Enabling Extractive Nutrient Recovery – A Disruptive Nutrient Management Strategy for a Circular Economy

Wendell O. Khunjar, PhD, PE
Ron Latimer, PE
Sam Jeyanayagam, PhD, PE, BCEE
Amit Pramanik, PhD, BCEEM
Acknowledgments

- Joe Rohrbacher, PE – Hazen and Sawyer
- Vivi Nguyen – Hazen and Sawyer
- Ron Latimer, PE – Hazen and Sawyer
- Paul Pitt, PhD PE – Hazen and Sawyer
- Chirag Mehta, PhD – University of Queensland, Australia
- Damien Batstone, PhD – University of Queensland, Australia
- Tim Muster, PhD – CSIRO
- Stewart Burns, PhD - CSIRO
- Ron Alexander – R. Alexander Associates Inc
- Glen Daigger, PhD, PE, BCEE – CH2M
- Todd Williams, PE, BCEE – CH2M
Nutrient planetary boundaries are being exceeded due to increased anthropogenic inputs.

Approximately 8% of reactive N and 14% of reactive P potentially processed through WRRFs.

Adapted from Rockstrom, J., et al. (2009), Nature 461 (7263), 472-5
Adapted from Penuelas, J., et al. (2012), Global Change Biology 18, 3-6
Nutrient usage cycle currently assumes an unlimited supply of resources and energy.

- Nitrogen gas is a renewable resource but is not readily available for plant growth.
- Energy required to convert from non-reactive to reactive and vice versa.

- Phosphorus is a NON-renewable resource.
- Phosphorus resources are declining both in quality and accessibility.
Nutrient recovery facilitates the recycling of reactive nutrients

Haber Bosch Process
\[ \text{N}_2 \rightarrow \text{NH}_3 \]
Phosphorus mining
Apatite → ortho-P

Non-Bioavailable Nutrient

Treatment

Bioavailable Nutrient

Recycling and reuse of resources
How do we facilitate a transition to nutrient recovery?

Need disruptive and sustaining innovations
Technical, economic and regulatory limitations restrict implementation

**Technical**
- Technologies are unknown entities.
- Insufficient time and staff to review technologies
- Insufficient data to evaluate technology performance
- Insufficient experience in operating technology
- Unknown maintenance requirements and long-term operational viability

**Economic**
- Insufficient and/or competing needs for funds
- Unknowns regarding cost of implementation, operating costs, etc.
- Uncertainty with respect to future demand for fertilizer product.
- Competition for product if many utilities adopt the technology

**Regulatory**
- Lack of regulatory drivers i.e., no effluent nutrient limits.
- Lack of public acceptance
Addressing Technical Considerations
From a technological perspective, a three step framework may be appropriate.

**Accumulation**
- Enhanced biological phosphorus removal (EBPR)
- Algae
- Purple non-sulfur bacteria
- Adsorption/Ion exchange
- Chemical precipitation
- NF/RO

**Release**
- Anaerobic digestion
- Aerobic digestion
- Thermolysis
- WAS release
- Sonication
- Microwave
- Chemical extraction

**Extraction**
- Chemical crystallization
- Electrodialysis
- Gas permeable membrane and absorption
- Gas stripping
- Solvent extraction

- Not all systems require all three components
- Can optimize each option separately
- Can also stage implementation

More details available in WERF NTRY1R12a and NTRY1R12 m
Consider a common scenario in which enhanced biological phosphorus removal is applied

<table>
<thead>
<tr>
<th>Nutrient recovery (% recovery efficiency)</th>
<th>Product (% wt nutrient)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>Accumulation</td>
<td>EBPR</td>
</tr>
<tr>
<td>Release</td>
<td>Anaerobic digestion</td>
</tr>
<tr>
<td>Extraction</td>
<td>Crystallization</td>
</tr>
</tbody>
</table>
Intentional struvite recovery helps minimize nuisance struvite formation and reduce P recycle.

- Fluidized bed reactor or CSTR used for struvite recovery
- High quality, slow release fertilizer – revenue offsets costs
- Reduction in ferric/alum – payback on capital

MgNH₄PO₄•6 H₂O

80-90% P removal
15-30% N removal

Centrate/Filtrate → High NH₃-N and PO₄-P

FBR → Effluent

Dewatering → Dryer → Struvite
There are several commercial options for struvite recovery

<table>
<thead>
<tr>
<th>Name of Technology</th>
<th>Pearl®</th>
<th>Multiform Harvest™</th>
<th>NuReSys™</th>
<th>Phospaq™</th>
<th>Crystalactor™</th>
<th>Airprex™</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of reactor</td>
<td>upflow fluidized bed</td>
<td>upflow fluidized bed</td>
<td>CSTR</td>
<td>CSTR with diffused air</td>
<td>upflow fluidized bed</td>
<td>CSTR with diffused air</td>
</tr>
<tr>
<td>Name of product recovered</td>
<td>Crystal Green®</td>
<td>struvite fertilizer</td>
<td>BioStru®</td>
<td>Struvite fertilizer</td>
<td>Struvite, Calcium-phosphate, Magnesium-phosphate</td>
<td>Struvite fertilizer</td>
</tr>
<tr>
<td>% Efficiency of recovery from sidestream</td>
<td>80-90% P 10-40% NH3-N</td>
<td>80-90% P 10-40% NH3-N</td>
<td>&gt;85% P 5-20% N</td>
<td>80% P 10-40% NH3-N</td>
<td>85-95% P for struvite 10-40% NH3-N &gt; 90% P for calcium phosphate</td>
<td>80-90% P 10-40% NH3-N</td>
</tr>
<tr>
<td># of full-scale installations</td>
<td>8</td>
<td>2</td>
<td>7</td>
<td>6</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>
Multiform Harvest

Images courtesy MFH
Crystalactor®

Images courtesy Procorp/Royal HaskoningDHV
Paques Phosphaq™

Images courtesy Paques
NuReSys

- Marketed by Schwing in USA

Images courtesy NuReSys bvba
Airprex

- Marketed by CNP in US

Images courtesy CNP
Enhanced biological phosphorus removal, anaerobic digestion & nutrient recovery
What about if we use chemical precipitation for mainstream P removal?

<table>
<thead>
<tr>
<th></th>
<th>Nutrient recovery (% recovery efficiency)</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>Accumulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical (Precipitation)</td>
<td>√</td>
<td>□</td>
</tr>
<tr>
<td>Release</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anaerobic digestion</td>
<td>√</td>
<td>-</td>
</tr>
</tbody>
</table>

- Release via Anaerobic digestion solubilizes limited amount of P

Extraction

<table>
<thead>
<tr>
<th></th>
<th>Nutrient recovery (% recovery efficiency)</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>Acidification or bioleaching followed by crystallization, liquid extraction, ion exchange</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>
There are options to allow us to recover nutrients from sludge

<table>
<thead>
<tr>
<th>Name of Process</th>
<th>Seaborne</th>
<th>Krepro</th>
<th>PHOXNAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product recovered</td>
<td>struvite; diammonium sulfate (DAS)</td>
<td>iron phosphate as a fertilizer</td>
<td>phosphoric acid</td>
</tr>
<tr>
<td>Process feedstock</td>
<td>sludge</td>
<td>sludge</td>
<td>sludge</td>
</tr>
</tbody>
</table>

- One full-scale installation of Krepro in Sweden
- Regulatory mandate for recycling P is needed to drive implementation of these technologies

Figure 1. The Krepro system [11].
Chemical precipitation, anaerobic digestion and nutrient recovery

Influent → Headworks → Primary Clarification → BNR → Secondary Clarification → Disinfection → Effluent

Septage → Thickener Filtrate → Thickening

WAS

Thickener Filtrate

Anaerobic Digestion → Dewatering filtrate → Dewatering → Biosolids

Nutrient Recovery

Nutrient Product
What about if we use have thermochemical stabilization (i.e., incineration)?

<table>
<thead>
<tr>
<th>Nutrient recovery (% recovery efficiency)</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>P</td>
</tr>
</tbody>
</table>

| Accumulation | Biological or Chemical | √ | √ (> 90 %) | - | Sludge |

- No release exists so P is bound into ash

| Option 1 - Release and Extraction | Enhanced WAS Lysis and crystallization | - | √ (20 to 50%) | √ | Sludge |

| Option 2 - Release and Extraction | Acidification of ash followed by crystallization, liquid extraction, ion exchange | √ | √ | √ | Struvite; diammonium sulfate (DAS), iron phosphate, phosphoric acid, calcium phosphate |
There are options to allow us to recover nutrients from ash/sludge

<table>
<thead>
<tr>
<th>Name of Process</th>
<th>SEPHOS</th>
<th>BioCon®</th>
<th>PASH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product recovered</td>
<td>aluminum phosphate or calcium phosphate (advanced SEPHOS)</td>
<td>phosphoric acid</td>
<td>struvite or calcium phosphate</td>
</tr>
<tr>
<td>Process feedstock</td>
<td>sewage sludge ash</td>
<td>sewage sludge ash</td>
<td>sewage sludge ash</td>
</tr>
</tbody>
</table>

- Post-processing to remove heavy metals may also be required
- Few full-scale installations are present
- Regulatory mandate for recycling P is needed to drive implementation of these technologies
- Ash can also be considered as direct fertilizer amendment
  - Consideration needs to be given to the heavy metal content
Enhanced biological phosphorus removal, WAS release & nutrient recovery
Addressing Regulatory Considerations
Nutrient recovery is another strategy for removing P from WRRF

Different scenarios

- No nutrient limits
- Nutrient limits on liquid effluent
- Nutrient limits on liquid effluent and biosolids

From Cornel et al. (2009)
Quantifying other benefits (cost and non-cost) can help make the case for nutrient recovery

- **Struvite recovery can:**
  - Provide factor of safety associated with Bio-P
    - Minimizes impact of sidestream return
  - Reduce energy and chemical consumption
    - Offsets due to reduction in aeration and supplemental carbon
    - Reduction in sludge quantity and hauling costs
  - Minimize nuisance struvite formation and reduce O&M costs
  - Reduce or increase the P content of biosolids
    - If land application P index limited, removing P in the form of struvite will shift N:P ratio
    - If more P is appreciated, selectively precipitating P into biosolids will increase biosolids P content
  - Improve sludge dewaterability
    - Result in higher sludge cake %TS
    - Reduce polymer demand
Addressing Economic Considerations
Magnesium struvite is the most commonly encountered product.

- Closest analogues are mono and diammonium phosphate.
- Based on historical pricing, can expect Mg-struvite value to range from $200 to $600/metric tonne.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Magnesium struvite</th>
<th>Monoammonium phosphate</th>
<th>Diammonium phosphate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical formula</td>
<td>MgNH$_4$PO$_4$•6H$_2$O</td>
<td>NH$_4$H$_2$PO$_4$</td>
<td>(NH$_4$)$_2$HPO$_4$</td>
</tr>
<tr>
<td>Average price/metric tonne</td>
<td>$200 - $600</td>
<td>$570 - $615</td>
<td>$420 - $680</td>
</tr>
<tr>
<td>Grade (N-P-K)</td>
<td>5-29-0</td>
<td>11-52-0</td>
<td>18-46-0</td>
</tr>
<tr>
<td>Water solubility at 20 °C</td>
<td>Insoluble - 0.2 g/L</td>
<td>328 - 370 g/L</td>
<td>588 g/L</td>
</tr>
<tr>
<td>Application description</td>
<td>Spread on soil</td>
<td>Normally spread of mixed in soil</td>
<td>Normally spread of mixed in soil</td>
</tr>
<tr>
<td>Typical application rates*</td>
<td>255 lb/A</td>
<td>142 lb/A</td>
<td>160 lb/A</td>
</tr>
</tbody>
</table>
There are multiple entry points for the nutrient fertilizer market

- **Multiple points of entry into the secondary market**
  - Most technology providers for struvite production facilitate interaction with the market
  - Facility has the choice of entering the market directly
What are the economics associated with implementing struvite recovery at WRRFs?
Case studies of full-scale facilities available from WERF

- NTRY1R12b

Developed case studies in 3 categories
- Category 1 – Currently operating or constructing struvite harvesting
- Category 2 – Performed desktop analyses and/or pilot
- Category 3 – No evaluation but may have piloted

Each case study describes:
- Nutrient limits,
- Plant configuration,
- Challenges faced,
- Drivers for nutrient recovery,
- Economics associated with struvite harvesting,
- Lessons learned where applicable

<table>
<thead>
<tr>
<th>Plant Designation</th>
<th>River 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Virginia, USA</td>
</tr>
<tr>
<td>Current Nutrient limits (mg/L)</td>
<td>TN - 3.0 mg/L, AA TP - 2.0 mg/L, AA</td>
</tr>
<tr>
<td>Emerging Nutrient limits (mg/L)</td>
<td>Expected 2017 TN reduction to 3.0 mg/L and TP reduction to 1.0 mg/L. Plan to treat with additional supplemental carbon and ferric chloride if needed.</td>
</tr>
<tr>
<td>BNR configuration</td>
<td>6-stage BNR</td>
</tr>
<tr>
<td>Solids management configuration</td>
<td>Primary sludge + CST co-thickened. Thickened sludge to anaerobic digesters then centrifuged. Cake is hauled and incinerated.</td>
</tr>
<tr>
<td>Biosolids disposal method</td>
<td>Biosolids transported to another plant within utility for incineration</td>
</tr>
<tr>
<td>Mainstream Design flow (MGD)</td>
<td>30</td>
</tr>
<tr>
<td>Mainstream current operation flow (MGD)</td>
<td>10</td>
</tr>
<tr>
<td>Minimum operating temperature (°C)</td>
<td>12</td>
</tr>
<tr>
<td>Effluent nutrient concentrations (June 2011 to February 2013)</td>
<td>TP - 1.5 mg/L, TN - 0.5 mg/L (excludes periods with 3 and 5 stage BNR)</td>
</tr>
<tr>
<td>Sidestream flow (MGD)</td>
<td>0.1</td>
</tr>
<tr>
<td>Sidestream nitrogen concentration (mg/L N)</td>
<td>Before implementation of nutrient recovery: 515 After implementation of nutrient recovery: 148</td>
</tr>
<tr>
<td>Sidestream ortho-phosphorus concentration (mg/L P)</td>
<td>Before implementation of nutrient recovery: 0.01 After implementation of nutrient recovery: 0.04</td>
</tr>
</tbody>
</table>
Tool for Evaluating Resource Recovery developed to facilitate preliminary evaluation

- Compare struvite crystallization with precipitation with coagulant (i.e., alum or ferric)

Search WERF website for NTRY1R12t
Who can use this tool?

- Utility managers, research and development personnel
- Consultants
- Regulators
- Students
- Public
- Anyone with interest in nutrient recovery

Why use this tool?

- Conceptual level evaluation of nutrient recovery capital and operating cost required
- Helps inform what information is useful for collection
- Informs master planning
Conclusions
Quantifying other benefits (cost and non-cost) can help make the case for nutrient recovery

**Struvite recovery can:**

- Provide factor of safety associated with Bio-P
  - Minimizes impact of sidestream return

- Reduce energy and chemical consumption
  - Offsets due to reduction in aeration and supplemental carbon
  - Reduction in sludge quantity and hauling costs

- Minimize nuisance struvite formation, reduce O&M costs and regain capacity

- Reduce or increase the P content of biosolids
  - If land application P index limited, removing P in the form of struvite will shift N:P ratio
  - If more P is appreciated, selectively precipitating P into biosolids will increase biosolids P content

- Improve sludge dewaterability
  - Result in higher sludge cake %TS
  - Reduce polymer demand
Next steps for nutrient recovery industry

- Understand true costs/benefits of operating recovery facilities
- Enhance recovery potential of existing facilities
- Explore recovery of other products
- Implement technologies that facilitate multiple benefits
  - P, N, K, Carbon, Energy
Questions and Contact Information

Wendell Khunjar  
Hazen and Sawyer, P.C.  
wkhunjar@hazenandsawyer.com

Ron Latimer  
Hazen and Sawyer, P.C.  
rlatimer@hazenandsawyer.com

Sam Jeyanayagam  
CH2M  
Samuel.Jeyanayagam@ch2m.com