Considerations For Water Resource Recovery Facilities of the Future

Wendell O. Khunjar, PhD, PE
June 12, 2015
Wastewater treatment has traditionally focused on removing contaminants.

Treatment goals:

**Generation 1:**
1. Remove solids and color

**Generation 2:**
1. Remove solids and color
2. Remove soluble organics

**Generation 3:**
1. Remove solids and color
2. Remove soluble organics
3. Remove soluble nutrients

Energy, chemicals

Reclaimed water, Biosolids
A new paradigm has emerged

**Treatment goals**

- **Generation 4:**
  1. Remove solids and color
  2. Remove soluble organics
  3. Remove soluble nutrients
  4. *Minimize energy and chemical consumption*
  5. *Maximize energy recovery*
  6. *Maximize resource recovery*

Wastewater ➔ Reclaimed water, Biosolids

Energy, Chemicals
How do we make this transition?

- **Nutrients**
- **Energy**
- **Water**
- **Other Resources**
Nutrients and Energy
Nutrient recovery should be considered as part of a holistic nutrient management plan.

- Combination of removal and recovery is necessary.

Flowchart:
- Haber Bosch Process: $N_2 \rightarrow NH_3$
- Phosphorus mining: Apatite $\rightarrow$ ortho-P
- Non-Bioavailable Nutrient
- Low energy treatment
- Bioavailable Nutrient
- Recovery processes
From a technological perspective, a three step framework is appropriate

- Accumulation step to increase nutrient content
  - N > 1000 mg N/L and P > 100 mg P/L
- Release step to generate low flow and high nutrient stream
- Extraction step produces high nutrient content product
WRRFs already accumulate nutrients within the solids process

Adapted from Cornel et al., 2009

Urine 67%
Feces 33%
Primary Sludge 10-15%
Secondary Sludge 25-40%
EBPR or Chem - P Removal 35-50%
Effluent 10%

Up to 90% of the influent P can be present in the solids stream

Adapted from Phillips et al., 2011

Urine 80%
Feces 20%
Sludge 20%

Gaseous emission 67%
Effluent 13%

Up to 20% of the influent N can be present in the solids stream
Nutrients are released using solids stabilization technology

Following ANA Digestion, digester sludge and dewatering supernatant can contain:
- 20-40% of P load to main plant
- 10-20% of N load to main plant
High nutrient loads in digester sludge and dewatering can result in nuisance struvite formation

- **Struvite** = Mg + NH$_4$ + PO$_4$
  - NH$_4$ & PO$_4$ released in digestion
  - Typically Mg limited
  - Mg addition (i.e. Mg(OH)$_2$) can promote struvite formation

- Miami Dade SDWRF
- NYC Newtown Creek WPCP
Intentional struvite recovery helps minimize nuisance struvite formation

- Struvite precipitation
  - N:P ratio in struvite = 0.45 lbs N required per lb P removed
  - N:P ratio in filtrate ~ 2.4-2.6, ammonia in excess

\[ \text{Mg}(\text{NH}_4\text{)}\text{PO}_4(s) = \text{struvite} \]
Magnesium struvite is a valuable slow release fertilizer

- 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>MgNH₄PO₄·6H₂O</td>
<td>NH₄H₂PO₄</td>
<td>(NH₄)₂HPO₄</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</td>
<td>Normally spread of</td>
</tr>
<tr>
<td></td>
<td></td>
<td>mixed in soil</td>
<td>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>
Benefits of recovery extend beyond nuisance struvite prevention

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

- Provide factor of safety associated with Bio-P

- Reduce energy and chemical consumption

- Reduce or increase the P content of biosolids

- Improve sludge dewaterability
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 (as of 2012)</td>
<td>8</td>
<td>2</td>
<td>7</td>
<td>6</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>
How can struvite recovery be applied?

Influents

<table>
<thead>
<tr>
<th>Headworks</th>
<th>Primary Clarification</th>
<th>BNR</th>
<th>Secondary Clarification</th>
<th>Disinfection</th>
<th>Effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Septage

<table>
<thead>
<tr>
<th>Thickener Filtrate</th>
<th>Anaerobic Digestion</th>
<th>Nutrient Recovery Option</th>
<th>Struvite</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

WAS

<table>
<thead>
<tr>
<th>Thickener</th>
<th>Dewatering Filtrate</th>
<th>Dewatering</th>
<th>Biosolids</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dewatering

<table>
<thead>
<tr>
<th>Nutrient Recovery Option</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>
How can struvite recovery be applied?

Diagram showing the process:
- Influent
- Headworks
- Primary Clarification
- BNR
- Secondary Clarification
- Disinfection
- Effluent
- Septage
- Thickener
- Anaerobic Digestion
- Dewatering
- Biosolids
- Struvite
- Nutrient Recovery Option
- Thickener Filtrate
- WAS
- WAS release
- Dewatering Filtrate
Tool for Evaluating Resource Recovery developed to facilitate preliminary evaluation

- High level economic evaluation of struvite recovery versus other technology
- [www.werf.org](http://www.werf.org)
  - Go to nutrient recovery challenge homepage
Nansemond Treatment Plant is a 30 MGD ENR Facility

- Ferric addition
  - Forms ferric phosphate and ferric hydroxide
  - Non-proprietary
  - Traditionally used for controlling sidestream P at this plant
  - High O&M requirement

- Struvite recovery
  - Treatment fee option
    - Technology provider would assume all maintenance of the facilities
  - Capital purchase option
    - Plant A purchases equipment and receives annual payments from Technology provider

Diurnal Sampling

Sidestream load represents up to 30% of the plant influent P load
Extractive nutrient recovery option was more cost effective than ferric addition option.

<table>
<thead>
<tr>
<th>Item</th>
<th>Treatment Fee Option</th>
<th>Capital Purchase Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Capital Cost</td>
<td>$1,080,000</td>
<td>$4,143,000</td>
</tr>
<tr>
<td>Present Worth Operating Costs</td>
<td>$(1,505,750)</td>
<td>$(8,129,160)</td>
</tr>
<tr>
<td>Net Present Worth</td>
<td>$(425,750)</td>
<td>$(3,986,050)</td>
</tr>
</tbody>
</table>
Orthophosphate and ammonia removal have been consistent throughout operation

- Ortho-P removal approaches 85%
- Ammonia removal approaches 25-30%
Struvite recovery has reduced the phosphorus content of the biosolids

Pre nutrient recovery = 39,000 mg/kg

Post nutrient recovery = 29,000 mg/kg

29% reduction in cake TP content
Manipulating the P content of the biosolids can reduce land application requirements

Projected land application requirements at WRRF in North Carolina

- **No struvite harvesting**
- **Struvite harvesting**
- **Struvite harvesting with WAS Release**
What about if we use chemical precipitation for mainstream P removal?

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

- Release via Anaerobic digestion solubilizes limited amount of P

| Extraction | Acidification or bioleaching followed by crystallization, liquid extraction, ion exchange | √ | √ | √ | Struvite; diammonium sulfate (DAS), iron phosphate, phosphoric acid, calcium phosphate, biosolids |
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
What about if we use have thermochemical stabilization (i.e., incineration)?

<table>
<thead>
<tr>
<th>Nutrient recovery (% recovery efficiency)</th>
<th>Product</th>
</tr>
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<tr>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>(&gt; 90 %)</td>
<td></td>
</tr>
</tbody>
</table>

- No release exists so P is bound into ash

<table>
<thead>
<tr>
<th>Option 1 - Release and Extraction</th>
<th>Enhanced WAS Lysis and crystallization</th>
<th>Nutrient recovery</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N</td>
<td>Sludge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>P</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>K</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(&gt; 20 to 50%)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Option 2 - Release and Extraction</th>
<th>Acidification of ash followed by crystallization, liquid extraction, ion exchange</th>
<th>Nutrient recovery</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N</td>
<td>Struvite; diammonium sulfate (DAS), iron phosphate, phosphoric acid, calcium phosphate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>P</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>K</td>
<td></td>
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<th>Product</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>N</td>
<td>Struvite; diammonium sulfate (DAS), iron phosphate, phosphoric acid, calcium phosphate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>P</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>K</td>
<td></td>
</tr>
</tbody>
</table>
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
What about nitrogen only recovery?

- Nitrogen can also be recovered from sidestreams via gas stripping and ion exchange

1. **pH adjustment** ($pH > 9.3$)
2. **Heating** (Temp $> 80^\circ C$)

Concentrated ammonia product (e.g. NH$_4$SO$_4$, NH$_4$NO$_3$)

1. **Acid scrubber**
   2. (e.g. H$_2$SO$_4$, HNO$_3$)
Nitrogen only recovery is more economical at high nutrient concentrations

- Low resale value of N only products
- N recovery as part of combined N and P product has higher revenue potential
- Nitrogen only recovery also limited by low cost alternatives for N treatment
  - E.g., Deammonification

From Fassbender 2001

**TABLE 1**
Centralized Ammonia Recovery Plant Budgetary Estimates

<table>
<thead>
<tr>
<th>GPM</th>
<th>[NH₃] ppm</th>
<th>No. Resin Beds</th>
<th>Size Resin Beds</th>
<th>Cap. Cost, $MM</th>
<th>O&amp;M, cents/gal</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>1000</td>
<td>3</td>
<td>8'</td>
<td>5.6 – 10.6</td>
<td>2.6</td>
</tr>
<tr>
<td>550</td>
<td>1000</td>
<td>3</td>
<td>12'</td>
<td>9.3 – 17.0</td>
<td>1.5</td>
</tr>
<tr>
<td>1000</td>
<td>1000</td>
<td>3</td>
<td>16'</td>
<td>15.2 – 24.3</td>
<td>1.2</td>
</tr>
<tr>
<td>2100</td>
<td>650</td>
<td>7</td>
<td>16'</td>
<td>35.8 – 44.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>
What is deammonification?

- Save ~63% on theoretical O₂ requirements
- Save ~100% of theoretical supplemental donor requirements
- Uses Anammox bacteria

Deammonification:

- Nitritation: 1 lb Ammonia (NH₃-N) → 1 lb Nitrite (NO₂⁻-N) → 1/2 lb Nitrogen gas (N₂)
  - 75% O₂

- Anaerobic oxidation: 1 lb Ammonia (NH₃-N) → 1/2 lb Nitrite (NO₂⁻-N) → 1/2 lb Nitrogen gas (N₂) & Small amount of Nitrate
  - 37.5% O₂

- Denitritation: 1 lb Nitrite (NO₂⁻-N) → 1 lb Nitrate (NO₃⁻-N)
  - 60% Carbon

- Denitrification: 1 lb Nitrate (NO₃⁻-N) → 1 lb Nitrite (NO₂⁻-N) → 1/2 lb Nitrogen gas (N₂)
  - 40% Carbon
Consider two 20 MGD facilities employing 5-stage BNR for N and P removal

- City of Durham, North Carolina operates two 20 MGD WRFs
  - North Durham WRF (Plant A)
  - South Durham WRF (Plant B)

- Similar operations
  - 5-stage BNR
  - 23-hour HRT
  - Historically similar influent characteristics
## Sidestream loads at N/SDWRF are significant

<table>
<thead>
<tr>
<th>Plant</th>
<th>Percent of Total Influent Nitrogen Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDWRF</td>
<td>19%</td>
</tr>
<tr>
<td>SDWRF</td>
<td>21%</td>
</tr>
</tbody>
</table>

Equalization\reduction of these loads is fundamental to all long-term planning scenarios
Deammonification is the most cost effective option

### South Durham

<table>
<thead>
<tr>
<th>Category/Parameter</th>
<th>Units</th>
<th>Deammonification</th>
<th>Nitrification and Denitrification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost per pound TN removed (capital)</td>
<td>$/lb</td>
<td>$0.74</td>
<td>$0.82</td>
</tr>
<tr>
<td>Cost per pound TN removed (O&amp;M)</td>
<td>$/lb</td>
<td>$0.39</td>
<td>$1.32</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$/lb</td>
<td><strong>$1.13</strong></td>
<td><strong>$2.14</strong></td>
</tr>
</tbody>
</table>

### North Durham

<table>
<thead>
<tr>
<th>Category/Parameter</th>
<th>Units</th>
<th>Deammonification</th>
<th>Nitrification and Denitrification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost per pound TN removed (capital)</td>
<td>$/lb</td>
<td>$0.54</td>
<td>$0.29</td>
</tr>
<tr>
<td>Cost per pound TN removed (O&amp;M)</td>
<td>$/lb</td>
<td>$0.39</td>
<td>$1.32</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$/lb</td>
<td><strong>$0.93</strong></td>
<td><strong>$1.61</strong></td>
</tr>
</tbody>
</table>
South Durham deammonification process is in startup

Utilizes Anitamox MBBR approach
Deammonification sidestream processes stably remove nitrogen.

Achieving ~80% TIN removal within 20 days of startup.

Slight decrease in TIN removal due to excessive biomass wasting.

System recovered within 3-4 days.
Perspectives on Sidestream Deammonification

• Savings from reduced aeration, supplemental carbon, lower sludge production

• Benefits to mainplant nitrification capacity
  – Seeding can also be utilized to help with nitrification performance

• Potential for seeding for mainplant deammonification
  – Sidestream biomass used to bioaugment
  – Sidestream system used to rejuvenated biomass
Energy and Other Resources
The energy contained in wastewater is significant.

Wastewater

- Thermal Energy
  - Heat
- Hydraulic Energy
  - Moving Water
- Chemical Energy
  - Soluble and insoluble contaminants

Images Courtesy Metro Wastewater Treatment Plant in MI and F. Wayne Hill Water Resources Center in GA
Managing chemical energy flow throughout the plant is a key element of plants of the future.

**Anaerobic digester**

100% → ~50% → 100% → ~25% → 100% → ~5%

~50% → ~20% → ~25%

~37% → Biogas

~5% → Effluent

Biosolids

Do we attempt to recover as much energy in the influent carbon through biogas production? 

Do we use the carbon for nutrient removal?

What if we converted carbon to useful forms other than biogas or in-plant carbon use?
FOG and food waste co-digestion at the F. Wayne Hill WRC

- Have 2.1 MW CHP recovery system
- How to utilize capacity?
- Assessed co-digestion to enhance energy recovery
  - Poultry DAF Skimmings
  - FOG Source A
  - Grocery DAF Skimmings
  - FOG Source B
  - Dewatered FOG Source B
  - Chewing Gum Waste (CGW)
Full-scale implementation of co-digestion has led to savings of up to $2 million per year

- Not just magnitude of production
- Store gas and utilize during peak hours to reduce electrical cost
- Energy procurement contracting cannot be ignored
Managing chemical energy flow throughout the plant is a key element of plants of the future.

Do we attempt to recover as much energy in the influent carbon through biogas production?

Do we use the carbon for nutrient removal?

What if we converted carbon to useful forms other than biogas or in-plant carbon use?

Anaerobic digester

~100% → ~50% → ~25% → ~5% → Effluent

~50% → ~50% → ~20% → Biosolids

~37% → Biogas
Nansemond Treatment Plant

- 30 mgd design flow
  - TN < 8 mg/L
  - TP < 1 mg/L

- Low C:N and C:P influent characteristics

- >10,000 lbs / day purchased supplemental carbon (as COD)
Recovering carbon can offset operational costs

- Preferentially produce volatile fatty acids through fermentation of PS, FOG, High strength food wastes
Co-fermentation of FOG and PS was piloted at HRSD in VA
Data from the pilot was used to develop conceptual level designs for a full scale fermentation facility.
Value of Carbon
Co-Fermentation and Co-Digestion

1 Gallon GTW
1.2 lb COD
0.1 lb sCOD

Co-fermentation

0.25 lb sCOD
13% pCOD solubilization

Supplemental Carbon
$0.15-$0.50 per lb COD

$0.04 - $0.13

Co-digestion

0.95 lb sCOD

5.7 scf CH₄
40% Conversion Efficiency

0.67 kWh/gal

$0.05 - $0.15 per kWh

$0.03 - $0.10
Implementing co-fermentation would result in savings over the 20 year lifetime.

- **Co-Fermentation vs. Co-Digestion**
  - Not always an either/or decision
  - Depends on supplemental carbon cost and electricity/natural gas cost
  - Site specific evaluation is necessary

![Graph showing cumulative cost of methanol + fermentation over 20 years with paybacks ranging from 9 to 12 years for NTP.](image)
Managing chemical energy flow throughout the plant is a key element of plants of the future.

Do we attempt to recover as much energy in the influent carbon through biogas production?

Do we use the carbon for nutrient removal?

What if we converted carbon to useful forms other than biogas or in-plant carbon use?

Anaerobic digester

100% → ~50% → ~25% → ~5%

Effluent

~37% → ~50% → ~50%

Biogas

~20% → Biosolids

~5%
Fermentation products can also be used for to produce other valuable resources.

- Bioplastic pre-cursors
- Biofuels
- Lipids

**WERF NTRY3R13-**
Beyond Nutrients: Recovering Carbon and Other Commodity Products from Wastewater

**WERF NTRY4R13-**
Multi-Platform Approach to Recovering High Value Carbon Products From Wastestreams
Today we sit at a crossroad of opportunity...

Business as usual

Utility of the Future

Liquid Treatment

Solids and Residuals Treatment

Stormwater

Sidestream Treatment

Reuse
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