Sidestream and mainstream deammonification – opportunities and challenges

Jacek Mąkinia
Gdańsk University of Technology (Poland)
Head of the Department of Sanitary Engineering

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Outline of presentation

- Fundamentals of the anammox and deammonification processes
- Sidestream vs. mainstream deammonification
- Challenges and recipe for implementation of mainstream deammonification
- Deammonification studies at Gdańsk University of Technology

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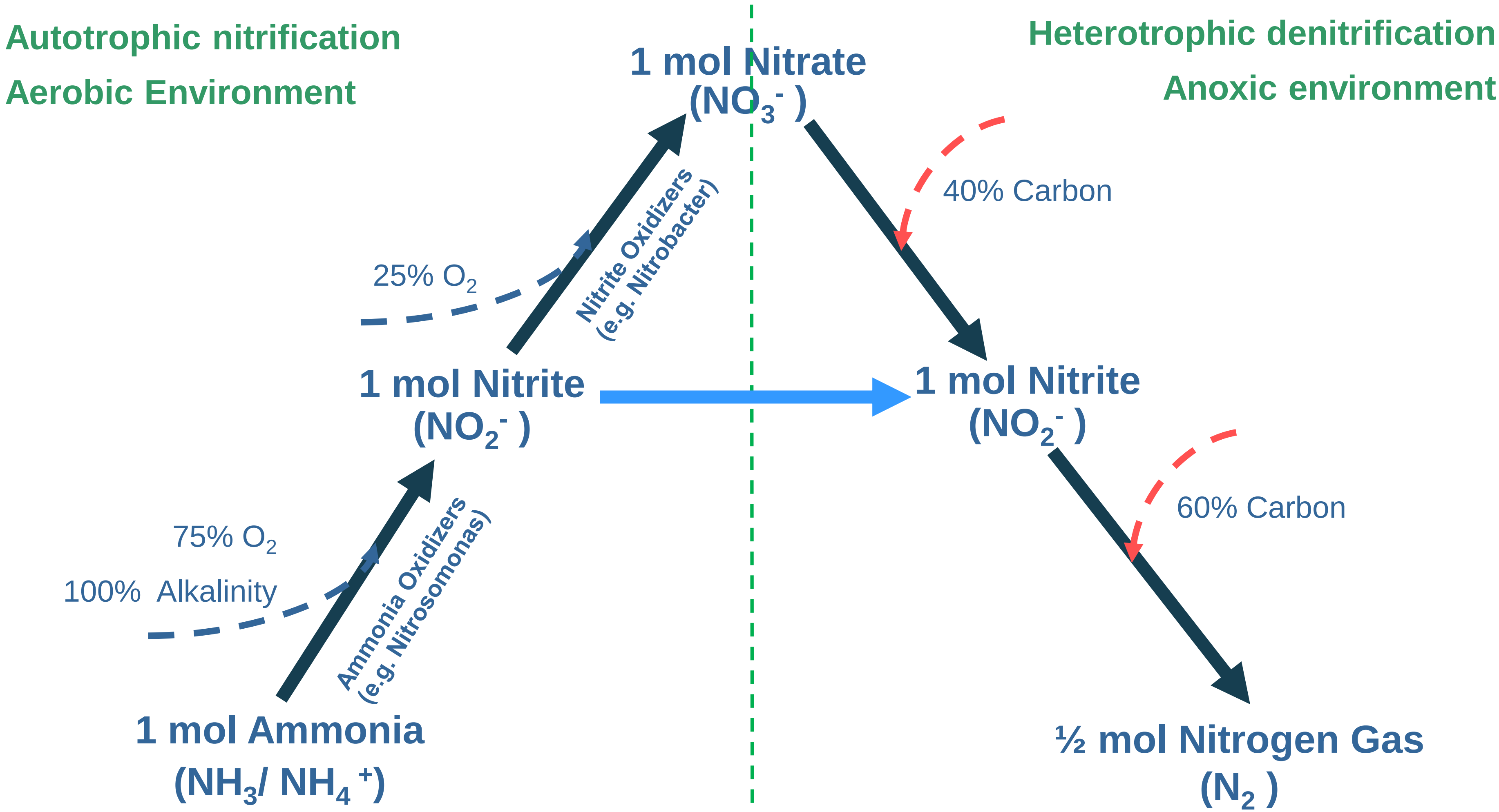
Fundamentals of nitrification-denitrification



Full nitrification-denitrification

O_2 demand 4.57 g/g NH^+_4-N oxidized

C demand 4.77 g COD/g NO^-_3-N reduced

Nitritation-denitritation

O_2 demand 3.41 g/g NH^+_4-N oxidized

C demand 2.86 g COD/g NO^-_3-N reduced

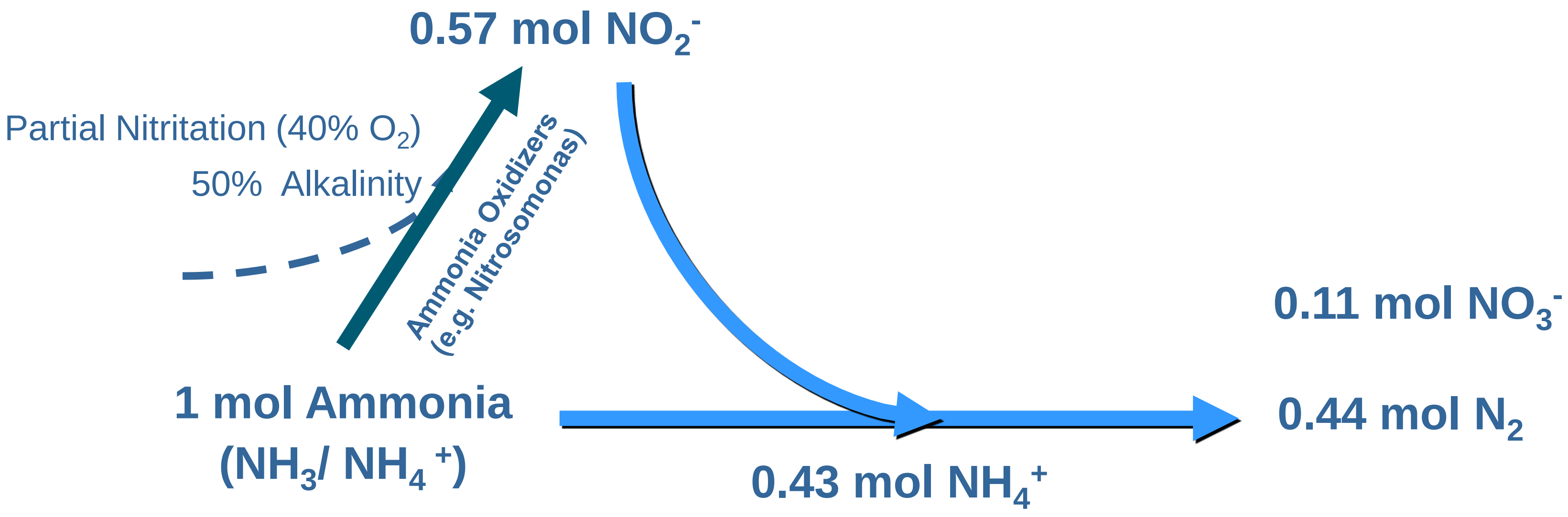
Fundamentals of deammonification

Partial Nitritation

Aerobic environment

ANAMMOX

Anoxic environment



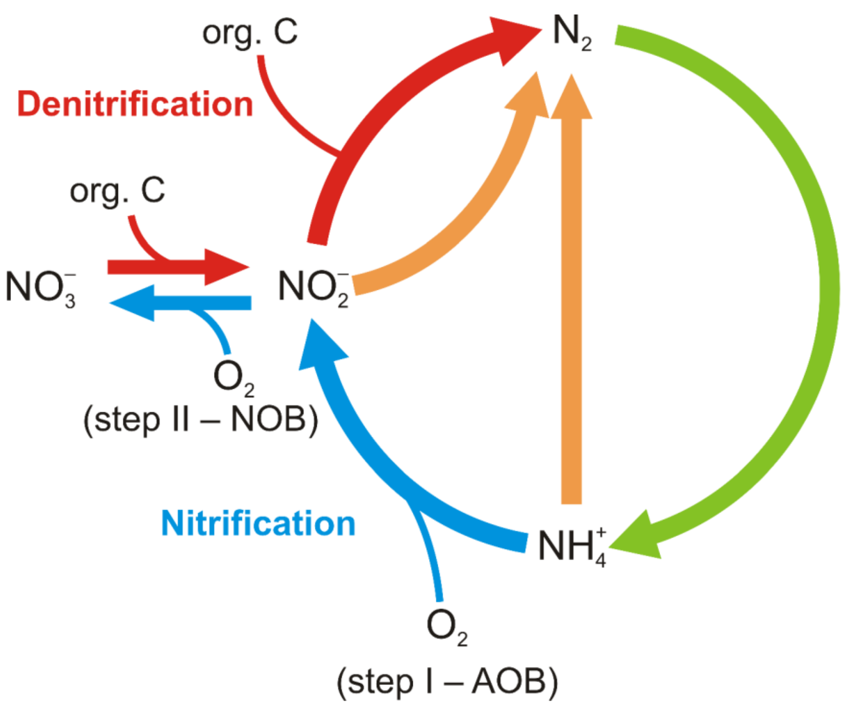
Deammonification (partial nitritation – anammox)

O_2 demand 1.9 g / g NH^+_4-N oxidized (60% reduction)

No carbon required

50% reduction in the alkalinity demand

Anammox advantages and disadvantages



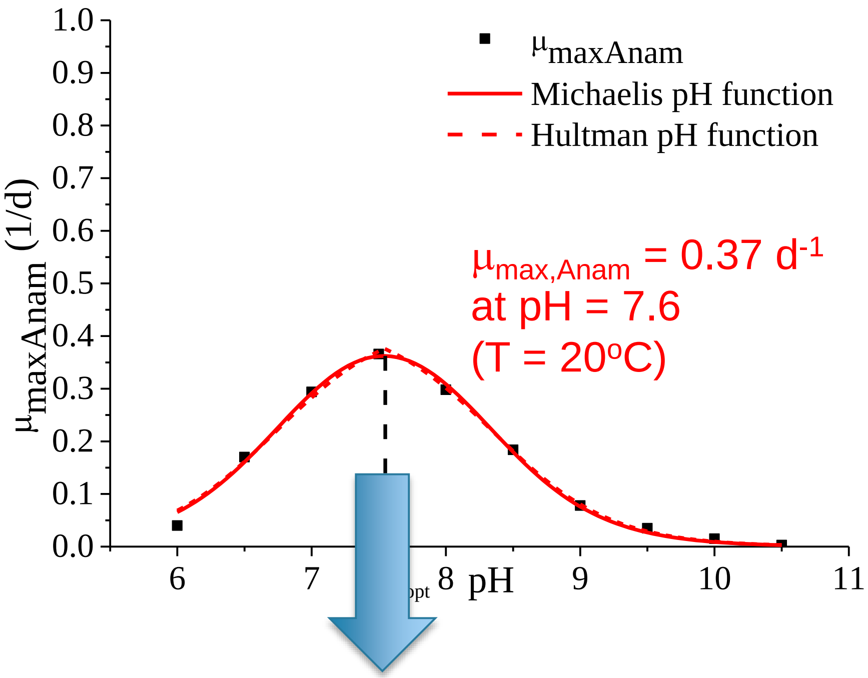
Advantages

- Less oxygen required
- No organic C required
- Less excess sludge produced

Disadvantages

- Very slow growing bacteria
  → need for long biomass retention
- Need for preventing nitrite oxidation
- Sensitive to nitrite, oxygen and ammonia

Growth rates of anammox bacteria



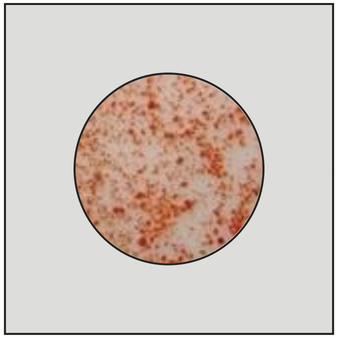
- Fast-growing anammox-enriched cultures (0.38-0.58 d^{-1} at 35-37°C) *(e.g. Isaka et al., 2006; Bae et al., 2010)*
- Slow-growing anammox cultures (0.02 d^{-1} at 30 °C; 0.04-0.077 d^{-1} at 32-33 °C; 0.13-0.19 d^{-1} at 37°C) (*e.g. van de Graaf et al., 1996; van der Star et al., 2007; Hao et al., 2009*)

Lu et al. (2016)

Specific growth rate (d^{-1})	Temp. (°C)	Reference
0.190-0.130	37	Tsushimaa et al., (2007)
0.084	nd	Van der Star et al., (2008)
0.150-0.092	nd	Van der Star et al., (2008)
0.230	nd	Van der Star et al., (2008)
0.140	30	Sobotka et al., (2017)
0.118	35	Liu and Ni (2015)
0.172	35	Liu and Ni (2015)
0.210	30	Lotti et al., (2014a)
0.334	30	Lotti et al., (2015c)
0.017	15	Lotti et al., (2014b)
0.020	20	Lotti et al., (2014c)
0.009	15	Lotti et al., (2014c)
0.038	29	Laureni et al., (2015)
0.0088	12.5	Laureni et al., (2015)
0.040	20	Hendrickx et al., (2012)
0.011	10	Hendrickx et al., (2014)

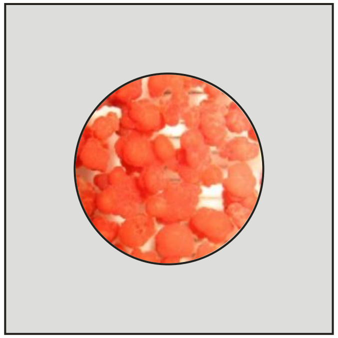
Tomaszewski et al. (2017)

Methods for anammox biomass retention



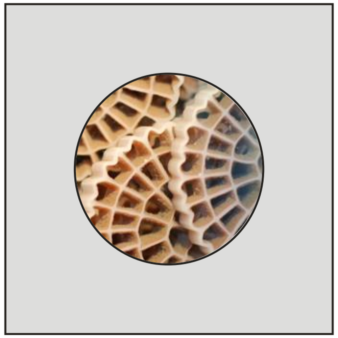
Suspended Growth Anammox Biomass

e.g. Activated Sludge Systems



Large Anammox Granules

e.g. Granular Sludge Systems



Hybrid Suspended and Attached Growth Biomass

e.g. IFAS, MBBR

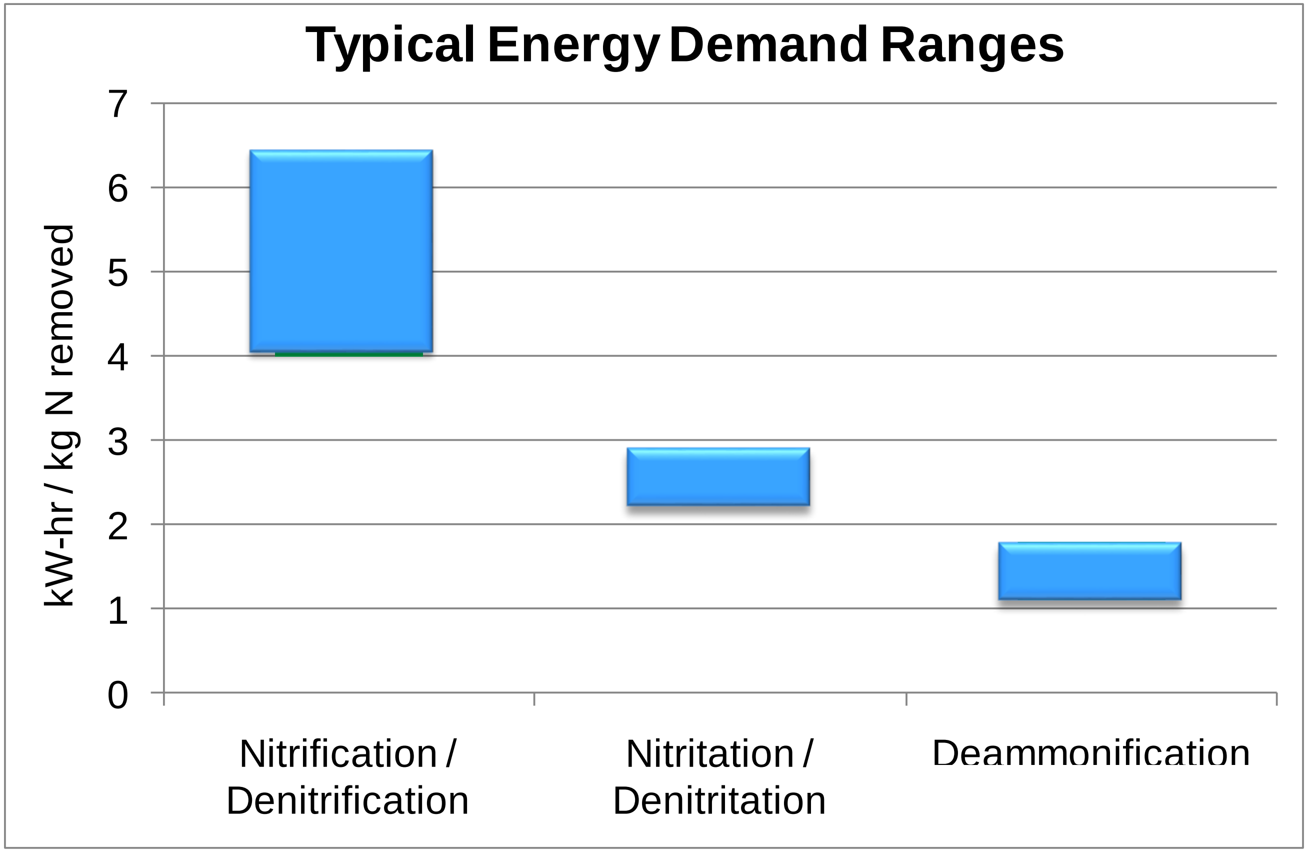
Increasing diffusivity or mass transfer resistance

Comparison of different deammonification technologies

Parameter	Unit	Process				
		ANAMMOX®	Demon®	Anita™Mox	DeAmmon®	Cleargreen™
Biomass carrier		Granular	Granular	MBBR	MBBR	Suspended biomass
Volumetric loading rates	kgN/m³/d	**1.7-2.0**	0.7-1.2	0.7-1.2	<1.2	<1.2
Performance TN removal	%	~90 (NH_3), ~85 (TN)	~90 (NH_3), ~85 (TN)	~90 (NH_3), ~85 (TN)	~90 (NH_3), ~85 (TN)	~90 (NH_3), ~85 (TN)
Energy demand	kWh/kgN removed	1.0-1.3	1.0-1.3	1.45-1.75	TBC	TBC
Start-up	months	1-3 (seed)	2-5 (seed & cyclone)	4-5 (seed)	2-5 (seed)	TBC
Sensitivity/ flexibility		Tolerates elevated NO_2	pH & DO control, NO_2 < 5 mgN/L	DO control, tolerates elevated NO_2	pH & DO control, NO_2 < 5 mgN/L	TBC

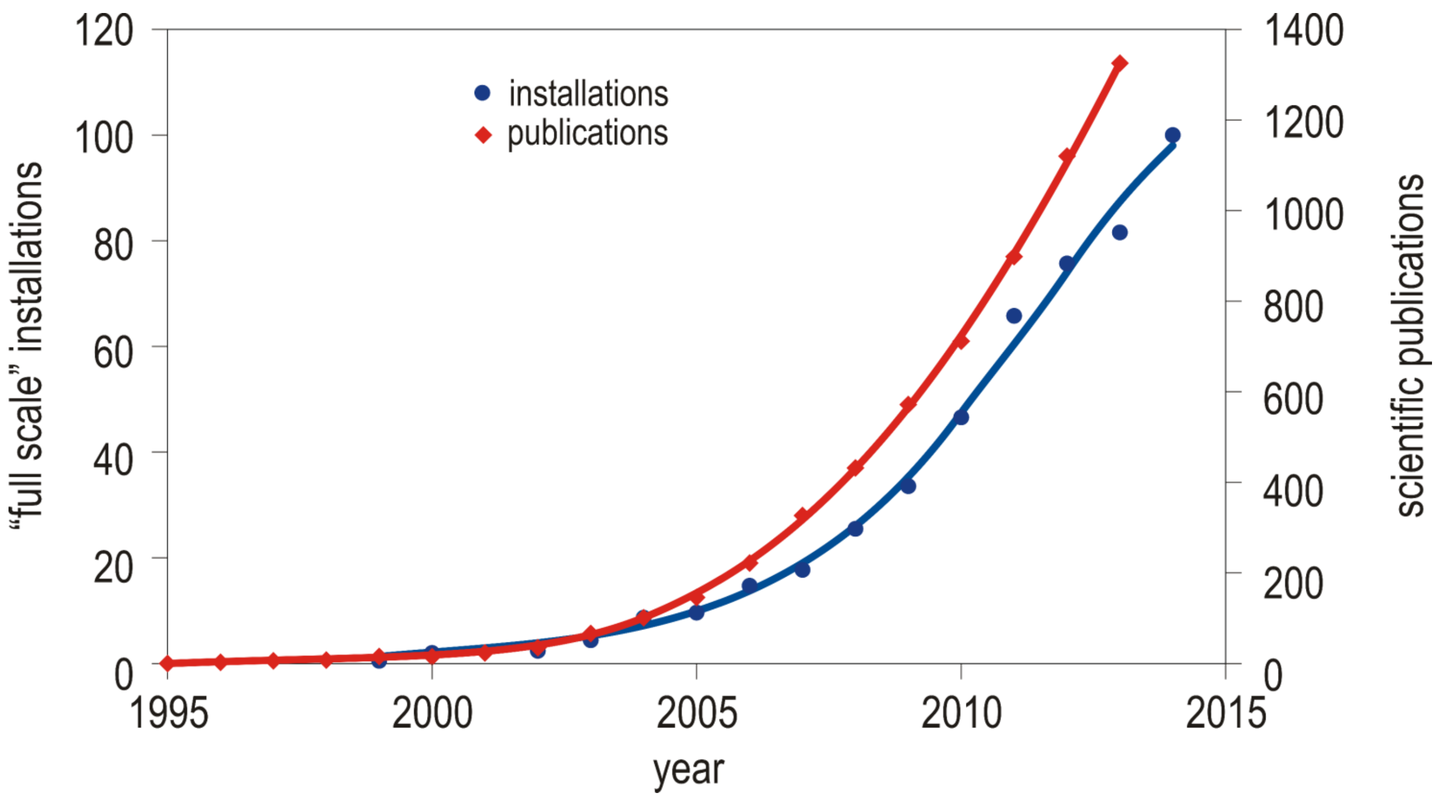
WERF (2015)

Comparison of energy demand for different N removal technologies



Stinson (2016)

Deammonification development – full-scale installations and scientific publications



Lackner et al. (2014)

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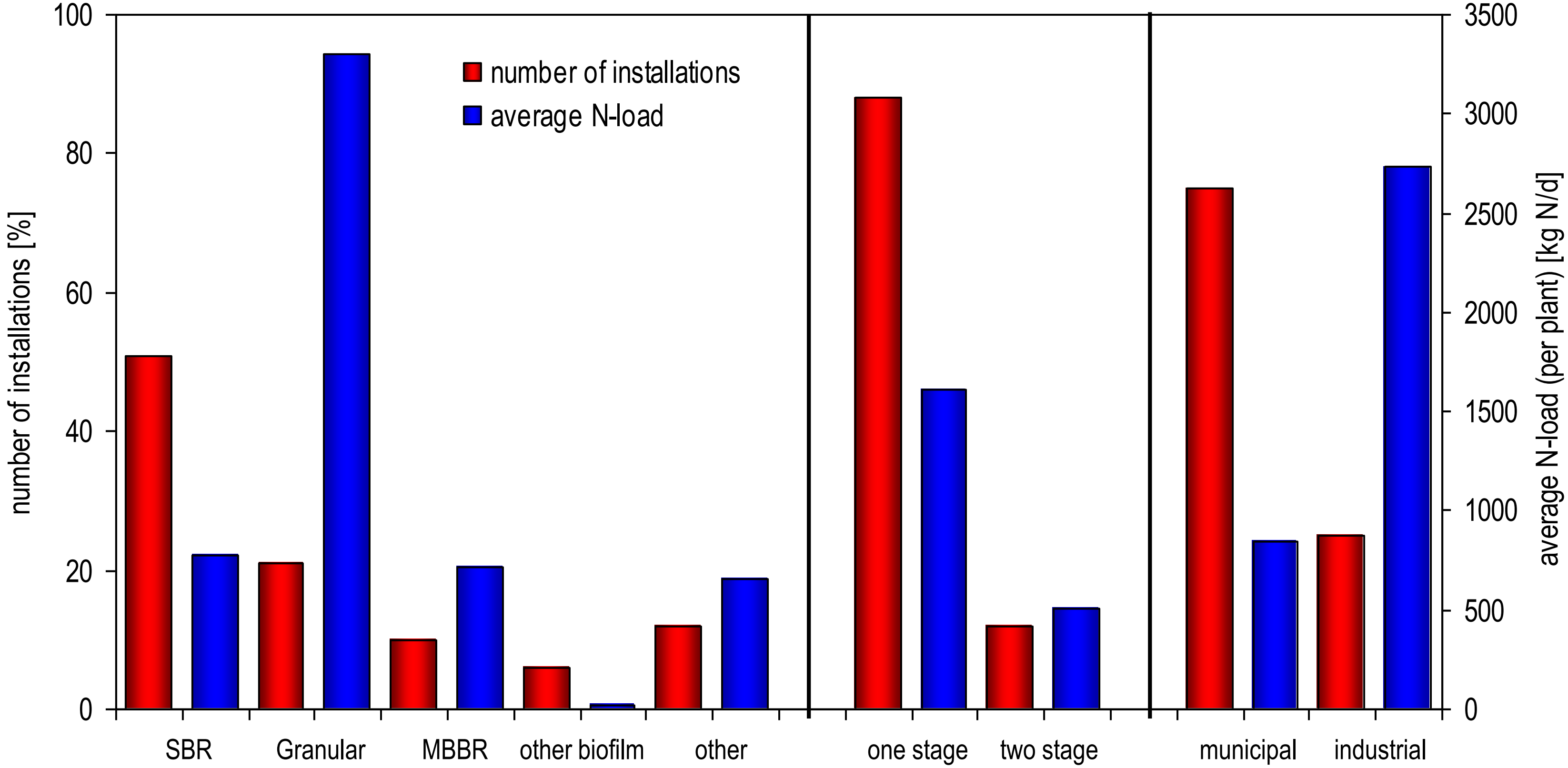
Distribution of deammonification applications

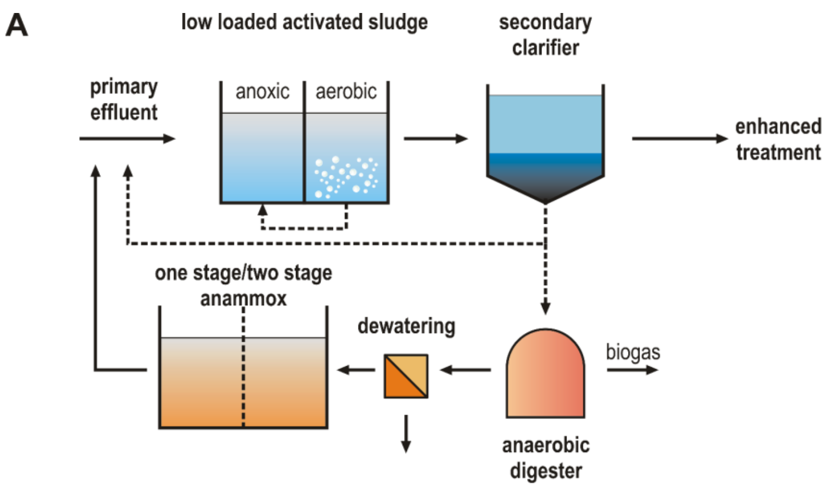


Lackner et al. (2014)

Sidestream vs. mainstream anammox systems

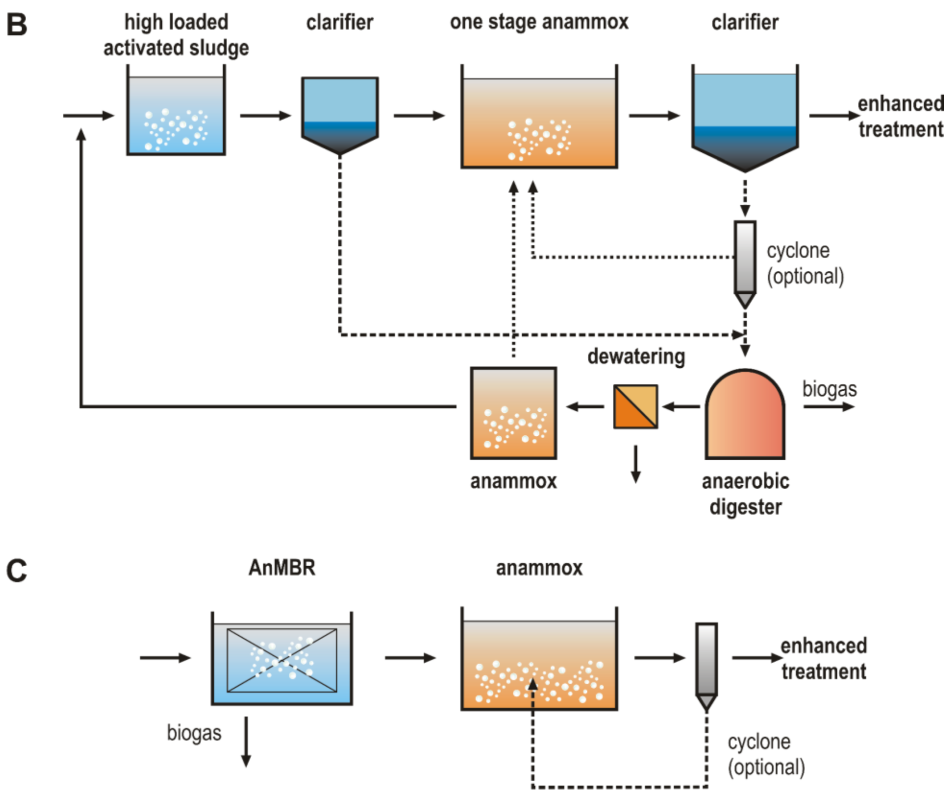
Sidestream treament

Emerged technology
Established state of the art



Mainstream treament

Emerging technology



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Beginnings of MD – IWA/WEF NRR conference Miami (2011)

Nutrient Recovery and Management 2011

January 9 – 12, 2011 • Hilton Miami Downtown • Miami Florida, USA

Session 15: Focused Discussion: Advances in Deammonification Processes

OLAND is Feasible to Treat Sewage-Like Nitrogen Concentrations at Low Hydraulic Residence Time
H. De Clippeleir, X. Yan, W. Verstraete, S. E. Vlaeminck, *Ghent University*

Implementation of a Full-Scale Anammox-Based Facility to Treat Anaerobic Digestion Sidestreams at the Alexandria Sanitary Authority Advanced Wastewater Treatment Facility
G. T. Daigger, P. Sanjines, *CH2M Hill;* K. Pallansch, J. Sizemore, *Alexandria Sanitation Authority;* B. Wett, *University of Innsbruck*

Deammonification of Dewatering Sidestream from Thermal Hydrolysis-Mesophilic Anaerobic Digestion Process
B. Figdore, *AECOM*; B. Wett,*ARAconsult;* M. Hell, *Achental-Inntal-Zillertal Wastewater Cooperation;* S. Murthy, *DC Water*

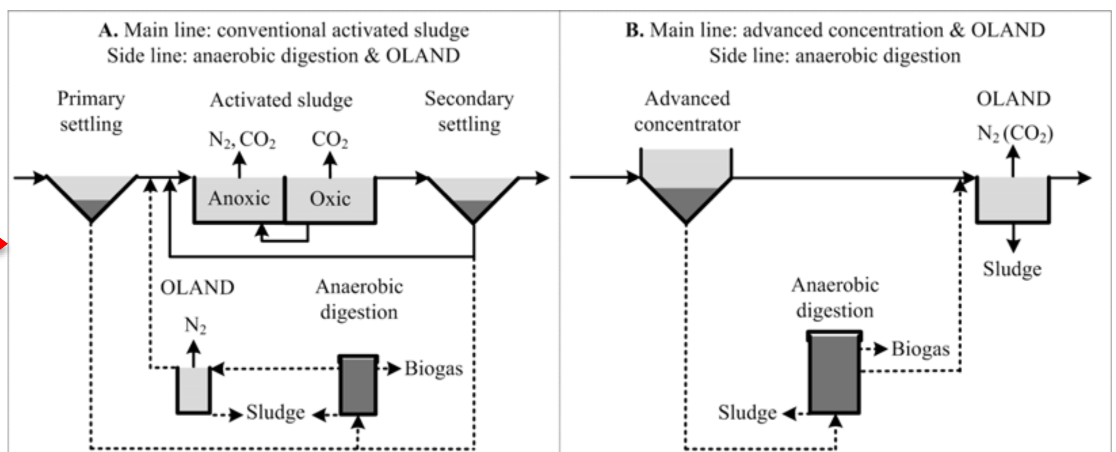
Influence of Aeration Conditions on Nitrogen Removal Rate in One Stage Partial Nitritation/Anammox Process
J. Yang, *Royal Institute of Technology;* M. Zubrowska-Sudol, *Warsaw University of Technology;* J. Trela, E. Plaza, *Royal Institute of Technology*

1-Stage Deammonification MBBR Process for Reject Water Sidestream Treatment: Investigation of Start-up Strategy and Carriers Design
R. Lemaire, *Veolia Water Research Centre;* I. Liviano, *Krüger A/S;* S. Ekström, C. Roselius, *AnoxKaldnes AB;* J. Chauzy, *Technical Direction Veolia Water;* D. Thornberg, *Copenhagen Development Cooperation*; C. Thirsing, *Lynettefaellesskabet I/S;* S. Deleris, *Veolia Water Research Centre*

Swedish Experience with Deammonification Process in Biofilm System
E. Plaza, *Royal Institute of Technology;* S. Stridh, J. Örnmark, *SYVAB AB;* L. Kanders, Purac, *Läckeby Water AB;* J. Trela, *Royal Institute of Technology*

The Positive Effect of Inorganic Carbon on Anammox Process
J. Yang, Li Zhang, *Kumamoto University;* Y. Fukuzaki, *Meidensha Corporation;* D. Hira, K.Furukawa, *Kumamoto University*

Anammox Process Inhibition by Oxytetracycline: Short-and Long-Term Experiments and Model Evaluation
P. Noophan, *University, Bangkok;* P. Narinkongnong, *Silpakorn University;* C. Wantawin, *King Mongkut's University of Technology Thonburi, Bangkok;* J. Munakata-Marr, *Colorado School of Mines, Golden, CO*



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Beginnings of MD – IWA/WEF NRR conference Vancouver (2013)

Session 14: Mainstream Deammonification I

Roadmaps Toward Energy Neutrality Chemical Optimization at Enhanced Nutrient Removal Facilities
Beverley M. Stinson, AECOM; Sudhir Murthy, DC Water; Charles Bott, Hampton Roads Sanitation District; Bernhard Wett, ARA Consult; Ahmed Al-Omari, DCWater; Gregory Bowden,Yalda Mokhyerie, AECOM; Haydee De Clippeleir, Columbia University

Mainstream Partial Nitritation–ANAMMOX Nitrogen Removal in the Largest Full-Scale Activated Sludge Process in Singapore: Process Analysis
Yeshi Cao, PUB; Bee Hong Kwok, Wei Hin Yong, PUB/Changi Water Reclamation Plant; Seng Chye Chua, Yuen Long Wah, Yahya ABD Ghani, PUB

Modification of a B-stage MLE to Take Advantage of SND and Nitrite Shunt in an A/B Process Pilot Study
Ryder Bunce, Old Dominion University; Mark Miller, Virginia Tech; Pusker Regmi, Old Dominion University; Daniel Hingley, David Kinnear, HDR; Charles Bott, Hampton Roads Sanitation District

Measuring Nitrite - The Key to Controlling Deammonification Reactions
Henryk Melcer, Brown & Caldwell; Charles B. Bott, Hampton Roads Sanitation District; Pushker Regmi, Old Dominion University; Leiv Rieger, InCNTRL Solutions Inc; Jiang Wan, Pierce County, Chandler Johnson, World Water Works, Oklahoma City; Kartik Chandran, Yiwei Ma, Columbia University

Effect of Temperature on Anammox Bacteria Cultivated Under Different Conditions
Tommaso Lotti, R. Kleerebezem, M.C.M. van Loosdrecht, Delft University

Effects of Organic Carbon Source, COD/N Ratio and Temperature on Anammox Organisms
Javier A. Sánchez Guillén, Yesuf A. Yimmam, Carlos M. Lopez Vazquez, UNESCO-IHE Institute for Water Education; Damir Brdjanovic, UNESCO-IHE Institute for Water Education/Delft University; Jules B. van Lier, Delft University/UNESCO-IHE Institute for Water Education

Mainstream Sewage Treatment with Partial Nitritation- Anammox: Potential Role of NO Production
Haydée De Clippeleir, Ghent University/Columbia University; Siegfried Vlaeminck, Fabian De Wilde, Robin Jordaens, Emilie Courtens, Pascal Boeckx, Willy Verstraete, Nico Boon, Ghent University

Competition Over Nitrite in Single Sludge Mainstream Deammonification Process
Ahmed A. Al-Omari, Gent University; Bernhard Wett, ARAconsult; Mofei Han, Delon Hampton and Associates; Haydee De Clippeleor, Columbia University; Charles Bott, HRSD; Ingmar Nopens, Ghent University; Sudhir Murthy, DCWater

Simultaneous Chemical Precipitation of Phosphate and Shortcut Nitrogen Removal by Aerobic Granular Sludge
Yongmei Li, Jinte Zou, Qi Zhou, Tongji University

Session 16: Mainstream Deammonification II

NOB Out-Selection in Mainstream Makes Two-Stage Deammonification and Nitrite-Shunt Possible
Pusker Regmi, Becky Holgate, Old Dominion University; Mark Miller, Virginia Tech; Ryder Bunce, Old Dominion University; Hongkeum Park, Kartik Chandran, Columbia University; Bernhard Wett, ARA Consult; Sudhir Murthy, DC Water; Charles Bott, Hampton Roads Sanitation District

Integration of Anammox into The Aerobic Granular Sludge Process for the Conversion of BOD in Wastewater Treatment at Ambient Temperatures
Mari-Karoliina Winkler, Robbert Kllerebezem, Mark C. van Loosdrecht, Delft University

Pilot Scale Evaluation of Anammox Based Main Stream Nitrogen Removal from Municipal Wastewater
Tommaso Lotti, R. Kleerebezema, Delft University; B. Kartal, Radboud University Nijmegen; M.K. de Kreuk, Delft University; C. van Erp Taalman Kip, Hollandse Delta; J. Kruit, T.L.G. Hendrickx, Paques BV; M.C.M. van Loosdrecht, TU Delft

Assessment of CFD and Biological Modelling with a Multiphase Euler-Euler Model for an Anammox Reactor
Albert Vilà, Mael Ruscalleda, Maria Dolors Balaguer, Jesús Colprim, LEQUIA - Institut of Environment

Enhancing Nitrogen and Tiny Suspended Particulates Removal by the Combination Process of Nitrogen Removal via Nitrite and Limited Filamentous Bulking
Jianhua Guo, Beijing University of Technology
***Manuscript Unavailable**

Net energy consumption in different wastewater treatment systems

Oxygen and energy demand	Mass Flux (g p^{-1} d^{-1})			Energy (Wh p^{-1} d^{-1})		
	Case A	**Case B**	**Case C**	**Case A**	**Case B**	**Case C**
Aeration for COD removal	40	30	15	-40	-30	-15
Aeration for Nitrogen removal	22	22	16	-22	-22	-16
Pumping/Mixing energy				-20	-20	-15
Methane-COD and electrical energy production from biogas	30	40	55	+38	+51	+70
Net Energy				**-44**	**-21**	**+24**

Case A - Conventional treatment;
Case B - Conventional treatment, with anammox used in the sidestream;
Case C - Optimized treatment, with anammox in the mainstream

Kartal et al.. (2010)

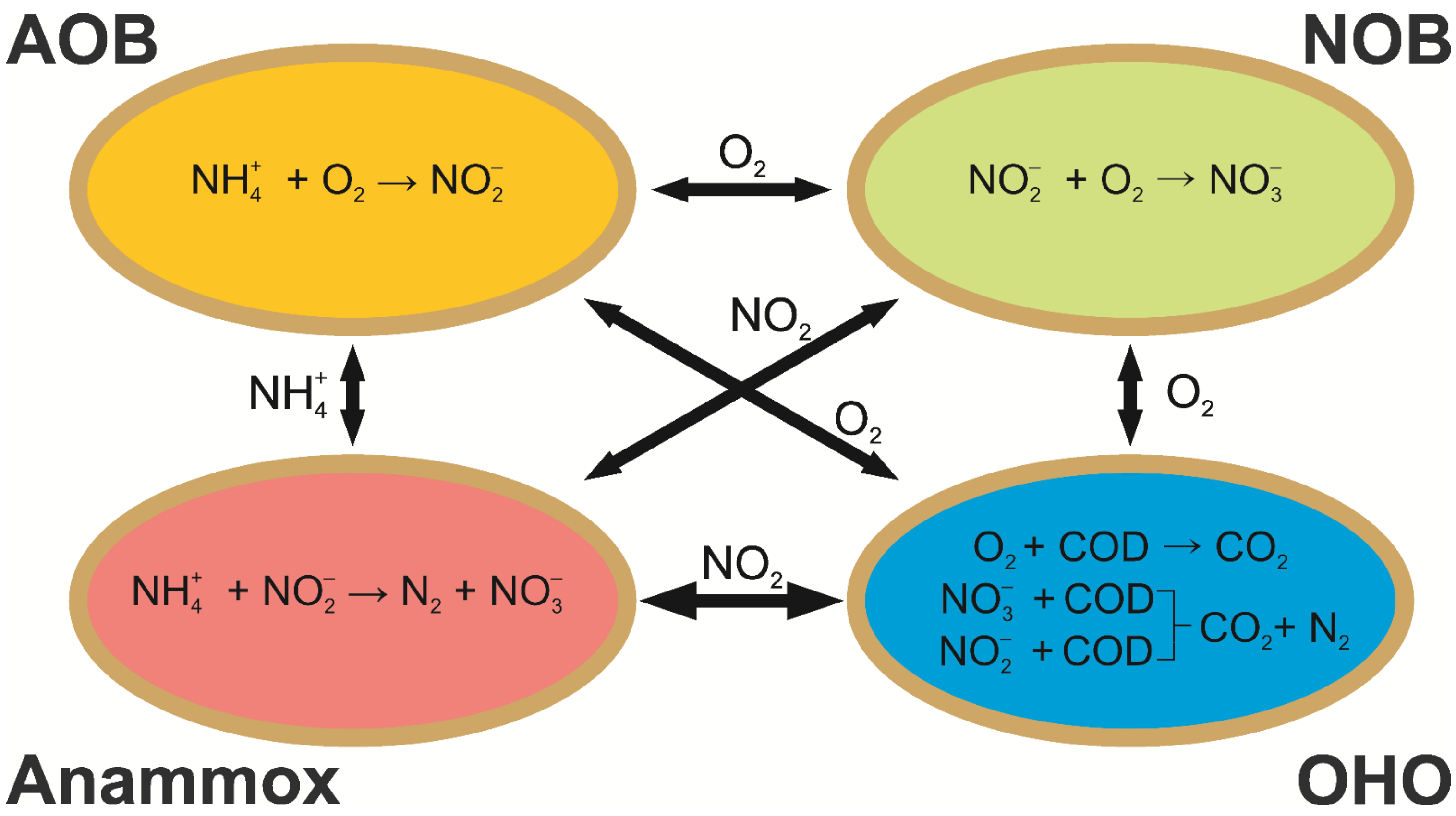
Comparison of typical mainstream and sidestream systems

- Different influent characteristics

Feature	Unit	Mainstream	Sidestream
Influent TN	mg N/L	20 - 100	500 - 3000
COD/N ratio	mg COD/mg N	>10	<2
Temperature	^{o}C	10 - 25	>30

- N effluent standards need to be considered for mainstream systems (e.g. 10-15 mg N/L in EU)
- More microbial competition in mainstream systems

Microbial competition in MD systems



Cao et al et al. (2017)

Drivers

- Eliminate External Carbon
- Energy
  - decreases aeration demand for N removal
  - decreases aerobic COD oxidation
  - diverts wastewater carbon to anaerobic digestion
- Intensification
  - carbon diversion = much smaller aeration tank volume required

Bott (2016)

Challenges

- Unstable performance of the carbon concentrating pretreatment
- Suppression of nitrite oxidizing bacteria (NOB), especially under low temperatures (10-15°C)
- Low activity of anammox bacteria under the low temperatures
- Effective retention of the anammox biomass in the system
- Effective final polishing step for N residuals

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Full-scale MD demonstration sites

Strass, Austria (cold with bioaugmentation)

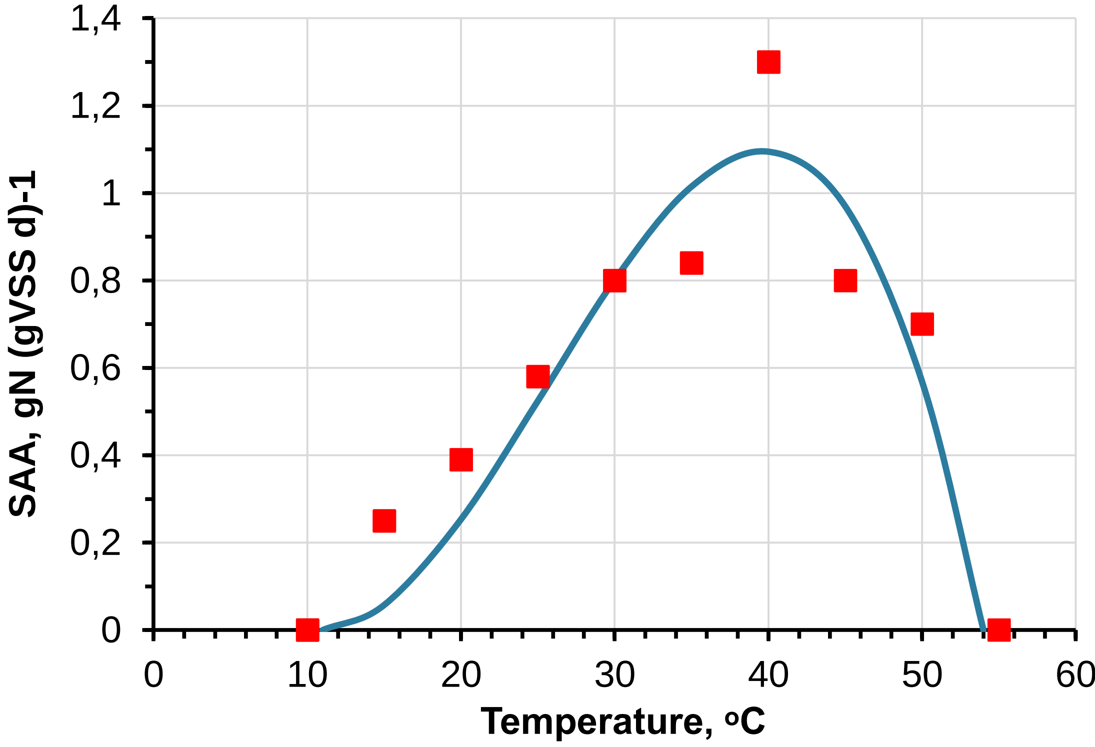
Changi, Singapore PUB (warm without bioaugmentation)

Short-term effects of temperature on anammox activity

Arrhenius vs. Ratkowsky equation

$$r(T) = r_{30} \cdot \theta^{(T-30)}$$

$$r(T) = [b \cdot (T - T_{min})]^2 \cdot (1 - \exp(c(T - T_{max})))$$



Ratkowsky eq.

b = 0.29

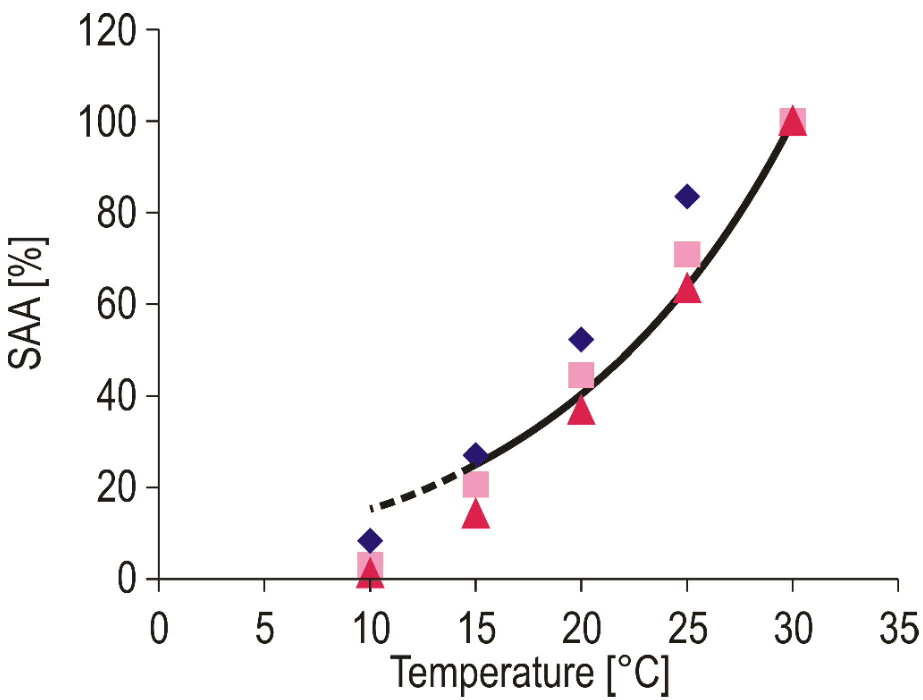
c = 0.001

Sobotka et al. (2016)

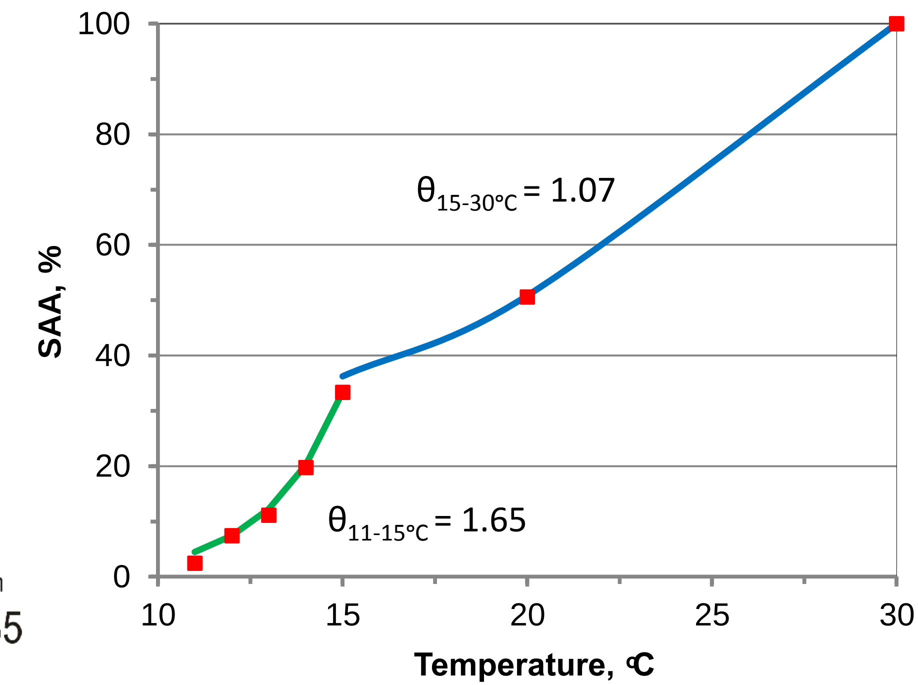
Effect of temperature change on anammox activity

IC reactor, airlift reactor and MBR

SBR



Lotti et al. (2015)



Sobotka et al. (2016)

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Recipe for implementation of MD

- AOB & anammox bioaugmentation from sidestream
- Effective anammox retention in mainstream
- Aggressive SRT Control
  - Lower SRT results in selective washout of NOB at warmer temperatures
- Intermittent high DO “transient anoxia”
  - At high DO AOB grow faster than NOB
  - NOB seem to have a delayed response as they move from anoxic to aerobic zones
- Rapid transition to anoxia
  - DO must be scavenged quickly to avoid a “low” DO environment
  - Step-feed to anoxic zones to deplete DO quickly
  - CEPT by-pass to enhance soluble COD as needed
- Maintain residual ammonia > 2 mg/l
  - Ensure higher ammonia oxidation rates so AOB outcompete NOB for DO
  - Ammonia-based aeration control (AvN controller)

Stinson (2016)

Long-term biomass cultivation

Anammox

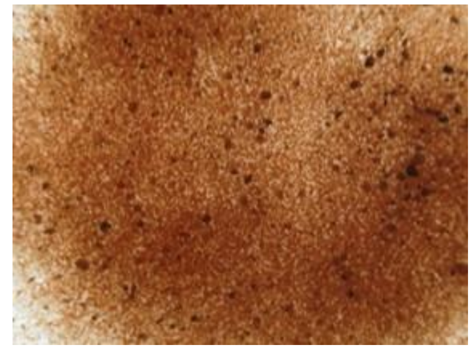
Inoculum

After 300 d

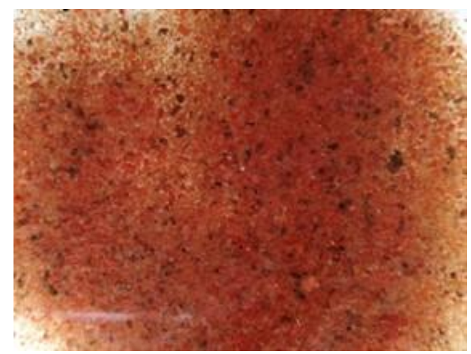
SBR (10 L)

Deammonification

Inoculum



After 300 d



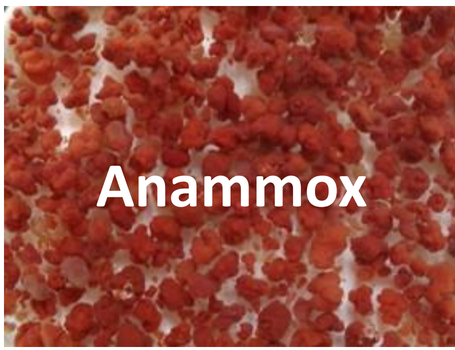
Lu et al. (2017)

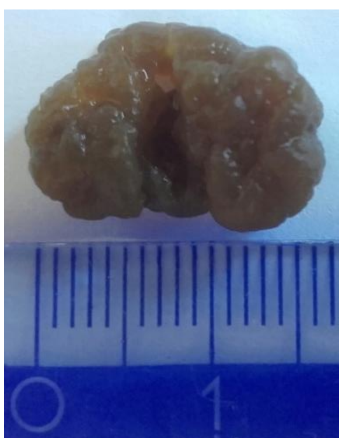
Separation of biomass on a sieve

Anammox

SBR (10 L)

Deammonification



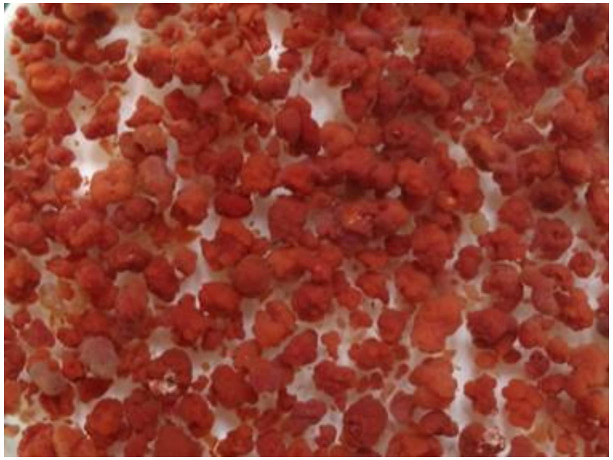


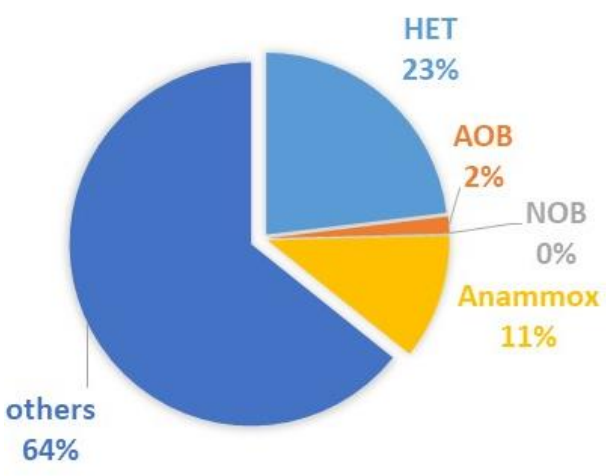
sieve
(200 µm)

Lu et al. (2017)

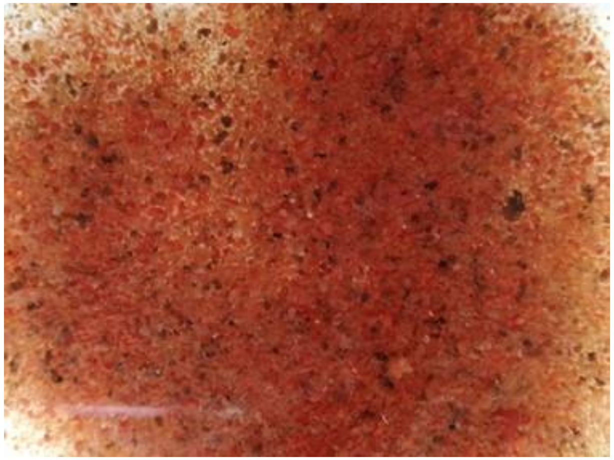
Microbial (metagenomic) analysis

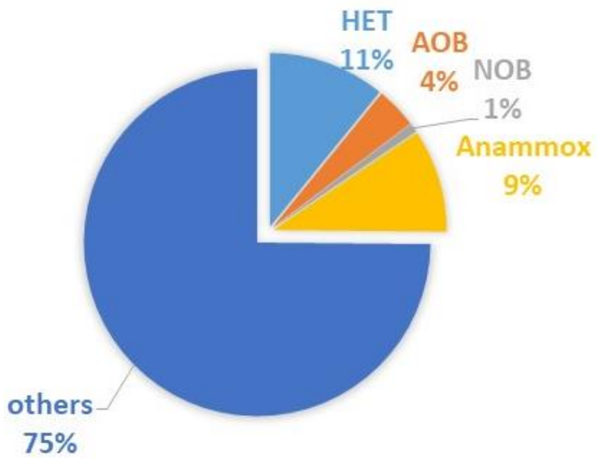
Anammox



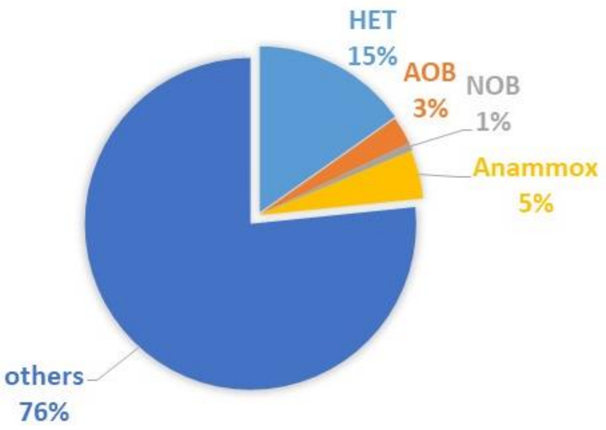


Granules (deammonification)



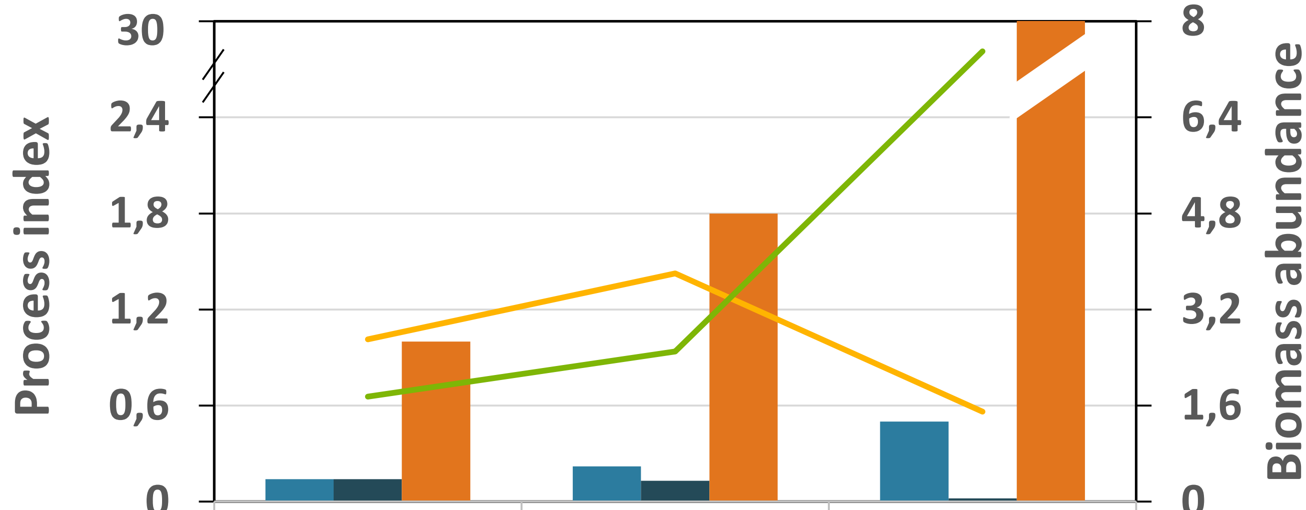


Flocs (deammonification)



Lu et al. (2017)

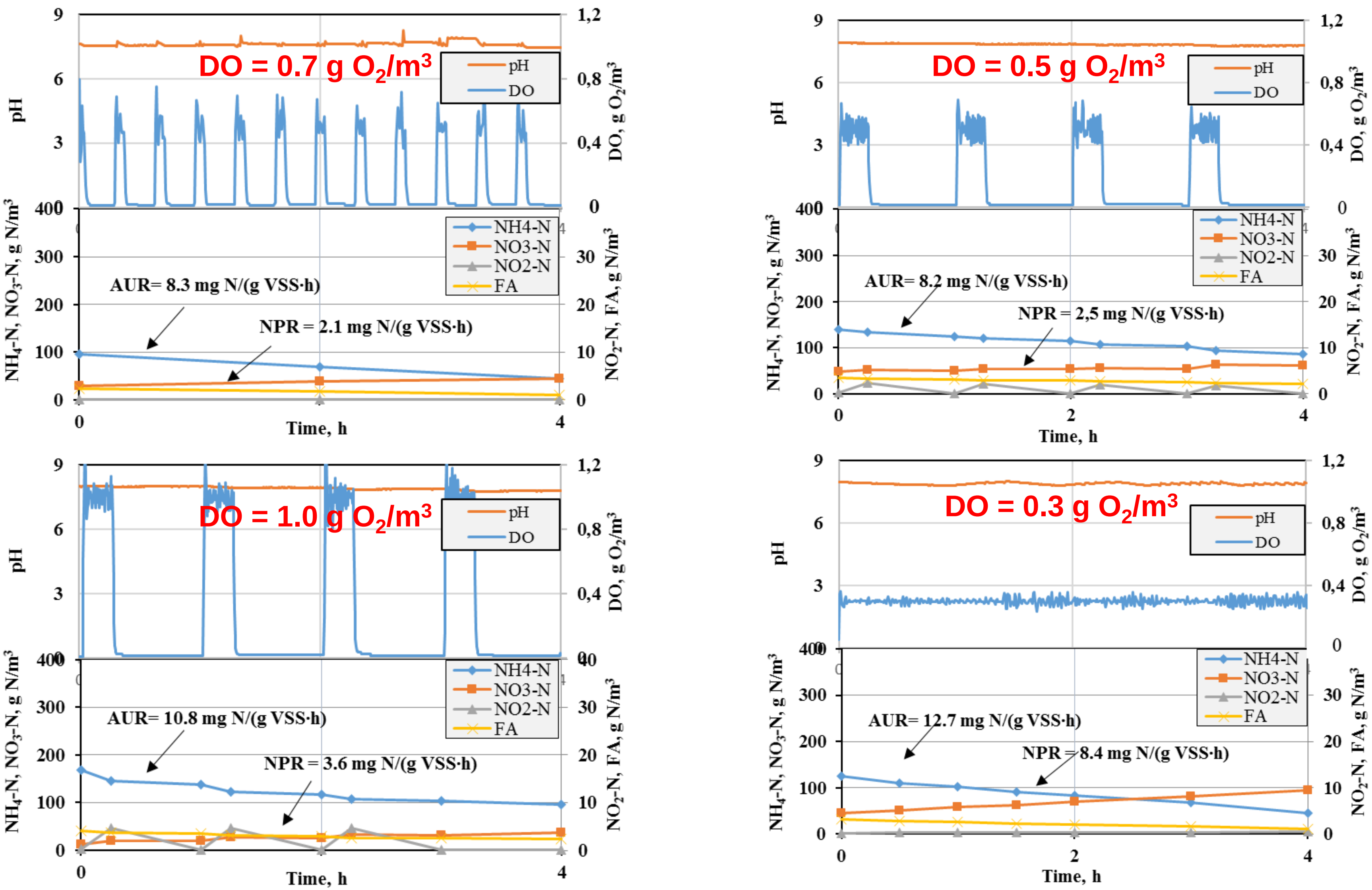
TN removal rates - measured



	Flocs	Granules	Anammox	
SAA	0,14	0,22	0,5	(g N/(g VSS·d))
NUR	0,14	0,13	0,02	(g N/(g VSS·d))
AVN	1	1,8	30	
AOB	2,7	3,8	1,5	
Anammox/AOB	1,75	2,5	7,5	

Lu et al. (2017)

Effects of aeration modes on deammonification (1)

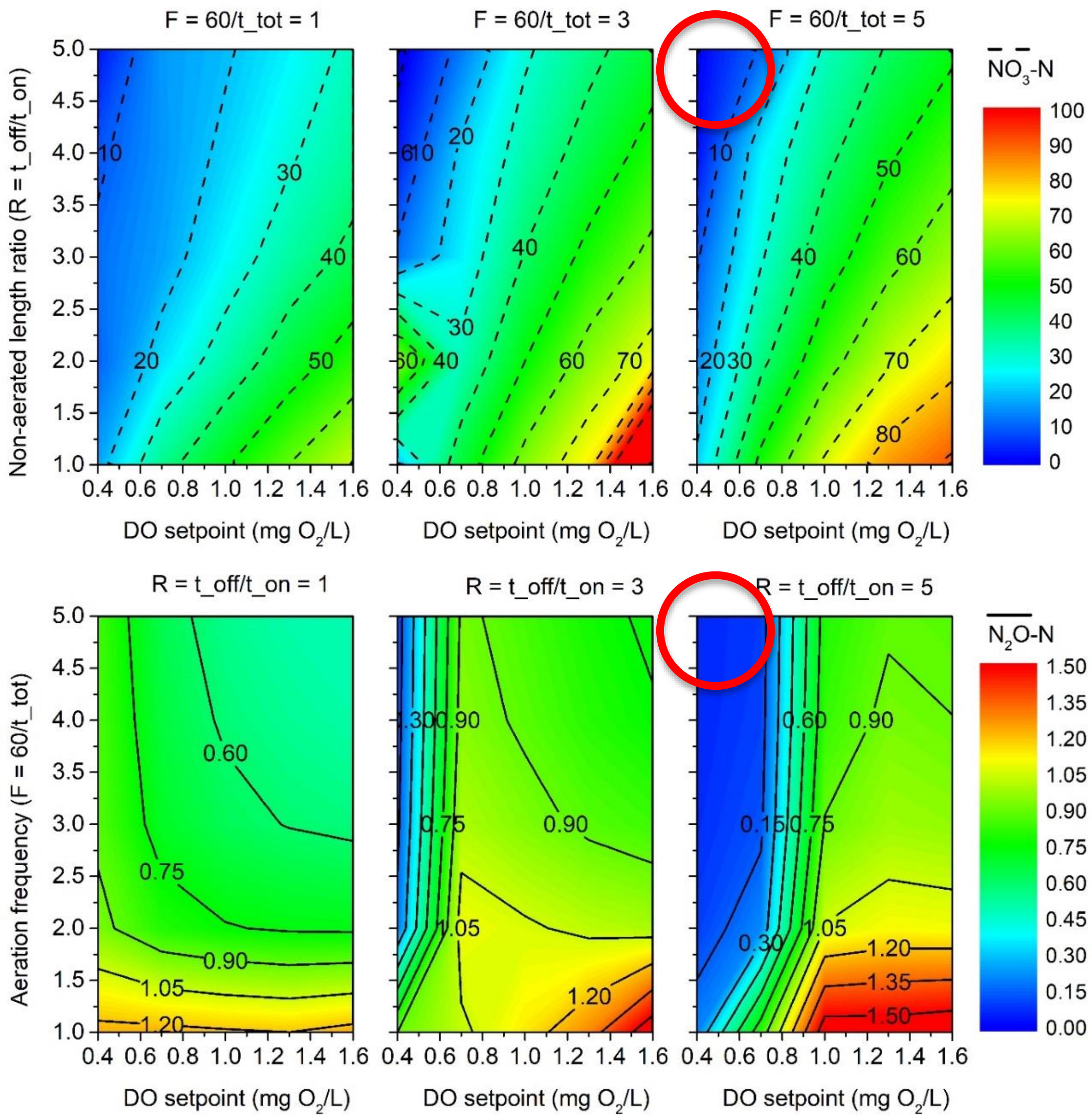


Al-Hazmi et al. (2017)

Effects of aeration modes on deammonification (2)

NO_3-N

N_2O-N



Al-Hazmi et al. (2018)

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Conclusions

- Mainstream deammonification (MD) is an emerging technology with a great potential for achieving a positive energy balance in WWTPs.

- There are five main challenges for implementation of MD in full-scale WWTPs.

- A potential recipe for MD consists of several factors that need to be taken into consideration.

- Long-term studies with granular sludge at GUT showed an effective way of suppression of the NOB activity and mitigation of N_2O production.

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THANK YOU FOR YOUR ATTENTION !

Questions???

Contact:
Jacek Mąkinia
jmakinia@pg.edu.pl