ADVANCING NOVEL PROCESSES FOR BIOLOGICAL NUTRIENT REMOVAL

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Presented by: Alexander Mockos, EIT

Co-Author: Dr. Erik Coats

University of Idaho, Civil Engineering Department
Presentation Outline

- Introduction
- Background
- Post-Anoxic Sequencing Batch Reactor (SBR):
  - Results
  - Benefits
- Dual Sludge SBR:
  - Results
  - Benefits
- Conclusion
Introduction

- The most pressing issue facing the health of U.S surface waters today is anthropogenic eutrophication.

- The principal nutrients contributing to eutrophication are phosphorus (P) and Nitrogen (N)

- Eutrophication results in:
  - Depletion of dissolved oxygen (D.O)
  - Loss of biodiversity
  - Public health problems
  - Decreased value of water bodies as resource

- Domestic Municipal Sewage is one of the principal contributors to excess nutrient loads
Introduction

- Biological Wastewater Treatment is the most common method used to remove N and P from domestic wastewaters.

- Consists of enriching microorganisms that:
  - Remove N (Nitrification/Denitrification)
  - Remove P (Enhanced biological phosphorus removal (EBPR))

- Increasing eutrophication has resulted in more stringent effluent limits.

- Potential limits as low as 2.2 mg/L Total N and 0.01 mg/L P.

- New processes and a better understanding of microorganisms’ metabolisms is necessary.
Background: Phosphorus Removal

Enhanced Biological Phosphorus Removal (EBPR):

- Facultative aerobes that possess a competitive advantage because they can uptake and store carbon anaerobically by using internal polyphosphate reserves.
- In conventional EBPR facilities microbes are initially exposed to an anaerobic environment where:
  - Carbon (VFAs) is sequestered from solution and stored as polyhydroxyalkanoates (PHA)
  - Polyphosphate reserves are hydrolyzed to generate energy
- In the following aerobic environment:
  - PHAs are utilized for growth
  - PO$_4$ is uptaken to replenish Polyphosphate reserves and in doing so remove PO$_4$ from solution
**Background: Phosphorus Removal**

1. VFAs are sequestered from solution and transported into the cell
2. The VFAs that are now in the cell are being converted to PHAs
3. The reducing equivalents for PHA synthesis are obtained from glycogen
4. Energy is derived from the hydrolysis of internal polyphosphate reserves resulting in a release of $\text{PO}_4^{3-}$ into solution

**Figure:**

- **X-axis:** Time (hr)
- **Y-axis:** Concentrations (mg/L)
- **Legend:**
  - Green square: $\text{PO}_4$ in solution
  - Orange square: PHA in Cell
  - Black triangle: VFA in solution
  - Blue square: Glycogen in Cell

**Graph Description:**
- **Anaerobic Phase:**
  - VOAs are sequestered from solution and transported into the cell
  - The VFAs that are now in the cell are being converted to PHAs
  - Energy is derived from the hydrolysis of internal polyphosphate reserves resulting in a release of $\text{PO}_4^{3-}$ into solution

**Aerobic Phase:**
- Carbon is now absent in solution therefore impeding other aerobes from growing
- The VOAs that are now in the cell are being converted to PHAs
- Energy is derived from the hydrolysis of internal polyphosphate reserves resulting in a release of $\text{PO}_4^{3-}$ into solution

**Net Phosphorus Removal from solution**
Background: Nitrogen Removal

- Nitrogen Forms Targeted at WWTFs:
  - Ammonia (NH$_3$)
  - Nitrate (NO$_3$)

- Total Nitrogen Removal is a sequential 2 step process:
  - **Nitrification:** NH$_3$ to nitrate (NO$_3$) ➔ Autotrophs
  - **Denitrification:** NO$_3$ to nitrogen gas (N$_2$) ➔ Heterotrophs
Background: **Nitrogen Removal**

**Process: NITRIFICATION**
- **Electron Acceptor:** OXYGEN
- **Electron Donor:** AMMONIA
- **Microorganisms involved:** AUTOTROPHS
  1. *Nitrosomonas*: \( \text{NH}_4^+ + 1.5\text{O}_2 \rightarrow 2\text{H}^+ + \text{H}_2\text{O} + \text{NO}_2^- \)
  2. *Nitrobacter*: \( \text{NO}_2^- + 0.5\text{O}_2 \rightarrow \text{NO}_3^- \)

**Process: DENITRIFICATION**
- **Electron Acceptor:** NITRATE
- **Electron Donor:** ORGANIC COMPOUNDS
  - *Pseudomonas*: \( \text{NO}_3^- + 5/6\text{CH}_3\text{OH} + 1/6\text{H}_2\text{CO}_3 \rightarrow 1/2\text{N}_2 + 4/3\text{H}_2\text{O} + \text{HCO}_3^- \)

**Aerobic = O_2 as t.e.a**

**Anoxic = Nitrate as t.e.a**
Background: P and N Removal at WWTFs

- Mixed Liquor Return (MLR)
- Return Activated Sludge (RAS)
- Waste Sludge
- Secondary Clarifier
- Effluent
- Influent
- Anoxic
- Aerobic
- Anaerobic

Disadvantages:
1. High MLR rates
2. O2 in the MLR
3. Dilution of influent carbon

a) MLE Process (Pre-Anoxic)

b) Single Sludge with External Carbon Addition (Post-Anoxic)

Disadvantages:
1. Cost of External Carbon
2. Excess carbon in effluent
Novel Processes

1) POST-ANOXIC SBR:
- Post-Anoxic SBR without the addition of external carbon at the beginning of anoxic period.
- Known process but typically not utilized due to low denitrification rates.
- Higher than expected SDNRs led to N removal efficiencies as high as 91% and effluent P consistently lower than 0.2 mg/L.

2) DUAL-SLUDGE SBR:
- 2 SBRs 2 separate sludges (Heterotrophic, Autotrophic).
- Autotrophic SBR: Ammonia oxidation to nitrate.
- New Process.
- Consistently yields total N lower than 2.2 mg/L and P lower than 0.1 mg/L.
Post-Anoxic SBR

- **Biomass**: Moscow WWTP
- **Feed**: 90% Raw WW from Moscow WWTP and 10% VFA rich fermentor liquor from Fermenter fed with primary solids from Pullman WWTP.
- **Solids Retention Time (SRT)** = 20 days
- **Hydraulic Retention Time (HRT)** = 18 hrs
Post-Anoxic Results

- Nitrate Reduction to Nitrogen Gas requires organic carbon as an electron donor.
- Since no external carbon is being added, PHA and Glycogen are the principal carbon sources in the system.
- PHA and Glycogen are critical to EBPR.
- Demonstrate that Post-Anoxic Denitrification using PHA/glycogen can occur without compromising EBPR.
- Reactor A was started - 90% Raw and 10% Fermenter Liquor.
Post-Anoxic Results
Post-Anoxic Results

- **Successful EBPR was achieved:**
  - P removal efficiencies on average exceeded 96%
  - P concentrations consistently below 0.14 mg P/L and as low as 0.05 mg P/L

- **High Specific Denitrification Rates (SDNRs)**
  - Total N removal = 74% - 92%
  - SDNRs in Reactor A: 0.85-1.17 mg NO₃⁻ (hr-g MLVSS)⁻¹
  - SDNRs for post-anoxic systems on carbon derived from endogenous decay: 0.2-0.6 mg NO₃⁻ (hr-g MLVSS)⁻¹

- **Where is carbon for denitrification coming from?**
  - Not endogenous decay: No MLVSS decrease anoxically
  - Not residual sCOD: all utilized prior to anoxic phase
  - Investigate other possible carbon sources
Post-Anoxic Results

Glycogen Utilization is driving Denitrification
Glycogen as a carbon source for denitrification is not covered in current wastewater treatment models.

Reactor A results led to the following questions:

- What effect do the length of the aerobic and anoxic cycle times have on glycogen cycling and the process as a whole?
- What effect does VFA augmentation have on post-anoxic denitrification?
- How can we further optimize the process?
- What population is responsible for post-denitrification?
Post-Anoxic Results: No VFA augmentation

INITIAL OPERATION (Still being Augmented)

AFTER PROCESS UPSET (No Fermenter Liquor)
Post-Anoxic Results: No VFA augmentation

- The reactor failure yielded 2 important conclusions:
  - Induction of EBPR metabolisms is fundamental for process success. VFA $\rightarrow$ PHA $\rightarrow$ Glycogen for denitrification
  - The process is sensitive to the amount of VFAs in influent
Post-Anoxic Results: Excess VFA augmentation
(90:10 augmented with acetic + propionic)
Post-Anoxic Results: Excess VFA augmentation
(90:10 augmented with acetic + propionic)

- The removal of P was comparable to non augmented with acetic + propionic (Effluent P averaged = 0.09 mg/L)
- High SDNRs (1.36 mg NO$_3$ (hr*gMLVSS)$^{-1}$)
- High N Removal efficiencies (84% or higher)
- Effluent Nitrate as low as 3.4 mg/L
- Conclusion: Denitrification is improved by increasing the amount of glycogen synthesized aerobically
Post-Anoxic Results: Extended Anoxic

AX

SGUR = 3.31 mg Gly/hr gMLVSS

SGUR = 0.81 mg Gly/hr gMLVSS

SDNR = 1.11 mg NO3-N/hr gMLVSS

SDNR = 0.19 mg NO3-N/hr gMLVSS

Glycogen (mg/L)

Nitrate (mg/L)

Time (hr)

0.0 1.0 2.0 3.0 4.0 5.0

0 5 10 15 20 25

Glycogen

Nitrate
Post-Anoxic Results: Extended Anoxic
Post-Anoxic Benefits

- No external carbon addition anoxically
- No RAS, No MLR
- No clarifiers
- Efficient use of internal storage products associated with EBPR
- High P removal efficiencies
- High TN removal efficiencies
- Existing SBRs can be retrofitted with process
Dual-Sludge SBR

**Heterotrophic SBR**

- Influent
- Anaerobic
- Completely Mixed
- Anoxic
- Anoxic
- Aerobic

**Autotrophic SBR**

- Aerobic
- Aerobic
- Aerobic
- Aerobic
- Completely Mixed
- Aerobic
- Aerobic
- Aerobic

Effluent
Waste

**Completely Mixed**

**Time**
Dual-Sludge SBR Results

Phosphate (mg/L)

Time (hr)

0.0 1.0 2.0 3.0 4.0 5.0

AN

Settle

AN

AX

AE

Phosphate

Ammonia

Nitrate

Ammonia, Nitrate (mg/L)

0 20 40 60 80

0 5 10 15

0.0 1.0 2.0 3.0 4.0 5.0 6.0

Nitrate, Ammonia (mg/L)

Time (hr)

AE

Settle

AE

Ammonia

Nitrate

0 5 10 15

0 0.0 1.0 2.0 3.0 4.0 5.0

0 10 20
**Dual-Sludge Results**

- **Successful EBPR was achieved:**
  - 96% of P removal occurs anoxically
  - P removal efficiencies always exceeded 97%
  - P concentrations consistently below 0.075 mg P/L and as low as 0.04 mg P/L

- **High Nitrogen Removal Efficiencies**
  - Total N removal consistently over 91%
  - Effluent NH$_4$ consistently below 0.44 mg/L
  - Effluent NO$_3$ consistently below 1.8 mg/L
  - Effluent total N below 2.2 mg N/L
Dual-Sludge SBR Results: Heterotrophs

**Phosphate (mg/L):**
- AN (Ammonia): Green line
- Nitrate: Red line
- Phosphate: Purple line

**VFAs, sCOD (mg/L):**
- PHA (% w/w): Orange line
- sCOD: Green line

**Time (hr):**
- Settle
- AX (Anammox): Yellow line
- AE (Anaerobic): Orange line

**Ammonia, Nitrate (mg/L):**
- AN (Ammonia): Green line
- Nitrate: Red line

**Settle (H):**
- PHA (% w/w): Orange line
- sCOD: Green line
Dual-Sludge SBR Results

- Induction of EBPR metabolisms is **fundamental** for process success. VFA $\rightarrow$ PHA $\rightarrow$ carbon for denitrification
- The process is sensitive to the amount of VFAs in influent
- If sufficient PHA is present at the beginning of the anoxic phase complete denitrification occurs in 45 minutes
- The process is also sensitive to the amount of influent NH4:
  - Affects the amount of NO3 going to Heterotrophic SBR
  - Affects the amount of NH4 that remains in the Heterotrophic SBR and therefore effluent concentration.
Dual-Sludge SBR Results

- VFA/NH4 ratio dictates the Total N removal efficiencies
- Denitrification kinetics are saturated
Dual-Sludge SBR Benefits

- Consistently very low effluent TN (< 2.2 mg/L) and effluent P (< 0.075 mg/L)
- Efficient utilization of influent carbon
- Reduced O2 demand
- Separate sludges
- No RAS, No MLR
- No primary or secondary clarifiers
- More Operational flexibility and control
Conclusion

- Better understanding of microorganisms’ metabolisms and internal storage products led to:
  - Reevaluation and optimization of known process:
    - Post-Anoxic SBR
  - Development and optimization of new process:
    - Dual Sludge SBR
- Both setups consistently achieved effluent P and N concentrations that are lower than expected for biological treatment systems.
THANK YOU!
Terminology and Reactor Operations

- **EBPR** = Enhanced Biological Phosphorus Removal
- **PHA** = Polyhydroxyalkanoates
- **VFAs** = Volatile Fatty Acids
- **t.e.a** = terminal electron acceptor
- **Anoxic** = Nitrate Rich, Oxygen Free environment
- **PO4** = Phosphate
- **NH3** = Ammonia
- **NO3** = Nitrate
- **N2** = Nitrogen Gas
- **MLR** = Mixed Liquor Return
- **RAS** = Return Activated Sludge
- **SBR** = Sequencing Batch Reactor
- **SDNR** = Specific Denitrification Rate
- **SGUR** = Specific Glycogen Utilization Rate
- **PAO** = Phosphate Accumulating Organism
- **DNPAO** = denitrifying PAO
- **GAO** = glycogen accumulating organism

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Food Type</th>
<th>Anaerobic Time (hr)</th>
<th>Aerobic Time (hr)</th>
<th>Anoxic Time (hr)</th>
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<tbody>
<tr>
<td>A</td>
<td>90% Raw, 10% Fermenter</td>
<td>1</td>
<td>2.5</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>100% Raw</td>
<td>1</td>
<td>2.5</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>90% Raw, 10% Fermenter</td>
<td>1</td>
<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td>D</td>
<td>90% Raw, 10% Fermenter, augmented with propionate and acetate</td>
<td>1</td>
<td>2.5</td>
<td>2</td>
</tr>
</tbody>
</table>