Achieving Resource Efficiency through Urine Separation and Nutrient Recovery: Advancing Hybrid Solutions for a Sustainable Future

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University of Michigan

@Love_H2O
Nitrogen Forms Influence Microcystin Concentration and Composition via Changes in Cyanobacterial Community Structure

Marie-Eve Monchamp, Frances R. Pick, Beatrice E. Boisnier, Roxane Maranger

Nitrogen limitation, toxin synthesis potential, and toxicity of cyanobacterial populations in Lake Okeechobee and the St. Lucie River Estuary, Florida, during the 2016 state of emergency event

Benjamin J. Kramer, Timothy W. Davis, Kevin A. Meyer, Barry H. Rosen, Jennifer A. Goleski, Gregory J. Dick, Genesok Oh, Christopher J. Gobler

The graph above illustrates the unusual peak in prices for major traded products DAP (phosphorus and nitrogen), Urea (nitrogen) and KCI (potassium) during 2008-9. www.indexmundi.com
"Water resource recovery facilities can achieve very low nutrient levels... but trade-offs exist between the nutrient removal and the chemicals and energy consumption it requires."


Conventional Nutrient Cycling
~80% of the US Population lives in large city regions*; this is projected to approach ~90% by mid-century

*defined as ≥150,000 inhabitants
# U.S. Households Estimated to use Septic Systems:
22 million (~17%)

Portion of homes relying on a septic system or cesspool by state, 1990.

Share of new homes built with septic systems by region, 2013.

Data: U.S. Census Bureau
https://www.circleofblue.org/2015/world/alabama-clean-water-polluti/

Data: National Association of Home Builders
https://www.circleofblue.org/2015/world/alabama-clean-water-polluti/
Urine contains a majority of the nutrients in wastewater that could be recovered for fertilizer use.

![Graph showing nutrient comparison between Wastewater and Urine]

- **Wastewater**
  - Nitrogen content: 40 mg N/L
  - Phosphorus: 7 mg P/L

- **Urine**
  - Nitrogen content: 6000 mg N/L
  - Phosphorus: 300 mg P/L

**Nutrient Cycling**

- Food to Fertilizer to Environment cycle
- Nitrogen (N$_2$) and Carbon Dioxide (CO$_2$) exchange

![Diagram of urine diversion nutrient cycling]

### Nutrient Recovery

- **Wastewater:**
  - Nitrogen: 40 mg N/L
  - Phosphorus: 7 mg P/L
  - Micropollutants: ≥50%

- **Urine:**
  - Nitrogen: 6000 mg N/L
  - Phosphorus: 300 mg P/L
  - Micropollutants: ≥50%

- **Recovery Rates:**
  - Nitrogen: 70-80%
  - Phosphorus: 50-65%
  - Micropollutants: >50%

- **Scales:**
  - Wastewater: ng/L scale
  - Urine: μg/L scale

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Urine Diversion can:

**Enhance food security** by recovering nitrogen (N) and phosphorus (P) in wastewater

**Reduce the energy** associated with fertilizer production & nutrient removal from wastewater

**Reduce water consumption** by reducing flushing, and **improve water quality**

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What if Urine Never Became Sewage or Septage?

1. **Urine Collection & Transport**
2. **Processing**
3. **Product Use**
Sponsored research has supported advancing all aspects of urine separation and processing to beneficial products: NSF, EPA, TWRF

- Modeling (Mass & Energy Balances, Environmental Impacts, Economics and Markets)
- Urine Collection & Transport
- Processing
- Product Use
- Risk Analysis
- Perceptions
The toilet revolution from LAUFEN

- Looks like “normal” toilet
- No change of behavior, but..
- men should sit
- No valves
- Separation by “teapot effect”
- Around 70-80% of urine separated
- www.urinetrap.com
The principle of the LAUFEN toilet

© EOOS

The principle of the LAUFEN toilet

© EOOS
### Urine processing methods to create urine-derived fertilizer (UDF) products.

<table>
<thead>
<tr>
<th>Processing Method Objective</th>
<th>Technology</th>
<th>Details</th>
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<tbody>
<tr>
<td><strong>Concentration</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Struvite precipitation</td>
<td>Add MgCl₂ to pasteurized urine in CSTR, mix for 30 mins, recover struvite via bag filter on reactor drain. We also used an Ostarase Pearl pilot system at HRSD to make prills.</td>
<td></td>
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<tr>
<td>Reverse Osmosis</td>
<td>Preacidified urine so that nitrogen remains as urea. Concentrate is retained.</td>
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<tr>
<td>Freeze-Thaw</td>
<td>Pasteurized urine is concentrated via freeze-thaw separation.</td>
<td></td>
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<tr>
<td>Cation Exchange</td>
<td>Urine that has been hydrolyzed, pasteurized and struvite precipitated to remove phosphorus and retain ammonium in liquid residual. Ammonium is concentrated to ammonium sulfate, using sulfuric acid as eluant.</td>
<td></td>
</tr>
<tr>
<td><strong>Odor Reduction</strong></td>
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<tr>
<td>Acidification</td>
<td>Vinegar dosing prevents urea hydrolysis</td>
<td></td>
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<tr>
<td>Ammonium-sorting biochar</td>
<td>Chemically treated cellulose material that is selective for ammonium gas.</td>
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<tr>
<td><strong>Mitigating chemical or biological contaminants</strong></td>
<td></td>
<td></td>
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<tr>
<td>Pasteurization</td>
<td>Heating to 70°C for 30 minutes or 80°C for 1.5 minutes (Vermont permitting requirements)</td>
<td></td>
</tr>
<tr>
<td>Adsorption</td>
<td>Activated carbon bed</td>
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Summer 2018 Fertilizer Production & Comparison Plan

Concentrating nutrients:

ACIDIFICATION + REVERSE OSMOSIS
- Concentrate retained
- Clear, low-nutrient water
- Problematic with Mg-rich waters

FREEZE/THAW CYCLING
- Concentrate through partial freezing followed by separating the liquid and ice fractions
- Two products: 1) fertilizer concentrate for agricultural use, and 2) clear, low-nutrient water
Removing Pharmaceuticals from Urine Concentrate

- Urine feedstock or concentrate to be passed through an activated charcoal treatment element to remove pharmaceuticals by sorption.
- AC removes >80-90% of pharmaceuticals.
  - Used on WWTP effluent and human urine.
- Can be sourced from agricultural waste biomass:
  - Coconut shells, olive pits, almond shells, etc.

Recovering Phosphate as Struvite

- Struvite: solid powder.
  \[ \text{Mg}^{2+} + \text{NH}_4^+ + \text{PO}_4^{3-} \rightarrow \text{MgNH}_4\text{PO}_4(s) \]
- Recover 100% P, 5% N.
- Slow-release fertilizer.
- High purity recovery.
- NPK: 6-29-0 + Mg 10.

Ali Gagnon, Hampton Roads Sanitation District, Virginia
Recovering Nitrogen as Ammonium Sulfate

- Common liquid fertilizer
- Selective recovery
- Up to 60 g N/L

Nitrogen Capture
Urine with $\text{NH}_4^+$ → $\text{NH}_4^+$ → Ion exchange resin → H+$^+$

Regeneration
$\text{H}_2\text{SO}_4$ → Ion exchange resin → (NH$_4$)$_2$SO$_4$ → Liquid Fertilizer

Profs Will Tarpeh (Stanford Univ) and Kara Nelson (Univ Cal Berkeley)

Application

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Is this really new?

2018 Field Trial

- Fertilizers Applied
  - Concentrated urine
  - Concentrated urine with pharmaceutical removal
  - Separately concentrated urine-derived N and P
  - No fertilizer
  - Synthetic Fertilizer
- Plant: lettuce and carrot
Sponsored research has supported advancing all aspects of urine separation and processing to beneficial products: NSF, EPA, TWRF

Source-separated urine contains microbial contaminants that need to be managed prior to fertilizer use.

Enteric viruses
Enteric bacteria
Non-enteric bacteria
Antibiotic resistance genes
Non-enteric viruses
Despite high pH and ammonia levels, intact bacteria are present in hydrolyzed urine stored over 100 days.

![Graph showing the relationship between pH and SYBR gold count over urine storage time.]

**Non-enteric bacteria**


Bacterial community compositions of the different urine samples converged after ~2 months of storage.

Community loses diversity through storage.

**Non-enteric bacteria**

Polyomavirus genes in high levels in fresh urine and stored urine.

Goetsch et al, AEM, 2018

Non-enteric viruses

Polyomavirus was rapidly inactivated in hydrolyzed urine.

Goetsch et al, AEM, 2018

Non-enteric viruses
The ability of the plasmids to transform tetracycline resistance decreased rapidly in hydrolyzed urine.

![Graph showing transformation frequency over time in hydrolyzed urine.]

The tetA genes decreased in abundance at a much slower rate in the stored urine.

![Graph showing transformation frequency over time in stored urine.]

What do we know about microbial risks associated with stored urine?

Enteric bacteria rapidly inactivated in hydrolyzed urine.

Some non-enteric bacteria thrive in hydrolyzed urine.

ssRNA viruses rapidly inactivated in hydrolyzed urine.

Human polyomavirus, human adenovirus are rapidly inactivated in hydrolyzed urine. dsDNA surrogate viruses T3 and T4 are very persistent.

Extracellular DNA containing ARGs rapidly lost its ability to transform into competent bacteria.

qPCR is an inappropriate method for assessing the microbial risks associated with urine-derived fertilizers.
Sponsored research has supported advancing all aspects of urine separation and processing to beneficial products: NSF, EPA, TWRF.
Generation 2 “Smart” Building-Scale Urine Processing Facility

GG Brown Building
University of Michigan
Ann Arbor
Sponsored research has supported advancing all aspects of urine separation and processing to beneficial products: NSF, EPA, TWRF

Modeling (Mass & Energy Balances, Environmental Impacts, Economics and Markets)

Urine Collection & Transport  
Processing  
Product Use

Risk Analysis

Perceptions

Would you consider eating food grown with a Urine-Derived Fertilizer?
Questions: “It is acceptance to use this fertilizer to grow fruits and vegetables for people to eat.” “It is acceptable to use this fertilizer to grow non-edible plants like flowers.” “It is acceptance to use this fertilizer to grow fruits and vegetables that will only be eaten by animals.” “It is acceptance to use this fertilizer on plants, trees, and grass that grow around my home.”

Question: “This fertilizer should be used more often than other kinds of fertilizers.” (Strongly Disagree – Strongly Agree)
Lucinda Li: How does long term urine fertilizer treatment impact soil chemical and microbial health?

Dr. Adey Desta: Metagenomic analysis of stored urine, PI of urine diversion program in Ethiopia

Zerihun Getaneh: Creating biochar with high affinity to ammonia gas for use as a soil enrichment

Question: “If I had a choice, I would eat food grown with this fertilizer.”
Rich Earth Institute

Vision: a world with clean water and fertile soil achieved by reclaiming the nutrients from our bodies as elements in a life sustaining cycle.

Mission: to engage in research, education and technological innovation to advance the use of human waste as a resource.
Urine Nutrient Reclamation Program

Advancing Nutrient Recovery through Urine-Derived Fertilizers (UDF) in the United States

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Neil Patel  Tatiana Schreiber

The Urinterns!

HRSD
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Brown & Caldwell
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New Water Resources

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