CIE4485
Wastewater Treatment

Dr.ir. M.K. de Kreuk

1. Introduction + Recap N removal

CT4485 Wastewater Treatment

Lecture 1: Intro + Recap N removal

Dr. Ir. M.K. de Kreuk and Prof.Dr.ir. Jules B. van Lier
15 November 2012

Outline CIE4485 - Wastewater Treatment

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After this course you will be able to:

- Design the basics of conventional aerobic and anaerobic wastewater treatment plants, based on different influent conditions and effluent demands;
- Identify and compare innovations in wastewater treatment technologies of the last decade;
- Reason and decide which treatment option is the most suitable choice in a given situation, considering surroundings, demands and focus.

Outline CIE4485 - Wastewater Treatment

This course will discuss the following topics:

- **New developments in treatment techniques** e.g. for reaching stringent effluent criteria (N, P, BOD), rejection water treatment, effluent upgrading, recovering cellulose fraction
- Introduction in the **aerobic granular sludge** technology (Nereda)
- **Interactions** between sewage collection and treatment
- **Anaerobic treatment technologies** for domestic & industrial wastewaters: fundamentals, dimensioning and performance calculations
- Developments in **resource oriented sanitation**: separate streams
- **Use of treated effluents** in agriculture
- **The Resource Factory** – a new approach for wastewater treatment
- Use of **Biowin** for modeling biological wastewater treatment.

Outline CIE4485 - Wastewater Treatment

Lectures at Thursday 8.45 till 12.30, Schedule at Blackboard under Course Information → Course Schedule

Simulation in Biowin – Thursday 13.45 till 17.30

Henri Spanjers

29/11 Introduction, use of kinetic models for wastewater treatment

6/12 Modelling exercise 1 - COD removal and Nitrification

exercise 2 – Denitrification

13/12 Modelling exercise 3 – UASB reactor startup

exercise 4 – UASB reactor with variable influent

20/12 Assignement – Designing a biological nutrient removal plant

Outline CIE4485 - Wastewater Treatment

Practicals *(Merle de Kreuk)*

- N-removal *(Steef de Valk, Dara Ghashimi)*
- SMA Test *(Yu Tao, Haoyu Wang)*
- Ultra Filtration *(Julian de Muñoz, Mostafa Zamatkesh, Patrick Andeweg)*

EXCURSION – 10/1/2013

Outline CIE4485 - Wastewater Treatment

Course Material

- Lecture Notes
- Black Board – reading material (readings)
- Collegerama
- Metcalf & Eddy (reference material)
- Practicum manuals
- BioWin hand outs

Final Mark

Exam (50%), Practical (25%), Biowin Simulation Assignment (25%)

RECAP N and P removal

Eutrophication

Eutrophication impacts…

Eutrophication and Algal Growth

Enrichment of Surface Waters With Plant Nutrients

ALGAL GROWTH (Stumm & Morgan, 1981):

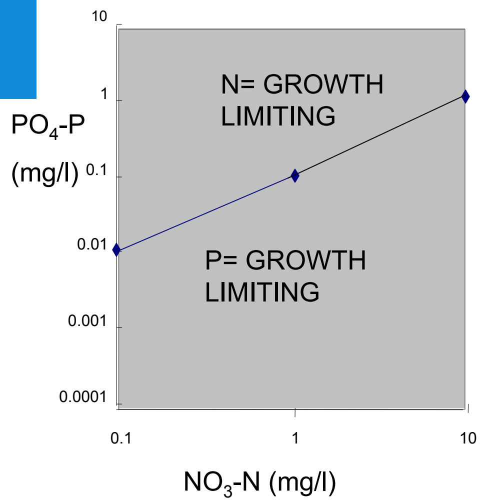
$106\ CO_2 + 122\ H_2O + 16\ NO_3^- + HPO_4^{2-} + 18\ H^+ + \text{ENERGY} \rightarrow$
$C_{106}H_{263}O_{110}N_{16}P + 138\ O_2$

Ideal N:P ratio ≈ 16 N : 1 P
or 7 mg N : 1 mg P

(1 mg P leads to 100 mg algae biomass)

What are the WWTP standards for N & P??

NO_3-N and PO_4-P concentrations in surface water



Combating algae growth:
Reduce the limiting factor!

P more easy than N:
- N = mobile
- Some algae may use N_2

At present:
Both N & P control at WWTP
- N limiting in sea water
- N affects groundwater / aquifers
- Uncontrolled denitrif. affects functioning WWTP
- P slowly released from soils

RECAP N and P removal

P Removal

P Removal processes

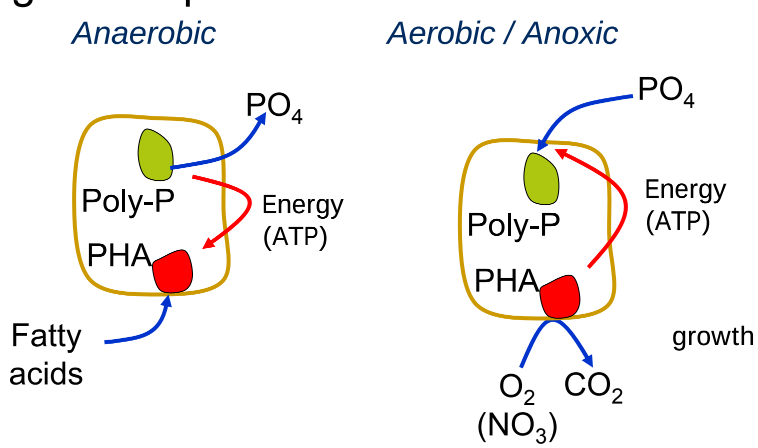
Processes:

- biological
  - => anabolic uptake (P incorporation in new cells)
  - => Biological P-removal
- Chemical precipitation
  - $Al^{3+} + H_nPO_4^{3-n} \leftrightarrow AlPO_4 + nH^+$
  - $Fe^{3+} + H_nPO_4^{3-n} \leftrightarrow FePO_4 + nH^+$

  Lime dosing → at pH 10:

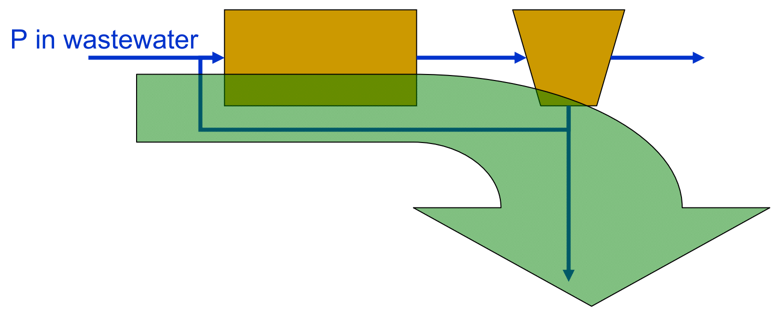
  $10\ Ca^{2+} + 6\ PO_4^{3-} + 2\ OH^- \leftrightarrow Ca_{10}(PO_4)*6(OH)_2$

Biological P-uptake



PHA = Poly Hydroxy Alkanoates

Route of P in activated sludge plant

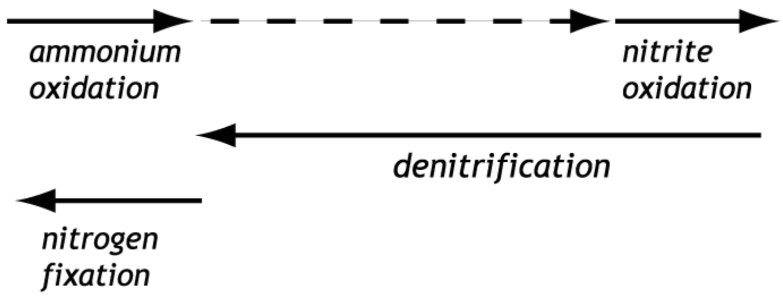


RECAP N and P removal

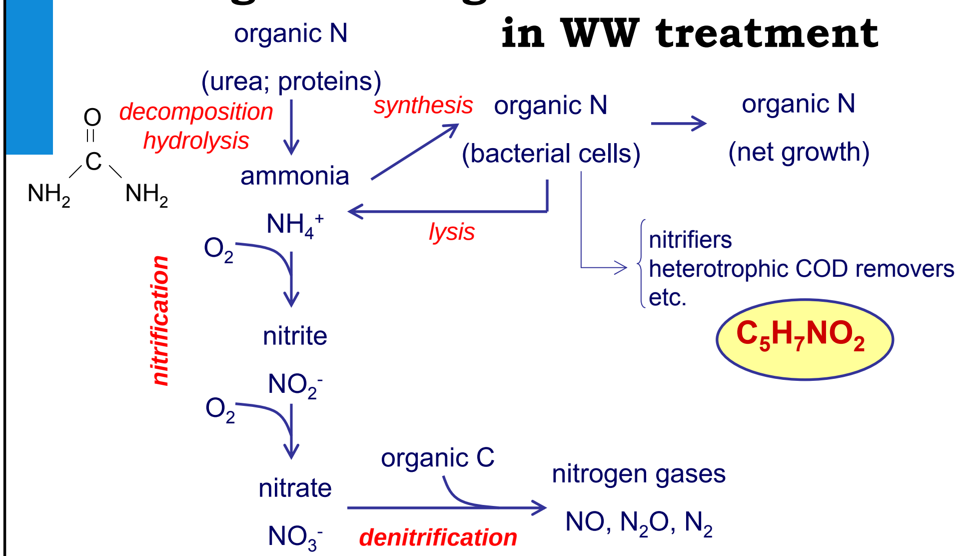
N Removal - General

N-species / N oxidation state

NH_4^+	N_2	N_2O	NO	NO_2^-	NO_3^-
-3	0	+1	+2	+3	+5



Biological Nitrogen Transformations in WW treatment



Removal processes

Processes

- biological
  - => anabolic uptake (N incorporation in new cells)
  - => nitrification
  - => denitrification
  - => anammox
- ammonia stripping
- ion exchange
- chemical precipitation
- NH_4NO_3 formation

Presence of Nitrogen N

- N-total: Organic N, NH_3, NH_4^+, NO_2^-, NO_3^-
- N-Kjeldahl: Organic N, NH_3, NH_4^+
- N-organic
- N-NH4
- N-NO_3
- N-NO_2
- N-SS

- N-NO_3 = (14/62) NO_3
- N-NH_4^+ = (14/18) NH_4^+

Question:
What is the N removal efficiency?*
Influent: 18 kg NH_4^+/h
Effluent: 18 kg NO_3/h

If all species are known:
Set-up of N mass balance!
N in = N out!

**100% x ((18x14/18) – (18x14/62))/(18x14/18) = 71%*

N-quantities in wastewater

- raw wastewater => 10-12 g N/(p.e.*d)
  => 45 mg N/L
- primary sedimentation => 0-20 % removal
  => remaining: 40 mg N/L
- biological treatment => sludge: 10 mg/L
  => remaining: 30 mg N/L
- effluent requirements:
  => N-Kj < 20 mg/L at T>10°C (before 1990)
  => N-total < 10 (20) mg N/L (present)
  => N-total < 2 mg N/L (future, WFD)

Biological N-removal: N uptake by biomass

Growth heterotrophic biomass ($C_5H_7O_2N$):

$$C_{18}H_{19}O_9N + 0.74\ NH_4^+ + 8.8\ O_2 \rightarrow$$
$$1.74\ C_5H_7O_2N + 9.3\ CO_2 + 0.74\ H^+ + 4.52\ H_2O$$

- $C_5H_7O_2N \Rightarrow$ 1 mol (14 g) N per mol (113 g) biomass (X) (≈ 12% in weight)

Actual values may deviate: why??

- $C_5H_7O_2N + 5O_2 \rightarrow 5CO_2 + NH_3 + 2H_2O$
  ⇒ 160 g COD per mol X
  ⇒14/160 = **0.087** gN per g X-COD
- $C_5H_7O_2N \Rightarrow$ 113 g VSS per mol X
  ⇒ 160/113 = **1.42** g X-COD/g VSS

RECAP N and P removal

N Removal - Nitrification

Biological N-removal: Nitrification

Nitrification:

1[st] step by *Nitrosomonas sp.*

$$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + 2H^+ + H_2O$$

2[nd] step by *Nitrobacter sp.*

$$NO_2^- + 0.5\ O_2 \rightarrow NO_3^-$$

Overall:

$$NH_4^+ + 2O_2 \Rightarrow NO_3^- + 2H^+ + H_2O$$

$\approx$ 4.3 gO_2 per gNH_4-N

including some N for biomass production / biosynthesis: 4.57$\rightarrow$ 4.3

Heterotrophic bacteria vs. Autotrophic Nitrifiers

Heterotrophic bacteria

Heterotrophic act. in bioreactor

- L_X
- θ_X
- O_2

Autotrophic nitrifying bacteria

Nitrification in bioreactor

- L_X
- θ_X
- O_2

Heterotrophic bacteria vs. Autotrophic Nitrifiers

Heterotrophic bacteria

- Need O_2
- Carbon source: organic C
- Energy source: organic C
- Fast growth: ~6 d^{-1} (Td = 2.8 h)

Heterotrophic act. in bioreactor

- L_X < 3 kgBOD.kgMLSS^{-1}d^{-1}
- θ_X > 1 day
- O_2 > 0.5 g m^{-3}

Autotrophic nitrifying bacteria

- Need lots of O_2
- Carbon source: CO_2
- Energy source: NH_4
- Slow growth: ~0.8 d^{-1} (Td = 21 h)
- High sludge age required
- pH range: 6.5 – 8.5 (opt.: 7.0-7.2)
- pH decrease during reaction
- Temperature and toxicants sensitive
- BOD conc. has to be low

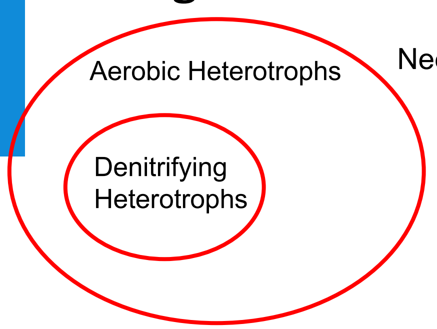
Nitrification in bioreactor

- L_X < 0.15 kgBOD_5.kgMLSS^{-1}d^{-1}
- θ_X > 2.5 days
- O_2 > 1.5 - 2 g m^{-3}
- Nitrification capacity: maximum 20-100 gN/(kg MLSS.d)

RECAP N and P removal

N Removal - Denitrification

Biological N Removal: Denitrification



Needs organic matter / electron donor!!

General formula for organic matter in wastewater: $C_{10}H_{19}O_3N$ (US-EPA, 1993)

$C_{10}H_{19}O_3N + 12\frac{1}{2}\ O_2 \rightarrow 10CO_2 + 8H_2O + NH_3 + \text{Energy}$

$C_{10}H_{19}O_3N + 10NO_3^- \rightarrow 5N_2 + 10CO_2 + 3H_2O + NH_3 + 10OH^- + \text{Energy}$

$5CH_3OH + 6NO_3^- \rightarrow 3N_2 + 5CO_2 + 7H_2O + 6OH^- + \text{Energy}$

Biological denitrification

- Chemo - heterotrophic bacteria
- increase of pH
- oxygen very low (< 0.5 mg/L)
- easily degradable organic material

- pH 5.8 - 9.2
- denitrification rate: 50 - 150 g N/(kg MLSS*d)

NO_3^- equivalence to Oxygen

- NO_3^- (N^{5+}) + 5 e- → N_2 (N^0)
  O_2 (O^0) + 4 e- → 2 O_2^{2-}
- 1 mol NO_3^- has the same e-acceptor capacity as 5/4 mol O_2
- (5/4) mol × 32 g O_2 / 14 g NO_3-N = 2.86 g O_2 / g NO_3-N
- this means that 1 g NO_3-N can oxidize 2.86 g of COD

design parameter

RECAP N and P removal

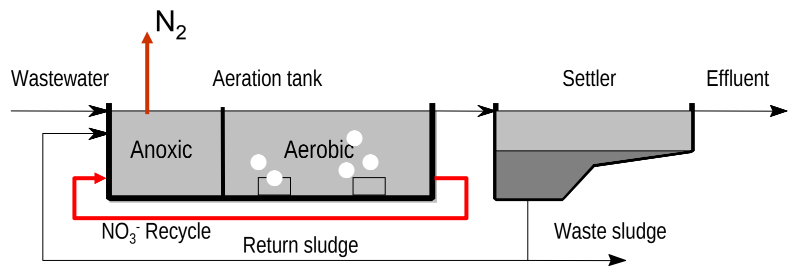
Nitrification and Denitrification in the WWTP

Pre-denitrification

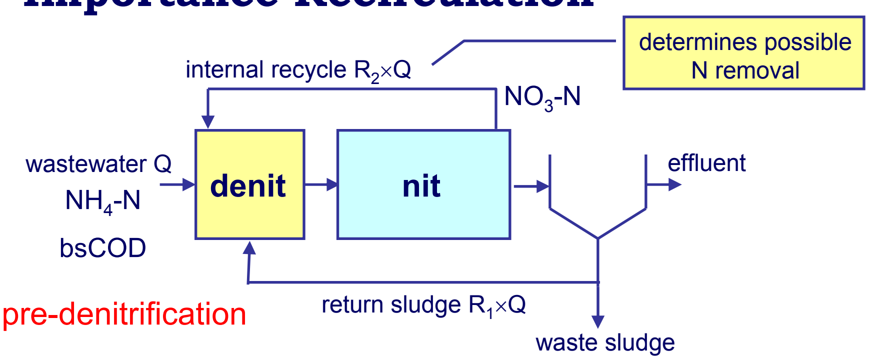
- in front of the aerated part
- anoxic (no aeration, mixing)
- BOD (wastewater composition)
- extra recirculation

- several configurations

Pre-denitrification



Importance Recirculation



pre-denitrification

- N removal only by denitrification
- only denitrified what is recycled
- f.e., R1=1; R2=3 → 80 % removal

$$\% \text{ N removal} = \frac{100 \times (R_1 + R_2)}{1 + R_1 + R_2}$$

assumptions:

complete nitrification

complete denitrification of recycled NO_3^-

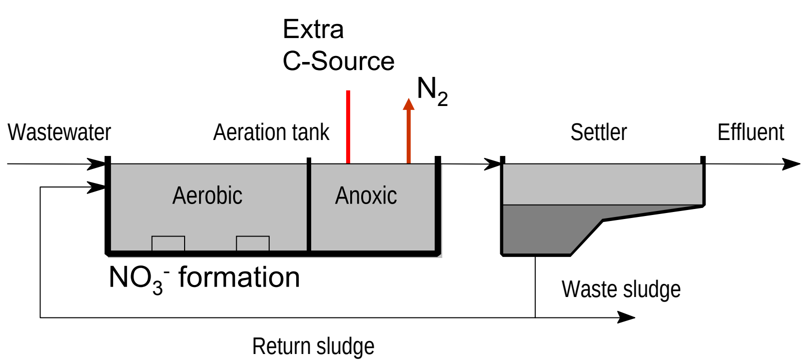
negligible N for synthesis

Post-denitrification

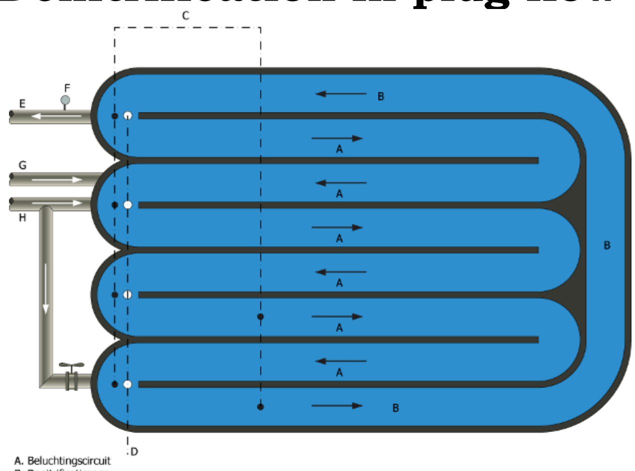
- after conventional treatment
- dosage of methanol
  3 - 4 kg / kg N-NO3
- sludge production

- fixed bed
- fluid bed
- suspended fixed film packing

Post-denitrification



Denitrification in plug-flow system



A. Beluchtingscircuit
B. Denitrificatiezone
C. Meting zuurstofconcentratie
D. Puntbeluchters
E. Effluent
F. Meting Nitraatconcentratie
G. Retour Slib
H. Aanvoer Afvalwater

Carroussel with denitrification area
Simultaneous nitrification - denitrification

Simultaneous nitrification-denitrification

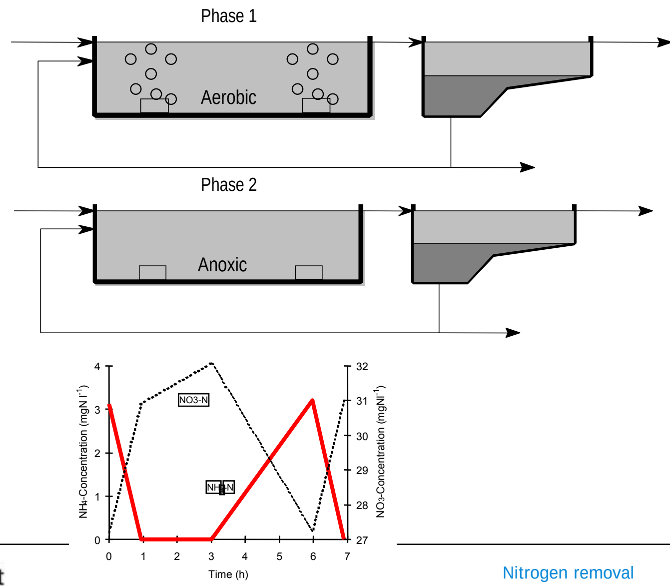
- ultra low loaded: F/M = 0.04 - 0.07 kgBOD/(kgMLSS*d)
- biomass, partly aerobic, partly anoxic
- concentration profiles in the flocs

Aerobic: O_2 > 1.5 mg/l
Transition: 0.5 < O_2 < 1.5 mg/l
Anoxic: O_2 < 0.5 mg/l

Question: calculate length of transition zone:
- O_2 consump. Rate = 0.36 kg O_2/m^3.d
- Velocity = 0.25 m/s

→ 0.0042 g O_2/m^3.s, transition from 1.5 to 0.5 g/m^3 takes 1/0.0042 = 240 sec or 60 m

Alternating Systems



RECAP N and P removal

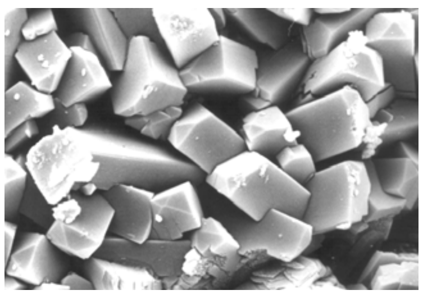
N Removal – Alternative techniques

Ammonium stripping

- Applied with small flows and high N concentrations (> 5 g/l)
- increase of pH (10 - 11)
- intensive liquid/gas contact
  - surface area (packing)
  - high air/liquid ratio (2,000 - 4,000)
- adsorption of ammonia by sulfuric acid
- Achieved efficiencies: 85-95%
- Effluent to conventional WWTP

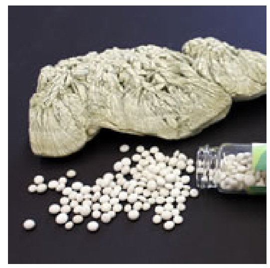
Ion exchange

- natural compounds: zeolite clinoptilolyth
- ammonium in, sodium out
- saturation
- regeneration
- brine ?



Chemical precipitation

- addition of magnesium oxide, fosforic acid
- precipitation of magnesiumammoniumfosfate (struvite)
  (high P costs...)

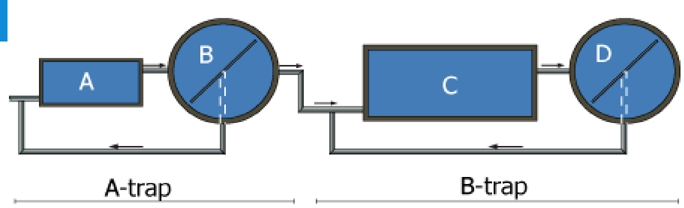


Two-stage activated sludge system

A-B-process

e.g. Dokhaven

(bovenaanzicht)



A. Activated sludge tank, small and highly loaded
B. Settling tank A stage
C. Activated sludge tank, large and low loaded
D. Final clarifier

Sludge load: 2 kg BOD/kg MLSS.d

Sludge load: 0.15 kg BOD/kg MLSS.d

N-removal possible?

Novel techniques for N removal

Bio-augmented Batch Enhanced nitrogen removal "BABE"