The role and potentials of Anaerobic Digestion (AD) in the circular economy

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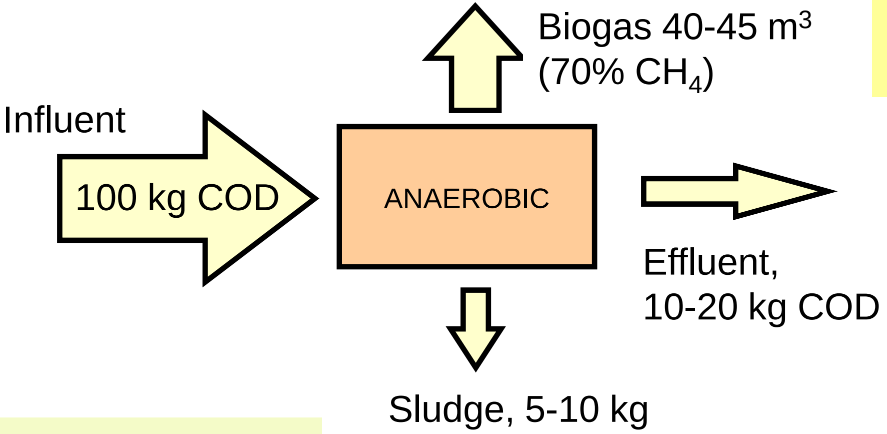
28 May 2025

Anaerobic treatment industrial wastewater:
No loss of biochemical energy!



100 kg COD ≅ 35 m^3 CH_4
≅ 1240 MJ ≅ 345 kWh*
*Theoretical energy equivalent, LHV

Energy savings applying AD instead of activated sludge:

Energy content organics (LHV):
≈ 12.4 MJ/kg COD

Savings in Aeration:
1.8 - 3.6 MJ/kg $COD_{rem.}$

So on prime fossil energy: (1.8-3.6) / 0.35

Max. energy gainings:
(compared to activated sludge)
≈ 17- 23 MJ/kg $COD_{rem.}$

Anaerobic treatment: Energy recovery, savings, and CO_2 emission reduction!

Brewery effluent: **17 tons COD/day**
Energy of 1 ton COD ≈ 12.4 GJ ≈ 3.4* MWh

Energy recovered via biogas (85% treatment efficiency):
17 ton COD/day → 49 MWh/day (thermal) → 19.7 MWh-elect/day (40% CHP eff.)

No energy consumption:
Saving ≈ (0.5 -) 1 kWh-e/kg COD removed →
Saved: up to 17 ton COD x 0.85 (eff.) = 14.5 MWh-e/day

Total benefit electricity: 19.7 + 14.5 = 34.2 MWh-e/day
≅ 8,200 €/d (with 0.24 €/kWh) ≅ **3,000,000 €/year**

CO_2 emissions electricity production (NL): 0.65 ton CO_2/MWh-e

Electricity from biogas: 19.7 MWh-e/day ≈ **12.8 ton CO_2 red./day**

No electricity for aeration: 17 ton COD x 0.85 (eff.) = 14.5 MWh-e/day
≈ **9.4 ton CO_2 reduction/day (NL)**

Total CO_2 emission reduction: 12.8 + 9.4 = 22.2 ton CO_2 /day
Tradable: 12.8 x 100 €/ton CO_2 = 1280 €/d **≈ 467,000 €/year**

Application high-rate Anaerobic Treatment in industries

2025: about 5000 (?) reactors

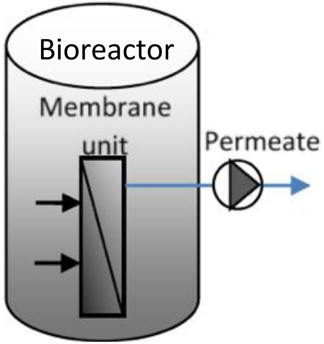
Beer, Brazil

Agro – food Industry 36%		Beverage 29%	Alcohol Distillery 10%	Pulp & Paper 11%	Miscellaneous 14%
Sugar	Cannery	Beer	Sugar cane juice	Recycle paper	Chemical
Potato	Confectionery	Malting	Sugar cane molasses	Mechanical pulp	Pharmaceutical
Starch	Fruit	Fruit juice	Sugar beet molasses	NSSC	Municipal sewage*
Yeast	Vegetable	Wine	Grape wine	Sulphite pulp	Landfill leachate
Pectin	Dairy	Coffee	Grain	Straw	Acid mine water
Citric acid	Bakery		Fruit	Bagasse	

Van Lier et al, 2020

https://online-learning.tudelft.nl/courses/high-rate-anaerobic-wastewater-treatment

TUD research: Anaerobic Membrane Bio-Reactors
→ from lab to full-scale!

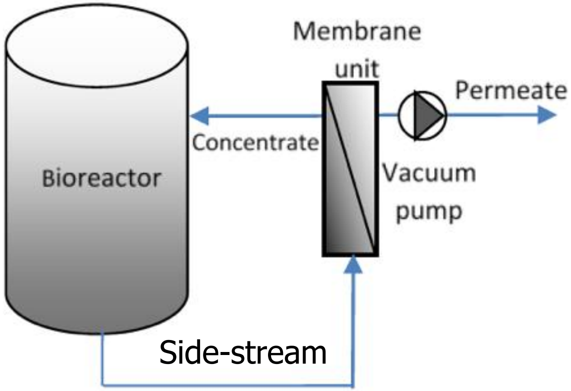


Submerged

David Jeison, PhD, 2007

Kaan Dereli, PhD, 2015

Jixian Yang, PhD, 2013



Why AnMBR ??:

- Simplification treatment train!
- Combined step for water treatment & reclamation

Magela Odriozola, PhD, 2022

Julian Munoz, PhD, 2022

Hale Ozgun, PhD, 2015

Victor Garcia, PhD, 2023

Rifki Kurnianto, PhD, 2026

Evrin Ersahin, PhD, 2015

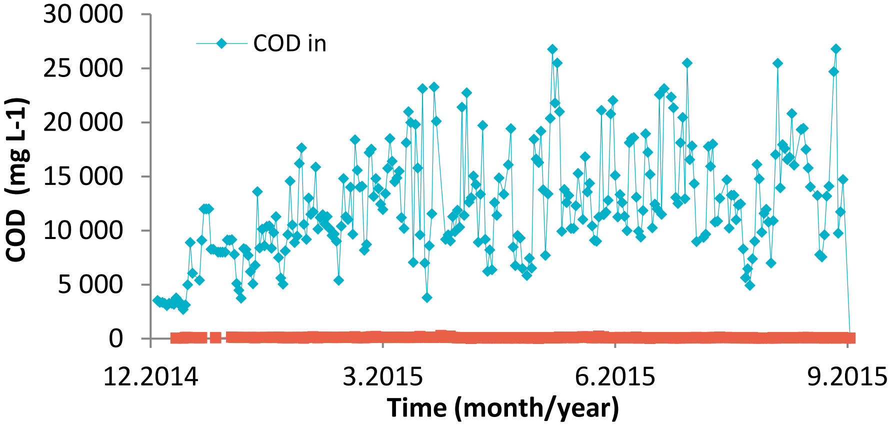
Anaerobic Membrane Bio-Reactors: high-quality effluents for reuse

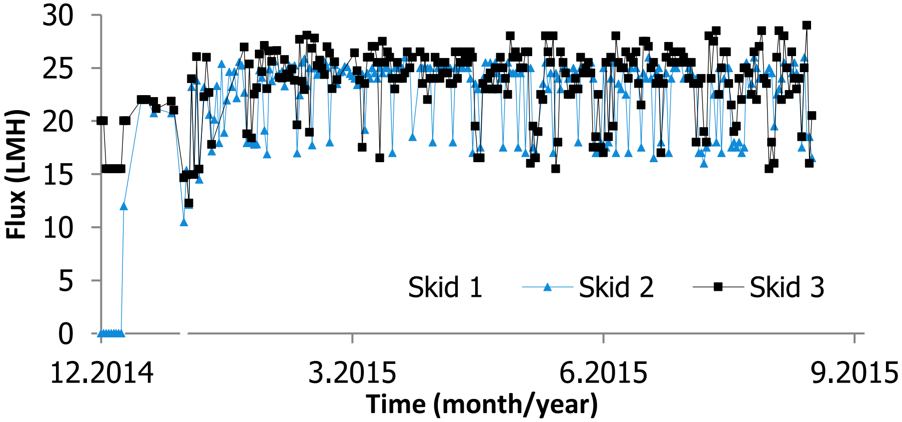
Full scale plant – Chocolate/Pet food (Poland):

- Design COD = 20 g COD L^{-1}
- FOG up to 1000 mg L^{-1}
- 98 % COD removal
- 99.9 % TSS removal
- VLR = 3 - 5 g COD L^{-1} day^{-1}

BIOTHANE

2025:
> 25 references





AnMBR for Water Reclamation

BIOTHANE

Digester + UF skid

VEOLIA WATER Solutions & Technologies

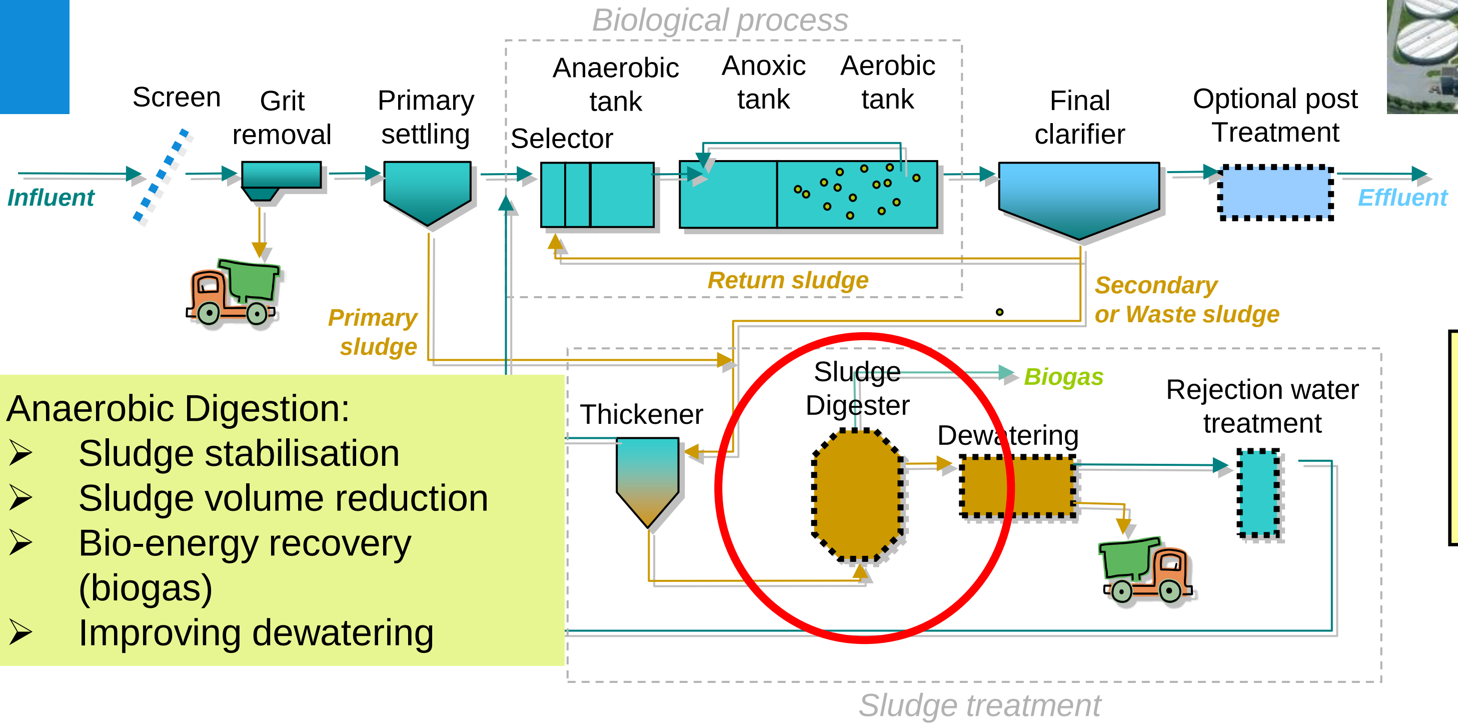
RO

Full-scale: Dairy, South Africa:

- Influent COD = 9,000 mg L^{-1}
- TSS = 2.700 mg L^{-1}
- FOG up to 1,850 mg L^{-1}

Coupling AnMBR directly to RO:
High-rate water reclamation + minimized biofouling!

The 'classic role' of AD in municipal WWTP: stabilization excess sludge



Anaerobic Digestion:

- ➢ Sludge stabilisation
- ➢ Sludge volume reduction
- ➢ Bio-energy recovery (biogas)
- ➢ Improving dewatering

Mostly applied:

- UCT
- Carroussels

Removes:
'C': BOD < 20 mg/l
'N': < 10-15 mg/l
'P': < 1-2 mg/l

Current standard (NL)

AD of waste(water): from treatment to resource recovery

European Green Deal

Energy

Phosphate

??

Reactive N (NH_4^+)

Water

Bio-plastic precursors (VFAs)

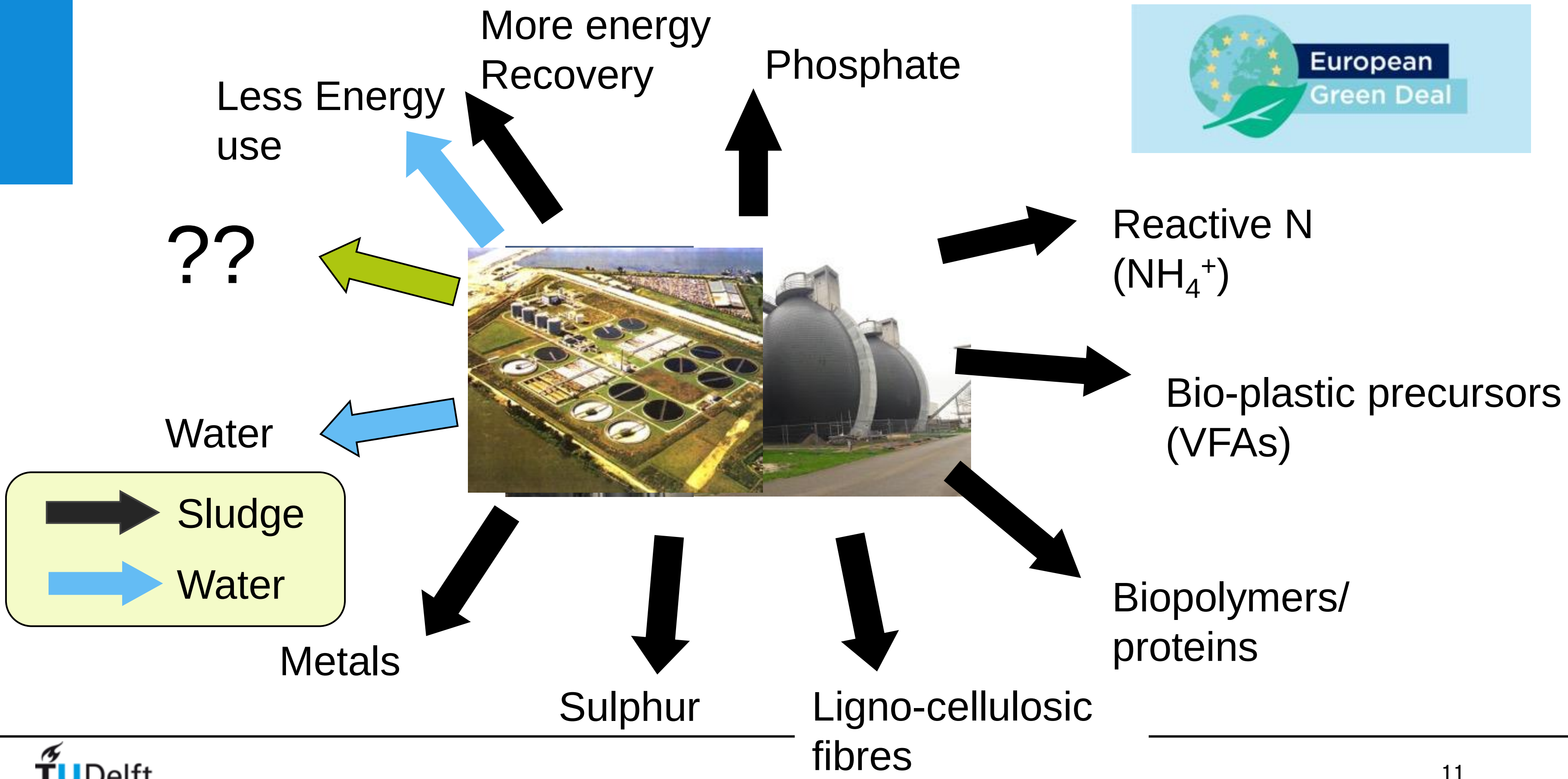
Biopolymers/ proteins

Metals

Sulphur

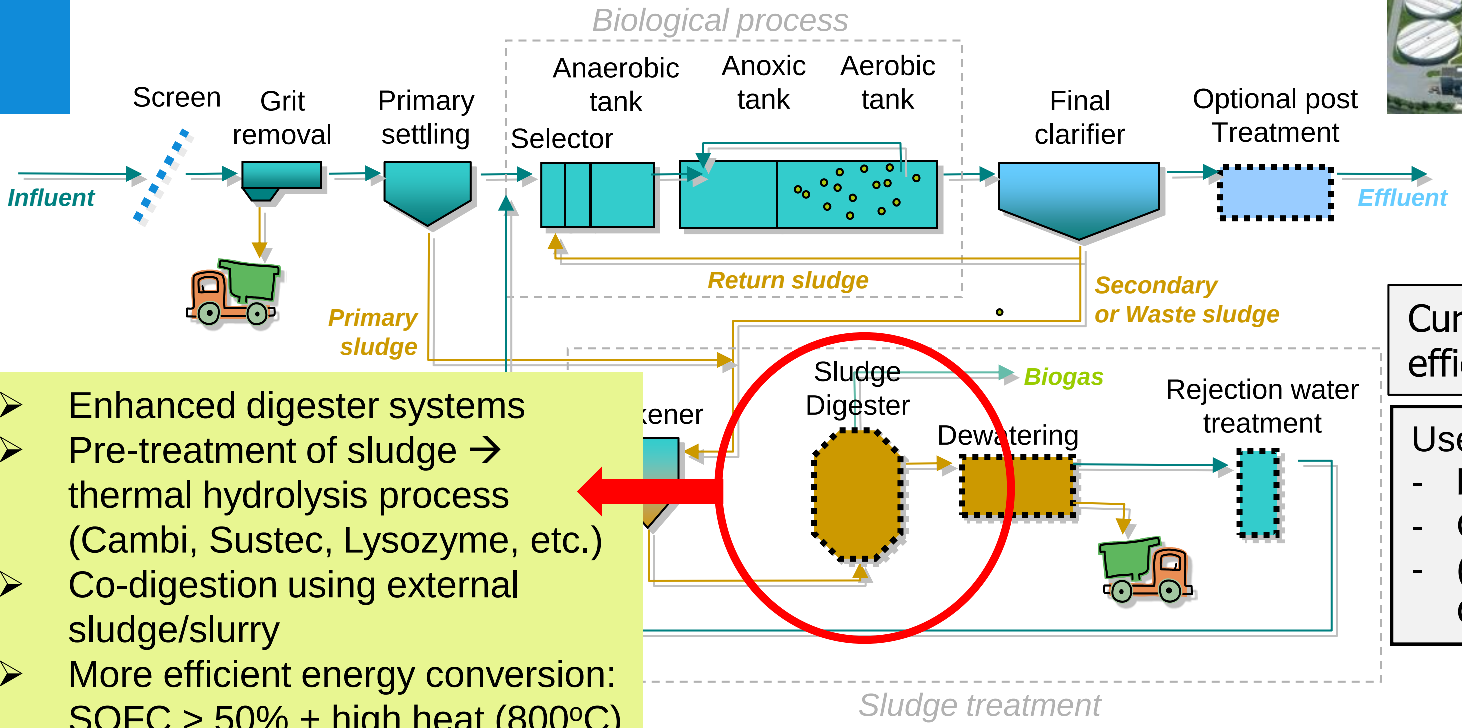
Ligno-cellulosic fibres

Sewage: resource recovery is linked to the 'sludge line'



Anaerobic Digestion: core to achieve energy neutrality?!

WWTP Harnaschpolder - Delft



Current WAS conversion efficiency: 30-40%

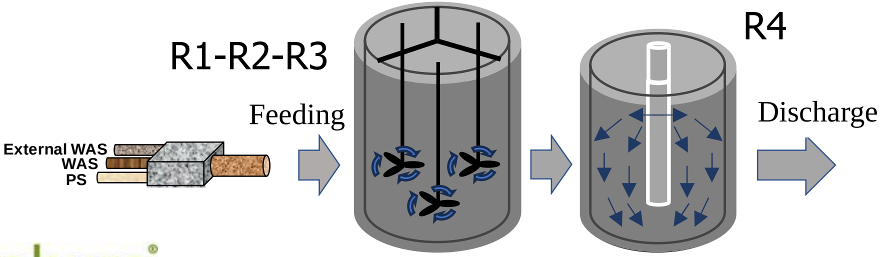
Useful energy recovery:
- biogas motor: 30-35%
- CHP: 40% + low heat
- (compressed) biogenic CH_4

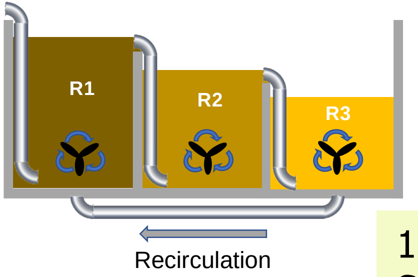
- Enhanced digester systems
- Pre-treatment of sludge → thermal hydrolysis process (Cambi, Sustec, Lysozyme, etc.)
- Co-digestion using external sludge/slurry
- More efficient energy conversion: SOFC > 50% + high heat (800ºC)

Enhanced sludge digestion applying cascade reactors:

Hongxiao Guo, PhD, 2024

Royal HaskoningDHV
Enhancing Society Together





Retro-fitting 2 parallel digesters into 4-stage-cascade AD (Tollebeek, NL)

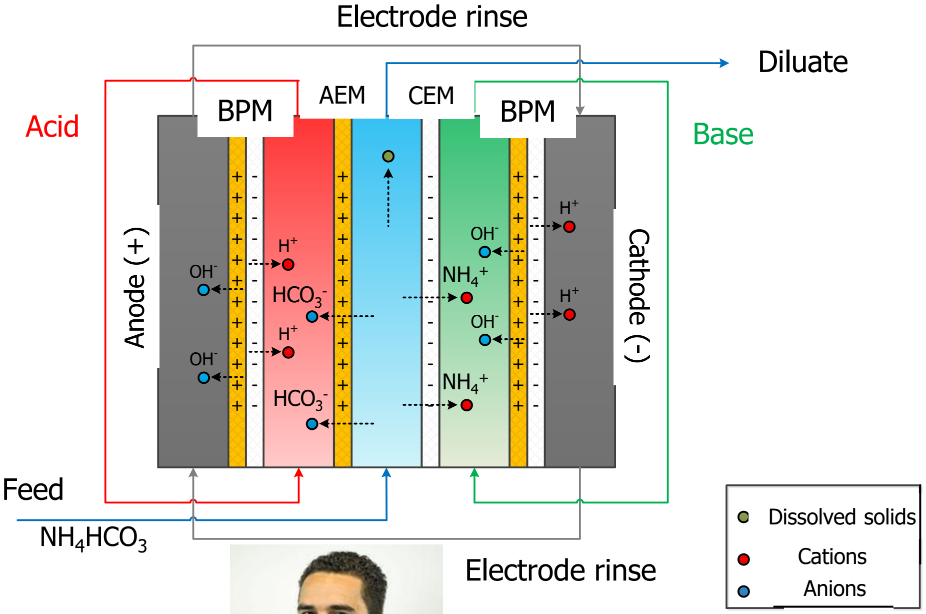
2025:

16 references:
SRT: 7-8 days!

Life · Rijksdienst voor Ondernemend Nederland · stowa · Royal HaskoningDHV · Zuiderzeeland · TU Delft · Logisticon Water Treatment · Endress+Hauser

What to do with reactive NH_4^+? → BiPolar Membrane (BPM) Electrodialyis (ED): NH_4^+ removal and NH_3 recovery in 1 step

Simulated **digestate reject water**:
- Feed water: 1.5 g NH_4^+/L as NH_4HCO_3, pH 7.8
- Direct production of NH_3 and CO_2…!!



Performance:
- Efficient ammonium removal at low energy costs
- Production of concentrated NH_4OH / gaseous NH_3 in the alkaline cell
- Avoidance addition of alkaline to volatilise NH_3
- Production of H_2CO_3/CO_2 in the acid cell

Energy use of ED & BPM-ED
- ED → concentrating and removing NH_4^+: 5 MJ/kg-N,
- BPM-ED → NH_3 production: up to 19 MJ/kg-N
- Combined ED+BPM-ED for most energy efficient NH_3 recovery

Niels van Linden, PhD, 2022

TUD Patent

Ammonium recovery from real reject water:

Complex matrix!!

- Competing cations: Fe^{3+}, Al^{3+}, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}
- Disturbing anions: Cl^{-} (HCl)
- Non-controlled precipitation
- Membrane fouling (organics)
- Membrane lifetime

Two options:

1. **Deal with the matrix → amend ED-BPMED technology**

Iosif Kaniadakis

- ***ED-reversal*** for up-concentrating NH_4^+
- ***Mono-valent selective cation exchange membranes*** in ED (less precipitation)
- ***2-chamber BPM-ED (BPC)*** for improved efficiency (less stack resistances, less NH_3 losses)
- ***Pulse-pause operation*** for ***low energy*** consumption

2. Extract TAN from the matrix via air stripping & acid scrubbing

Dhavissen Narayen

Gladys Mutahi

- ***Current standard:*** Acid scrubbing using H_2SO_4 to produce $(NH_4)_2SO_4$
- ***However:*** H_2SO_4 is hazardous and more costly than the product
- ***NEW:*** Use **BPM-ED** to recover the acid and produce NH_3/H_2O (NH_4OH)
- ***NEW-NEW:*** Use **organic acids** → less competing H^+ transport → low energy consumption

Take-home messages:

- Looking for real sustainability? Go **anaerobic**s!
- NH_3 / NH_4^+ is a resource! → recover instead of destruct!

Thanks to all (and especially PhDs..!) who have contributed!
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