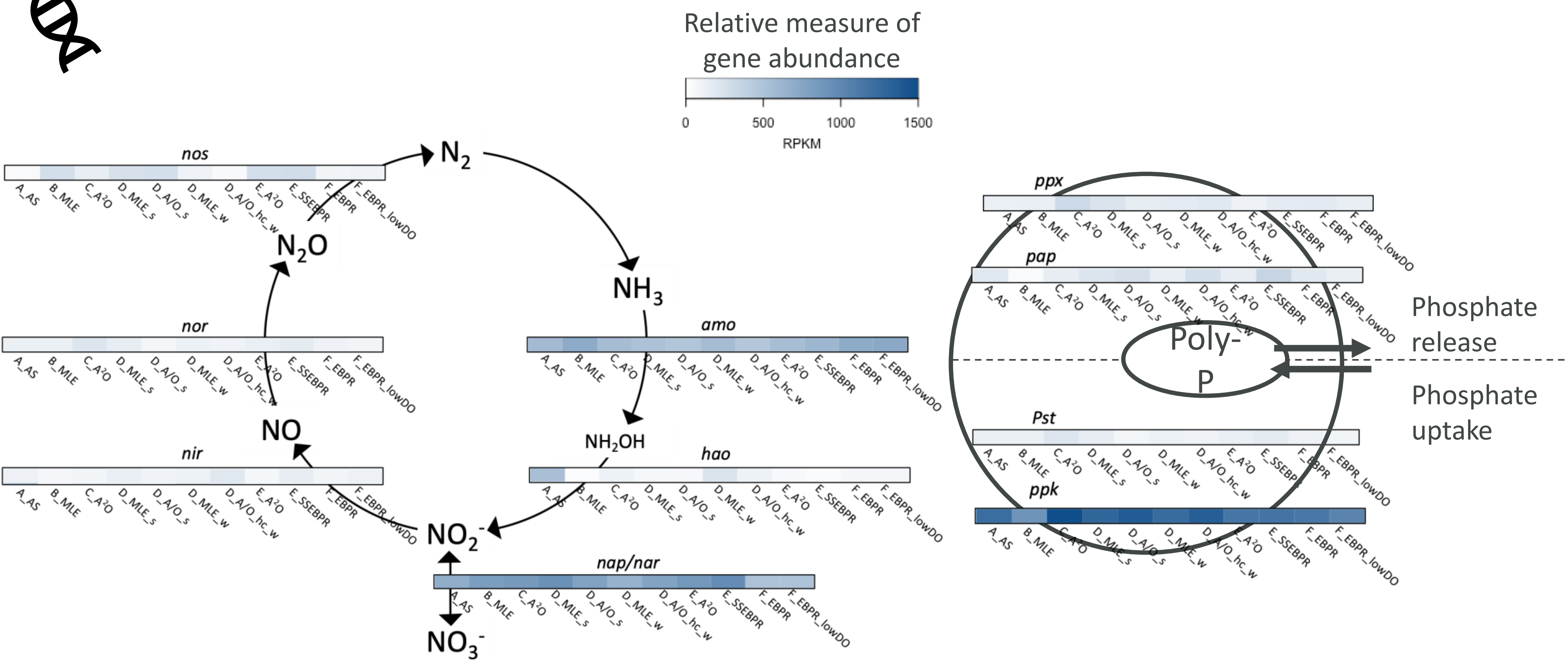
AOB: *Nitrosomonas* spp.

NOB: *Nitrospira* spp.

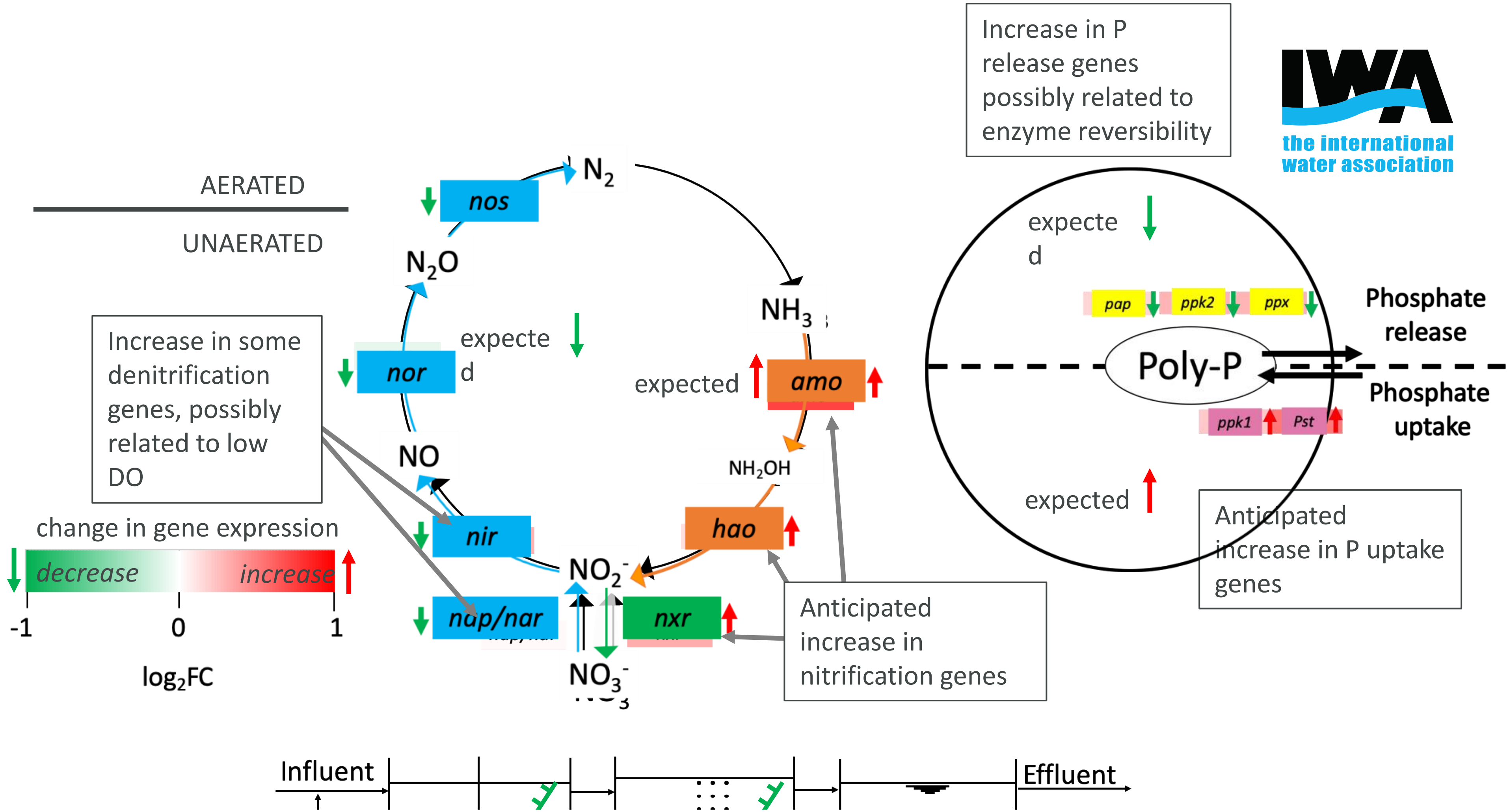
PAOs: ‘*Candidatus* Accumulibacter’ spp.

Similar overall microbial community structures and dominant nitrogen- and phosphorus-removing general





Complete pathways for N and P removal present at all facilities, despite differences in configurations and operating conditions



Expression of nitrification and phosphate uptake genes consistent with expected activity

Increased expression of some dentification genes in aerated zone may be linked to low DO operating conditions

Expression of P release genes inconsistent, possibly due to enzyme reversibility

Thank You!

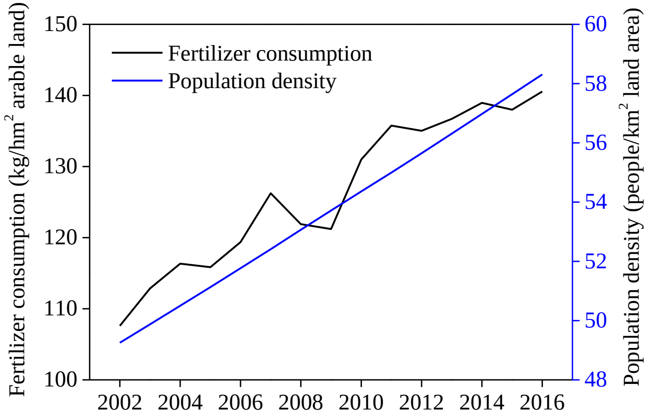
A SIDE-STREAM PROCESS DESIGNED FOR NUTRIENT REMOVAL AND P RECOVERY FROM MUNICIPAL WASTEWATER

YONGMEI LI
COLLEGE OF ENVIRONMENTAL SCIENCE AND ENGINEERING, TONGJI UNIVERSITY

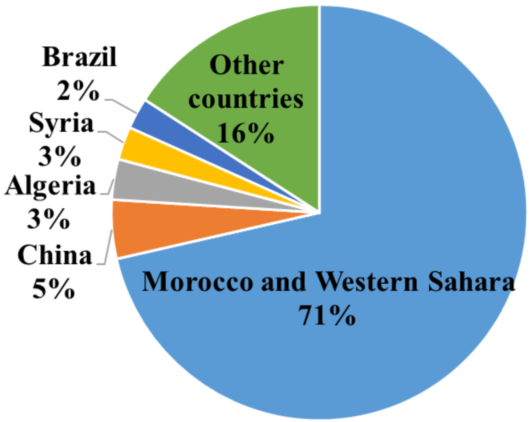
inspiring change

GLOBAL PHOSPHORUS SCARCITY

- Phosphorus (P) is consumed primarily as a principal component of fertilizers. As the global population density grows, the demand for phosphate fertilizer continues to grow.
- It was reported that the economically available phosphate mineral reserves can only be maintained for ~30 years, after which the global demand for phosphate will exceed supply and lead to global P scarcity.



Global population density and fertilizer consumption (World Bank, 2019)

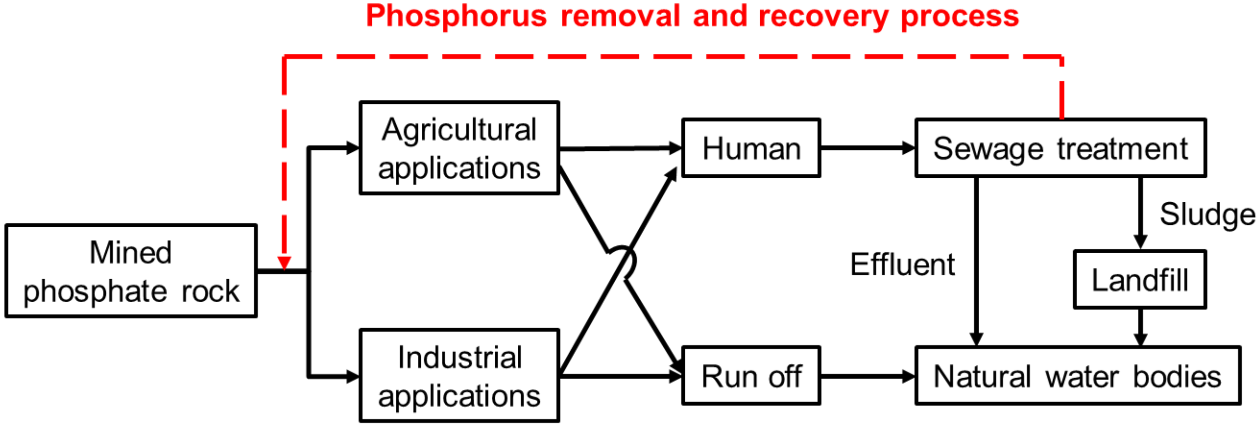


The top 5 countries for phosphate rock reserves in 2018.(USGS, 2019)

PHOSPHORUS LIFE CYCLE

One-way flow of phosphate from mines to natural water bodies

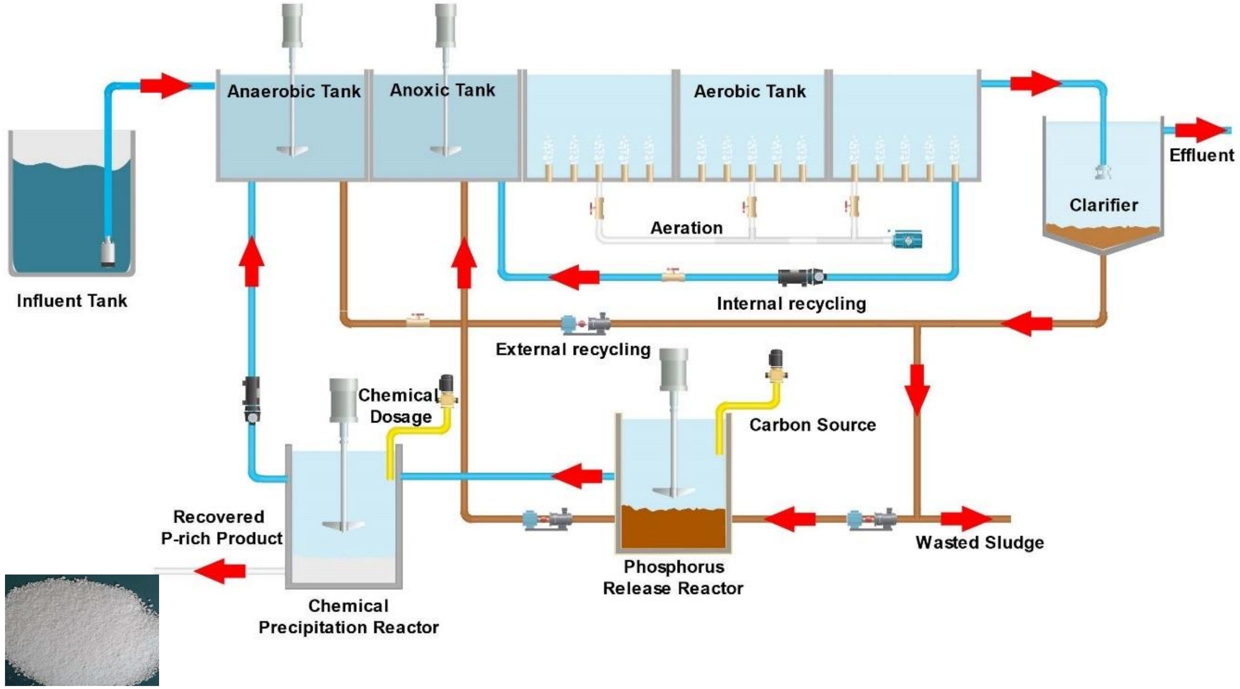
Closed phosphorus cycle by phosphorus recovery process



Desmidt et al., Crit Rev Env Sci Tec, 2015, 45(4): 336-384

Phosphate recovery from sewage is increasingly being used.
(van Loosdrecht et al., Science, 2014, 344(6191): 1452-1453)

P RECOVERY FROM A SIDE-STREAM PROCESS: AAO-SBSPR PROCESS



Schematic diagram of the AAO-SBSPR process

Recovering P from side-stream liquor

- Side-stream P recovery can easily integrated with established EBPR processes
- Simultaneous nutrient removal and P recovery
- Carbon in sludge can be used
- Low operation cost
- Less contaminants

P RECOVERY FROM A SIDE-STREAM PROCESS

the international water association

Requirement for the side-stream P recovery process

- P recovery rate > 60%
- Phosphorus concentration in side-stream supernatant > 50 mg/L
- EBPR process associated

Adverse effect of P recovery in the side-stream process

- Negative correlation between P recovery rate and P content in activated sludge
- High extraction of the P may lead to the depletion of the poly-P in biomass

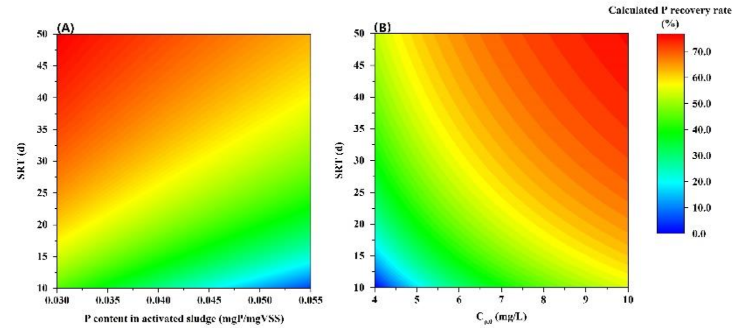
P RECOVERY FROM THE AAO-SBSPR PROCESS

the international water association

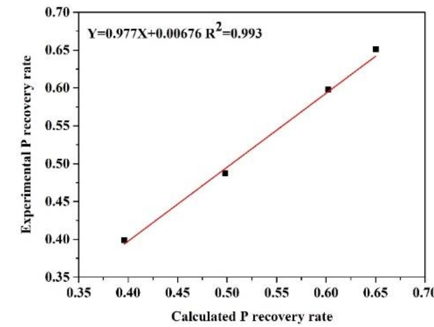
Novel operation strategy based on P mass balance

- P recovery rate was correlated with SRT
- SRT was increased with the expected P recovery rate so as to reduce the amount of the P leaving the system by excess sludge discharge
- The relationship between P recovery rate, SRT and P content in biomass was described by the following equation:

$$R = 100 \cdot \left(1 - \frac{C_{p,eff}}{C_{p,0}} - \frac{P_S \cdot Y \cdot \Delta S}{C_{p,0} \cdot (1 + K_d \cdot SRT)}\right)$$



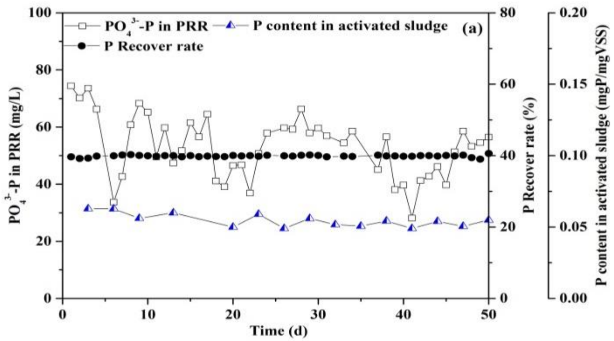
Relationship between SRT, P content, influent TP and P recovery rate



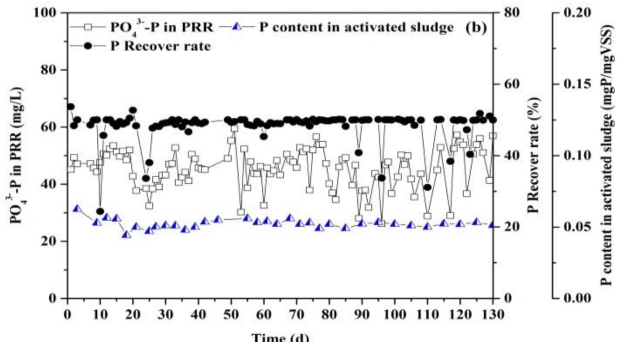
Equation was validated by experiment

P RECOVERY FROM THE AAO-SBSPR PROCESS

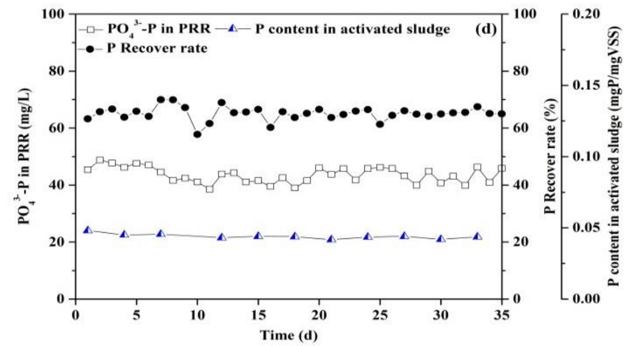
P concentration，recovery rate，and P content in activated sludge at various SRT



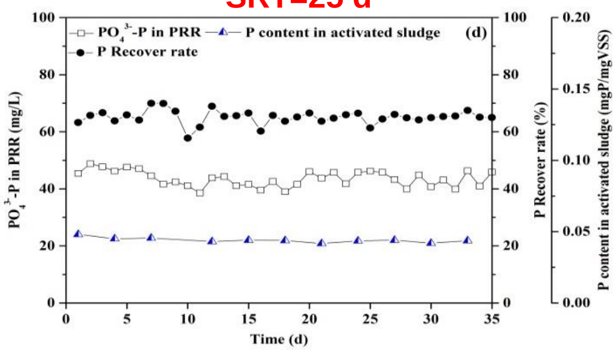
SRT=25 d



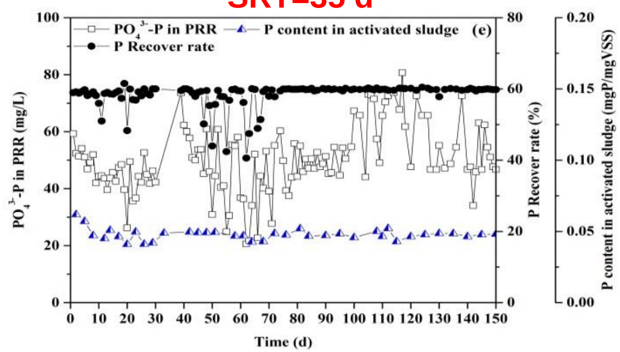
SRT=35 d



SRT=35 d



SRT=35 d



SRT=50 d

Up to 65% influent P could be steadily recovered using synthetic wastewater

Influent: C/P≈45, TP=7 mg/L

P RECOVERY FROM THE AAO-SBSPR PROCESS

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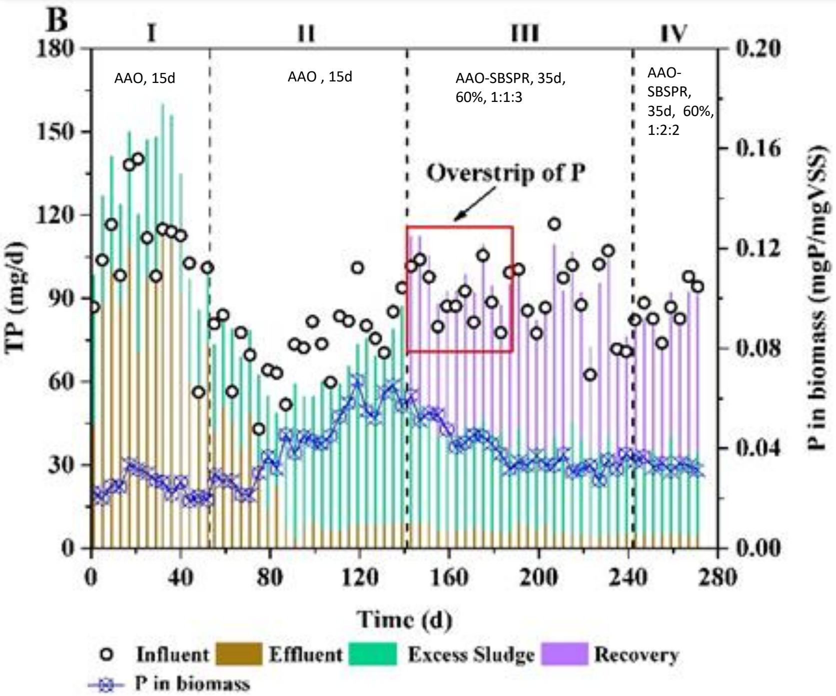
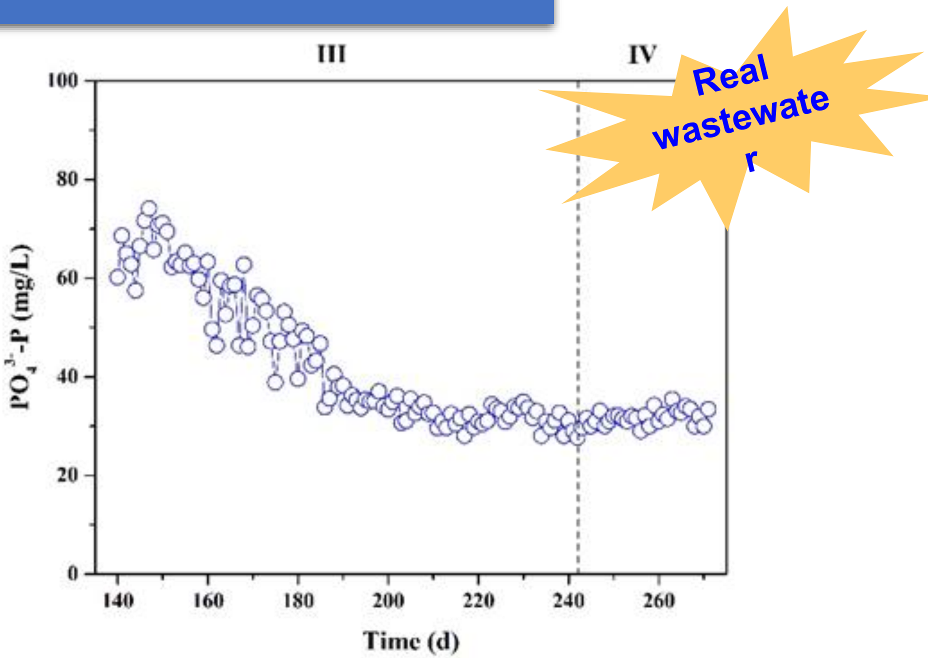
P concentration, recovery rate, and P content in activated sludge at various SRT



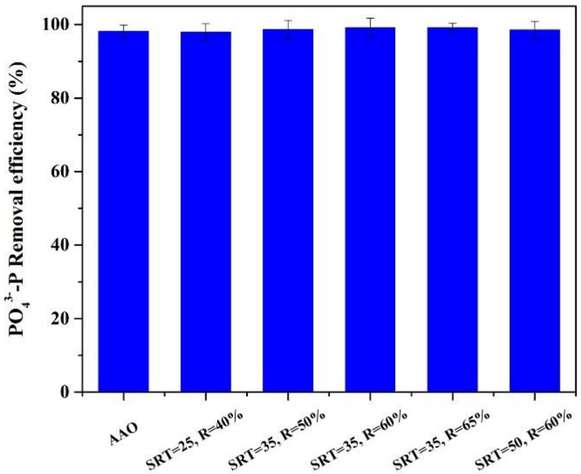
P balance of the AAO-SBSPR process fed with real wastewater



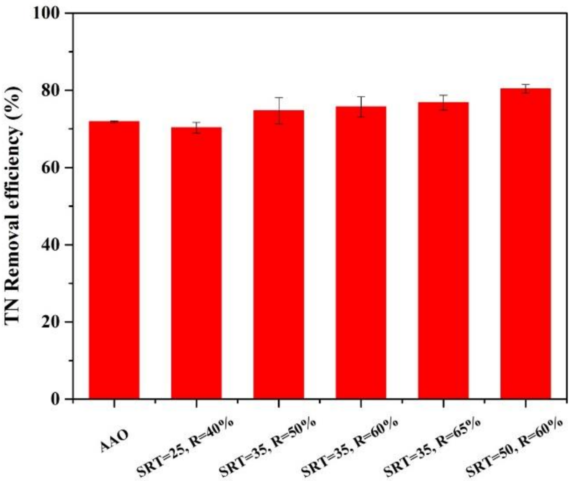
P concentration in the side-stream supernatant

P RECOVERY FROM THE AAO-SBSPR PROCESS

Contaminants removal performance



P removal efficiency



TN removal efficiency

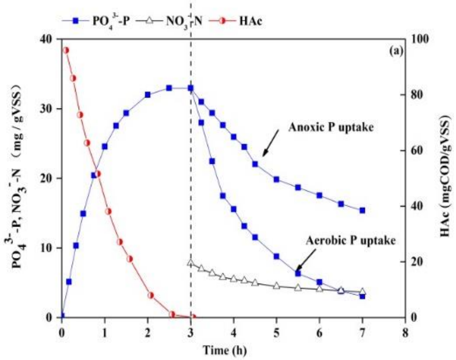
- **P recovery rate and SRT had little effect on the performance of P removal**
- **TN removal efficiency was enhanced at high P recovery rate and long SRT**

P RECOVERY FROM THE AAO-SBSPR PROCESS

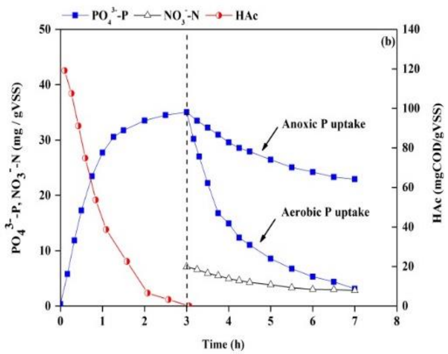
EBPR activity

Stoichiometry and kinetics of the activated sludge in AAO and AAO-SBSPR processes obtained by batch tests

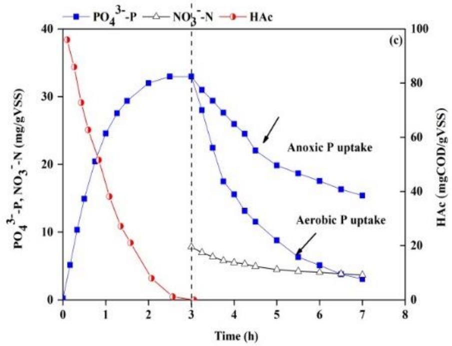
Operation mode	Max P release rate	Max acetate uptake rate	P/C ratio	Max aerobic P uptake rate	Max anoxic P uptake rate	Ratio of anoxic to aerobic P uptake rate	Max NO_x-N uptake rate	P/N ratio
	mgP/(gVSS . h)	mg-Hac/(gVSS . h)	mmol-P/mmol-C	mgP/(gVSS . h)	mgP/(gVSS . h)		mgN/(gVSS . h)	mg-P/mg-N
AAO, SRT=15d	32.9	78.0	0.50	18.8	4.3	22.7%	1.7	2.48
AAO-SBSPR, SRT=35d, R=60%	31.2	83.9	0.39	23.9	5.2	21.6%	2.2	2.40
AAO-SBSPR, SRT=50d, R=60%	29.6	63.5	0.35	21.1	7.1	33.5%	2.7	2.61



SRT=25 d



SRT=35 d

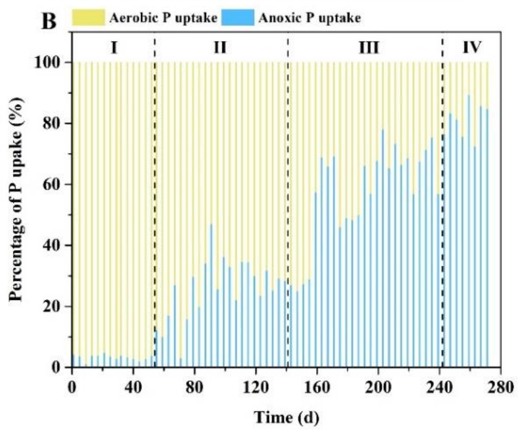


SRT=50 d

- **The EBPR activity was not significantly affected by P recovery and extended SRT.**

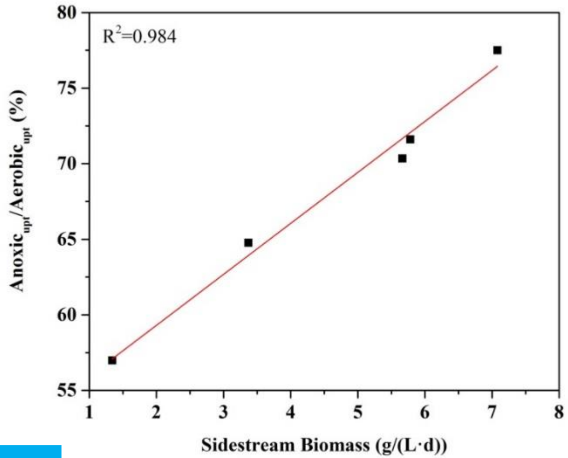
P RECOVERY FROM THE AAO-SBSPR PROCESS

Denitrifying P uptake



Denitrifying P removal was enhanced:

- Ratio of anoxic P uptake to aerobic P uptake of the whole process increased.
- Anoxic P uptake rate and denitrification rate during the anoxic phase in batch tests were increased.



The correlation between the ratio of anoxic PUR to aerobic PUR and the average biomass pumped to the side-stream.

P release and uptake in different operation mode.

Operation mode	Max aerobic P uptake rate	Max anoxic P uptake rate	Ratio of anoxic to aerobic P uptake rate	Max NO_x-N uptake rate	P/N ratio
	mgP/(gVSS . h)	mgP/(gVSS . h)		mgN/(gVSS . h)	mg-P/mg-N
AAO, SRT=15d	18.8	4.3	22.7%	1.7	2.48
AAO-SBSPR, SRT=35d, R=60%	23.9	5.2	21.6%	2.2	2.40
AAO-SBSPR, SRT=50d, R=60%	21.1	7.1	33.5%	2.7	2.61

P RECOVERY FROM THE AAO-SBSPR PROCESS

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Sludge reduction

The average concentration of the mixed liquor suspended solid and the observed biomass yield coefficient in each operation mode at different SRT.

Operation mode	MLSS	MLVSS	MLVSS/MLSS	Daily excess sludge	Y_{obs}
	mg/L	mg/L	-	mgVSS/d	kg VSS/kg COD
AAO, SRT=15 d	3267±215	2687±174	0.82	1790	0.29
AAO-SBSPR, SRT=25 d, R=40 %	3628±129	2954±185	0.80	1162	0.20
AAO-SBSPR, SRT=35 d, R=50 %	4156±289	3372±200	0.81	961	0.15
AAO-SBSPR, SRT=50 d, R=60 %	4668±214	3855±191	0.82	771	0.12

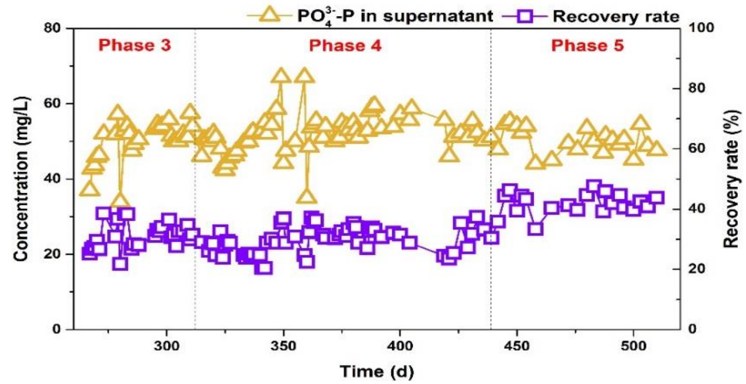
- MLVSS increased while the Y_{obs} decreased with the increase of SRT.
- Y_{obs} decreased significantly when SRT of the AAO-SBSPR process increased to 50 d, which resulted in 58 % sludge reduction

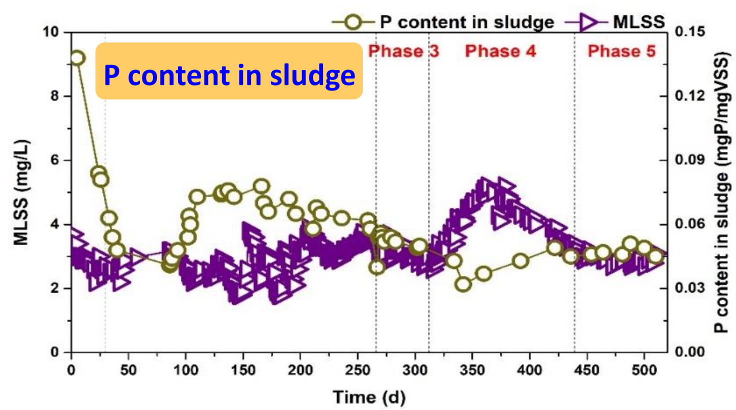
P RECOVERY FROM THE AAO-SBSPR PROCESS

Pilot scale operation

- Influent flowrate 25-30 m^3/d
- Influent COD: 120-360 mg/L
- Influent TP: 4.0-6.0 mg/L
- Influent TN: 30-40 mg/L
- SRT: 15-50 d
- Temperature: 15-35 ℃

P concentration in supernatant and P recovery rate





- The average P recovery rate was 41.9%, at the SRT of 35 d
- The P concentration in the supernatant was about 50 mg/L
- The P content in activated sludge was 0.047 mgP/mgVSS when SRT was 35 d

P RECOVERY FROM THE AAO-SBSPR PROCESS

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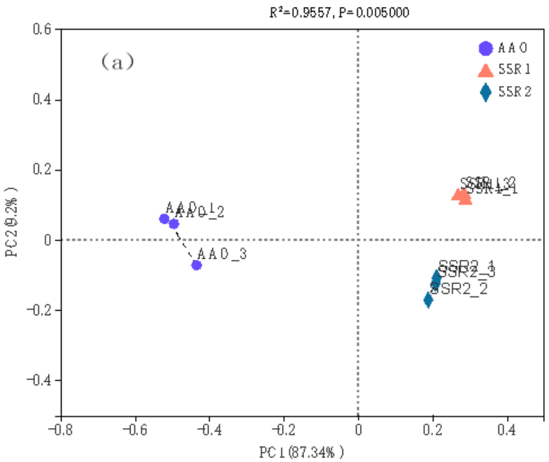
Microbial community

- The microbial richness of the AAO-SBSPR process increased significantly compared with AAO process
- The microbial community of the AAO-SBSRP process had higher diversity than the AAO process.

Samples	Effective reads	OTUs	CHAO1 index	ACE index	Shannon index	Simpson index	Good’s Coverage
R1-AAO	36764	552	567	563	4.79	0.0210	0.999
R1-AAO-SBSPR	83801	1060	1141	1125	5.10	0.0198	0.999
R2-AAO	35437	494	532	527	3.72	0.0974	0.998
R2-AAO-SBSPR	108376	1153	1266	1231	4.57	0.0357	0.998



Principal coordinate analysis (PCoA) based on bray-curtis distance (OTU level)

P RECOVERY FROM THE AAO-SBSPR PROCESS

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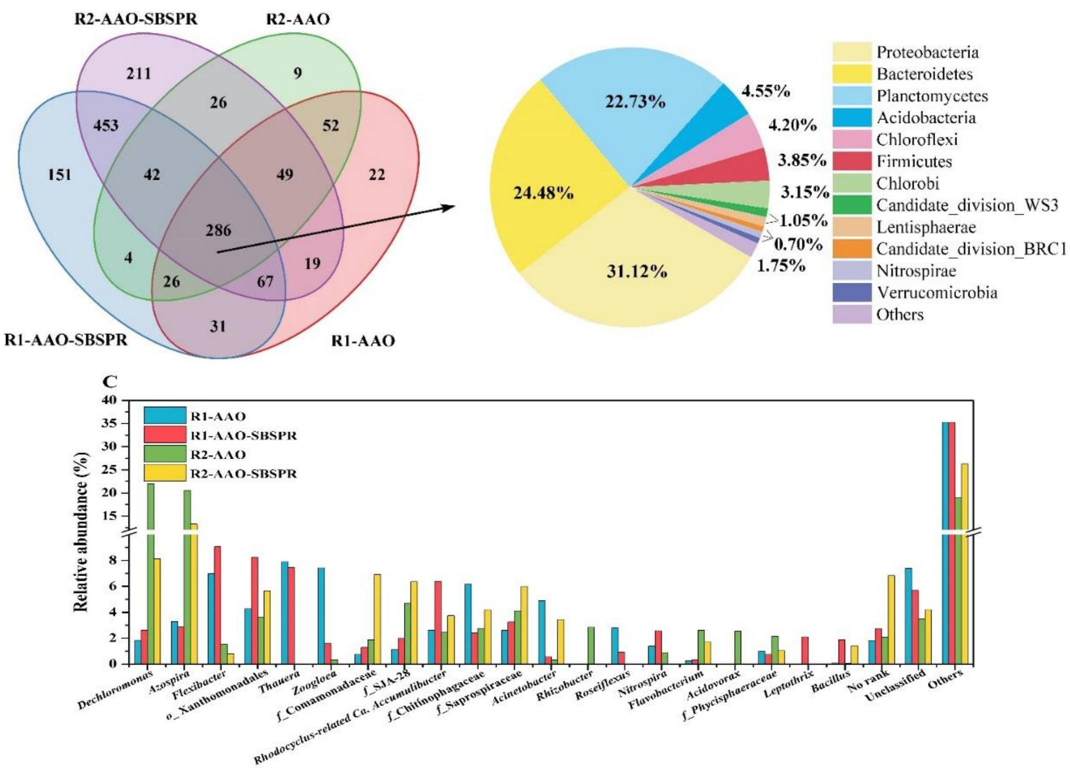
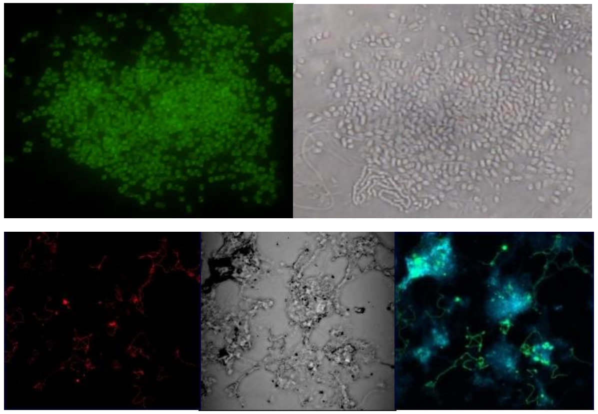
PAOs in AAO-SBSPR process

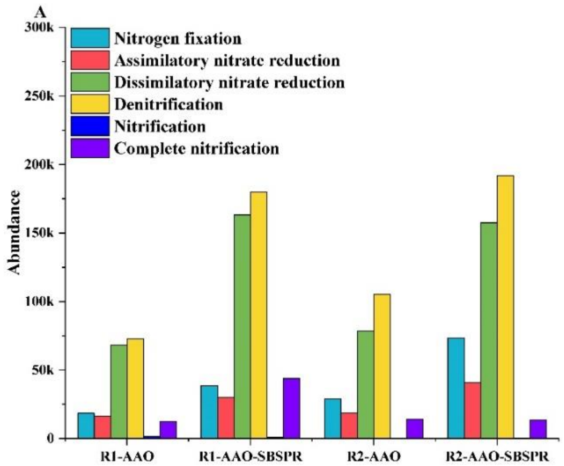


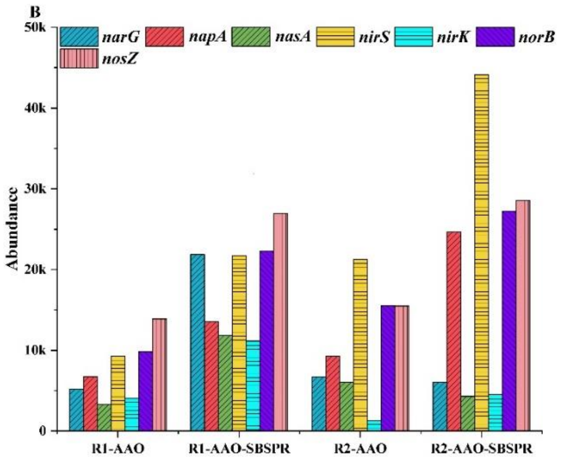


- Relative abundance of *Ca.* Accumulibacter was not affected by the P recovery and extended SRT
- Other PAOs such as *Tetrasphaera*, *Dechloromonas*, and *Thriothrix* were also presented or enriched

PHOSPHORUS RECOVERY FROM SIDE-STREAM PROCESS

N metabolism pathway





The abundance of KEGG modules subject to N metabolism pathway (KEGG entry number: map00910) (A) and primary functional genes subject to KEGG denitrification module (KEGG entry number: M00529) (B)

- metabolic pathways associated with the KEGG-annotated N-related metabolism, particularly the denitrification pathway, were strengthened after the systems shift from the AAO process to the AAO-SBSPR process
- The AAO-SBSPR process could improve the denitrifying P uptake by promoting the growth of *Ca.* Accumulibacter.

TAKE HOME MESSAGE

- Based on the P mass balance of the process, the SRT of the AAO-SBSPR process was extended to increase the potential of P recovery and reduce the impact of P recovery on the P content of the activated sludge
- The denitrifying P uptake was improved in the AAO-SBSPR. Thus. a higher TN removal was achieved compared with the AAO process.
- The microbial community structure was changed significantly by the addition of the side-stream, and the AAO-SBSPR process had higher microbial richness and diversity.
- The important functional bacteria such as nitrifiers, denitrifiers, PAOs and DPAOs were all enriched in the AAO-SBSPR process.
- Challenge: More sophisticated control of the process is required!

Thanks for your attention！

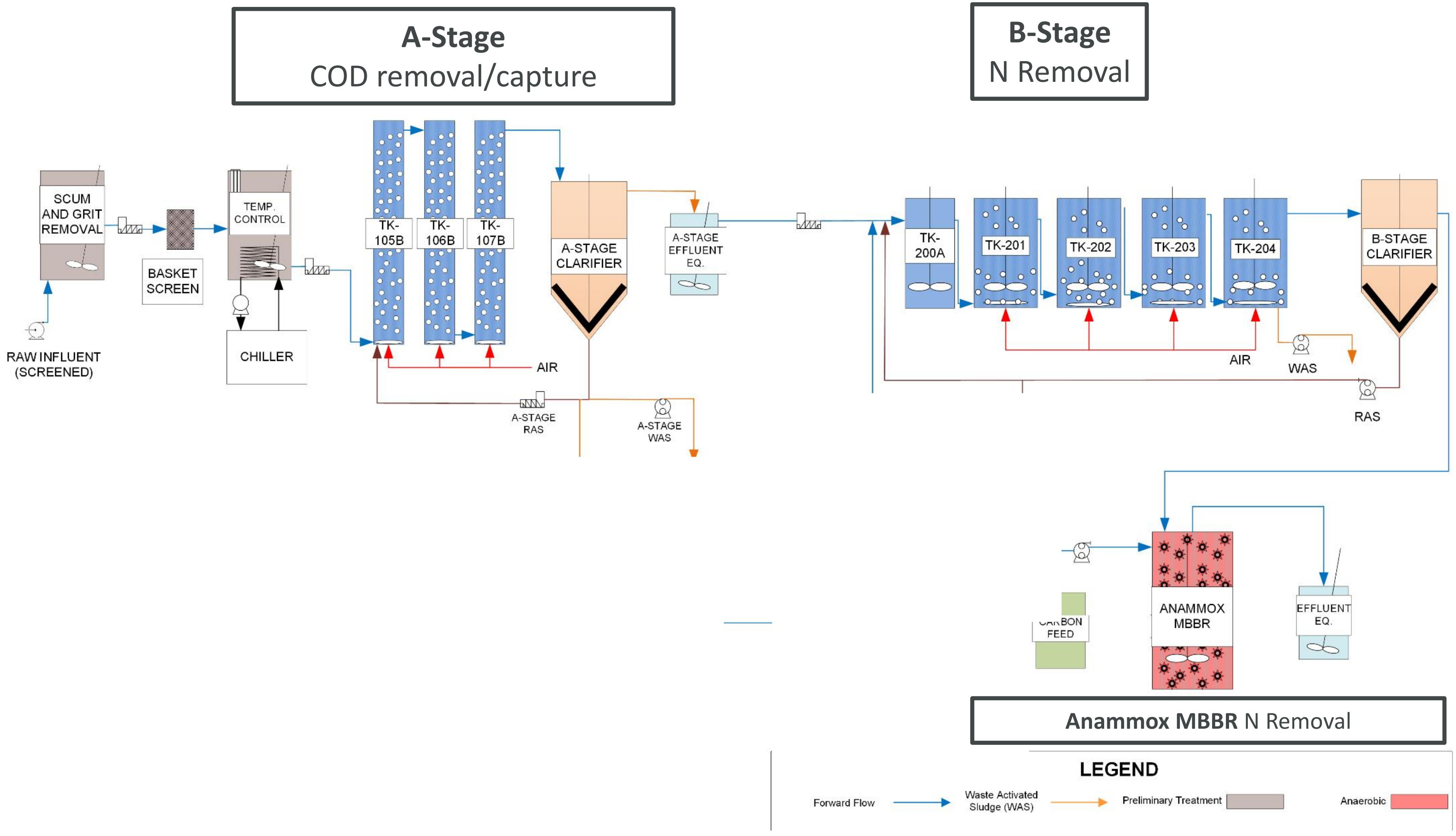
EBPR AND MAINSTREAM DEAMMONIFICATION – BRINGING TWO APPROACHES TOGETHER

KESTER MCCULLOUGH
HRSD

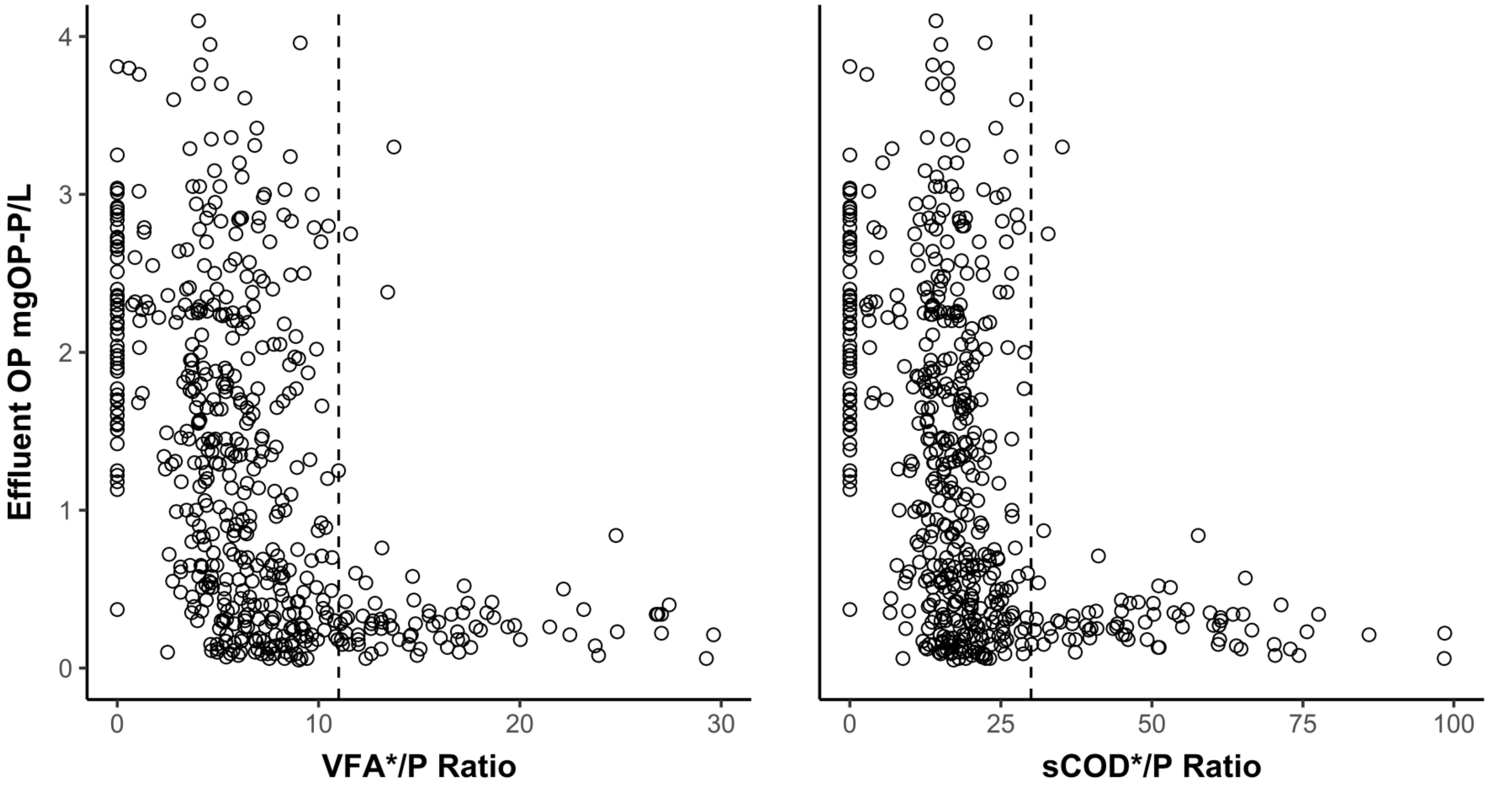
the international water association

inspiring change

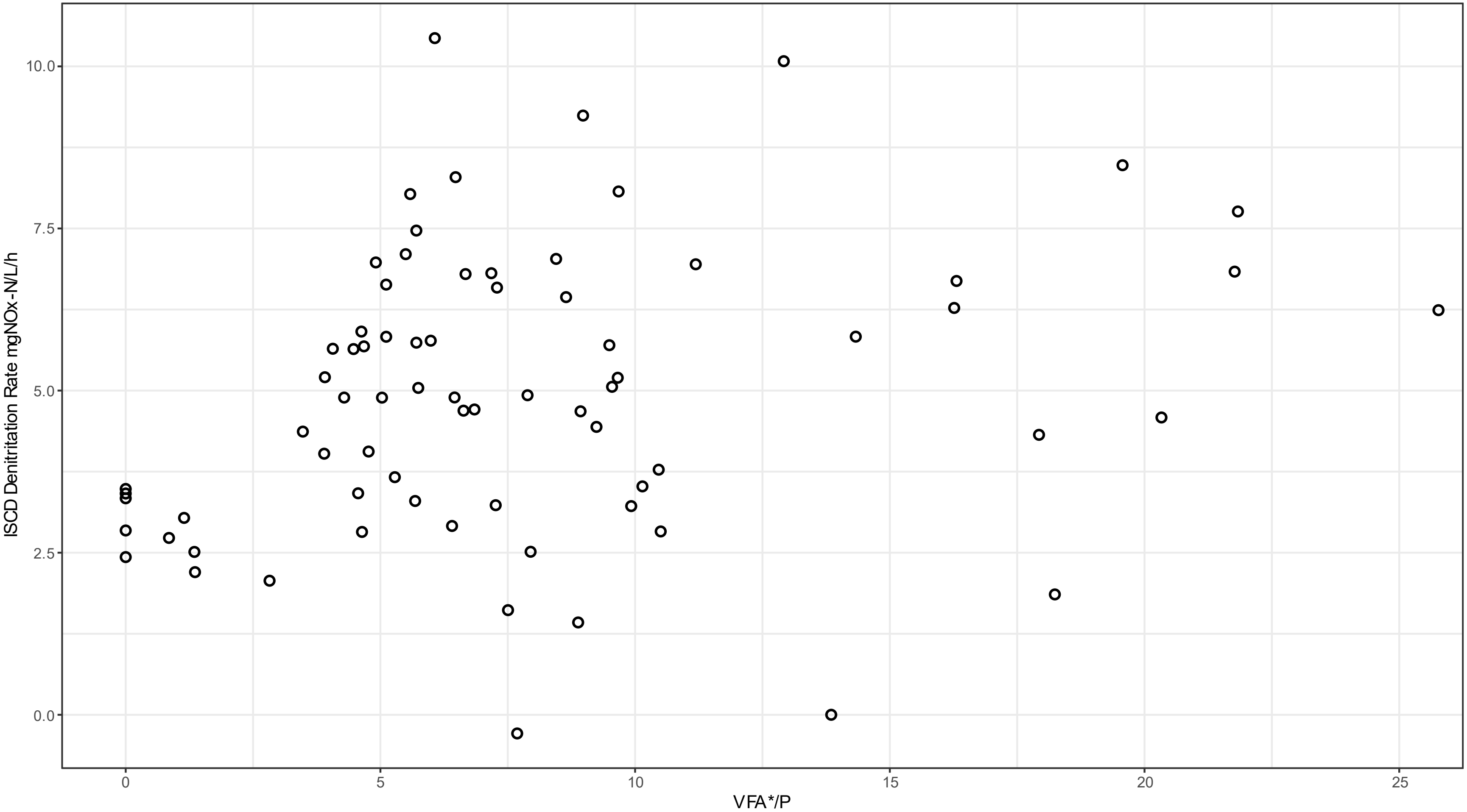
A/B PILOT WITH S2EBPR AND MAINSTREAM ANAMMOX



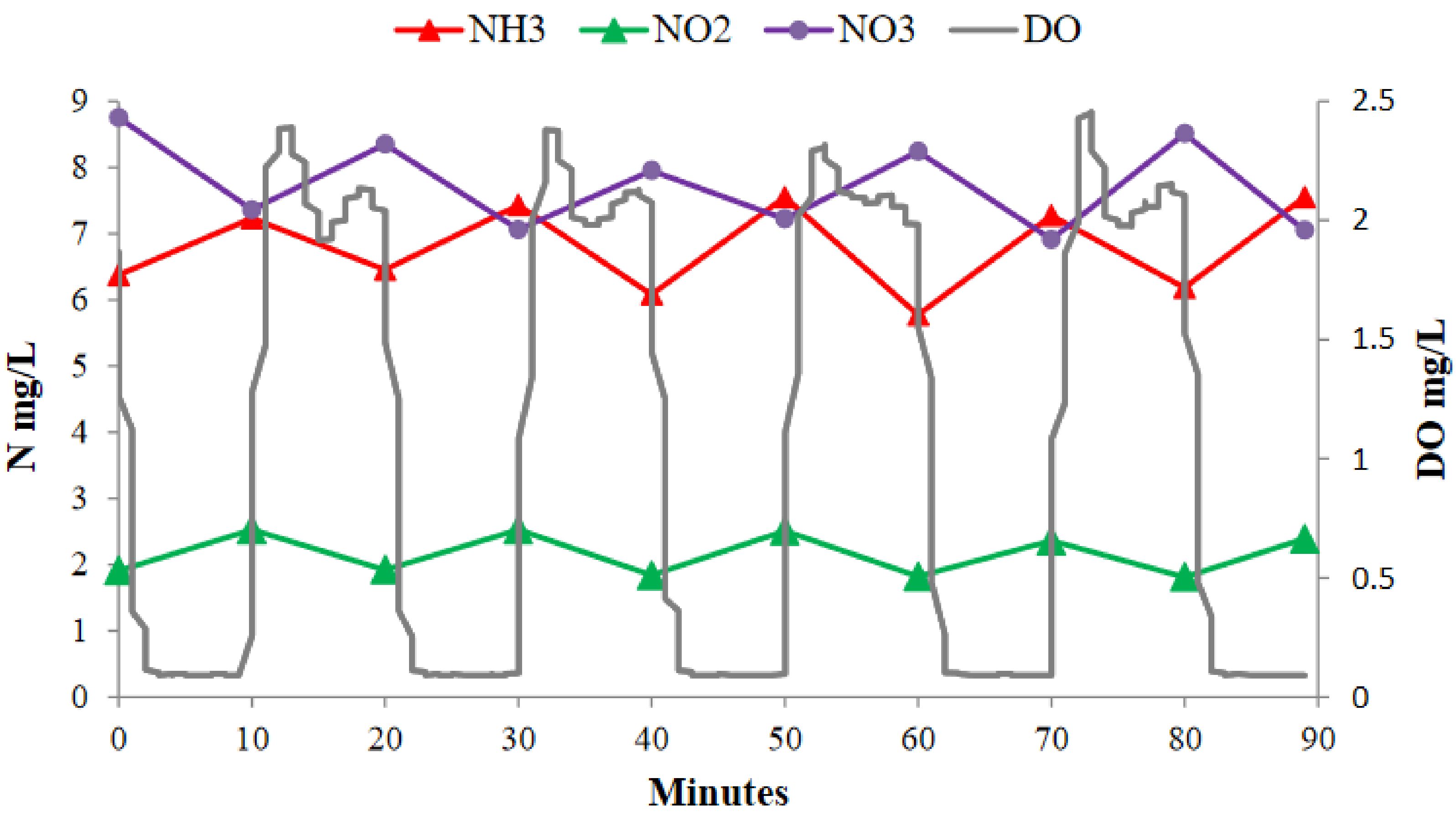
VFA ADDITION (FROM A-STAGE WAS FERMENTATE) ENABLES SIDESTREAM BIOP



ENDOGENOUS DENITRIFICATION BATCH TESTS SHOWED MUCH HIGHER RATES THAN EXPECTED

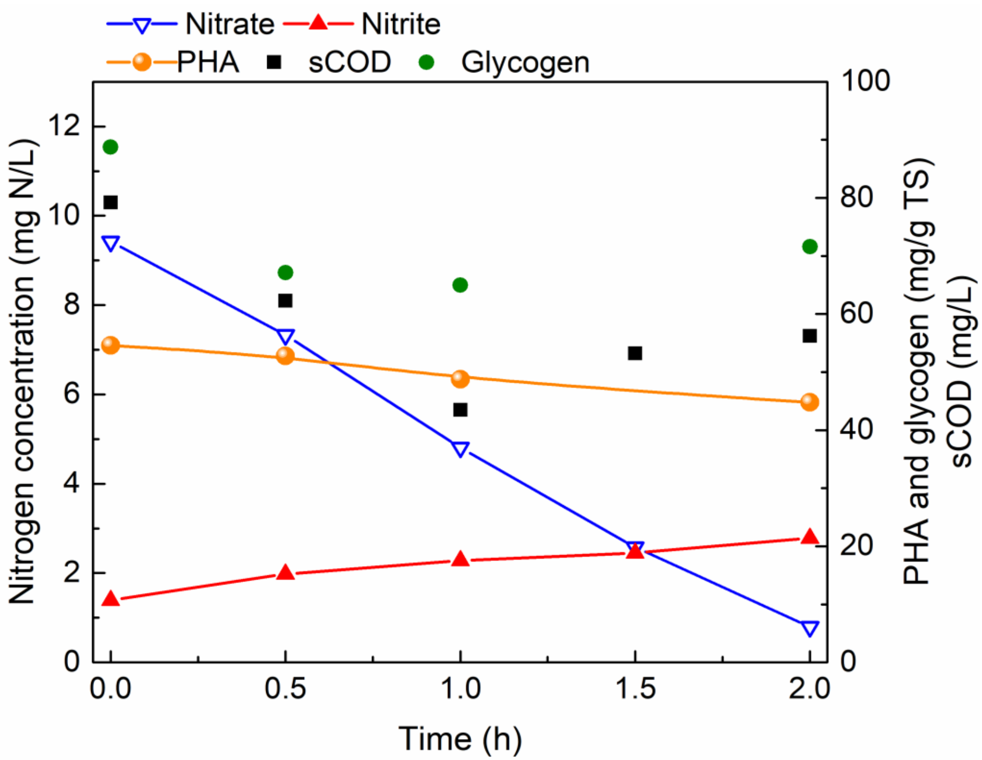


SIDESTREAM CAN SELECT FOR PARTIALLY DENITRIFYING INTERNAL CARBON STORING ORGANISMS

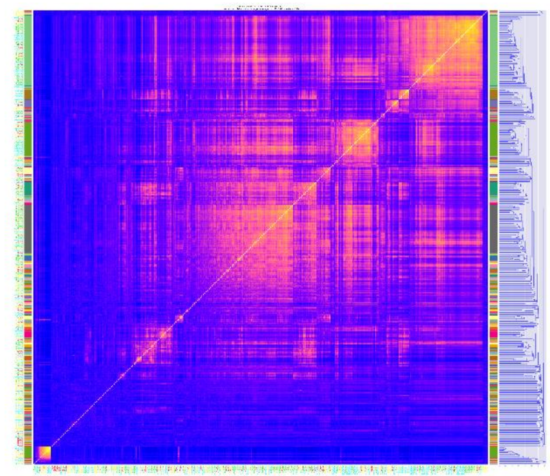


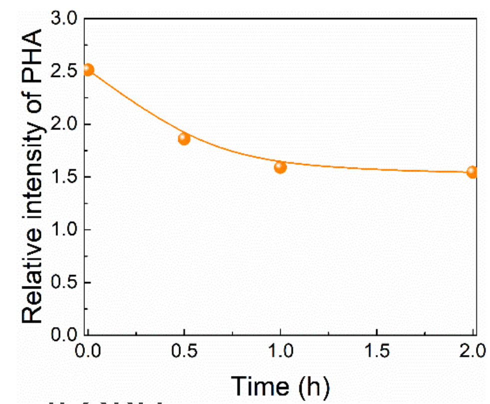
INTERNAL CARBON SOURCE FOR PARTIAL DENITRIFICATION WAS PHA NOT GLYCOGEN

Batch denitrification activity test



Single-cell Raman micro-spectroscopy

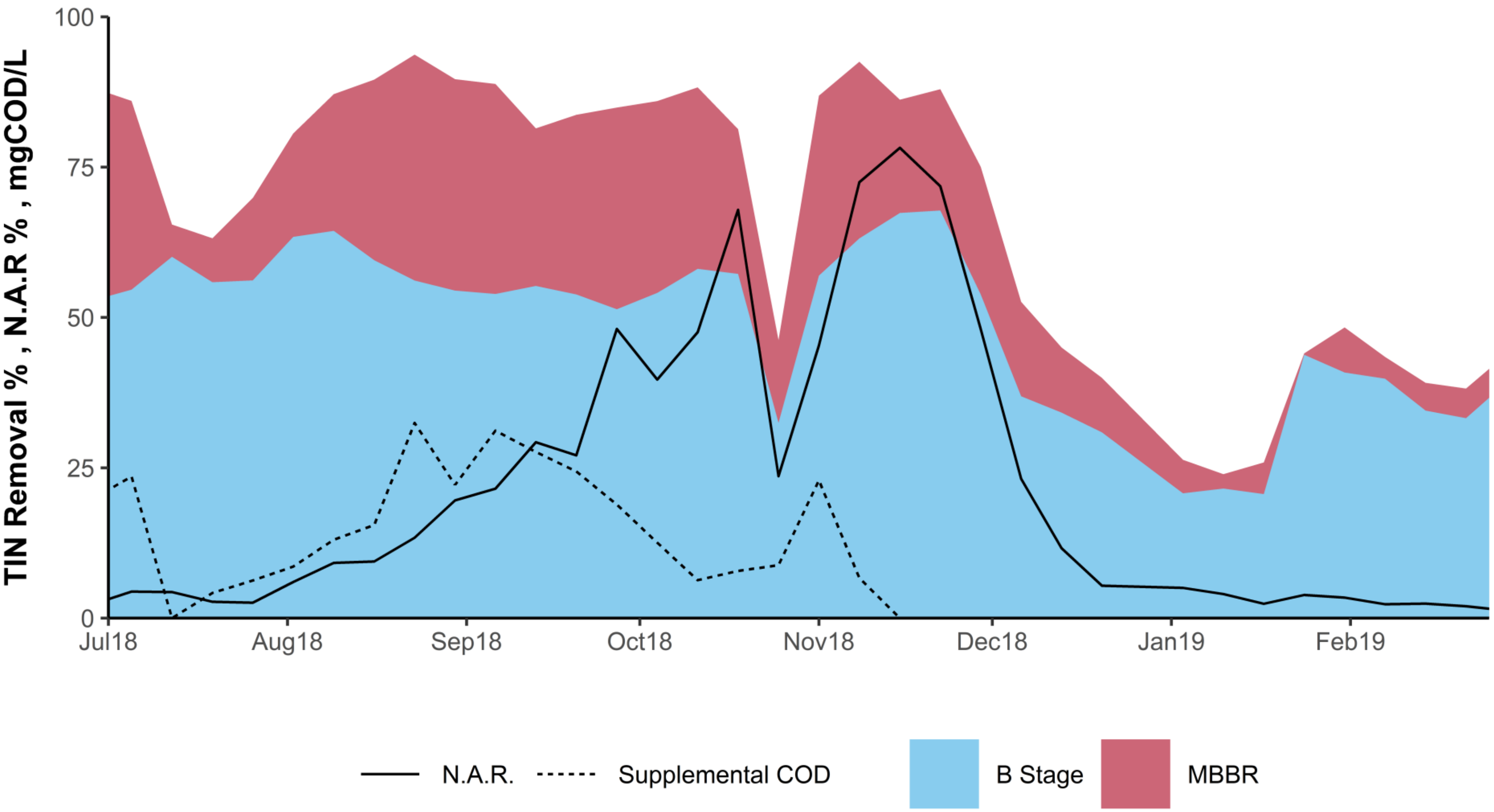




PHA decreased over time in OPU1, Negligible glycogen in all OPUs

OPU1 likely related to Acinetobacter or Comamonadaceae OTUs

ANAMMOX IN THE MBBR PROVIDES HIGH NITROGEN REMOVAL WITH PARTIAL DENITRIFICATION



PLANTWIDE CARBON BALANCE – DIVERTING AND TRANSFORMING CARBON FOR MAXIMUM BENEFIT

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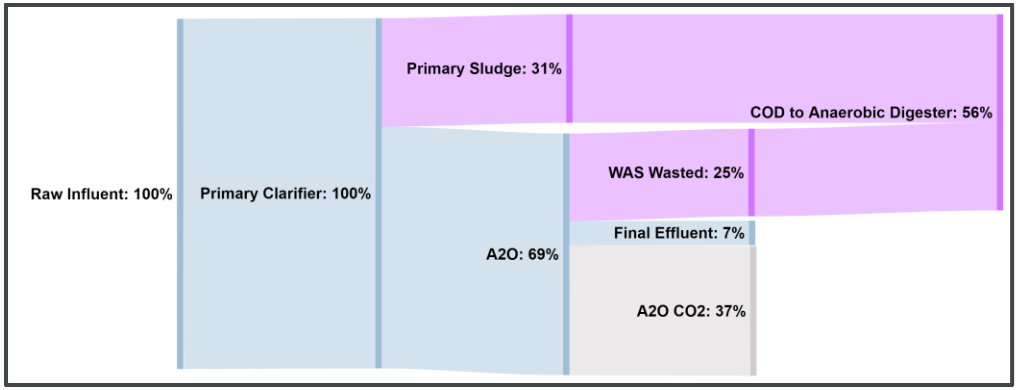
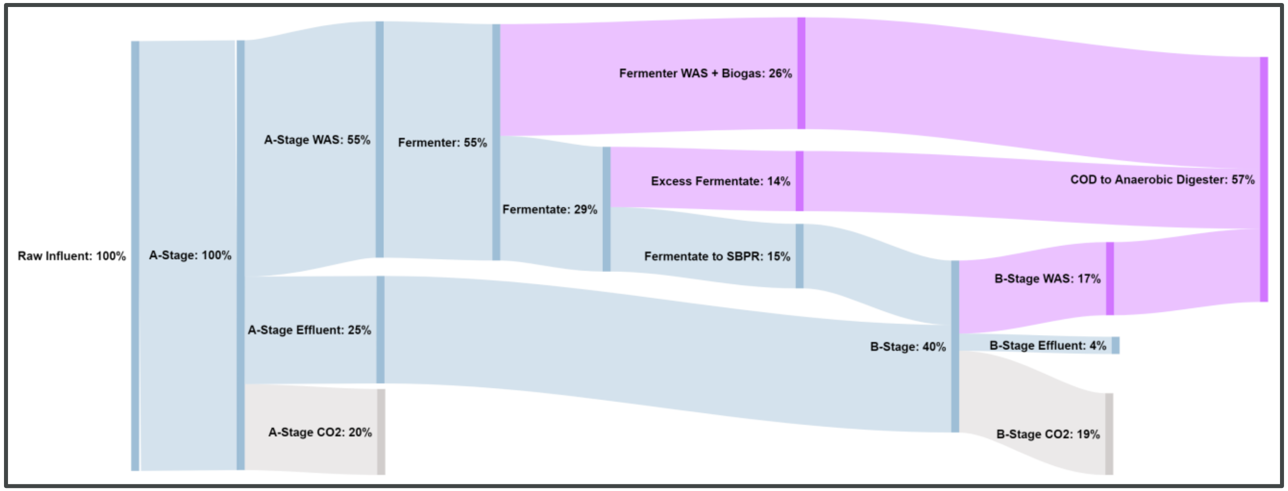
A2O:



CE A/B Pilot:



PARTIAL DENITRIFICATION/ANAMMOX (PDNA) USING INTERNALLY STORED CARBON

STEPHANIE KLAUS
HRSD

inspiring change

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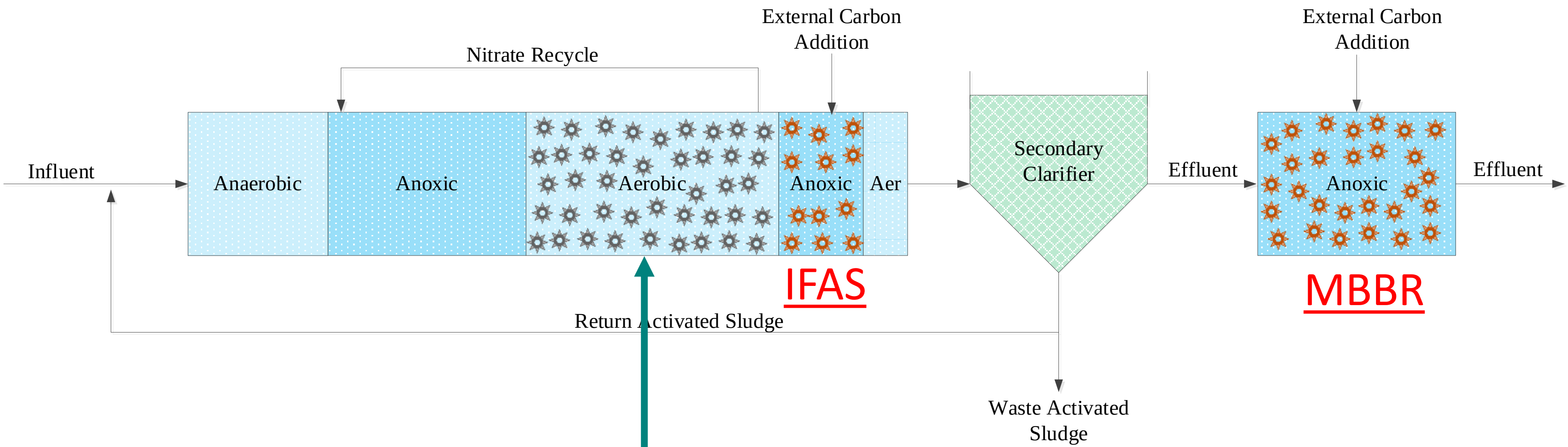
JAMES RIVER TREATMENT PLANT, NEWPORT NEWS VA

PDNA PLANS FOR THE JAMES RIVER UPGRADE



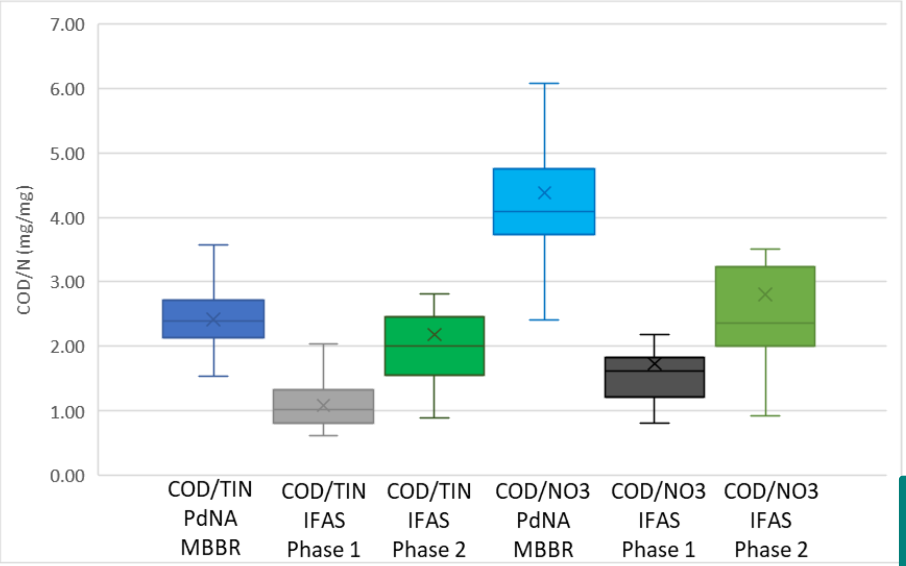
Ammonia vs NOx (AvN) aeration control

PDNA PLANS FOR THE JAMES RIVER UPGRADE

IFAS AND MBBR MAIN POINTS

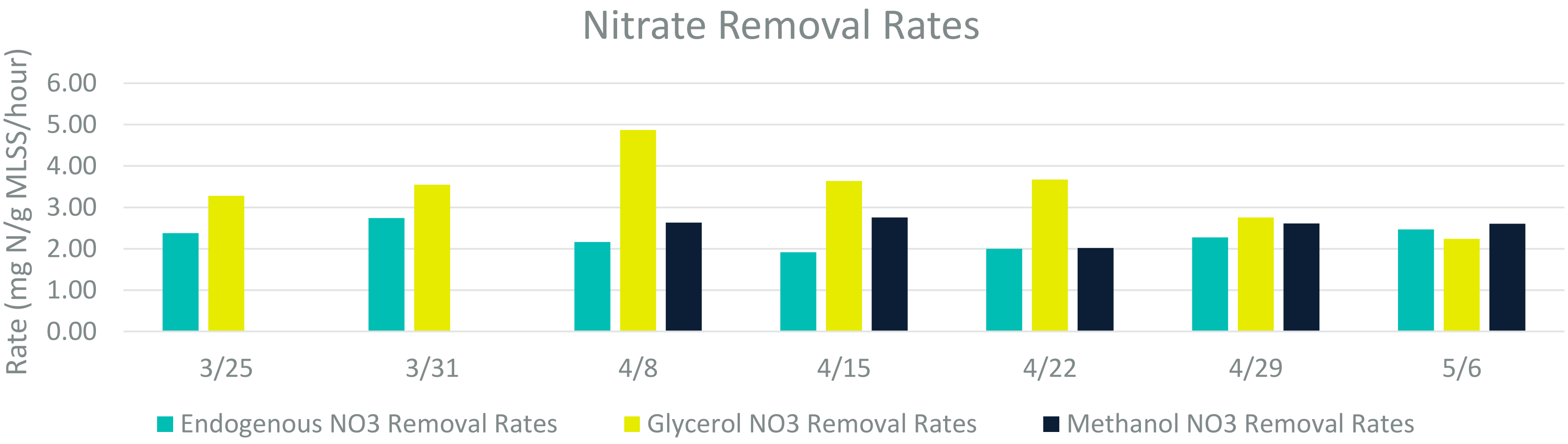
- Mainstream anammox startup took about 3 months
- Both reactors where able to reach low TIN limits as long as the upstream AVN was properly controlled
- PdNA IFAS in a second anoxic zone is a viable treatment process for mainstream anammox
  - This applies to any plant with a second anoxic zone (potentially 5 more in HRSD)
  - IFAS PdNA can take advantage of internally stored carbon for PdN

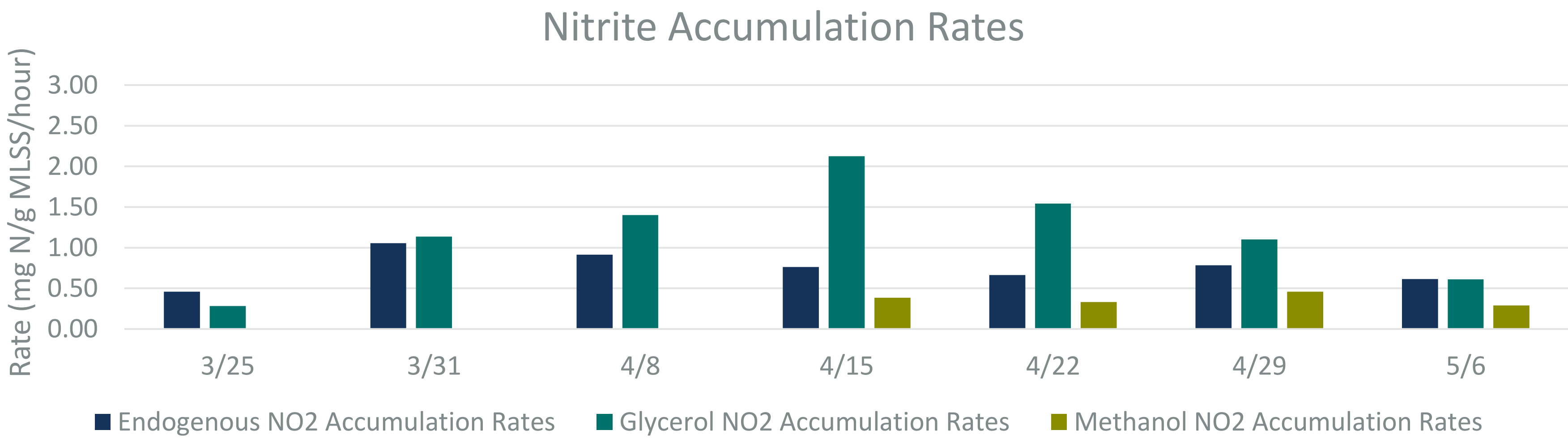
COD ADDED PER TIN REMOVAL



	MBBR	IFAS Phase 1	IFAS Phase 2
Eff TIN Conc. (mg/L)	3.75 ± 1.25	4.07 ± 1.66	3.30 ± 0.96
NH3-N Rem (mg/L)	1.51 ± 0.48	0.77 ± 0.30	0.94 ± 0.34
NO2-N Rem (mg/L)	2.89 ± 0.89	2.68 ± 0.59	3.57 ± 0.92
NO3-N Rem (mg/L)	2.43 ± 0.98	2.36 ± 0.78	3.60 ± 0.76
TIN Removed (mg/L)	4.14 ± 1.23	3.45 ± 0.83	4.51 ± 1.05

SPECIFIC DENITRIFICATION RATES



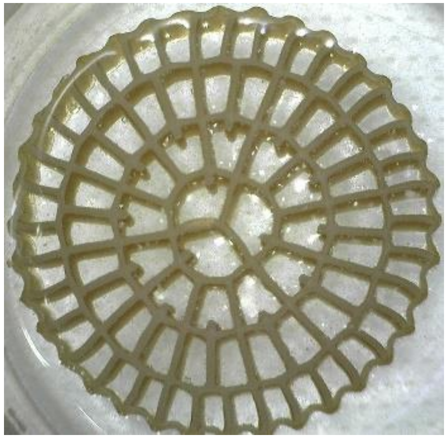


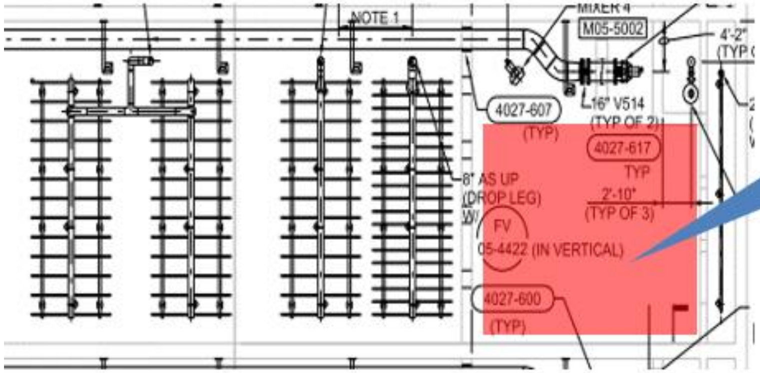
IFAS AERATION TANKS – SECOND ANOXIC ZONE

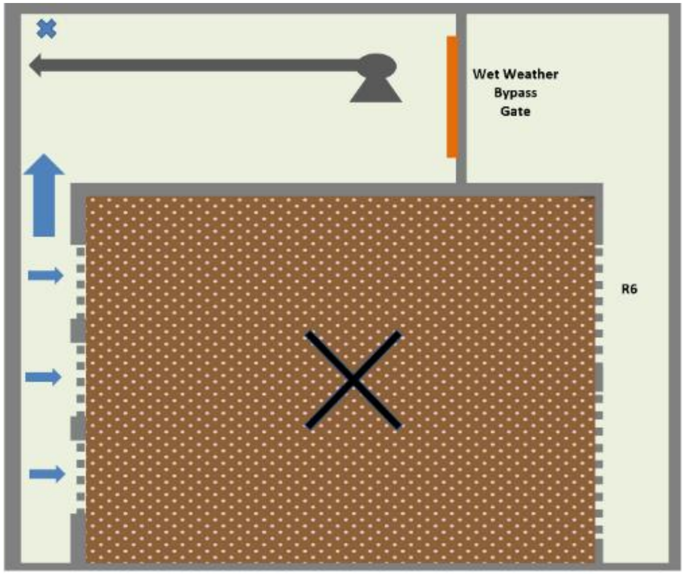
- A2O with aerobic IFAS
- Converting 2 trains to PdNA in second anoxic zone
  - Fixed media
  - Moving media
- HRT is roughly 20 minutes

MOVING MEDIA IFAS

- Media type and surface area
  - Lots of good choices
- Wet weather management
- Construction
  - Baffle walls
  - Screens
  - Mixer

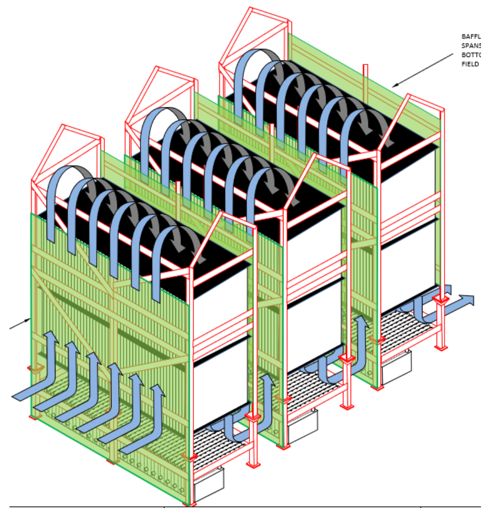


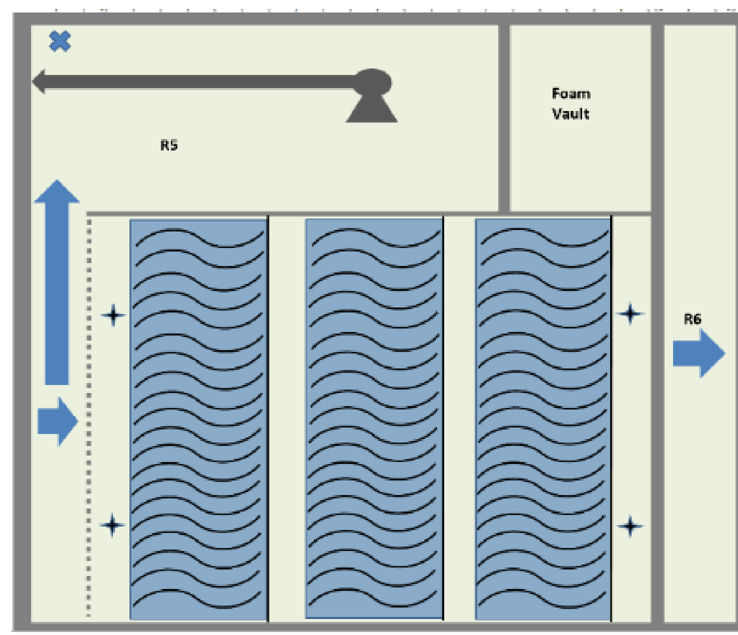


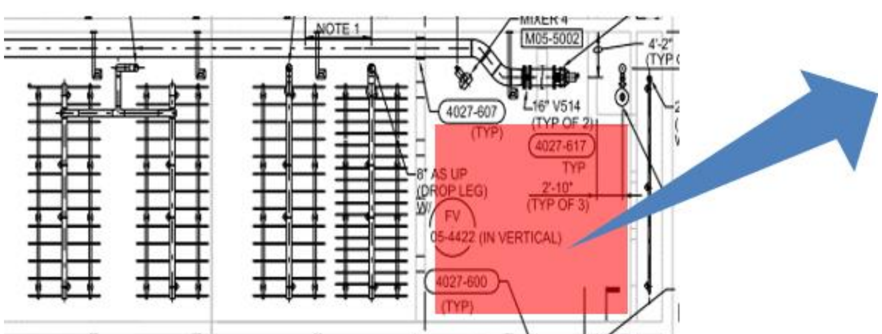


FIXED MEDIA IFAS

- Media type and surface area
  - Limited options and data
- Wet weather management
- Construction
- Concerns
  - Provide effective mixing
  - Provide effective biofilm control







POST-ANOXIC ZONES AND RELEVANT PARAMETERS OF THE 5-STAGE PLANTS

AB

NP

VIP

	AB	NP	VIP	
Flow (MGD)	10.5	17.0	27.4	
# CSTRs in series	2	3	40 (train 1)	30 (train 2)
HRT (hr)	1.0	2.4	1.8	
Mixing	Mechanical	Mechanical	Big bubble	
NRCY (%)	201 (± 3)	342 (± 4)	118 (± 2)	
Effluent TN (mg N/L)	4.90 (± 0.18)	4.73 (± 0.12)	5.01 (± 0.16)	
Methanol Dose (lb COD/lb N removed)	**2.11 (± 0.15)**	**1.48 (± 0.06)**	**0.49 (± 0.03)**	

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LEVERAGING INTERNAL CARBON STORAGE AND REDIRECTION IN NEW PROCESSES FOR THE FUTURE

APRIL Z. GU
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING, CORNELL UNIVERSITY

inspiring change

LOW CARBON FOOTPRINT AND ENERGY EFFICIENT BNR PROCESS

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~3% of global electricity consumption

~1.6% of greenhouse gas emissions

Carbon footprint reduction

Carbon and GHGs reduction

- **Direct emissions reduction** → **CO2** – **N2O** – **CH4**
- **Indirect reduction** → **Energy cost** – **Chemical usage** – **Sludge disposal**

Lu et al., 2018, Nature Sustainability

DECARBONATION IN BNR PROCESSES

Processes	Advantages	Challenges
Short-cut Nitritation-denitritation (nitrite shunt)	• less aeration • less carbon usage	• No well-established in full-scale, low-strength WW • Potential emission of N_2O
PN/A and PDNA	• less aeration • less carbon usage • less sludge production	• Full-scale demonstration • Fundamentals ?? • Reliability/Stability? • Potential emission of N_2O
Coupled S2EBPR/PNA/PDNA	• less aeration/energy • Less and efficient carbon usage. • less sludge production	• Pilot demonstration • Full-scale reliability?

DECARBONATION METHODS IN BNR PROCESSES

Decarbonation via innovations in P removal process	Advantages	Challenges
Side-stream enhanced biological P removal (S2EBPR)	• Maximize internal C usage • Enhance internal C-driven DN • Improved performance without external C addition • Improved denitrification	• Fermentation unit required • Design guidance not well-established
S2EBPR-Internal Carbon-driven denitrification process	• Both N and P removal with a minimized aeration and carbon usage	• DPAOs? • PHA-accumulating organisms??

INFLUENT RBCOD/P RATIO CORRELATES WITH EBPR STABILITY

Sufficient rbCOD required for EBPR
Carbon supplement – *external C, fermentate*

EBPR Is Considered as Unfavorable for:

- Low influent C/P
- Fluctuating loading
- A/B processes
- Not compatible with short-cut N removal processes
- Stringent limits: Chemical back-up needed for compliance

Gu *et al*., 2008, WER- survey of EBPRs in US

Liu *et al*. 1994; Schuler *et al*., 2003

ALTERNATIVE TECHNOLOGY: SIDE-STREAM EBPR (S2EBPR)

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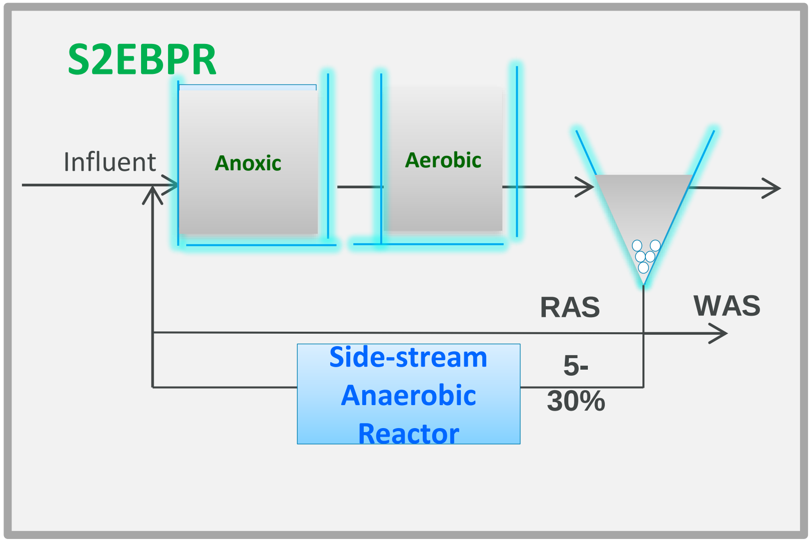
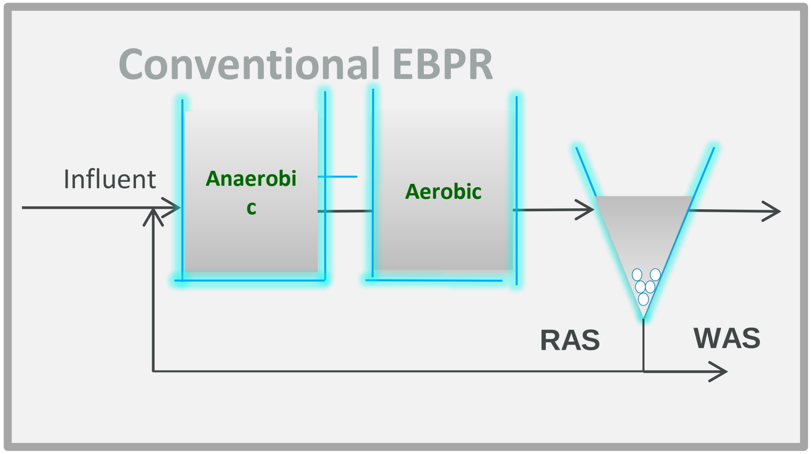
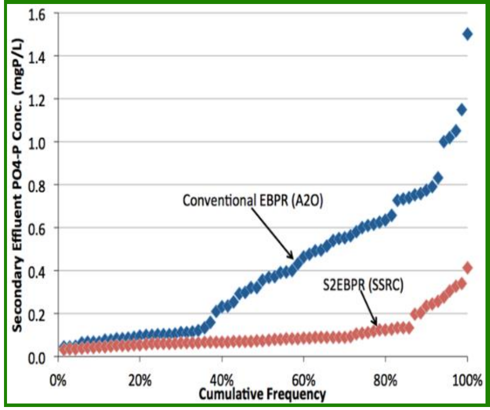




S2EBPR

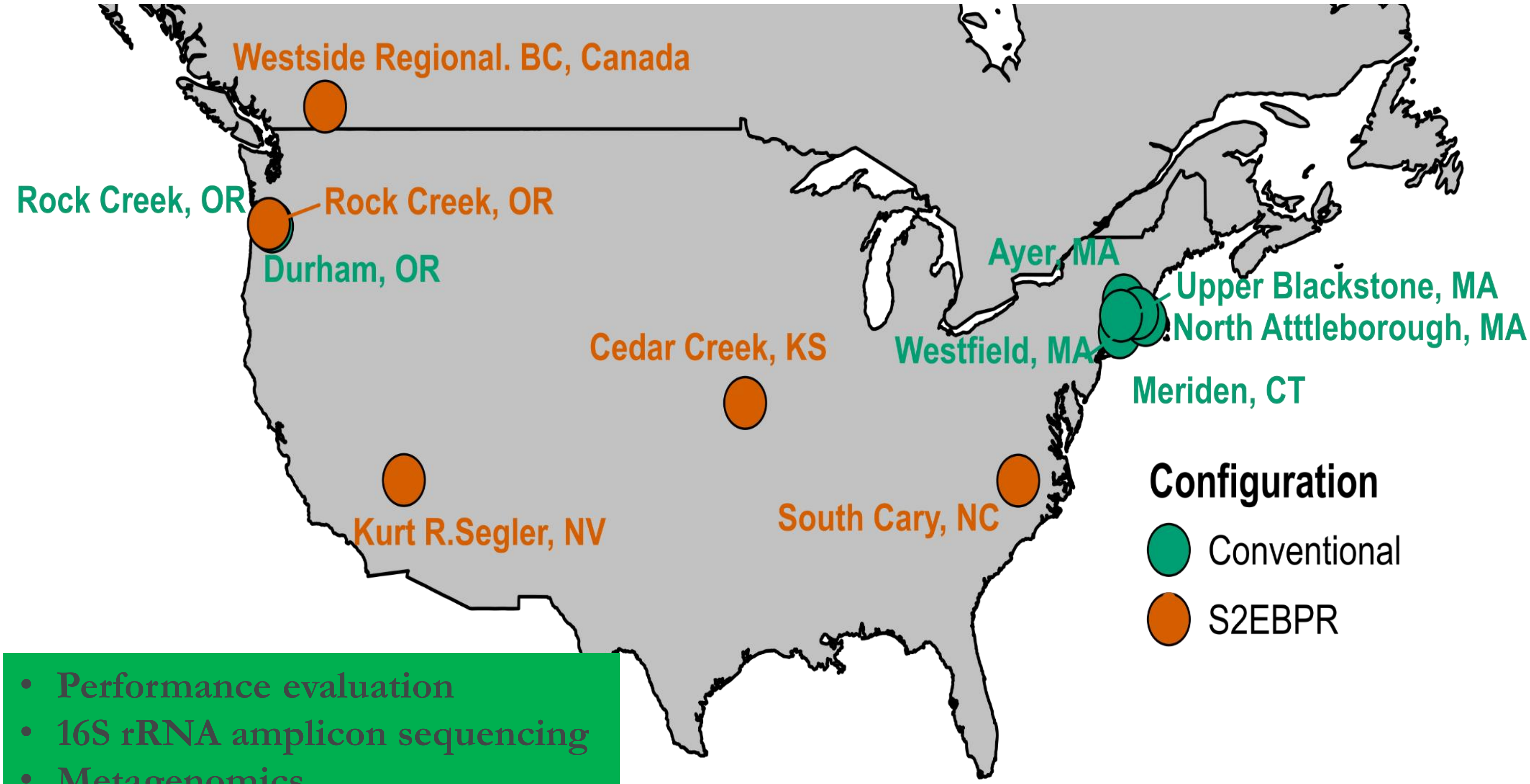
- Emerging technology integrating on-site sludge fermentation
- Offer advantages over conventional
  - Influent C/P-independent
  - Controlled anaerobic zone
  - Favorable condition for PAOs
  - Flexible implementation

S2EBPR outperform conventional EBPR



(*Vollertsen et ;a.,2006; Barnard et al.,2017; Gu et al, 2019*)

SURVEY OF 12 FACILITIES – 5 S2EBPR, 7 CONVENTIONAL



- Performance evaluation
- 16S rRNA amplicon sequencing
- Metagenomics
- Single cell Raman phenotyping

PERFORMANCE SURVEY OF S2EBPR
3-YEAR PERFORMANCE DATA

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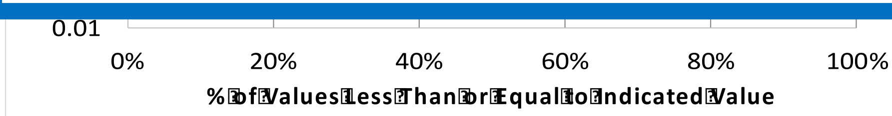
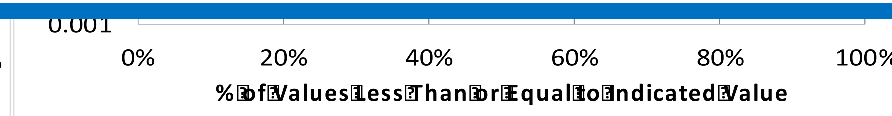
	South Cary	Westside Regional	Cedar Creek	Henderson	Conventional EBPR*
50th percentile	0.28	0.04	0.82	0.32	0.05-0.8 [0.26]
90th percentile	0.89	0.10	1.10	1.00	0.2-2.5 [1.6]
90th/50th ratio	3.17	2.39	1.34	3.13	2-24 [11.5]

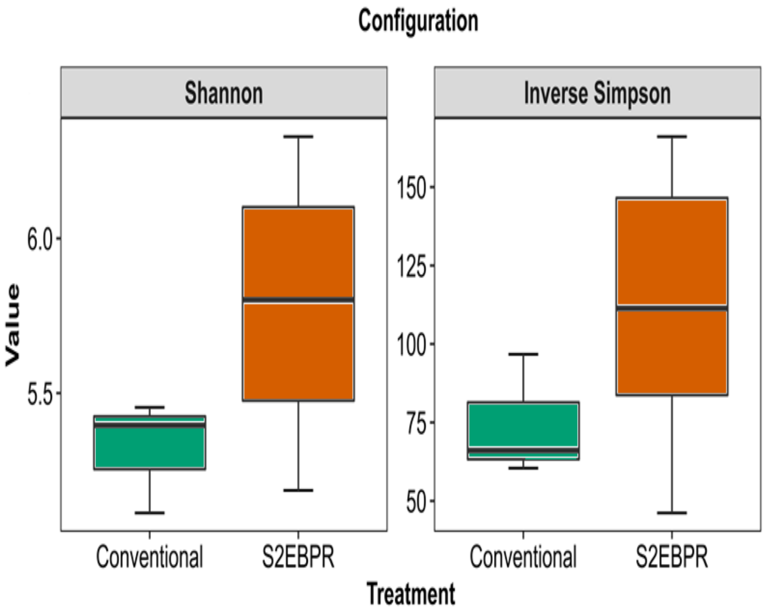
- **Relatively stable performance** were shown for all the 4 S2EBPR facilities, as indicated by the 90th to 50th percentile ratio (90%/50%) for effluent P levels.





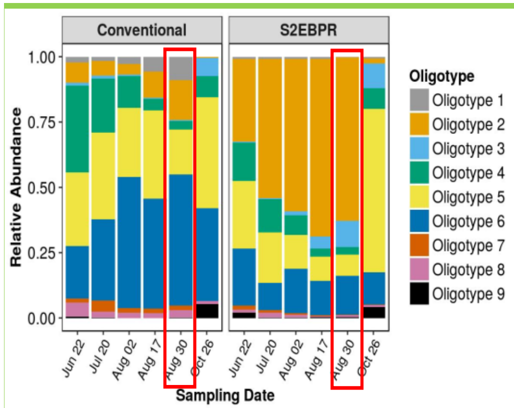
MICROBIAL DIVERSITY IN S2EBPR PLANTS IS HIGHER THAN THOSE IN CONVENTIONAL EBPRS

S2EBPR exhibit consistently higher community diversity index



Gu et al., WERF report 2019, Onnis-Hayden et al., WER, 2019

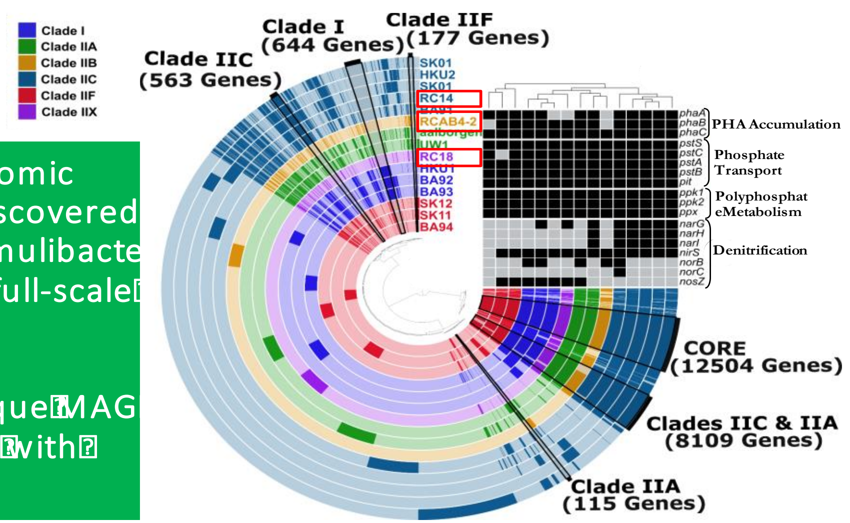
Micro-diversity of Accumulibacter



Oligotype 5 and 6 were predominant in Conventional EBPR

Oligotype 2 was predominant in S2EBPR

Gu et al., 2019 WERF, Wang et al., 2019 WR



*Metagenomic analysis discovered new Accumulibacte MAGs for full-scale EBPR

* One unique MAG associated with S2EBPR

Srinivasan et al., WR, 2021

Conventional | Mechanisms | S2EBPR

Conventional

C-source:

- Influent-dependent acetate-dominant
- Acetate-using PAOs/GAOs
- Susceptible to influent changes

PAO/GAO competition:

- Hac uptake kinetics
- Ks based competition

Anaerobic Zone:

- impacted by recycles/influent

Configuration flexibility:

- Requires rbCOD/anaerobic
- Not compatible with carbon diversion (A/B)

S2EBPR

C-source:

- *In situ* C production, more complex carbon mixture
- Optimized carbon utilization
- Directing carbon to favor PAOs over GAOs

PAO/GAO competition:

- Favorable VFAs (propionate)
- PAOs- phenotypic shift
- Suppress GAO by differential decay

-Better controlled-VFA optimization
-Minimize NOx, DO
-Higher internal/external C utilization

- Flexible implementation
- Compatible with A/B process

S2EBPR ENABLES MORE FLEXIBLE AND IMPROVED C UTILIZATION

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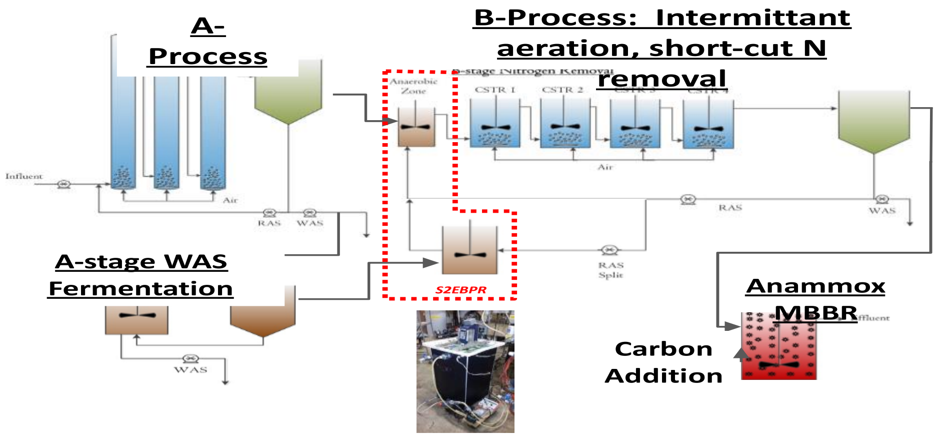
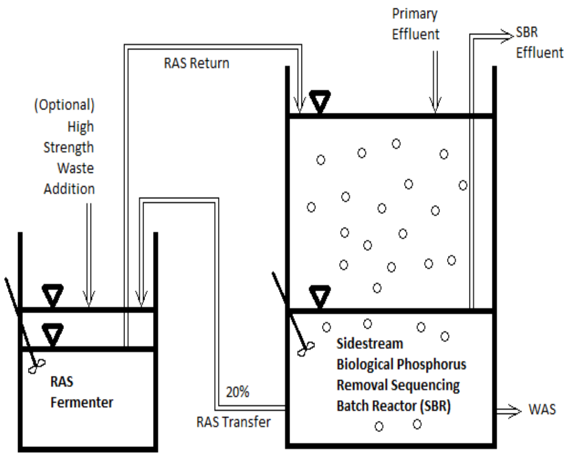
A/B Process + S2EBPR _ short-cut N removal

Credit to: HRSD team



S2EBPR with Unfavorable Low Carbon, Highly Variable Influent Wastewater

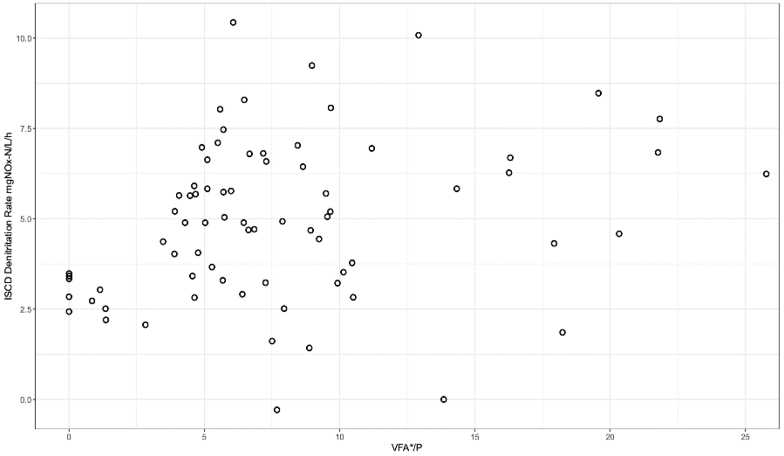
Credit to: Cindy Qin, MWRGDC



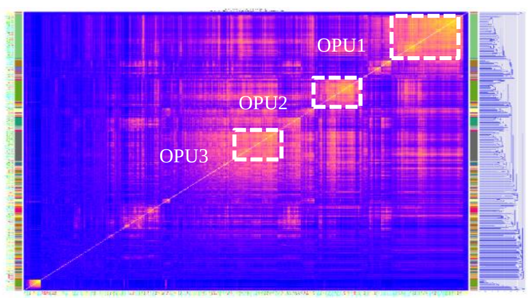
- S2EBPR process is a means for improving P removal performance as an alternative to adding large amount of external carbon source with low strength influent.
- Our goals are to overcome the challenge and meet the upcoming NPDES P permit in a sustainable way

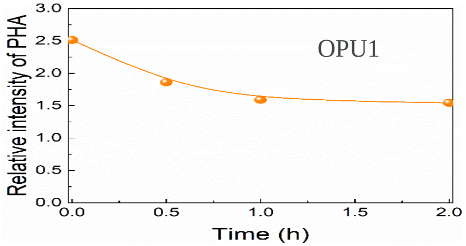
S2EBPR ENHANCE INTERNAL C-DRIVEN DN

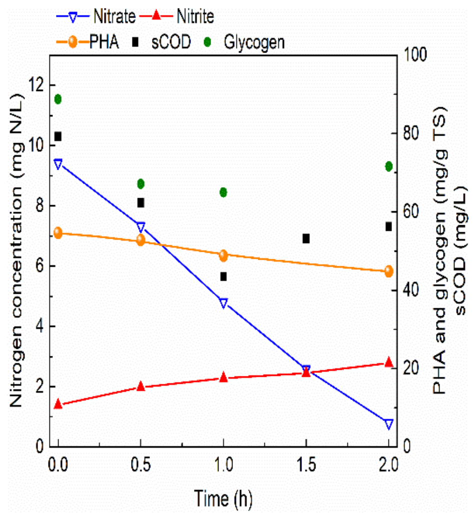
Endogenous denitrification much higher rates than expected



Single-cell Raman micro-spectroscopy







Internal carbon source for partial denitrification (PDN)

REVEAL INTRACELLULAR C AT SINGLE-CELL LEVEL VIA RAMAN

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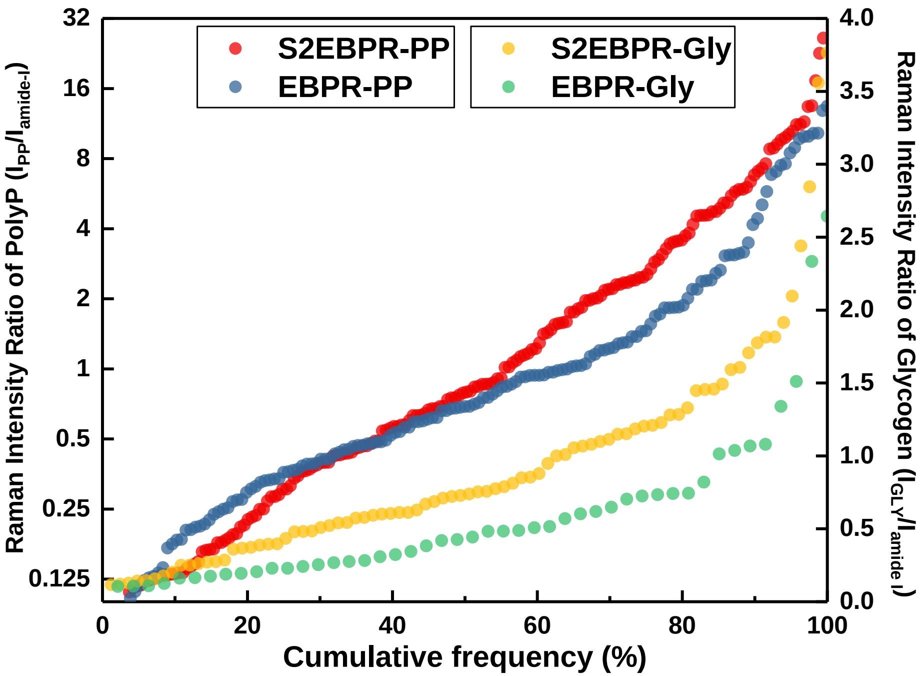
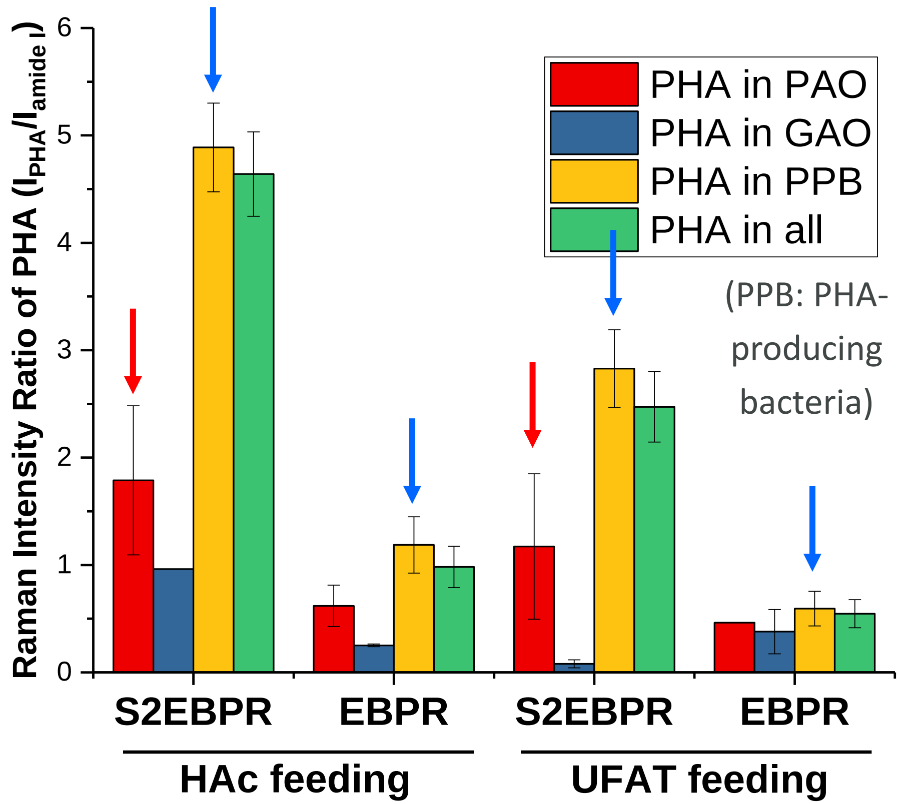
Increase in polyP, glycogen intensity among individual PAO cells



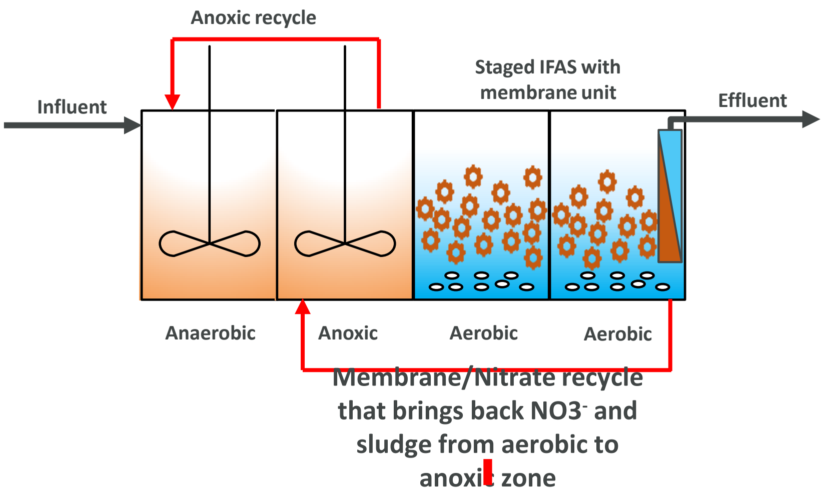
Normalized PHA intensity in individual cells



Improved performance and stability in S2EBPR maybe associated with:

- Higher polyP and glycogen storage
- Higher cellular PHA available for P uptake

IMPACT OF NITRATE RECYCLE RATION ON DPAO ACTIVITIES



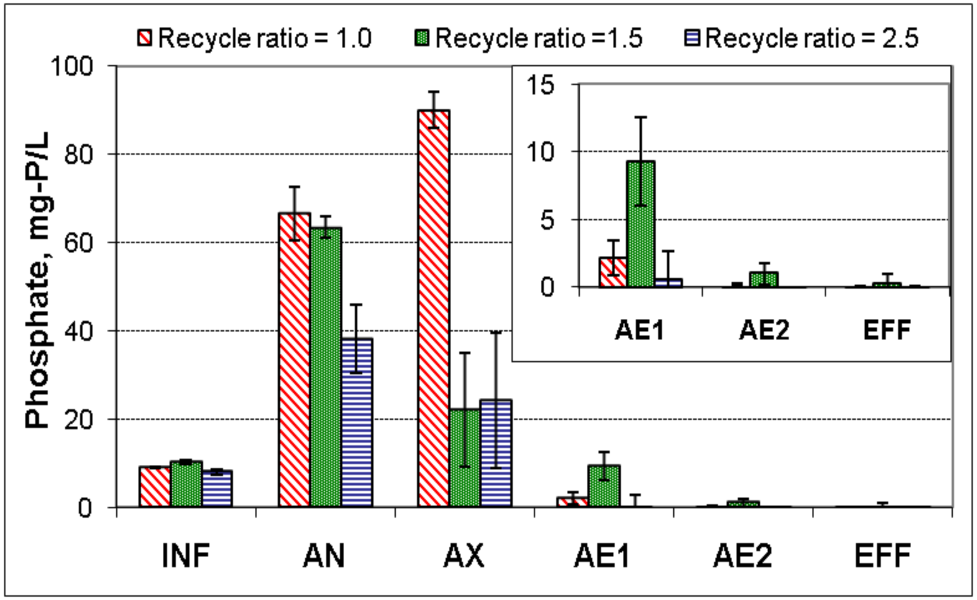
Recycle ratios studied:
1 Qin, 1.5 Qin, 2.5 Qin

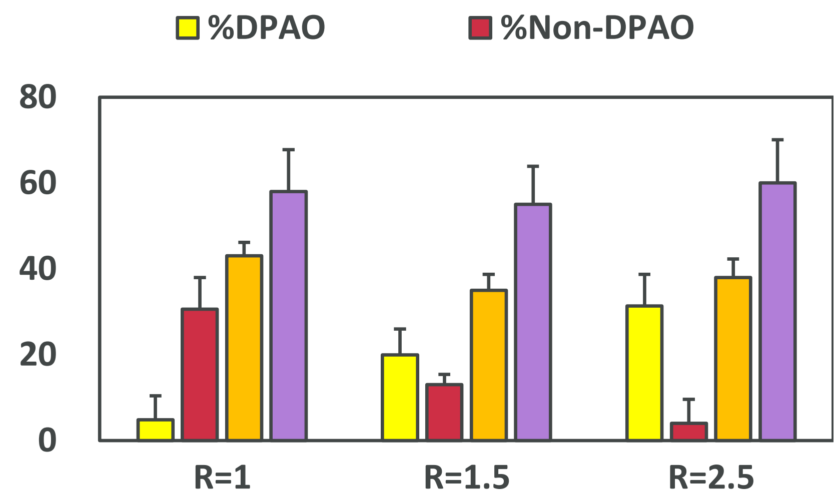
As recycle ratio 1.0, 1.5 2.5Q

% Acc. DPAOs (clade IA)

% Acc. non-DPAOs (clade IIA)

Credit to GuangYu Li, DongQi Wang





CONTRIBUTION OF DPAOS TO TOTAL DENITRIFICATION

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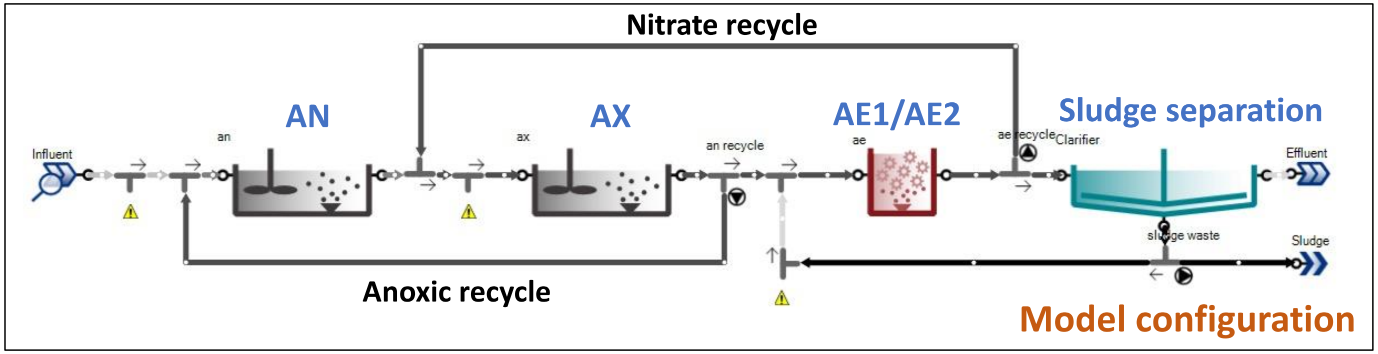
SUMO (ver. 19, Dynamita) simulated this lab-scale IFAS-EBPR-MBR system to estimate the denitrification contributions from DPAOs, base on 1-step nitrification model (SUMO1)

- Percentage of denitrification contribution from DPAOs decreases with recycling ratio
- Majority of denitrification contributed by non-PAO denitrifiers



Recycle ratio	Modeled DPAO NOx consumption	Total NOx utilization rate	DPAO denitrification contribution
1.0	0.340 mgN/h/L	3.66 mgN/h/L	9.3%
1.5	0.324 mgN/h/L	4.37 mgN/h/L	7.4%
2.5	0.171 mgN/h/L	3.31 mgN/h/L	5.2%

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Q&A Discussion

MODERATOR: APRIL GU

REMEMBERING DAVID STENSEL (1945-2021)

Dave was a dedicated husband, father, grandfather,

Who originally dreamed of being a math teacher

A loving, kind family member

Son James

Science Center- Grand kids

Dave loved Friday fajita and margarita nights, Caribbean murder mysteries, **great wine**, and raved about his wife's delicious cooking.


LCP 1

REMEMBERING DAVID STENSEL (1945-2021)

From Patricia Stensel: I am still feeling too emotional about David's unexpected passing to speak publicly about him. But these are my thoughts about him as a person. David loved being a father and a grandfather. He made a point of attending his grandkids' concerts, games, and science fairs. He loved being a husband and was a loving, generous guy. He also loved his work and believed strongly in what he was doing to contribute to society. I recently found at least a hundred photos of waste water treatment plants on my I-pad that he had taken over the years. I have no idea where they were taken but it was so typical of him to want to record these as well as to treat me to tours of plants wherever we traveled! But on the other hand, he participated in a great many garden tours with me- willingly!

David enjoyed his years as a teacher and mentor at the University of Washington. Many of his connections with his grad students endured through the years. I have heard such warm comments from them since his passing. I only wish he could have known how much he was revered by them. Our house became a gathering place during those years where they could enjoy dinner, wine and conversation without a closing hour.

David also loved good food and wine. He became quite a red wine connoisseur over the years. Our trip to Italy definitely contributed to that. He became quite a good cook in his retirement years too. I think he considered cooking a little chemistry experiment so he enjoyed combining different ingredients instead of following a recipe to the letter. Chili was his specialty – the hotter the better!

Probably the most delightful quality David possessed was his sense of humor. His take on life always surprised me. I could never anticipate what would come out of his mouth! His unique perspective always kept my life with him interesting. Speaking for David's family and myself - we miss him every day but have such fond memories of our lives with him.

UPCOMING WEBINARS

Stay tunned for our next webinars:

https://iwa-network.org/learn/water-reuse-in-the-united-states-a-trend-on-the-rise/

Learn more at

http://www.iwa-network.org/iwa-learn/