# Enhancing Struvite Recovery: Optimizing Solubility and Energy with Adaptive Technology

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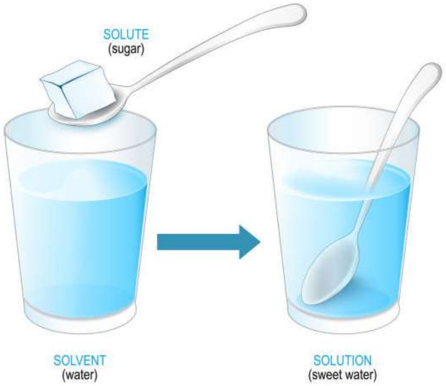
# HIGHLIGHTS

- Struvite chemistry and morphology
- Chemical equilibrium models & critical parameters of struvite precipitation
- Experimental Inference from Electromagnetic Field (EMF) – Rapid Nucleation
- Technologies for nutrient recovery in wastewater treatment
- Previous lab findings and results
- UVM filter phlo trailer
- Potential research pathways for the optimization of struvite recovery.
- Key takeaways

# Struvite Chemistry & Morphology

Struvite was first identified in 1939, and its buildup in wastewater pipes has since been reported as a frequent issue.

Nutrient overload`



Associated problems`

**Struvite Formation**

Ion activity product

IAP = $\{Mg\}\,\{\mathrm{NH}^{4+}\}\,\{PO_4^{3-}\}_{\text{solid phase}}$ > Thermodynamic solubility product ($K_{sp}$)

**Preceded by two primary stages:**

- Nucleation (crystal birth)
- Crystal growth

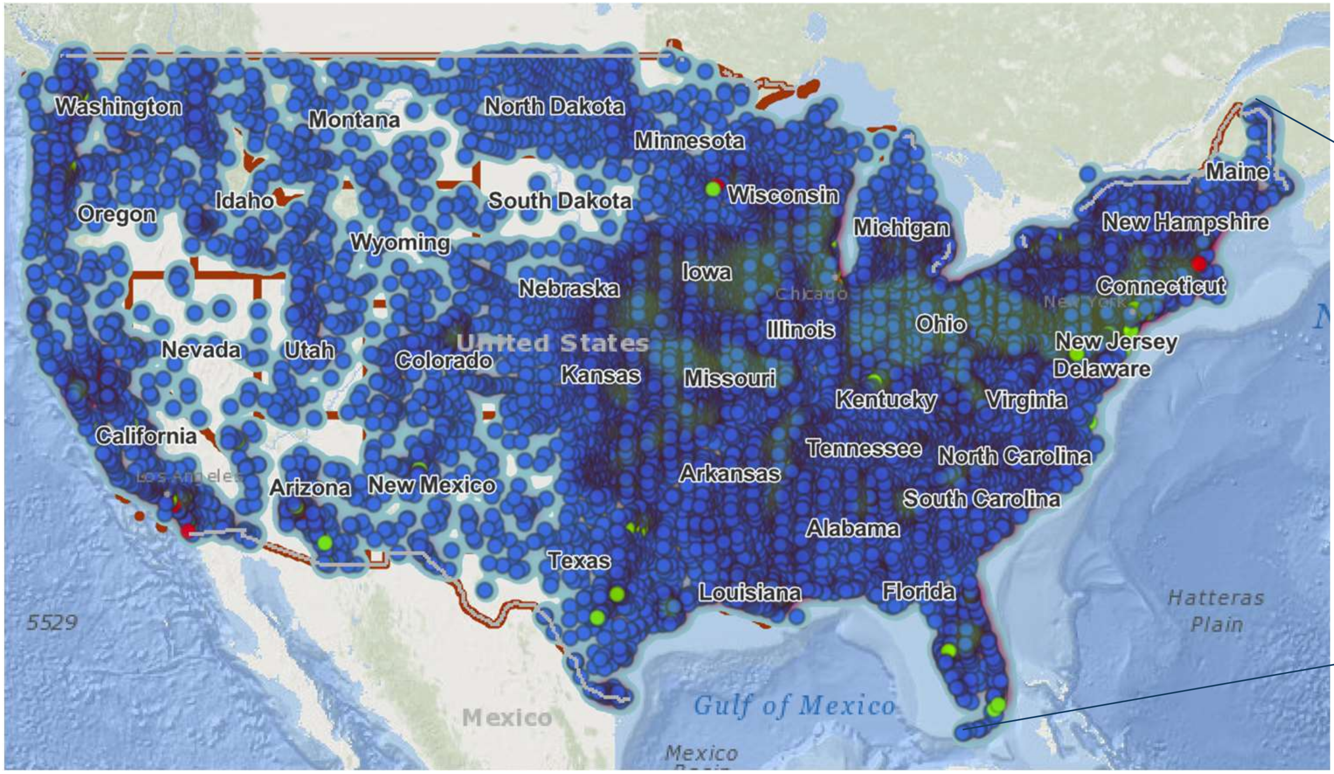
**General Equation** $\mathbf{Mg^{2+} + NH_4^+ + H_nPO_4^{3-n} + 6H_2O \rightarrow MgNH_4PO_4.6H_2O + nH^+}$ where n = 0, 1, or 2

# Wastewater Treatment Facilities (WTF) Across CONUS

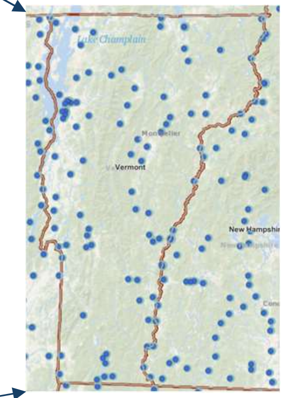
**Number of Plants**
**16k**

**Avg Pop Served**
**17.4k**

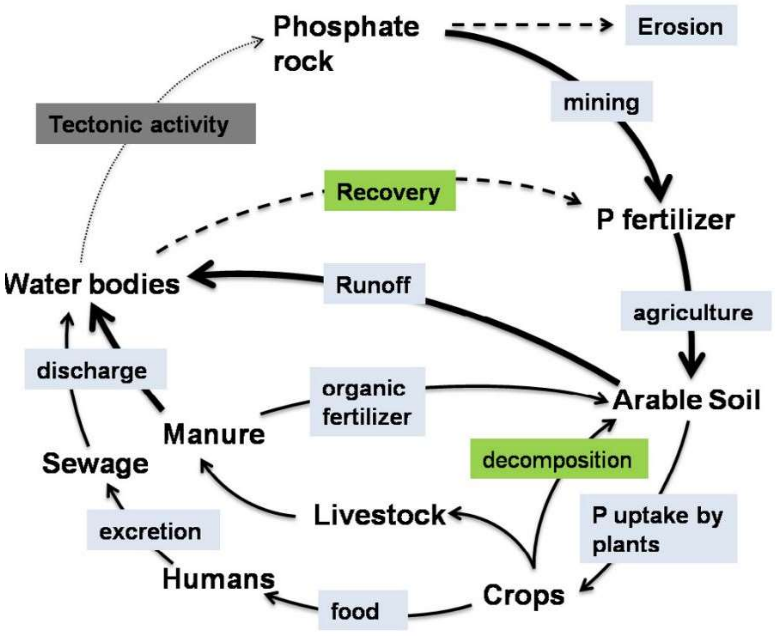
**Avg Design Capacity (m3/day)**
**13k**



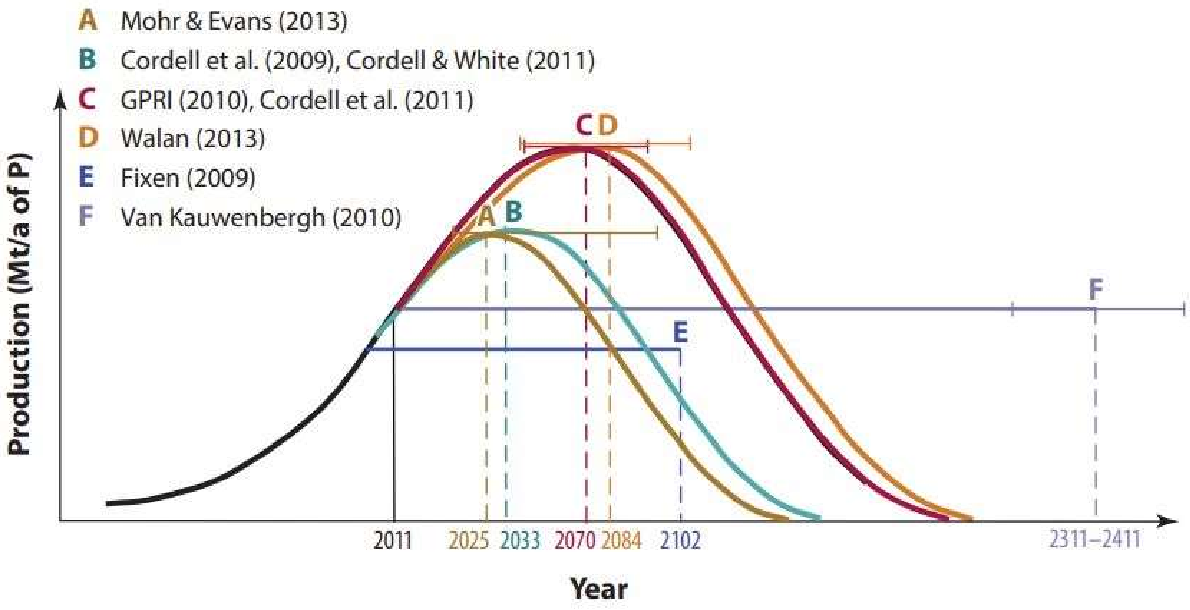
**Large WTF: 21%**
**Small WTF: 79%**



# Trajectory of Phosphorus



**Phosphorus cycle**



*Various author's projections on global phosphate depletion scenarios. Source: (Cordell & White, 2014)*

# Chemical Equilibrium Models (CEM)

Numerous studies have explored the precipitation kinetics and the conditions under which struvite crystallizes using chemical equilibrium models (CEM), which is guided by solution chemistry and thermodynamic principles.

## Literature Review on CEM

**Hanhoun et al., (2013)** developed a population balance model with a thermodynamic framework to predict particle size distribution and control struvite nucleation and growth kinetics.

**Gadekar & Pullammanappallil, (2010)** formulated a mathematical model for the precipitation process, integrating physicochemical equilibrium principles, mass balance calculations for struvite recovery.

**Jia et al., (2017)** leveraged the Visual MINTEQ chemical equilibrium model to precisely improve fundamental system variables, from anaerobic digester effluent in a wastewater treatment plant.

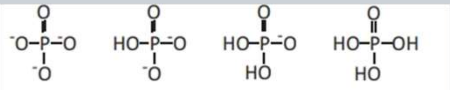
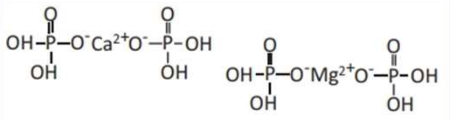
**Martín-Hernández et al., (2020)** utilized a probability framework embedded in the Monte Carlo method, to develop surrogate models for predicting the formation of struvite and calcium precipitates from cattle waste.

**CEM Benefits:**

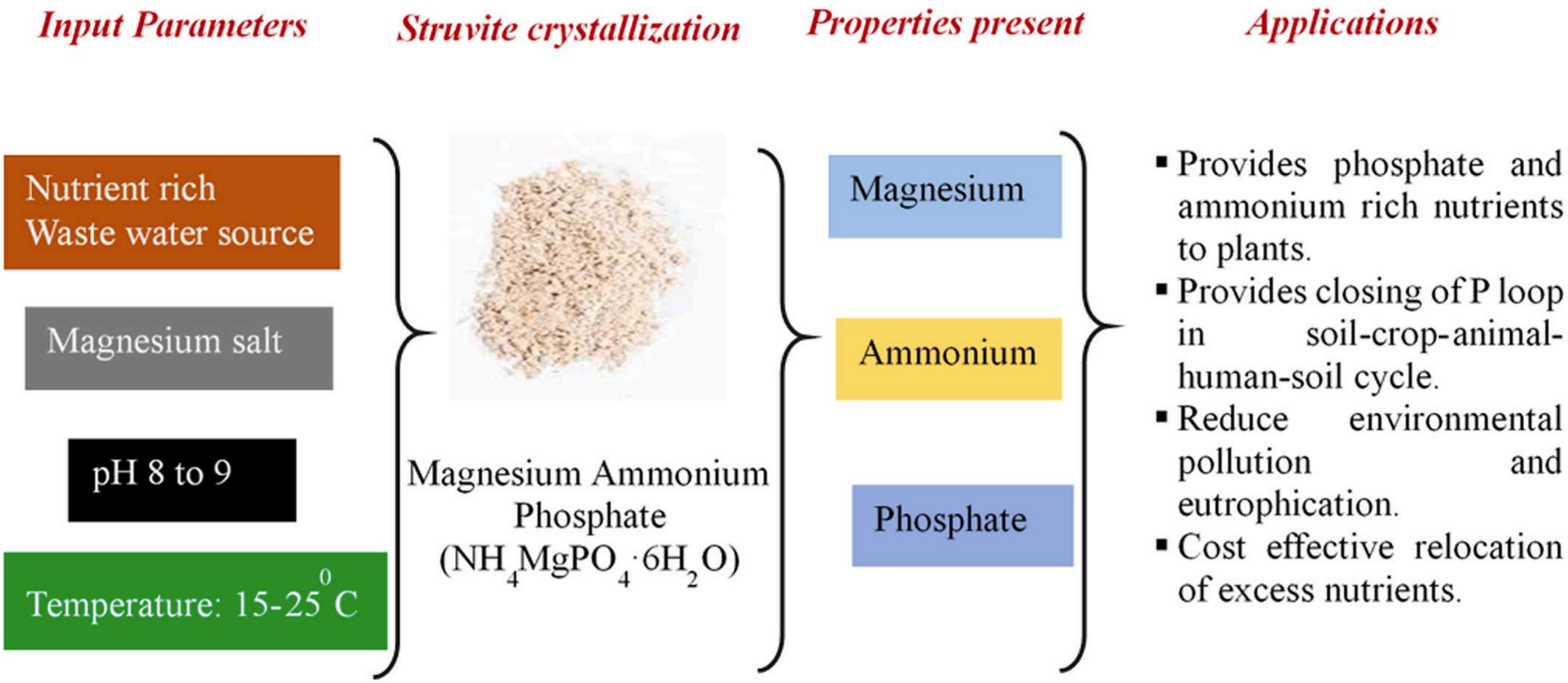
- Reduce reagent costs.
- Somewhat mitigate the impact of inhibitory ions such as $Ca^{2+}$, $K^{+}$, $CO_3^{2-}$, and
- Improve struvite recovery efficiency and purity.

**CEM Struggle:** Chemical equilibrium models often struggle to accurately capture nucleation, crystal growth, and overall struvite precipitation due to the complex interplay of factors such as pH, temperature, ionic strength, and reactant concentrations.

# Critical Parameters of Struvite Precipitation

| pH | Temperature | Supersaturation | Inhibitory ions |
|---|---|---|---|
| Based on various studies, the optimal pH range for struvite precipitation is between 7.5 and 9.5.<br><br>Orthophosphates<br><br>Divalent cation precipitates | Plays a crucial role in influencing the solubility, morphology, and the processes of formation and dissolution of struvite crystals (Siciliano et al., 2020). Struvite precipitation is most effective at typical ambient temperatures, ranging from 25 to 35°C. | A supersaturated solution (SS) promotes crystallization through the chemical reaction of free ions. Saturation Index ($SI_{MAP}$) directly influences the solution's pH by governing the solubility behaviour of struvite.<br>**$SI_{MAP}$**<br>= - means undersaturation<br>= + means Supersaturation<br>$SI_{MAP} = \log \frac{[Mg^{2+}].[NH_4^+].[PO_4^{3-}]}{\left(\frac{K_{SMAP}}{\gamma Mg.\gamma NH_4.\gamma PO_4}\right)}$ | The composition of wastewater varies in terms of ionic species and concentrations (e.g., $Ca^{2+}$, $Zn^{2+}$, $Cu^{2+}$, $Al^{3+}$, $CO_3^{2-}$, and $SO_4^{2-}$), which can adversely impact the process by reducing nutrient recovery efficiency, compromising product purity, altering crystal morphology, and slowing down reaction rates. |

# Consistent findings from literature



***Input Parameters***

- Nutrient rich Waste water source
- Magnesium salt
- pH 8 to 9
- Temperature: 15-25 $^0$C

***Struvite crystallization***

Magnesium Ammonium Phosphate ($NH_4MgPO_4 \cdot 6H_2O$)

***Properties present***

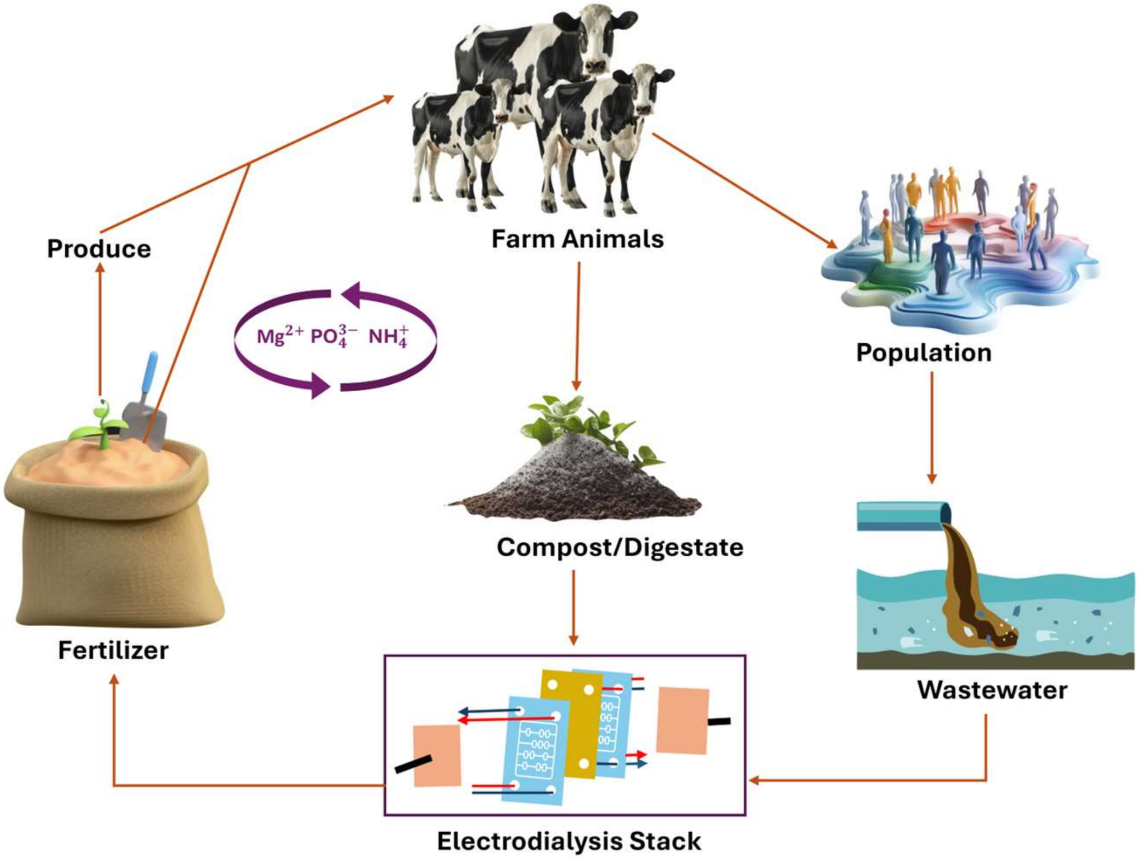
- Magnesium
- Ammonium
- Phosphate

***Applications***

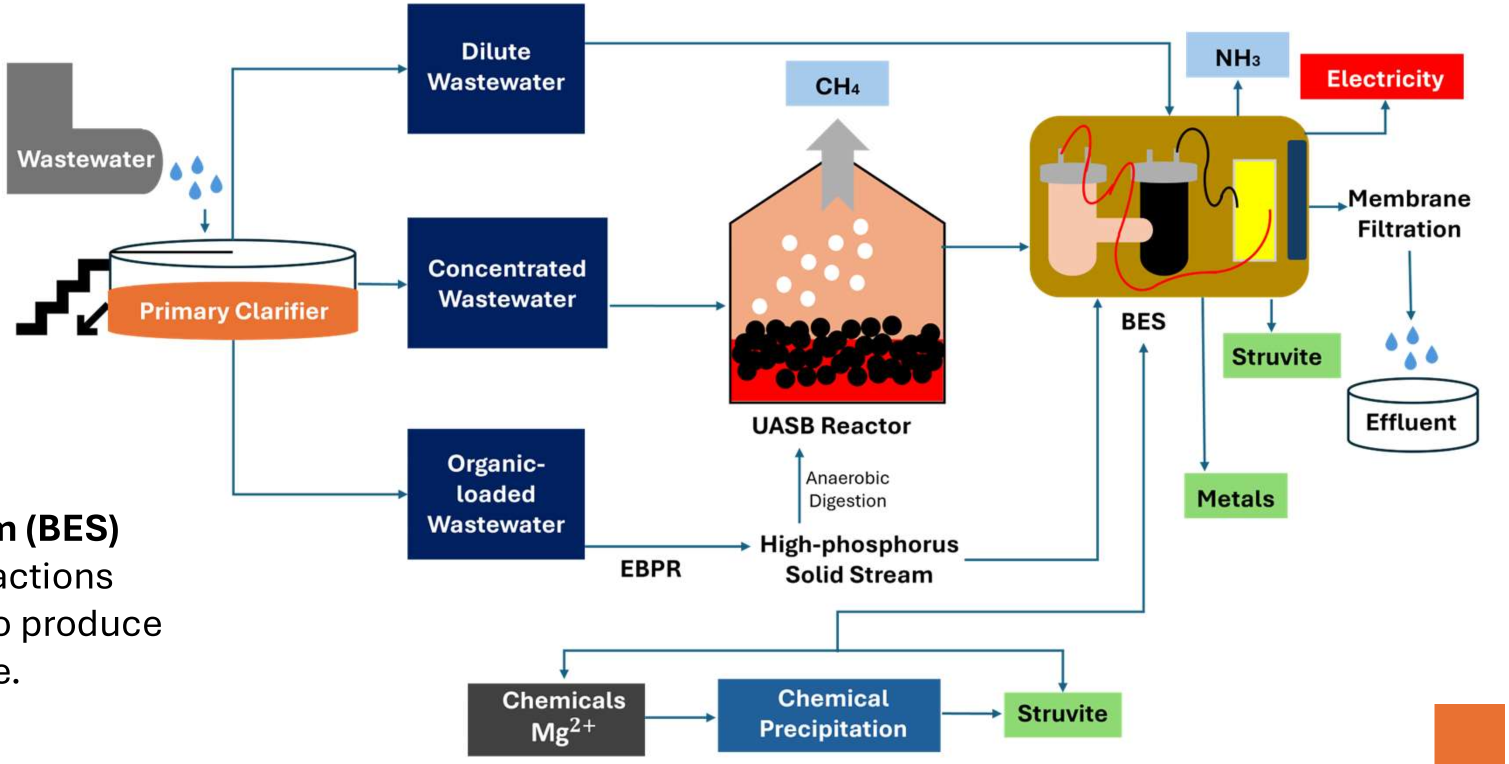
- Provides phosphate and ammonium rich nutrients to plants.
- Provides closing of P loop in soil-crop-animal-human-soil cycle.
- Reduce environmental pollution and eutrophication.
- Cost effective relocation of excess nutrients.

# Technologies for nutrient recovery in wastewater treatment

**Electrodialysis**
ED is an advanced membrane-based technology that operates on the principle of ion migration through selective ion exchange membranes (IEMs), offering a highly efficient method for ion separation and concentration.



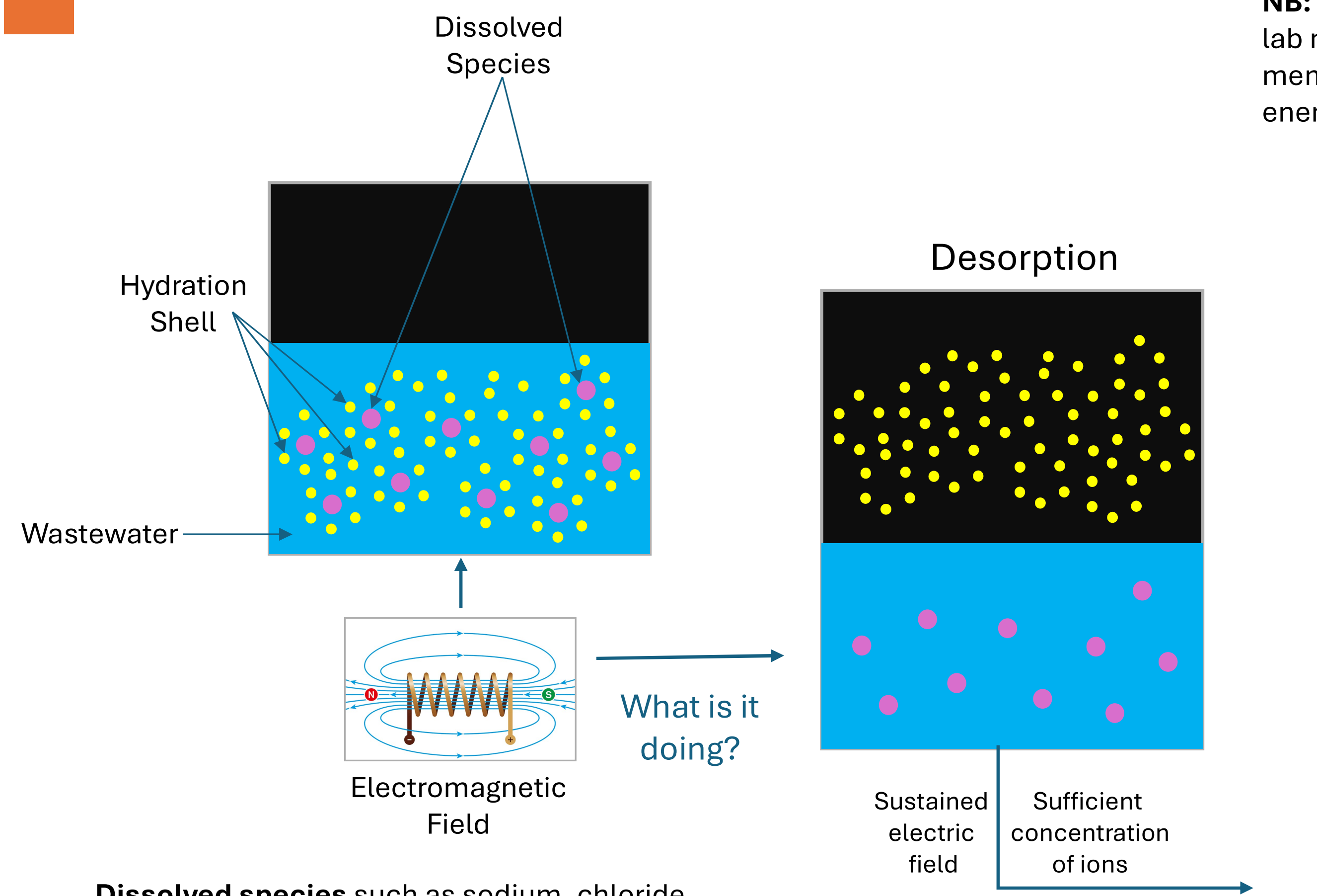
# Technologies for nutrient recovery in wastewater treatment



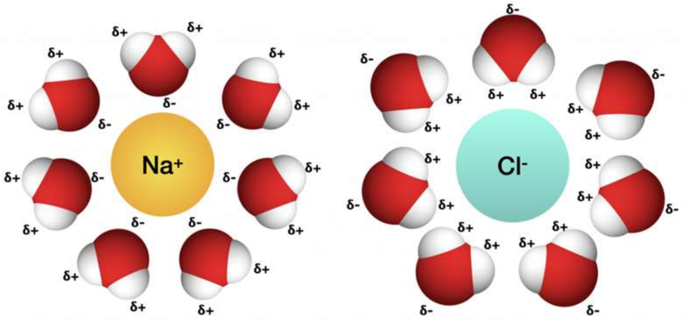
**Bioelectrochemical System (BES)** harness electrochemical reactions and microbial metabolism to produce electricity as shown in Figure.

# Previous Lab Findings: Experimental Inference

**NB:** This research builds upon the prior hypothesis of my lab member Khan (2023), who found that electrified membranes show significant potential as an external energy source to improve ion mobility and reaction kinetics.

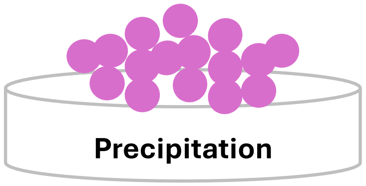


New **pH** happens



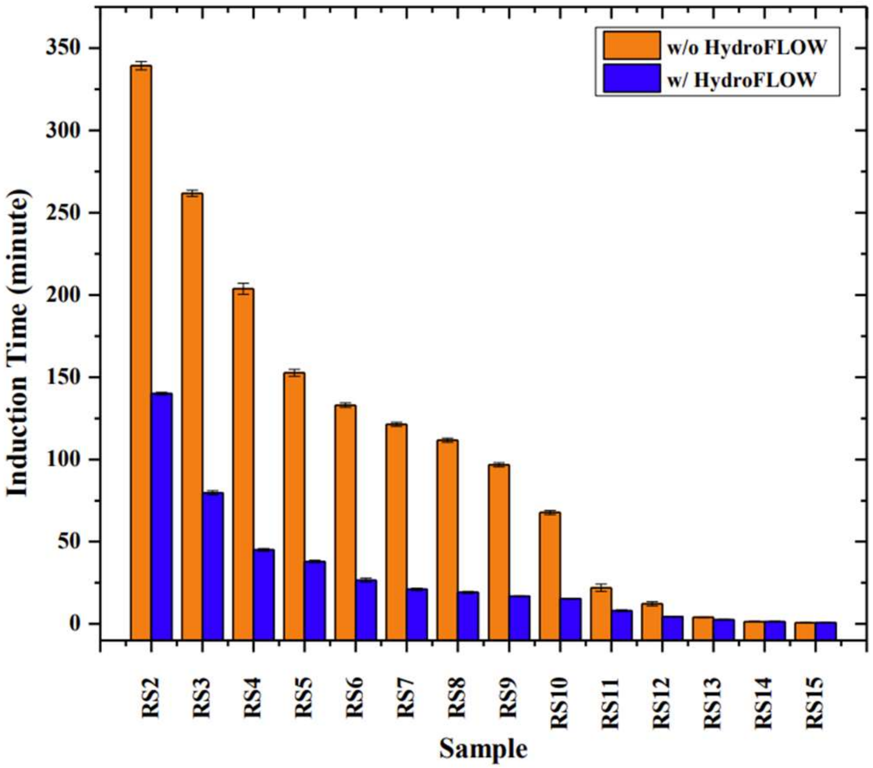
**Benefits**

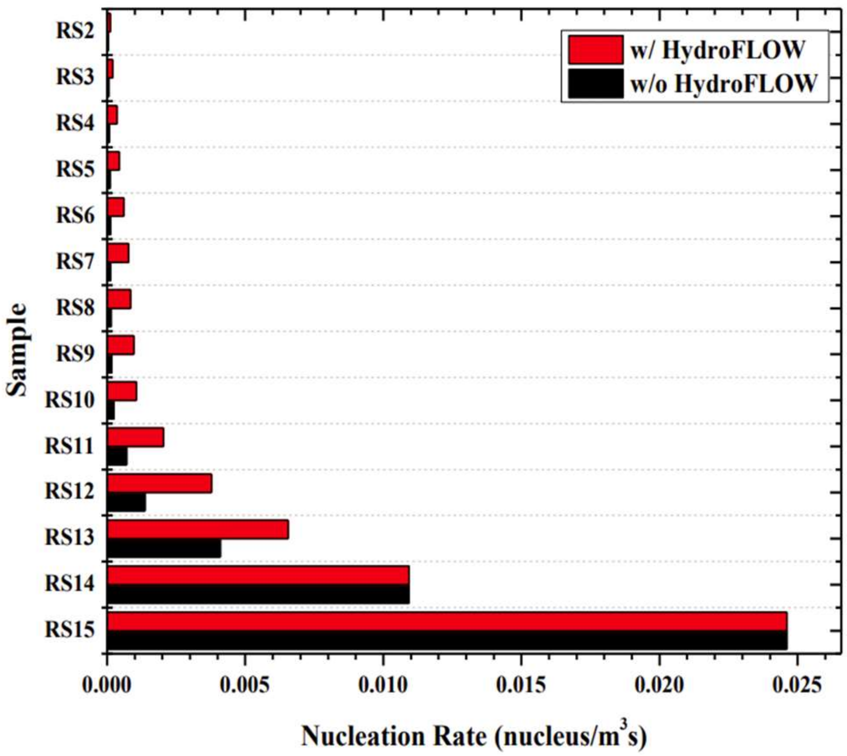
- Reduced induction time
- Increased crystal growth



● **Dissolved species** such as sodium, chloride, magnesium, phosphate, potassium, ammonium, bicarbonate, sulfate.

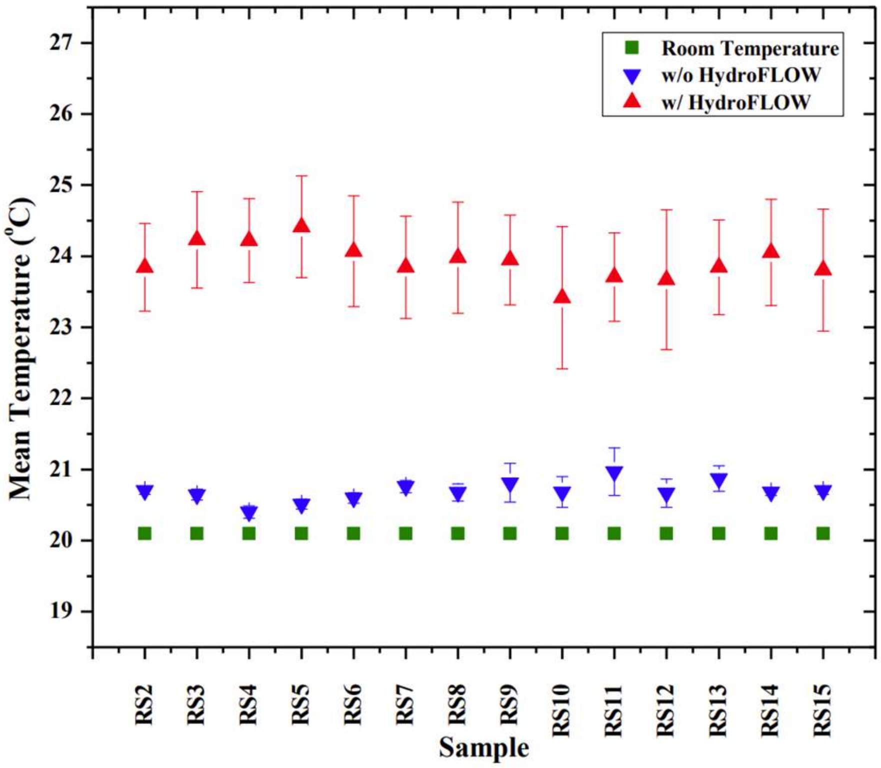
# Previous Lab Findings: Struvite Induction Time and Nucleation Rate with and without Hydroflow

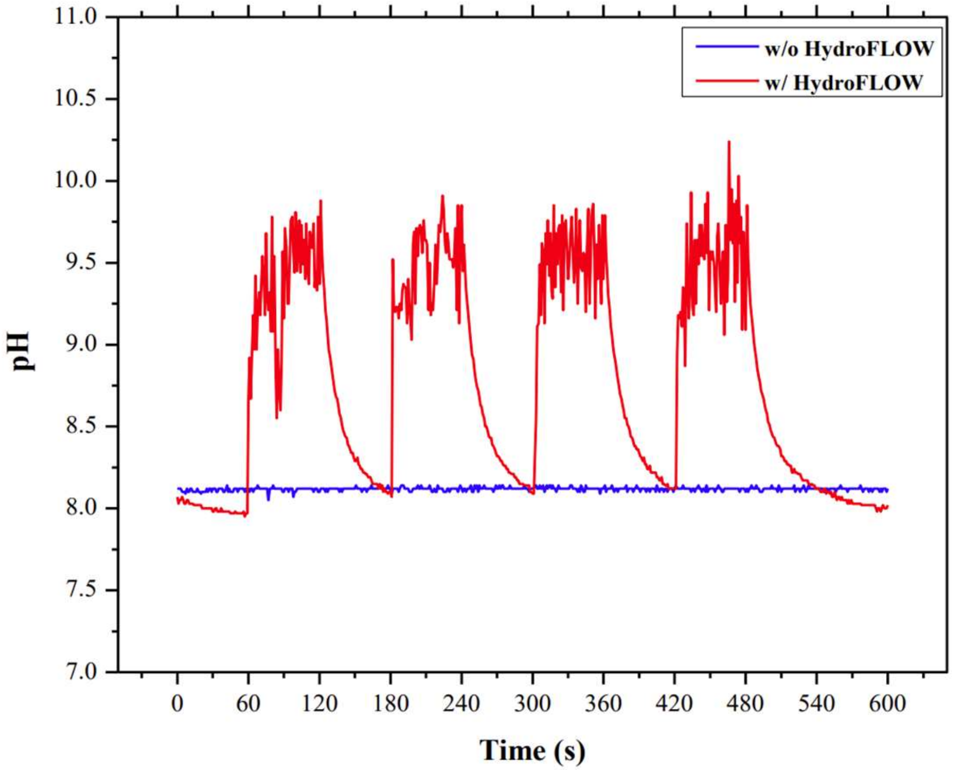




*Khan, K. (2023). SARS-CoV-2 Surveillance and Assessment of Oscillating Electric Field-Assisted Phosphorus Recovery and Inactivation of Escherichia coli in Wastewater. The University of Vermont and State Agricultural College.*

# Previous Lab Findings: Effect of Hydroflow on Temperature and pH





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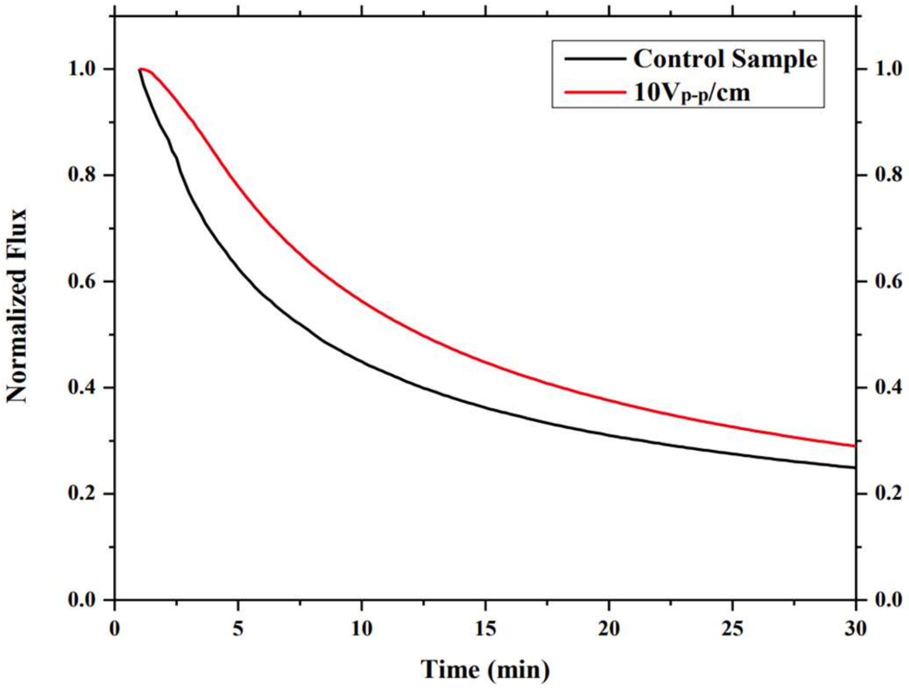
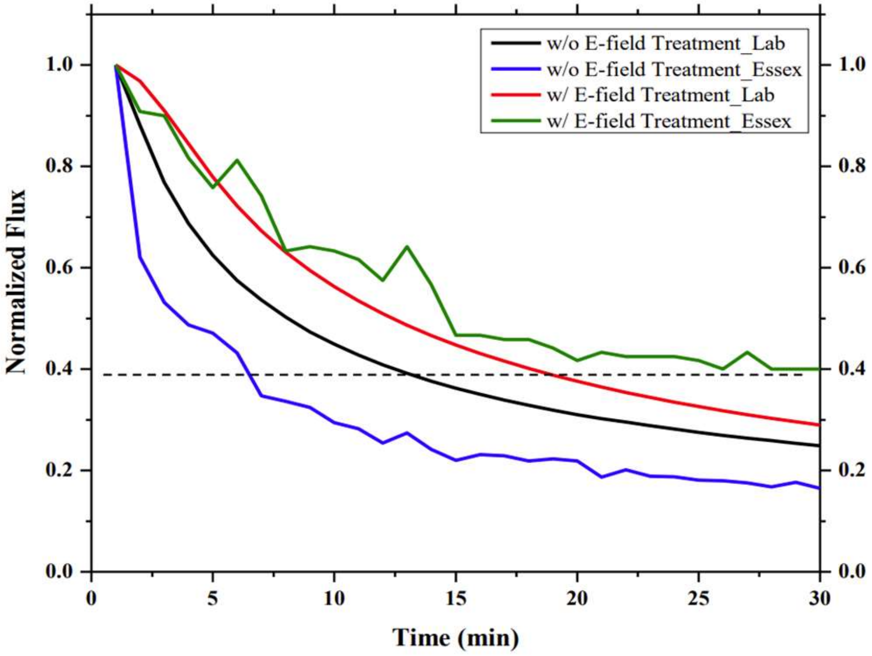
# Previous Lab Findings: Visualization of Membrane Fouling



a) electrical field (10Vp-p/cm) treated (bench-scale)



b) Comparison of pilot-scale and bench-scale flux

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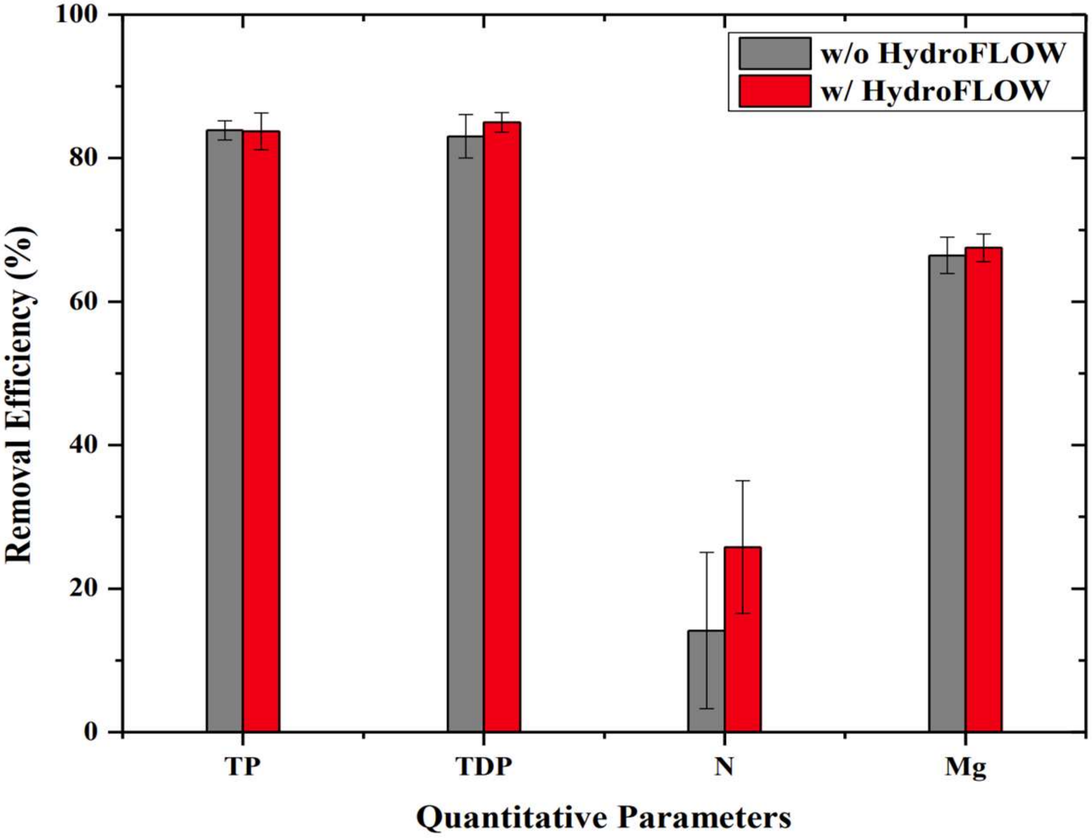
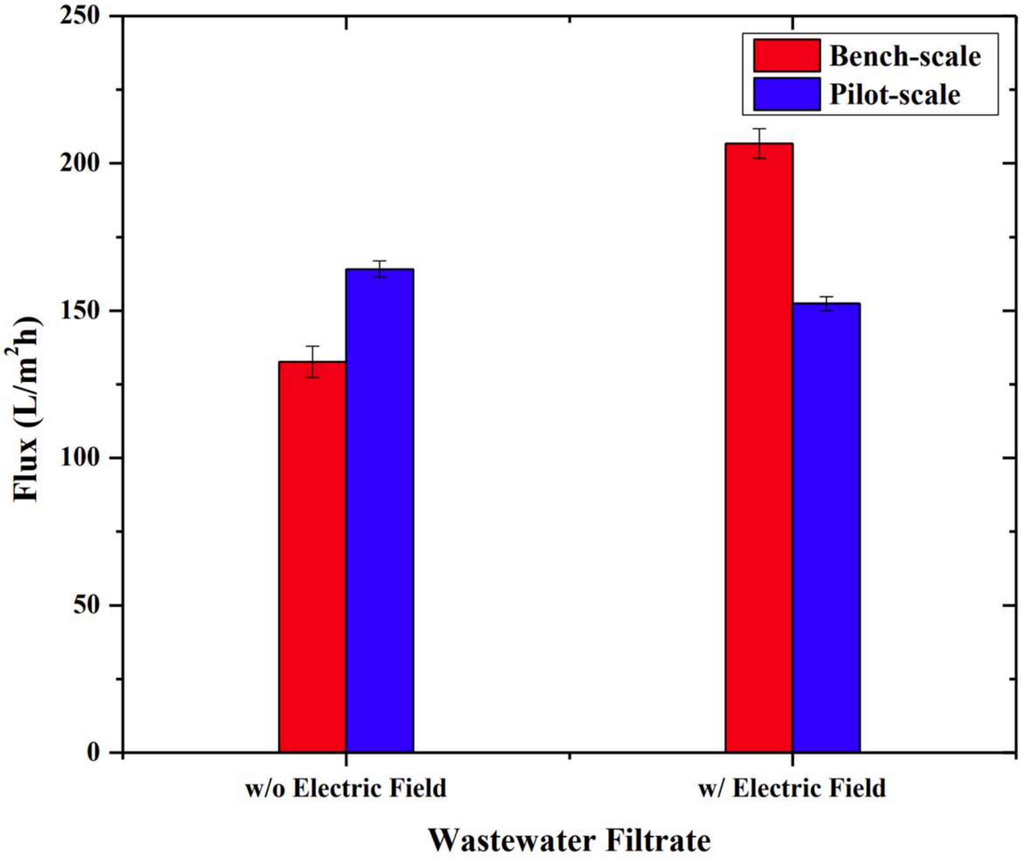
# Previous Lab Findings: Removal Efficiency from Side-stream Wastewater



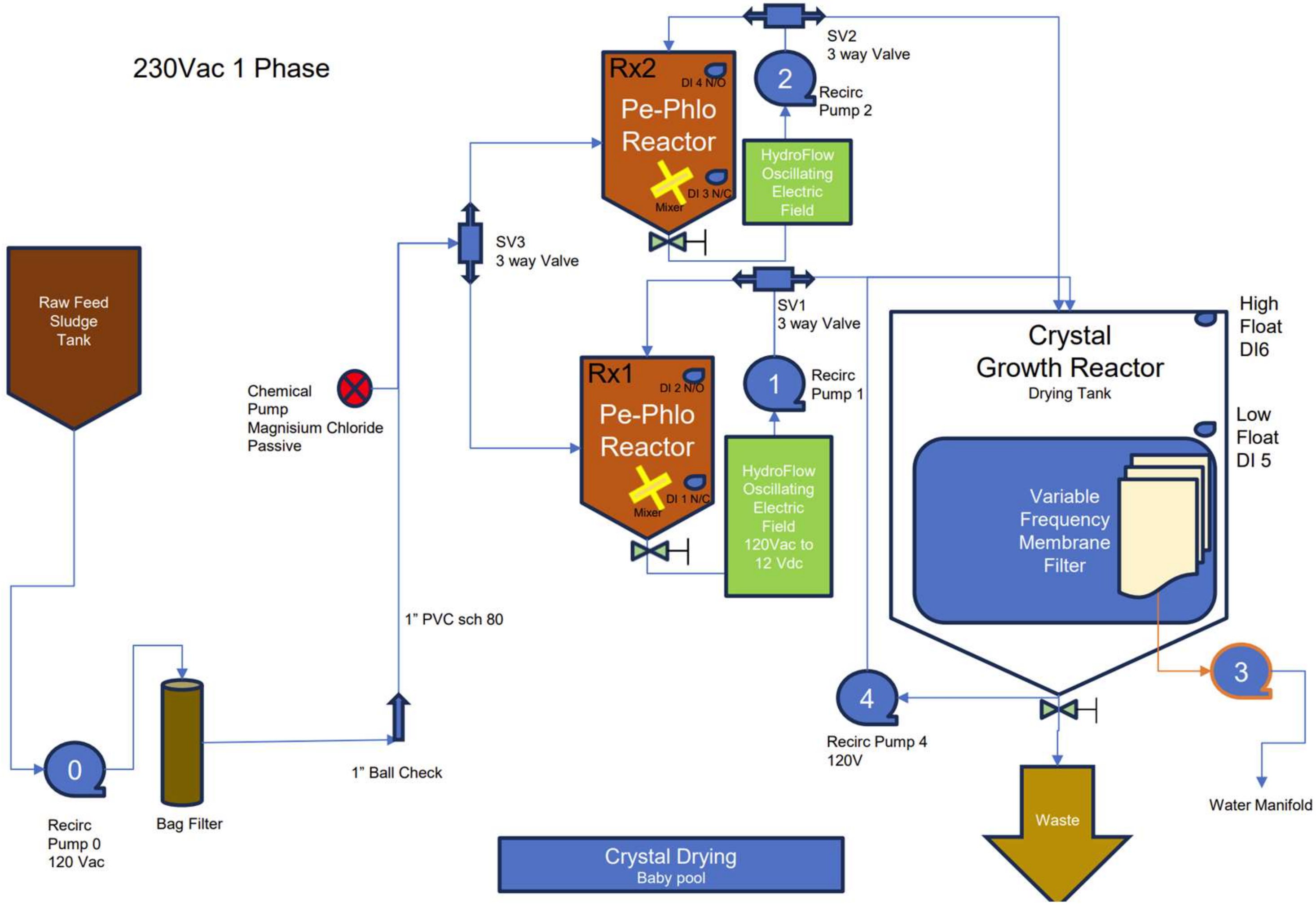
*Khan, K. (2023). SARS-CoV-2 Surveillance and Assessment of Oscillating Electric Field-Assisted Phosphorus Recovery and Inactivation of Escherichia coli in Wastewater. The University of Vermont and State Agricultural College.*

# Previous Lab Findings: Flux Data for Bench- & Pilot-scale



*Khan, K. (2023). SARS-CoV-2 Surveillance and Assessment of Oscillating Electric Field-Assisted Phosphorus Recovery and Inactivation of Escherichia coli in Wastewater. The University of Vermont and State Agricultural College.*

# UVM Filter Phlo Trailer



230Vac 1 Phase

Raw Feed
Sludge
Tank

Recirc
Pump 0
120 Vac

Bag Filter

1” Ball Check

1” PVC sch 80

Chemical
Pump
Magnisium Chloride
Passive

SV3
3 way Valve

Rx2
DI 4 N/O
Pe-Phlo
Reactor
DI 3 N/C
Mixer

SV2
3 way Valve

Recirc
Pump 2

HydroFlow
Oscillating
Electric
Field

SV1
3 way Valve

Rx1
DI 2 N/O
Pe-Phlo
Reactor
DI 1 N/C
Mixer

Recirc
Pump 1

HydroFlow
Oscillating
Electric
Field
120Vac to
12 Vdc

Crystal
Growth Reactor
Drying Tank

High
Float
DI6

Low
Float
DI 5

Variable
Frequency
Membrane
Filter

Recirc Pump 4
120V

Waste

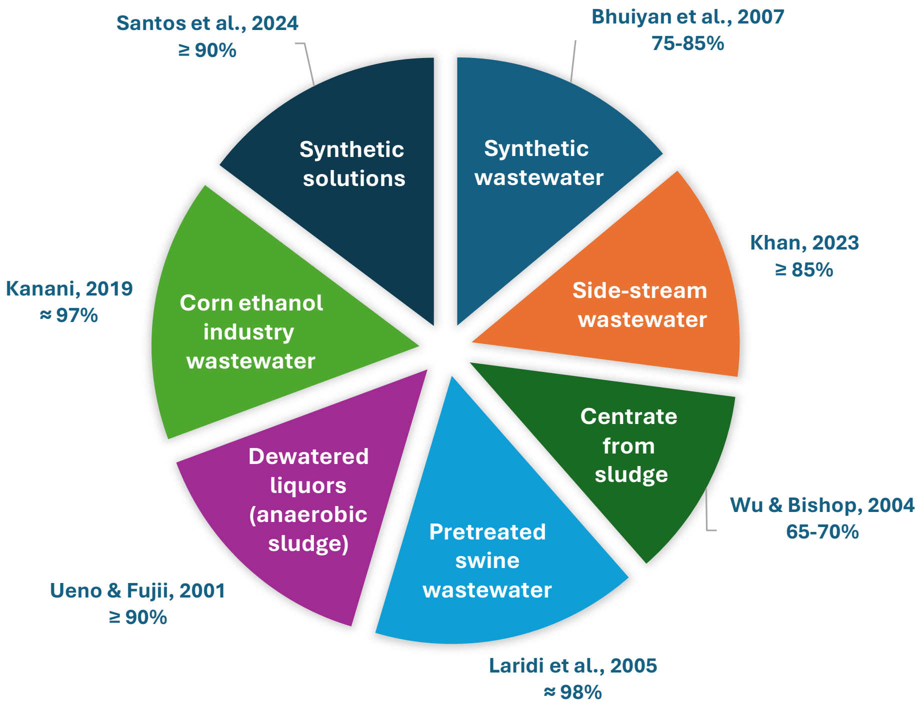
Water Manifold

Crystal Drying
Baby pool

# UVM Filter Phlo Trailer

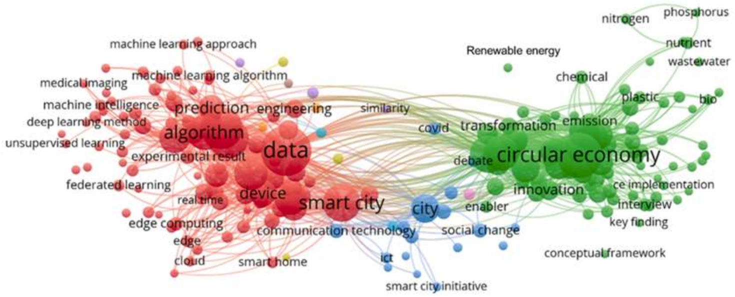
Some of the components in the mobile Pe-Phlo system.

# Phosphorus recovery rates categorized by associated technologies and operational scales.



| **Process/Technology** | **Scale** |
|---|---|
| 🟦 Fluidized bed reactor (FBR) | Bench-scale & Pilot scale |
| 🟧 Pe-Phlo reactor | Bench-scale & Pilot scale |
| 🟩 2L Beakers seeded with sand | Bench-scale |
| 🟦 Stirred reactor | Pilot scale |
| 🟪 Fluidized bed reactor (FBR) | Full scale |
| 🟩 Stirred batch reactor | Bench-scale |
| ⬛ Beakers seeded with biomass ash | Bench-scale |

# Future Research Pathway



In process control, two different types of modeling are most commonly seen: mechanistic models (MM) and black-box models (BBM).

**MM:** work best if the theory of system is known explicitly through either experimental or theoretical correlations.

**BBM:** deterministic modeling with inherent non-linearity such as ANN. Works best with loosely organized data structure.

Advanced Chemical Modeling and Optimization of Struvite Recovery for Sustainable Wastewater Treatment Systems

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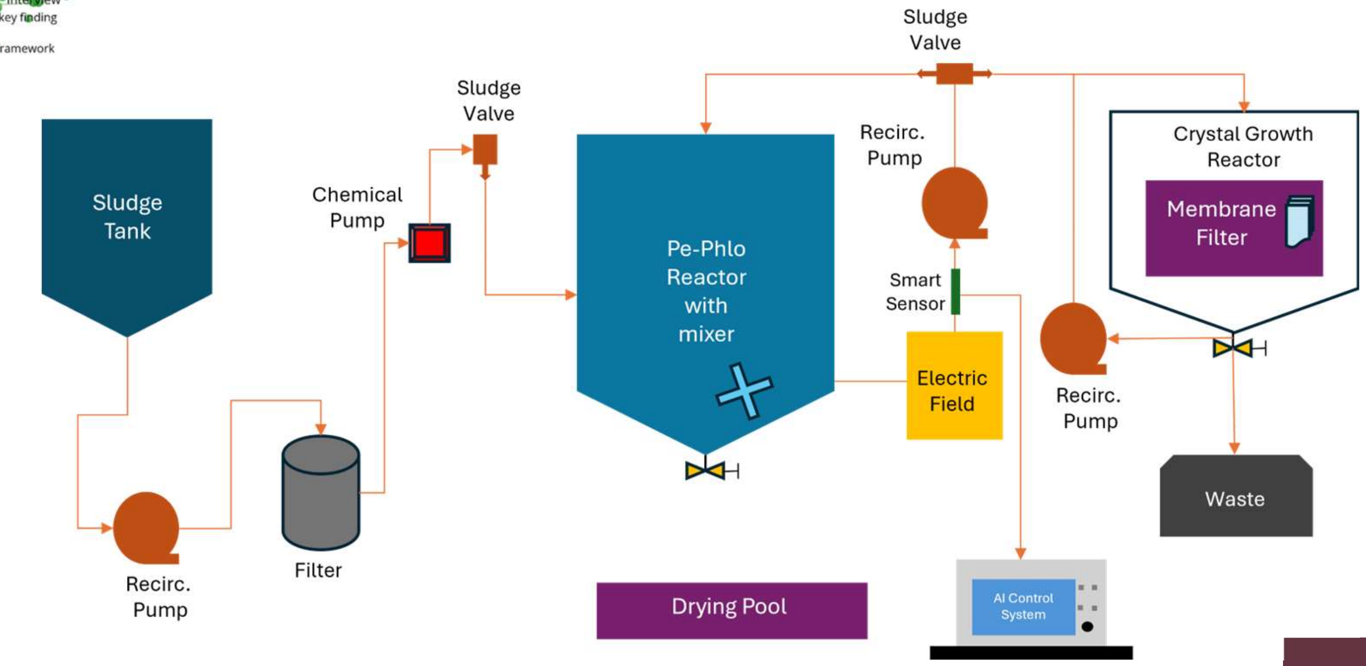

# Key Takeaways

- Struvite precipitation occurs when solution is supersaturated.
- Pe-Phlo system works well for small-medium scale operation.
- EMF can induce rapid nucleation (reduced induction time & increased crystal growth).
- Factor indicative of the total effect of EMF and model(s) that truly explain this mechanistically is of significant interest.
- AI-driven control can predict supersaturation level, improve chemical dosing, regulate ammonia levels through microbial activity, and ultimately reduce process variability and operational cost.

# WTEN Lab Members

**Water Treatment & Environmental Nanotechnology**

**Previous Lab Member:**
Kamruzzaman Khan

Abhina Chonnambi

Kehinde Ojasanya

Monireh Dehabadi

**Appala Raju Badireddy**

Eshita Jhahan

Sajjad Eftekhary

University of Vermont

# Project Funders/Collaborators

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**Kenneth Mcgowan**

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