Can Nutrient Recovery Be a Financially Sustainable Development Objective?

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Kennedy/Jenks Consultants
P-Recovery Feasibility Study at HCTP
Phosphorus Recovery by Struvite Crystallization

\[
\text{Mg}^{2+} + \text{NH}_4^+ + \text{PO}_4^{3-} + 6 \text{H}_2\text{O} \leftrightarrow \text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}
\]

Commercialized Technologies

- OSTARA (US)
- Phosnix (Japan)
- Crystalactor® (Netherlands)

Phosphorus Rock Reserves

Economical phosphate deposits around the world (A.K.A. “Reserve deposits”)

Source: *Use of Phosphate Rocks for Sustainable Agriculture*

Phosphate mining in Florida

Source: *Mosaic*
Phosphorus Rock Production

Source: Potash of Saskatchewan
PR Production vs. World Population

Source: *Peak Phosphorus*
Impacts of a Changing Diet

Daily Caloric Intake Per Capita
Increased Food Consumption, More Balanced Diets

Source: Potash of Saskatchewan
Impacts of Agrofuels

U.S. Ethanol Production

Source: EIA and Mosaic

Gal

Percent

Actual
Forecast
Percent of Gasoline Use

95 96 97 98 99 00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15

0 2 4 6 8 10 12 14 16

0% 2% 4% 6% 8% 10% 12% 14% 16%
Phosphorus - Production Peak?

Modeling Phosphorus Production using Hubbert Curve

Source: Peak Phosphorus: the sequel to Peak Oil, Cordell & White, 2009
A Compelling Financial Argument for Phosphorus Recovery

✓ Production of a saleable product that has no substitutes and is limited in supply
✓ Reduced aeration for nitrification of return ammonia
X Reduced maintenance and replacement costs
X Reduced chemical usage for P removal
X Reduced supplemental carbon for denitrification
X Reduced chemical sludge handling and disposal costs

Struvite formation in a pipe

Photo courtesy of Bryce Richter/University of Wisconsin-Madison

Kennedy/Jenks Consultants

Engineers & Scientists
Is Phosphorus Recovery a Financially Sustainable Development Objective?

Metrics of financial sustainability

- **Costs**
  - equipment, building, electricity, labor, chemical, maintenance

- **Savings**
  - maintenance/replacement costs, chemical (P-removal, supplemental carbon), solids handling and disposal, aeration

- **Revenue**
  - Amount of product generated, sale price of product

- **Period of Analysis**
  - Acceptable payback period
Costs at HCTP (provided by OSTARA)

Cost Components (contact OSTARA for detail)

- **Equipment**
  - Reactors – $1.8 M/Reactor for 1 Reactor, $1M/Reactor for 4 Reactors
  - Building Space – 1 Reactor ~2400 SF, 4 Reactors ~5000 SF, $160-$200/SF

- **Chemical**
  - Magnesium Chloride (provided by OSTARA) – $250/ton
  - Caustic (pH adjustment) - Varies

- **Labor**
  - 2 hours/reactor/day @ $35/hour

- **Electricity**
  - 250-320 kWh/day/reactor @ $0.15/kWh

- **Maintenance**
  - $15,000-$27,000 /reactor/year

- **Total Cost**
  - $2.40 to $3.70/lb of P Recovered (cost distributed over 15 year period)
Savings at HCTP

Savings Components

- Reduced Maintenance/Replacement Costs
  - $2,000 to $10,000 per MGD (Parsons et al. 2001)
  - Exceed $100,000 for a 25 MGD treatment Plant (Doyle and Parsons 2002)

- Reduced Chemical usage
  - Ferric/Alum – $2.00 to $4.00/lb P removed
  - Methanol - $0.23/lb P removed
  - Acetic Acid - $1.32/lb P removed

- Reduced Chemical Sludge Handling/Disposal
  - Ferric – ~6.5 lbs sludge (dry)/lb P removed @ variable cost
  - Alum - ~5.3 lbs sludge (dry)/lb P removed @ variable cost

- Reduced Nitrification Load
  - Aeration - $0.34 to $0.58 /lb P removed

- Total Savings
  - HCTP - $0.37 /lb P removed
  - Total - $6.61 /lb P removed
Revenue Components

Production:
How much struvite could be produced?

Price:
How much can struvite be sold for (now and in future)?

Magnified Struvite Pellets
Source: http://www.phosphorus-recovery.tu-darmstadt.de/index.php
Struvite Production – Soluble P in Filtrate

- Digested sludge filtrate survey (Münch and Barr, 2001, Ivanov et al. 2005)
  - 10 mg/L to 300 mg/L of Ortho-P
  - 500 mg/L to 800 mg/L of ammonium-nitrogen

- Nutrient concentrations in filtrate highly variable
  - Spray wash water
  - Nutrient removal in liquid stream treatment
  - VS destruction in digester

Source: www.geocities.com/rainforest/5161/BFP.htm
Struvite Production - Estimating Soluble P

- If VS destruction known in digester
  - TP content of VS – 3-5% typical
  - Ortho-P content of TP – 65% typical
  - Approximate Ortho-P using VS destruction (for verification)

Anaerobic Digester at HCTP, Thousand Oaks, CA
Struvite Production at Full and Pilot Scale Facilities

- Published data (pilot and full scale)
  - Durham, Oregon (Bio-P, OSTARA) – 135 lbs/MGD
  - Lake Shinji, Japan (Bio-P, Phosnix) – 90 to 100 lbs/MGD
  - Geestmerambacht WWTP, Holland (Bio-P, Crystalactor) - 40 lbs/MGD
  - Gold Bar WWTP, Canada (Bio-P, OSTARA) – 75 lbs/MGD
  - Nansemond WWTP, Virginia (Bio-P, OSTARA) – 120 lbs/MGD
  - Truckee Meadows, Nevada (Bio-P, OSTARA) – 155 lbs/MGD
  - Lulu Island WWTP, Canada (TF/AS, OSTARA) – 50 lbs/MGD
  - 75 MGD WWTP?, (Non Bio-P, OSTARA) – 90 lbs/MGD?

- Struvite production summary
  - Bio-P – 100 lbs struvite/MGD (3.5 mg/L of influent P)
  - Non Bio-P – 50 (70?) lbs struvite/MGD (1.7 mg/L of influent P)
Conclusions on Estimating Struvite Production

- Filtrate characterization or pilot study recommended
- Look to full-scale facilities for long-term production rates (where data is available)

OSTARA Reactors at Durham WWTP

PhotoCourtesy of Rob Baur

OSTARA Reactor at Gold Bar WWTP

Photo Courtesy of OSTARA Kennedy/Jenks Consultants Engineers & Scientists
How much can struvite be sold for?

**Literature References Inconsistent**
- $200 to $1,885 per tonne (Doyle and Parsons 2002, Münch and Barr 2001, Ueno et al. 2001)

**Other Techniques for Price Estimation**
- “Component cost” – determine production cost by adding up cost of input elements
- Cost of comparables – price relative to agronomic value as compared to other commercial fertilizers
Component Price – July 2008

Spot Price DAP, $1400/ton
P - A.W. ~31
PO_4^{3-}
2.33 $/lb P

Spot Price Ammonium Nitrate, $515/ton
NH_4 - A.W. ~18
NH_4^+
0.77 $/lb N

Spot Price Mg (metal), $4640/ton
Mg - A.W. ~24
Mg^{2+}
2.32 $/lb Mg

A.W. ~108
6 H_2O
0.00 $/lb

MgNH_4PO_4·6H_2O
(Struvite/MAP)
1160 $/ton

Atomic Weight ~245

July 2008 Prices – Graphic adapted from “About the economy of phosphorus recovery”, T. Dockhorn, Institute of Sanitary and Environmental Engineering.
Component Price – August 2009

Spot Price DAP, Tampa
$270/ton

Spot Price Ammonium Nitrate, Tampa
$170/ton

Spot Price Mg (metal)
$3200/ton

$PO_4^{3-}$
0.41 $/lb P

$NH_4^+$
0.30 $/lb N

$Mg^{2+}$
1.60 $/lb Mg

6 $H_2O$
0.00 $/lb

$MgNH_4PO_4 \cdot 6H_2O$
(Struvite/MAP)
466 $/ton

August 2009 Prices – similar methodology.
Agronomic Value of Struvite as Fertilizer

- Three year field experiments with MAP showed no statistically significant benefit in terms of increased grain yield over unfertilized soil or phosphate rock (Weinfurtner et al, 2009)
- Pot experiments suggest struvite has a relative fertilizer efficiency of 64%-134% of TSP (R. Cabeza Perez et al, 2009)
- Struvite has same fertilizer potential as rock phosphate (Gonzales Ponce and De Sa, 2007)
- Struvite was equally as efficient as DAP when finely ground (Ghosh et al, 1996)
Conclusions on Price

- Data on price inconsistent – no developed market in US
- “Component” cost not a reliable method of estimation
- Demonstrated agronomic value comparison inconclusive
- Supporting higher struvite prices
  - Strong demand fundamentals
  - High willingness to pay (price inelasticity)
- Not supporting higher struvite prices
  (Sources: J. Von Horn and C. Sartoriosus, 2009 and Mosaic)
  - Production near 100% capacity in 2007, now below 50%
  - New production capacity can be brought online in 2 years
  - High prices change behavior – “demand destruction”
Where might P-recovery make sense now?

- **Basic Guidance**
  - Consider: NPV > $0 excluding revenue from fertilizer sales?

- **Technical requirements**
  - <200 mg/L TSS in stream (Durham?)
  - >140 lbs/d phosphorus in recycle for OSTARA Reactor

- **Best to characterize filtrate or pilot**
  - 100 lbs struvite/MGD for Bio-P – ~10 MGD
  - 50 lbs struvite/MGD for non Bio-P – ~20 MGD

- **Hill Canyon Treatment Plant – 10 MGD, non Bio-P**
  - 15-year payback period
  - Did not recommend P recovery
Will this technology become more widespread?

- Production Cost of DAP in Q3 2008 (Source: PotashCorp)
  - Non-Integrated DAP Producer: $1,600 - $2,400/ton P₂O₅
  - Integrated DAP Producer: $1,000 - $1,400/ton P₂O₅
  - Thousand Oaks (Struvite): $2,400 to $3,700/ton P₂O₅
References

9. An economic evaluation of phosphorus recovery as struvite from digester supernatant, Bioresource Technology 97, pages 2211-2216, 2006
References

13. Plant Availability of P-Fertilizers Recycled from Sewage Sludge and Meat-and-Bone Meal in Field and Pot Experiments, R. Cabeza Perez et al., International Conference on Nutrient Recovery from Wastewater Streams, 2009.


References


References


How can you explain prices in 2008?

- Broad-based price increase
- Speculation
- Rising energy prices
- Short-term production limitations

(J. Von Horn and C. Sartorius, 2009)

- Typical at end of economic cycles
Phosphorus - Production Peak?

Modeling Phosphorus Production using Hubbert Curve

Source: Peak Phosphorus: the sequel to Peak Oil, Cordell & White, 2009
10-Year Commodity Price Chart for Phosphate Rock – Phosphate Rock ($/metric ton)

Source: World Bank Commodity Price Data

USGS PR “Reserves”
(Billions of Tons)
Production Peak in Period of Analysis?

GLOBAL OIL & GAS PRODUCTION PROFILES

Billions of Barrels of Oil Equivalent Per Year (Gb/a)


Regular Oil | Heavy etc | Deepwater | Polar | NGL | Gas | Non-Con Gas

ASPO 2008 Base Case (Produced 2009)
USGS Definition of Phosphorus “Reserves”

Exploration of underwater PR mining off shore of Namibia and New Zealand

Source: Bonaparte Diamond Mines
### Heavy Metals in Struvite

#### Table 2: Relative Concentrations of Nutrients and Metals in Pure Struvite and Phosphorus Recovery Products

<table>
<thead>
<tr>
<th></th>
<th>Pure Struvite</th>
<th>Struvite from Phosnix(^{(a)})</th>
<th>Struvite from Crystalactor(^{(b)})</th>
<th>Struvite from OSTARA (^{(c)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia nitrogen (as N)</td>
<td>5.71%</td>
<td>5.40%</td>
<td>9%</td>
<td>5%(^{(c)})</td>
</tr>
<tr>
<td>Phosphorus (as P(_2)O(_5))</td>
<td>28.97%</td>
<td>27.98%</td>
<td>46%</td>
<td>28%(^{(c)})</td>
</tr>
<tr>
<td>Magnesium (as Mg)</td>
<td>9.7%</td>
<td>8.8%</td>
<td>16%</td>
<td>10%(^{(c)})</td>
</tr>
<tr>
<td>Titanium (as Ti)</td>
<td>0.0028%</td>
<td></td>
<td>0.00053%(^{(e)})</td>
<td></td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
<td>0.000006%</td>
<td></td>
<td>0.00005%(^{(e)})</td>
<td></td>
</tr>
<tr>
<td>Lead (as Pb)</td>
<td>0.0003%</td>
<td></td>
<td>N/S</td>
<td></td>
</tr>
<tr>
<td>Chromium (as Cr)</td>
<td>0.0001%</td>
<td></td>
<td>0.00021%(^{(c)})</td>
<td></td>
</tr>
<tr>
<td>Arsenic (as As)</td>
<td>0.00028%</td>
<td></td>
<td>0.0001%(^{(e)})</td>
<td></td>
</tr>
<tr>
<td>Nickel (as Ni)</td>
<td>0.0029%</td>
<td></td>
<td>0.00087%(^{(e)})</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- \(^{(a)}\) Nakamura et al. 2006.
- \(^{(b)}\) Information provided by Procorp Enterprise LLC. Typical content of seed material 5-10% in the final product.
- \(^{(d)}\) Phosphorus oxide.
- \(^{(e)}\) Britton et al. 2007.
Sources of Phosphorus for Fertilizer

- Nearly all P for inorganic fertilizer comes from phosphate rock
  - DAP – diammonium phosphate
  - MAP - monoammonium phosphate
  - APP – ammonium polyphosphate
  - WWTP Struvite? (30% P$_2$O$_5$, 5% N)

- Organic P fertilizers
  - Manures, plant residues

Table 1. Total N, P$_2$O$_5$, and water soluble phosphate percentage of various P sources.

<table>
<thead>
<tr>
<th>Source</th>
<th>N</th>
<th>P$_2$O$_5$</th>
<th>Water soluble P$_2$O$_5$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAP</td>
<td>18-21</td>
<td>46-53</td>
<td>90-100</td>
</tr>
<tr>
<td>MAP</td>
<td>11-13</td>
<td>48-55</td>
<td>90-100</td>
</tr>
<tr>
<td>APP</td>
<td>10-15</td>
<td>34-37</td>
<td>100</td>
</tr>
<tr>
<td>PR</td>
<td>---</td>
<td>25-40</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 6. Nutrient content (lb/ton) for various manures.

<table>
<thead>
<tr>
<th>Manure type</th>
<th>Total N</th>
<th>N available 1st year</th>
<th>P$_2$O$_5$</th>
<th>K$_2$O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swine, fresh</td>
<td>10</td>
<td>8</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>Beef, without bedding</td>
<td>21</td>
<td>12</td>
<td>14</td>
<td>23</td>
</tr>
<tr>
<td>with bedding</td>
<td>21</td>
<td>11</td>
<td>18</td>
<td>26</td>
</tr>
<tr>
<td>Dairy, without bedding</td>
<td>9</td>
<td>6</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>with bedding</td>
<td>9</td>
<td>6</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Sheep, with bedding</td>
<td>14</td>
<td>7</td>
<td>9</td>
<td>25</td>
</tr>
<tr>
<td>Poultry, without litter</td>
<td>33</td>
<td>28</td>
<td>48</td>
<td>34</td>
</tr>
<tr>
<td>with litter</td>
<td>56</td>
<td>42</td>
<td>45</td>
<td>34</td>
</tr>
<tr>
<td>Horse, with bedding</td>
<td>14</td>
<td>6</td>
<td>4</td>
<td>14</td>
</tr>
</tbody>
</table>

Source: Commercial Phosphorus Fertilizer...Know Your Sources, Dr. W.M. Stewart, News & Views, February 2002

Source: Fertilizing Fruit Crops, Eric Hanson, Department of Horticulture MSUE Bulletin E-852, Major Revision 1996
Cost of Magnesium Chloride

- Magnesium Chloride
  - 0.26 pounds of magnesium per pound of magnesium chloride
  - 0.79 pounds of magnesium required per pound phosphorus (1:1 molar removal ratio)
  - $0.35/lb Magnesium Chloride

\[
\frac{0.79 \text{ lbs } Mg}{\text{ lbs } P} \times \frac{1 \text{ lbs } MgCl_2}{0.26 \text{ lbs } Mg} \times \frac{0.35 \text{$/lb MgCl_2}}{} = 0.98 \text{}$/lbP
\]
Chemical Removal of P – Costs and Sludge Quantities

- **Alum (Aluminum sulfate, \( \text{Al}_2\text{SO}_4\cdot14\text{H}_2\text{O} \))**
  - $0.22 per 1 lbs of 48.5% alum = $4.99 per 1 lbs of Al

  \[
  \frac{0.22}{1 \text{ lbs Liquid Alum}} \times \frac{1 \text{ lbs Al}_{2}\text{SO}_4 \cdot 14\text{H}_2\text{O}}{0.485 \text{ lbs Al}_{2}\text{SO}_4 \cdot 14\text{H}_2\text{O}} \times \frac{594 \text{ lbs Al}_{2}\text{SO}_4 \cdot 14\text{H}_2\text{O}}{2 \times 26.98 \text{ lbs Al}} = \frac{4.99}{1 \text{ lbs Al}}
  \]

  - (1:1 molar) For 1 lbs of P: 0.87 lbs of Al\(^{3+} \) ($4.34) required and 3.9 lbs of AlPO\(_4\) produced (plus 1.35 EPA SF)

- **Ferric chloride (FeCl\(_3\))**
  - $0.17 per 1 lbs of 40% FeCl\(_3\) = $1.23 per 1 lbs of Fe

  \[
  \frac{0.17}{1 \text{ lbs Liquid FeCl}_3} \times \frac{1 \text{ lbs FeCl}_3}{0.40 \text{ lbs FeCl}_3} \times \frac{162.2 \text{ lbs FeCl}_3}{55.847 \text{ lbs Fe}} = \frac{1.23}{1 \text{ lbs Fe}}
  \]

  - (1:1 molar) For 1 lbs of P: 1.80 lbs of Fe\(^{3+} \) ($2.21) required and 4.9 lbs of FePO\(_4\) produced (plus 1.35 EPA SF)

Ferric is cheaper but produces more chemical sludge.

Chemical costs from Cascade Columbia.
Acetic and Methanol Costs

- Methanol - $0.50/lb NOx-N removed (Katehis and Metcalf & Eddy 2006)
- Acetic Acid - $2.93/lb NOx-N removed (Katehis and Metcalf & Eddy 2006)
- 0.45 pounds of ammonia removed per pound phosphorus (1:1 molar removal ratio)

\[0.45 \text{ lbs N} \times \$0.50 \text{ to } \$2.93 = \$0.23 \text{ to } \$1.32 / \text{lb P removed}\]
Energy for Nitrification

- **Nitrification Load**
  - 4.6 lbs of oxygen per pounds of oxygen saved per pound of ammonia removed
  - 1.1 to 1.94 pounds of oxygen per kWH (US EPA Fine Pore Aeration Manual)
  - 0.45 pounds of ammonia removed per pound phosphorus (1:1 molar removal ratio)
  - $0.15/kWh

\[
\frac{0.45 \text{ lbs N} \times 4.6 \text{ lbs O}_2 \times 1.1 \text{ to } 1.94 \text{ kWh/lb}}{} \times $0.15 \text{ / kWh} = \frac{}{}
\]

\[
$0.34 \text{ to } $0.59 / \text{lbP}$
\]
Phosphorus Fertilizer Prices (2006-2009)

Source: Potash of Saskatchewan
Environmental Benefits

- Environmental benefits
  - P-removal
  - No mining
  - Slow release (pelletized, crystalline, 8 month release profile in soil and 4 months in running water)