Nutrient recovery from municipal wastewater for sustainable food production systems: An alternative to traditional fertilizers

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Importance of Nutrient Management

- Eutrophication - enrichment of an ecosystem with chemical nutrients, typically compounds containing nitrogen (N), phosphorus (P), or both.

- Clean Water Act (CWA) requires wastewater treatment plants (WWTPs) to reduce nutrient discharge levels to prevent eutrophication.
Study Objectives and Approach

- Aims to address:
  1) how regulations drive system changes;
  2) how conventional systems can be transitioned to more cost effective and sustainable alternatives using nutrient management.

- Use emergy to provide system analysis:
  - Emergy quantifies direct and indirect contributions from the elemental resource flow to the entire treatment plant operational requirements.

- Influent wastewater flow and nutrient levels, capital, and operational data were collected from previous nutrient removal studies and for nutrient recovery from Ostara Nutrient Recovery Technologies, Inc.

- All UEVs used and given hereafter (including those referenced in the text) were normalized to the 1.20 E25 sej/yr (solar emjoules/year) global emergy baseline (Brown et al., 2016)
Nutrient Recovery and Benefits

- Nutrient recovery - practice of recovering nutrients (N and P) from wastewater and converting them into an environmental friendly fertilizer

- Industrial phosphate ($\text{PO}_4^{3-}$) fertilizers - manufactured using $\text{PO}_4^{3-}$ rock (non-renewable resource)

- Nutrient recovery provides a self-sustainable solution to WWTPs
  - revenue generation from fertilizers
  - reduces fouling of equipment with involuntary precipitation of struvite
  - helps meet discharge limits

- $\text{PO}_4^{3-}$ precipitation from wastewater is less energy intensive and economical compared to manufacture of phosphate fertilizers
Struvite Formation and Production

- Recovered from municipal wastewater (MWW)/urine source - slow-release mineral fertilizer given by the simplified equation

\[
\text{Mg}^+ + \text{NH}_4^+ + \text{PO}_4^{3-} + 6\text{H}_2\text{O} \rightarrow \text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O} \text{ (solid)}
\]

Magnesium Ammonium Phosphate

- Methods of struvite recovery from MWW have been under development, this study cites WASSTRIP™ and PEARL® process by Ostara Nutrient Recovery Technologies, Inc.

- Marketed fertilizer - 5% N, 28% PO$_4^{3-}$, and 0% potash, with 16.6% MgO (10% Mg)
In addition to P precipitation, partial nitration anammox was considered for nitrogen reduction in the nutrient recovery alternative.
Emergy definition and concept

- Available energy of any kind previously used both directly and indirectly to make another form of energy, product or service.

- Evolution of the theory during the past thirty years was documented by H.T Odum in Environmental Accounting, 2016.

- Emergy (emjoules/yr or emjoules/unit) synthesis strives for understanding by grasping the wholeness of system.

- Able to investigate systems that are outside of human activities and evaluate in a quantitative way (metrics) the quality of resource flows and storages.
Emergy Systems Diagram for Nutrient Recovery

External forcing functions (circles) provide inflow energy materials and information to the producers (bullet-shape symbols). Internal storages (tank symbols) and economic and social subsystems (boxes) are shown.
Energy Systems Diagram for DAP Production

P Fixation

Phosphorus Acid Production

DAP Production

External forcing functions (circles) provide inflow energy materials and information to the producers (bullet-shape symbols). Internal storages (tank symbols) and economic and social subsystems (boxes) are shown.
# Results of Traditional Fertilizer Vs. Nutrient Recovery

## Diammonium Phosphate (DAP)

**Chemical formula:** (NH$_4$)$_2$HPO$_4$

**Composition:** 18% N, 46% P$_2$O$_5$ (20% P)

| Note | Description | Data | Unit | UEV (sej/unit) | EMERGY (E sej/yr) |
|------|-------------|------|------|----------------|-------------------|
| Infrastructure input | Capital | $1.14E+01$ | $2.02E+12$ | $2.31E+13$ | |
| Operational inputs per year (2013) | 1 Materials | Phosphate Rock | $1.50E+06$ g | $3.61E+09$ | $5.40E+15$ |
| | Ammonia | $1.44E+05$ g | $6.48E+09$ | $9.35E+14$ | |
| | Sulfur | $3.97E+05$ g | $9.50E+10$ | $3.77E+16$ | |
| | Limestone | $3.02E+04$ g | $2.20E+08$ | $6.65E+12$ | |
| 2 Energy | Electricity | $1.16E+08$ J | $7.26E+05$ | $7.85E+12$ | |
| | Fuels | $4.34E+08$ J | $6.13E+05$ | $4.01E+13$ | |
| 3 Services | Water | $5.12E+02$ m$^3$ | $8.22E+11$ | $1.23E+13$ | |
| Total EMERGY | | | | **5.03E+16** | |
| 5 Transformity | | | | **5.03E+10** sej/g DAP | |
| | | | | **5.03E+10** sej/g DAP | |
| | | | | **1.18 E+10** sej/g P | |

## Struvite

**Chemical Formula:** Crystal Green®, NH$_4$MgPO$_4$·6H$_2$O (5-28-0 +10% Mg)

| Note | Description | Data | Unit | UEV (sej/unit) | EMERGY (E sej/yr) |
|------|-------------|------|------|----------------|-------------------|
| Infrastructure input | Capital | $2.47E+02$ $ | $2.02E+12$ | $5.01E+14$ | |
| Operational inputs per year (2013) | 1 Materials | Phosphate, eq. to elemental phosphorus (PO$_4$-P) | 1.40E+05 g | | 0.00E+00 |
| | Ammonia, equivalent to elemental Nitrogen (NH$_3$-N) | 2.10E+05 g | | 0.00E+00 |
| | Sodium hydroxide (NaOH) | 4.90E+04 g | | 4.14E+09 | 2.03E+14 |
| | Magnesium chloride (MgCl$_2$) as Mg | 1.47E+05 g | | 4.34E+10 | 6.38E+15 |
| 2 Energy | Electricity | 6.40E+08 J | | 2.21E+05 | 1.41E+14 |
| 3 Services | Water | 5.33E+01 m$^3$ | | 3.26E+05 | 8.56E+07 |
| Total EMERGY | | | | **7.10E+15** | |
| 5 Transformity | | | | **7.10E+09** sej/g CG | |
| | | | | **7.60E+09** sej/g CG | |
| | | | | **8.96 E+08** sej/g P | |
## Results of Traditional Fertilizer Vs. Nutrient Recovery

### Diammonium Phosphate (DAP)

**Chemical formula:** \((\text{NH}_4)_2\text{HPO}_4\)  
**Composition:** 18% N, 46% P\(_2\text{O}_5\) (20% P)

| Note | Description (sej/unit) | (E sej/yr) |
|------|------------------------|------------|
| **Infrastructure input** | | |
| * Capital | 1.14E+01 $ | 2.02E+12 | 2.31E+13 |

| Operational inputs per year (2013) | | |
| 1 Materials | | |
| 1a Phosphate Rock | 1.50E+06 g | 3.61E+09 | 5.40E+15 |
| 1b Ammonia | 1.44E+05 g | 6.48E+09 | 9.35E+14 |
| 1c Sulfur | 3.97E+05 g | 9.50E+10 | 3.77E+16 |
| 1d Limestone | 3.02E+04 g | 2.20E+08 | 6.65E+12 |
| 2 Energy | | |
| 2a Electricity | 1.16E+08 J | 7.26E+05 | 7.85E+12 |
| 2b Fuels | 4.34E+08 J | 6.13E+05 | 4.01E+13 |
| 3 Services | 5.12E+02 $ | 2.02E+12 | 1.04E+15 |
| 4 Water | 3.56E+01 m\(^3\) | 8.22E+11 | 1.23E+13 |

| **Total EMERGY** | | |
| w/o capital invest | 5.03E+10 sej/g DAP |
| with capital invest | 5.03E+10 sej/g DAP |
| w/o capital invest | 1.18 E+10 sej/g P |

**Transformity**
## Results of Traditional Fertilizer Vs. Nutrient Recovery

### Struvite

Chemical Formula: Crystal Green®, \( \text{NH}_4\text{MgPO}_4\cdot6\text{H}_2\text{O} \) (5-28-0 +10% Mg)

| Note | Description | Data | Unit | UEV (sej/unit) | EMERGY (E sej/yr) |
|------|-------------|------|------|----------------|-------------------|
| **Infrastructure input** | | | | | |
| * | Capital | 2.47E+02 $ | 2.02E+12 | | 5.01E+14 |
| **Operational inputs per year (2013)** | | | | | |
| 1 | Materials | | | | |
| 1a | Phosphate, eq. to elemental phosphorus (PO\(_4\)-P) | 1.40E+05 g | | | 0.00E+00 |
| 1b | Ammonia, equivalent to elemental Nitrogen (NH\(_3\)-N) | 2.10E+05 g | | | 0.00E+00 |
| 1c | Sodium hydroxide (NaOH) | 4.90E+04 g | 4.14E+09 | | 2.03E+14 |
| 1d | Magnesium chloride (MgCl\(_2\)) as Mg | 1.47E+05 g | 4.34E+10 | | 6.38E+15 |
| 2a | Electricity | 6.40E+08 J | 2.21E+05 | | 1.41E+14 |
| 3 | Services | 5.33E+01 $ | 2.02E+12 | | 1.08E+14 |
| 4 | Wastewater | 2.63E+02 g | 3.26E+05 | | 8.56E+07 |
| **Total EMERGY** | | | | | 7.10E+15 |

1. Transformity
   1. w/o capital invest: 7.10E+09 sej/g CG
   2. with capital invest: 7.60E+09 sej/g CG
   3. w/o capital invest: 8.96E+08 sej/g P
Biological Nutrient Removal (BNR)

- BNR treatments remove TN and TP from wastewater through the use of chemicals and microorganisms under different environmental conditions (Metcalf and Eddy, 2003)

- Levels of nutrient removal processes:

| Treatment Level (Effluent Limits) | Removal/Recovery Process Name | Processes Chosen for this Study |
|----------------------------------|-------------------------------|--------------------------------|
| Recovery                         | Phosphorus Recovery           | Phosphorus Recovery - Anammox  |
| Level 2                          | Nitrification or Oxidation Ditch with or without Phosphorus Precipitation (chemical addition) | Nitrification                   |
| Level 3                          | Modified Ludzack Ettinger (MLE) 4 Stage and 5 Stage Bardenpho (Bardenpho), Modified University of Cape Town (MUCT), Sequential Batch reactor (SBR) + Phosphorus Precipitation (chemical addition) | MLE MLE - High Energy Bardenpho - No Chemical Addition Bardenpho - Chemical Addition Bardenpho - High Energy MUCT - No Chemical Addition MUCT - Chemical Addition MUCT - High Energy |
| Level 4                          | Level 3 process with either Denitrification Filter Membrane Filter, Membrane Bioreactor (MBR) + Phosphorus Precipitation (chemical addition) | Bardenpho - Denitrification Filter Bardenpho - Membrane Filter MUCT - Membrane Filter Bardenpho - MBR |
| Level 5                          | Level 3 or Level 4 processes with Sidestream Reverse Osmosis | Bardenpho - RO Bardenpho - Membrane Filter & RO MUCT - Membrane Filter & RO |
# Processes Considered for the Study

| Treatment Level (Effluent Limits) | Nutrient Removal/Recovery Process | Energy (kWh/m³) | Influent Ammonia (mg/L as NH₃-N) | Influent P (mg/L as P) |
|-----------------------------------|----------------------------------|-----------------|----------------------------------|----------------------|
| Recovery                          | Phosphorus Recovery - Anammox     | 0.14            | 20                               | 7                    |
| Level 2 (TN – 8 mg/L, TP – 1 mg/L)| Nitrification                     | 0.23            | 24                               | 10                   |
| Level 3 (TN – 4-8 mg/L, TP – 0.1-0.3 mg/L) | MLE                               | 0.28            | 23                               | 8                    |
|                                   | MLE - High Energy                 | 0.59            | 32                               | 8                    |
|                                   | Bardenpho - No Chemical Addition  | 0.29            | 23                               | 8                    |
|                                   | Bardenpho - Chemical Addition     | 0.29            | 23                               | 8                    |
|                                   | Bardenpho - High Energy           | 0.58            | 22                               | 5                    |
|                                   | MUCT - No Chemical Addition       | 0.35            | 23                               | 8                    |
|                                   | MUCT - Chemical Addition          | 0.35            | 23                               | 8                    |
|                                   | MUCT - High Energy                | 0.56            | 22                               | 5                    |
| Level 4 (TN – 3 mg/L, TP – 0.1 mg/L) | Bardenpho - Denitrification Filter| 0.53            | 22                               | 5                    |
|                                   | Bardenpho - Membrane Filter       | 0.4             | 23                               | 8                    |
|                                   | MUCT - Membrane Filter            | 0.45            | 23                               | 8                    |
|                                   | Bardenpho - MBR                   | 0.53            | 22                               | 5                    |
| Level 5 (TN - <2 mg/L, TP<0.02 mg/L) | Bardenpho - RO                   | 0.60            | 22                               | 5                    |
|                                   | Bardenpho - Membrane Filter & RO  | 2.4             | 23                               | 8                    |
|                                   | MUCT - Membrane Filter & RO       | 2.45            | 23                               | 8                    |
Total Emergy Comparison between Different Nutrient Removal and Recovery Technology

Same BNR vary due to chemical and energy inputs

Emergy (sej/m³)
Total Emergy Comparison between Different Nutrient Removal and Recovery Technology
Results and Discussions

- Stringent nutrient reduction regulations lead to trade-offs that need further evaluation to choose the most sustainable treatment alternative.

- Emergy analysis justifies nutrient recovery from wastewater sludge and provides sound economic and ecological comparison of removal and recovery treatment alternative independent of perceived monetary value.

- DAP process depends ~70% on non-renewable energy sources and a scarce material (phosphate rock), Struvite has potential of utilizing 100% of renewable sources, making recovery of phosphorus as fertilizer less emergy intensive.

- DAP with an order of magnitude higher total emergy relative to struvite, displays a bigger environmental ‘footprint’.

- Among the nutrient removal treatment alternatives, the study results show that energy and non-energy (chemicals) inputs can lead to significant variation in process emergy.
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Account for the benefits of nutrient recovery via efficient use of the struvite fertilizer and the flow of N and P nutrients in the food system, the economic, environmental and societal benefits of struvite recovery would be more perceptible.
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Thank you! Questions?
Backup Slides
Struvite vs. DAP

Recovered Struvite

Manufactured DAP

Energy Value (sej/gP)

Water

Services

Energy

Materials

Capital
Struvite vs. DAP - Major emergy contributors

- Sulfur: 84%
- Phosphate rock: 12%
- Ammonia: 2%
- Capital, Energy, Services and Water: 2%

- Magnesium chloride: 93%
- Sodium hydroxide: 3%
- Capital, Energy, Services and Water: 4%
Level 2-2 (3-Sludge System)
Level 3-1 (5-Stage Bardenpho)
Level 3-2 (Mod, U of Cape Town)
Level 4-1 (5-S Bardenpho+DenitFil)
Level 4-2 (4-Stage Bardenpho MBR)
Level 5-1 (5-S Bardenpho+UF/RO)
Level 5-2 (5-S Bardenpho MBR+RO)
Emergy Comparison between Nutrient Removal and Recovery Technology - Percent Contribution