

Optimization of Magnesium-Ammonium-Phosphate (Struvite) Precipitation for Nutrient Recovery from Synthetic Distilling Wastewater

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ABSTRACT

Phosphorus (P) and nitrogen (N) are finite yet indispensable nutrients whose excessive discharge into aquatic systems accelerates eutrophication, while their depletion from natural reserves poses a global sustainability concern. This study explores the optimization of struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$) precipitation as a cost-effective and environmentally sound approach for nutrient recovery from synthetic distillery wastewater. Batch experiments were conducted to investigate the influence of the molar ratios of $\text{NH}_4\text{:PO}_4$ (1:1–5:1) and Mg:PO_4 (1:1–2:1) at a controlled pH of 9.0 under ambient conditions. The maximum nutrient recovery was observed for $\text{NH}_4\text{:PO}_4$ (3:1) and Mg:PO_4 (1.5:1), with 98.5% phosphate and 96.5% ammonium removal efficiencies. The purity of the recovered struvite, as determined through ammonium nitrogen quantification and X-ray diffraction (XRD) analysis, confirmed the predominance of crystalline struvite phases. These findings underscore that optimal molar ratios significantly enhance nutrient crystallization kinetics and product quality. This work demonstrates the potential of controlled struvite precipitation as a scalable pathway for nutrient circularity and sustainable wastewater management within the distillery sector.

Keywords: Struvite crystallization, nutrient recovery, magnesium-ammonium-phosphate, wastewater valorization, optimization, resource recovery.

Introduction

Phosphorus (P) and nitrogen (N) are fundamental to global food production and ecosystem function, yet their management poses a dual challenge: on the one hand, excessive releases into surface waters drive eutrophication, algal blooms and aquatic-ecosystem disruption; on the other hand, finite phosphate rock reserves and rising demand for fertilizer indicate that nutrient scarcity is now a serious concern (Siciliano et al., 2020; Wang et al., 2021). The recovery of nutrients from wastewater streams is increasingly framed as a key pillar of the circular economy, enabling both pollution control and resource reuse (Siciliano et al., 2020).

In this context, the precipitation of magnesium-ammonium-phosphate (struvite, $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$) has emerged as a compelling strategy: it efficiently captures both ammonium-N and phosphate-P, produces a crystalline, slow-release fertiliser material, and generates less sludge than conventional chemical treatments (Issac, 2023; Chen et al., 2021). For example, Issac (2023) found that struvite precipitation eliminated a significant amount of both N and P from urban wastewater streams, resulting in a material that matched commercial fertiliser release behaviour.

Nutrient loads in industrial wastewaters, such as those from distilleries, are frequently concentrated, making them prime targets for recovery technology. A case study at Tain (UK) on distillery effluent found that struvite precipitation produced around 80% P recovery from distillery-derived wastewater sludge liquor (Water Europe case study, 2024). However, reaching high efficiencies and good product quality necessitates careful optimisation of process parameters (e.g., Mg:P and $\text{NH}_4\text{:PO}_4$ molar ratios, pH, and reaction duration), as well as management of interfering ions and organics (Siciliano et al., 2020; Chen et al., 2021).

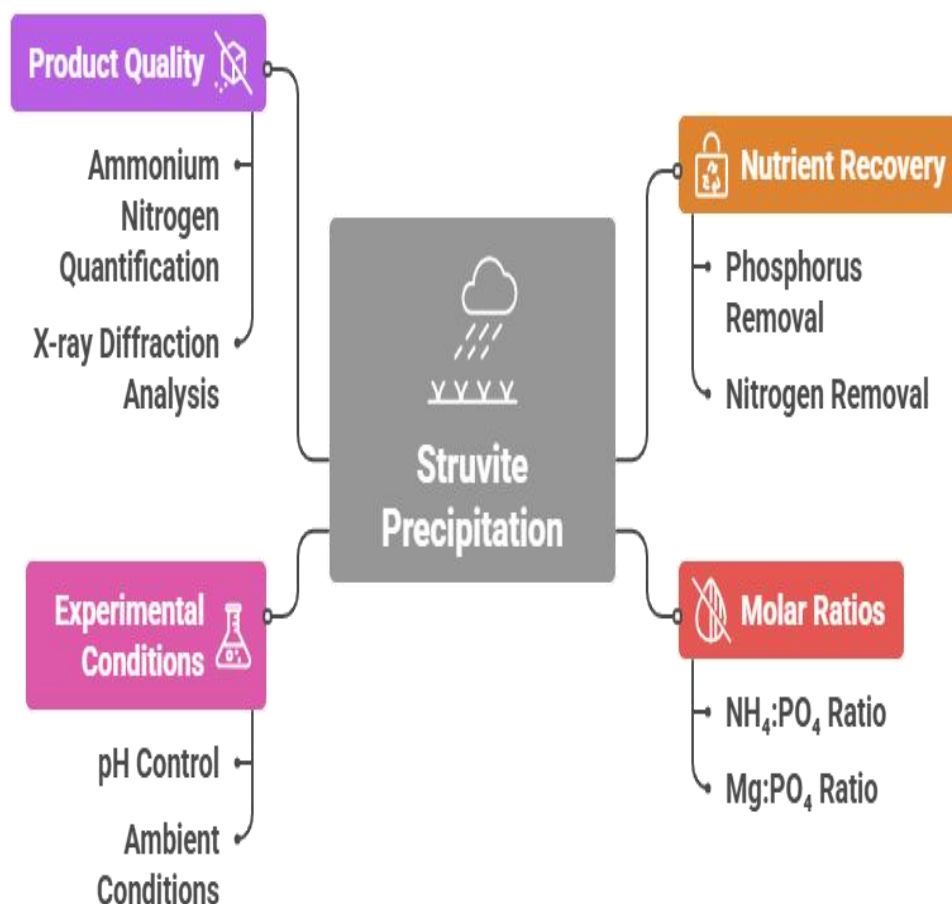
Our study used synthetic distillery wastewater and batch experiments to test the effects of varying $\text{NH}_4\text{:PO}_4$ ratios (from 1:1 to 5:1) and Mg:PO₄ ratios (from 1:1 to 2:1) at pH 9.0. According to thesis data, $\text{NH}_4\text{:PO}_4 = 3:1$ and $\text{Mg:PO}_4 = 1.5:1$ resulted in the highest phosphate removal (~98.5%) and ammonium removal (~96.5%) rates. These findings are consistent with those of Wang et al. (2021) and Funani (2025), who found that optimal Mg:P and $\text{NH}_4\text{:P}$ ratios had a considerable

influence on the recovery efficiency and purity of struvite crystals. Importantly, the prevalence of crystalline struvite phases (confirmed by XRD) at optimised conditions supports the possibility of producing a high-quality fertiliser product.

Despite these encouraging results, problems persist. Competing ions like Ca^{2+} or K^{+} , as well as complex organic materials like melanoidins found in distillery-spent washes, can hinder nucleation and modify crystal shape, resulting in reduced recovery and product quality (Chen et al., 2021). Furthermore, the ideal parameters discovered in synthetic systems must be reliable when applied to real commercial matrices with varying ionic strengths and organic contents. This explains the current study's emphasis on optimisation under controlled synthetic settings as a crucial precursor to ultimate real-effluent use.

Thus, the purpose of this study is to (i) systematically optimise the key molar ratios ($\text{NH}_4\text{:PO}_4$ and Mg:PO_4) for struvite precipitation from synthetic distillery wastewater; (ii) evaluate the removal efficiencies of N and P, as well as the crystallinity/purity of the precipitated product; and (iii) provide insight into how these optimised conditions may inform scale-up and real-wastewater applications in the distillery sector. By doing so, we contribute to the larger goal of closing the nutrient loop, lowering reliance on mined phosphate, and mitigating eutrophication risks.

Struvite Precipitation for Nutrient Recovery



Graphical abstract for the Optimization of Magnesium-Ammonium-Phosphate (Struvite) Precipitation for Nutrient Recovery from Synthetic Distilling Wastewater

Materials and Methods

Chemical Reagents

All analytical-grade reagents were obtained from Merck (Germany) and utilised without additional purification. The main components were magnesium chloride hexahydrate ($\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$), ammonium chloride (NH_4Cl), and potassium dihydrogen phosphate (KH_2PO_4), which are sources of magnesium, nitrogen, and phosphorus, respectively. pH control and interference investigations used many

reagents, including CaCl_2 , K_2SO_4 , phenol, dextrose, NaOH , and HCl .

All glassware was acid-washed (10% HCl) and rinsed with deionized (DI) water prior to use to avoid contamination. A digital pH meter (Hanna HI 2211) was calibrated daily using standard buffers of pH 4.0, 7.0, and 10.0.

Preparation of Synthetic Distillery Wastewater

A synthetic distillery wastewater matrix was developed to approximate the nutrient and organic composition of genuine distillery wasted washes using the compositions reported by Kumari et al. (2019). The model solution had $4.3 \text{ g L}^{-1} \text{KH}_2\text{PO}_4$, $11.8 \text{ g L}^{-1} \text{Na}_2\text{SO}_4$, 14 g L^{-1} phenol, and 100 g L^{-1} dextrose, replicating the high-strength organics and phosphate content found in distillery effluents.

The stock solutions were prepared as follows: To make $10 \text{ g L}^{-1} \text{NH}_4\text{-N}$, dissolve 38.6 g NH_4Cl in 1 L DI water. For $10 \text{ g L}^{-1} \text{PO}_4\text{-P}$, dissolve 4.3 g KH_2PO_4 . Mg^{2+} stock solutions were made from $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ with modified concentrations to achieve the necessary Mg:P molar ratios. To avoid chemical deterioration or microbiological influence, the synthetic wastewater was generated anew for each batch experiment.

Experimental Design for Struvite Precipitation

Batch studies were carried out in 250 mL Erlenmeyer flasks, each with 100 mL of synthetic wastewater. The flasks were placed on a magnetic stirrer (180 rpm) and kept at room temperature ($28 \pm 2 \text{ }^\circ\text{C}$). The pH was adjusted to 9.0 ± 0.1 using 1 M NaOH or 1 M HCl , which is known to encourage maximum struvite nucleation and crystal development (Parsons and Doyle, 2002; Wang et al., 2021). The studies were carried out over a 40-minute reaction time, followed by two hours of settling to allow the precipitates to mature.

Two molar ratios were optimized independently:

- $\text{NH}_4\text{:PO}_4$ varied from 1:1 to 5:1, and
- The Mg:PO_4 ratio was varied from 1:1 to 2:1.

After equilibration, the samples were filtered through $0.45 \text{ }\mu\text{m}$ cellulose-acetate membranes. The collected solids were oven-dried at $40 \text{ }^\circ\text{C}$ for 48 h, ground gently, and stored in airtight desiccators for analysis.

Evaluation of Interfering Ions (Ca^{2+} , K^+ , and Melanoidins)

To simulate realistic effluent conditions, separate tests were conducted to examine the effects of interfering ions on nutrient recovery and crystal morphology. Calcium and potassium were introduced as CaCl_2 and K_2SO_4 at molar ratios (Ca:Mg and K:Mg) of 0:1, 0.5:1, 1:1, 2:1, and 3:1.

Melanoidin complex brown polymeric compounds responsible for the color of the distillery spent wash were prepared synthetically following the glucose–glycine model described by Chen et al. (2021). Their effects on struvite formation were assessed under identical precipitation conditions (pH 9.0, 180 rpm, 40 min of reaction).

Analytical Procedures

The contents of ammonium nitrogen ($\text{NH}_4\text{-N}$) and phosphate phosphorus ($\text{PO}_4\text{-P}$) were measured using conventional procedures for water and wastewater analysis (APHA, 2017). $\text{NH}_4\text{-N}$ was quantified using the phenate colorimetric method (4500- NH_3 F), and $\text{PO}_4\text{-P}$ was calculated using the vanadomolybdophosphoric acid yellow method (4500-P C). The absorbance measurements were taken using a Shimadzu UV-1900 spectrophotometer at 640 nm for $\text{NH}_4\text{-N}$ and 470 nm for $\text{PO}_4\text{-P}$.

The percent recovery (R%) of nutrients was calculated as follows:

$$R(\%) = \frac{C_i - C_f}{C_i} \times 100$$

where C_i and C_f are the initial and final concentrations (mg L^{-1}) of the respective ions, respectively.

Determination of Struvite Purity

The purity of the precipitated struvite was determined using the stoichiometric nitrogen content of magnesium ammonium phosphate, as described by Li et al. The dried precipitate was redissolved in minimum DI water with a few drops of strong HCl, and $\text{NH}_4\text{-N}$ was measured using the phenate method. The computed molar ratio of N, Mg, and P was compared to the theoretical 1:1:1 composition of pure struvite.

Crystallographic and Morphological Characterization

The crystal morphology was investigated using a compound optical microscope (Leica DM 1000) and digital imaging software. X-ray diffraction (XRD) patterns

were acquired using a PANalytical X'Pert PRO diffractometer (Cu K α radiation, $\lambda = 1.5406 \text{ \AA}$) at 40 kV/30 mA. The diffraction angles (2θ) were scanned from 10° to 70° , and phases were identified by comparing to the Joint Committee on Powder Diffraction Standards (JCPDS PDF# 01-071-2089) for struvite.

Data Analysis and Quality Assurance

To ensure reproducibility, each experiment was performed in triplicate. Data are shown as means $\pm$ standard deviations. Statistical analyses were performed using OriginPro 2024 (OriginLab, USA) to discover significant differences ($p < 0.05$) between treatments. All operations were carried out in a controlled laboratory environment to ensure consistency and traceability.

Struvite Precipitation Process and Analysis



Analytical analysis flow diagram and materials and methods for Optimization of Magnesium-Ammonium-Phosphate (Struvite) Precipitation for Nutrient Recovery from Synthetic Distilling Wastewater

Results

Nutrient Recovery Efficiency

Nutrient recovery ability was evaluated by removing phosphate-phosphorus ($\text{PO}_4\text{-P}$) and ammonium-nitrogen ($\text{NH}_4\text{-N}$) from synthetic distillery wastewater at different molar ratios. The overall pattern indicated a progressive improvement in recovery up to an optimum ratio, followed by a slow drop (Figure 1A).

In the nutrient recovery a 3:1 $\text{NH}_4\text{:PO}_4$ ratio resulted in the best recovery rates of 98.5% for $\text{PO}_4\text{-P}$ and 96.6% for $\text{NH}_4\text{-N}$, indicating almost full nutrient precipitation. Lower ratios (1:1 and 2:1) produced 88-92% recovery, however higher ratios (4:1 and 5:1) resulted in a modest decline, most likely due to ionic supersaturation and the development of colloidal precipitates rather than well-defined crystals. The purity of struvite improved with increasing $\text{NH}_4\text{:PO}_4$ ratios, reaching 78.6% at 3:1 and decreased at 4:1 and 5:1 (Figure 1B).

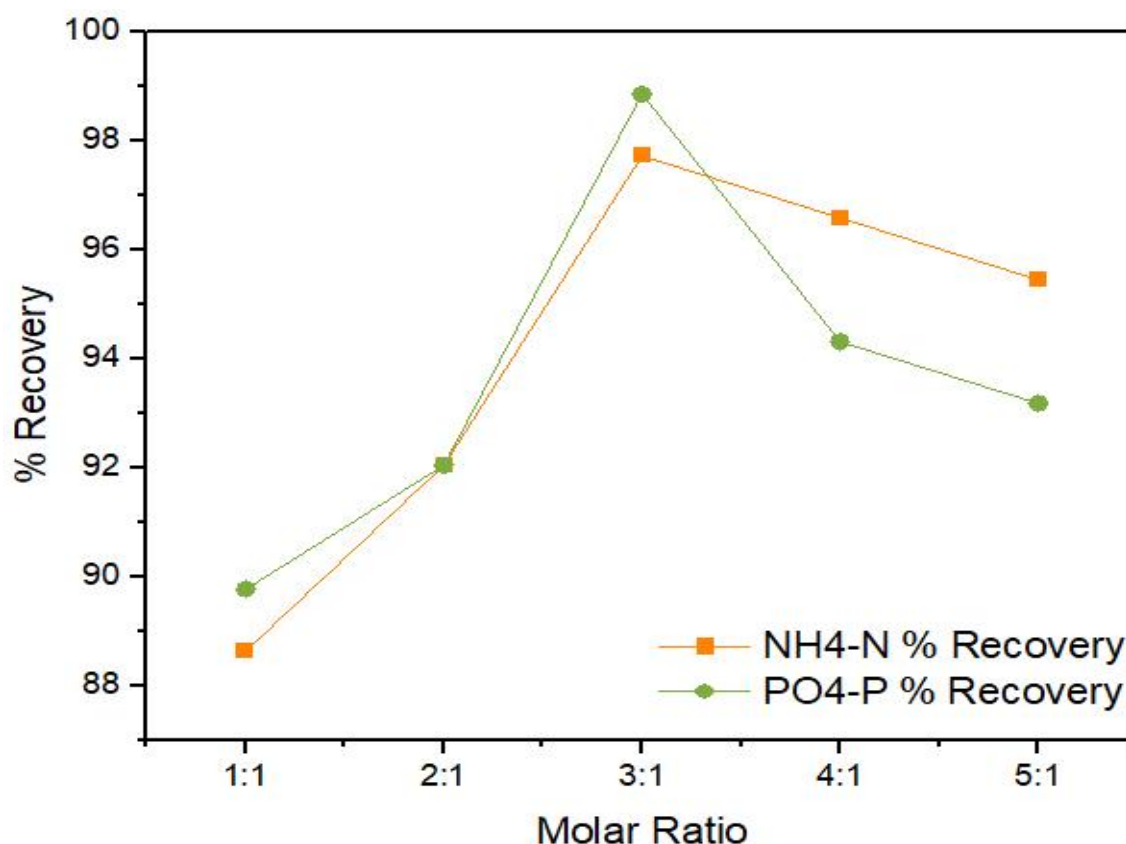


Figure 1 (1A-1B): Ammonium-Nitrogen and Phosphate-Phosphorus Recovery (%) (A), % Purity of Struvite at varying $\text{NH}_4\text{:PO}_4$ ratios (B).

Effect of Magnesium to Phosphate Ratio

The Mg:PO₄ ratio was optimised to assess its impact on nutrient recovery and struvite formation. The recovery rate increased dramatically as the ratio increased from 1:1 to 1.5:1, with 96.5% phosphate and 94% ammonium recovery. Further increases to 1.75:1 and 2:1 resulted in a little decrease, indicating that extra magnesium did not improve crystallisation efficiency (Figure 2A).

The maximum struvite purity (59.7%) was discovered at Mg:PO₄ = 1.75:1, suggesting that the optimum stoichiometric range occurs near 1.5:1, where crystallisation is stable and selective. The graph reveals that the percentage purity of struvite of ammonia is 39.0% at Mg:P (1.5:1), 59.7% at Mg:P (1.75:1), and 57.7% at Mg:P (1.25:1) (Figure 2B).

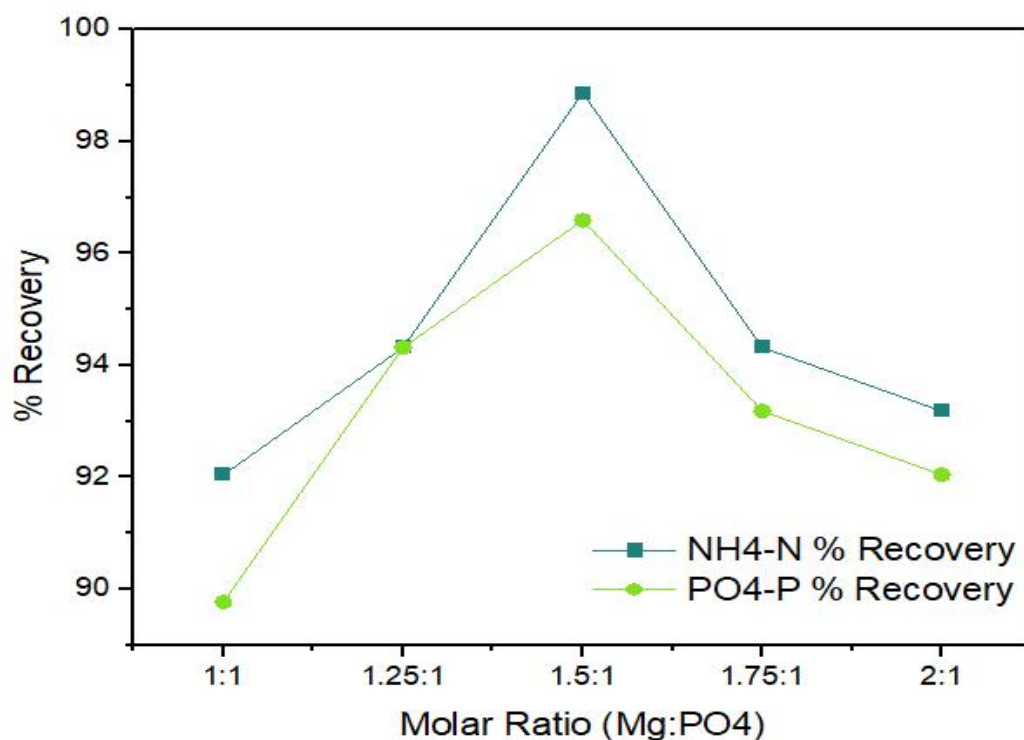


Figure 2 (2A-2B): Effect of Mg:PO₄ Ratio on Nutrient Recovery (A), % Purity of Struvite at different Mg:PO₄ ratios (B)

Influence of Interfering Ions

To explore the influence of various interfering ions on struvite precipitation, i.e., C is the control (media), T1 is sulphate, T2 is phenol, and T3 is dextrose, different ions are employed to investigate the effect on recovery percent of both phosphorus and

nitrogen, as shown in Fig.4.5. The recovery of $\text{NH}_4\text{-N}$ was similarly impacted by changing the different ions; at C (control), $\text{NH}_4\text{-N}$ recovery was 89.5%, which increased to 94% at T1 (sulphate), then increased to 95.5% at T2 (phenol), and then declined to 91.5% at T3 (dextrose). $\text{PO}_4\text{-P}$ recovery was 89.5% at C (control), increasing to 91.5% at T1 (sulphate), 94% at T2 (phenol), and 95.5% at T3 (dextrose). To understand process robustness, the effects of interfering ions such as calcium (Ca^{2+}), potassium (K^+), and organic compounds (melanoidins) were evaluated.

(a) *Effect of Different Interfering Ions*

When sulphate, phenol, and dextrose were added as interfering components, $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$ recoveries improved somewhat compared to the control. The most effective recovery method was phenol (95.5% $\text{NH}_4\text{-N}$ and 94% $\text{PO}_4\text{-P}$), followed by dextrose and sulphate. This data suggests that organic chemicals at moderate quantities did not prevent, and in some cases promoted, struvite crystallisation (Figure 3A).

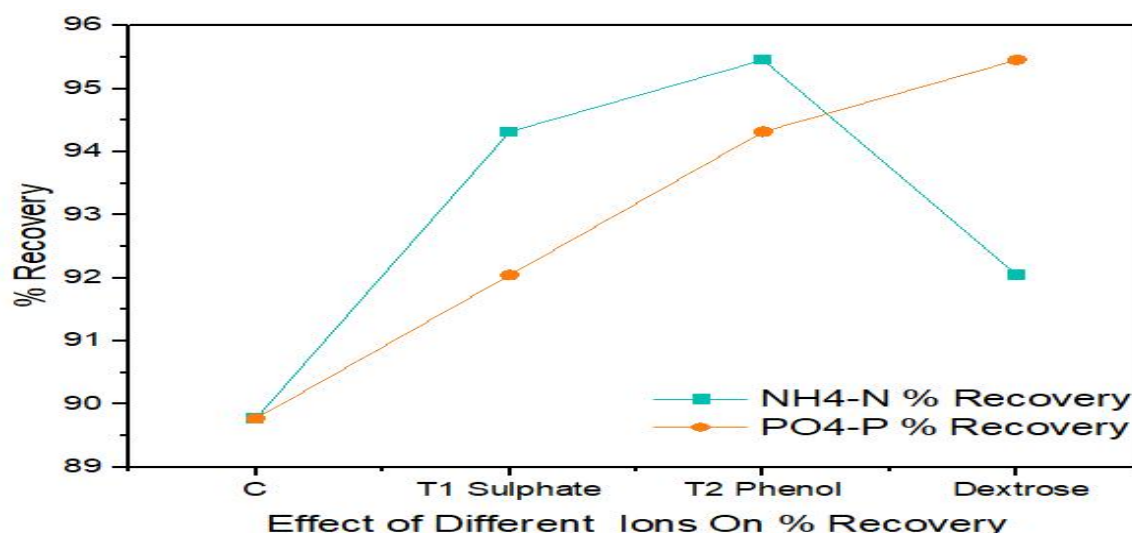


Figure 3 (3A-3B): Effect of Different Interfering Ions on Nutrient Recovery

(A), % Purity of Struvite in presence of interfering ions (B).

(b) *Effect of Calcium Ions (Ca^{2+})*

The addition of calcium ions affected both recovery and purity. At $\text{Ca:Mg} = 2:1$, the highest phosphate recovery of 95.5% was achieved; however, the crystal purity decreased slightly because of the potential formation of amorphous calcium phosphate. At higher calcium concentrations (3:1), the recovery decreased to 93%,

indicating an inhibitory effect (Figure 3A & 3B).

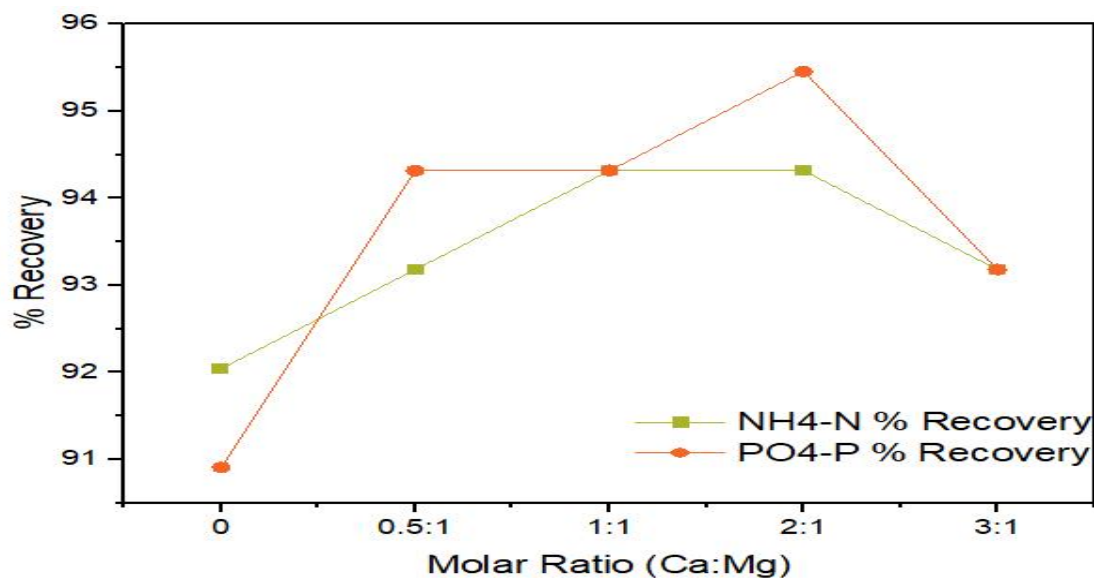


Figure 4 (4A-4B): Effect of Calcium Ion on Nutrient Recovery (A), % Purity of Struvite at various Ca:Mg ratios (B).

(c) Effect of Potassium Ions (K^+)

The recovery of NH₄-N was 92 % at K: Mg (0), where as it increasing up to 93 % K: Mg (0.5:1), at K: Mg (1:1) showing again increasing up to 95.5 %, at K: Mg (2:1) sowing decline 94 % and sharply increasing at K: Mg (3:1) 95.5 %. The PO₄-P recovery was 90 % at K: Mg (0), which increase up to 93% at K: Mg (0.5:1), whereas consequently up to 94 % at K: Mg (1:1), and sharply increasing 95.5 % at K: Mg (2:1), at K: Mg (3:1) shows decreasing in percentage 93%.

Potassium ions had a rather beneficial affect. Maximum recoveries of 95.5% for both NH₄-N and PO₄-P were recorded at K:Mg = 2:1, with a purity of 91.4 percent. Beyond this ratio, recovery slowed slightly. The presence of brilliant, homogeneous prismatic crystals suggested that potassium was incorporated into the struvite lattice, resulting in the development of mixed-type (Mg,K) ammonium phosphate phases (Figure 5A-5D).

(d) Effect of Melanoidins

Melanoidins, high-molecular-weight polymers characteristic of distillery effluent, did not significantly inhibit precipitation. Across all tests, PO₄-P removal exceeded 99%, whereas NH₄-N recovery remained above 97%, confirming the process stability

even in the presence of complex organics.

Struvite Precipitation at Different Dilutions of Real Distillery Wastewater

When applied to real distillery spent washes diluted at 25×, 50×, 75×, and 100×, nutrient recovery remained high. The best performance was achieved at 50× dilution ($\text{NH}_4\text{:PO}_4 = 3\text{:}1$), where the phosphate recovery reached 98% and the ammonium recovery reached 96%. Further dilution reduced the recovery efficiency due to lowered ion concentrations.

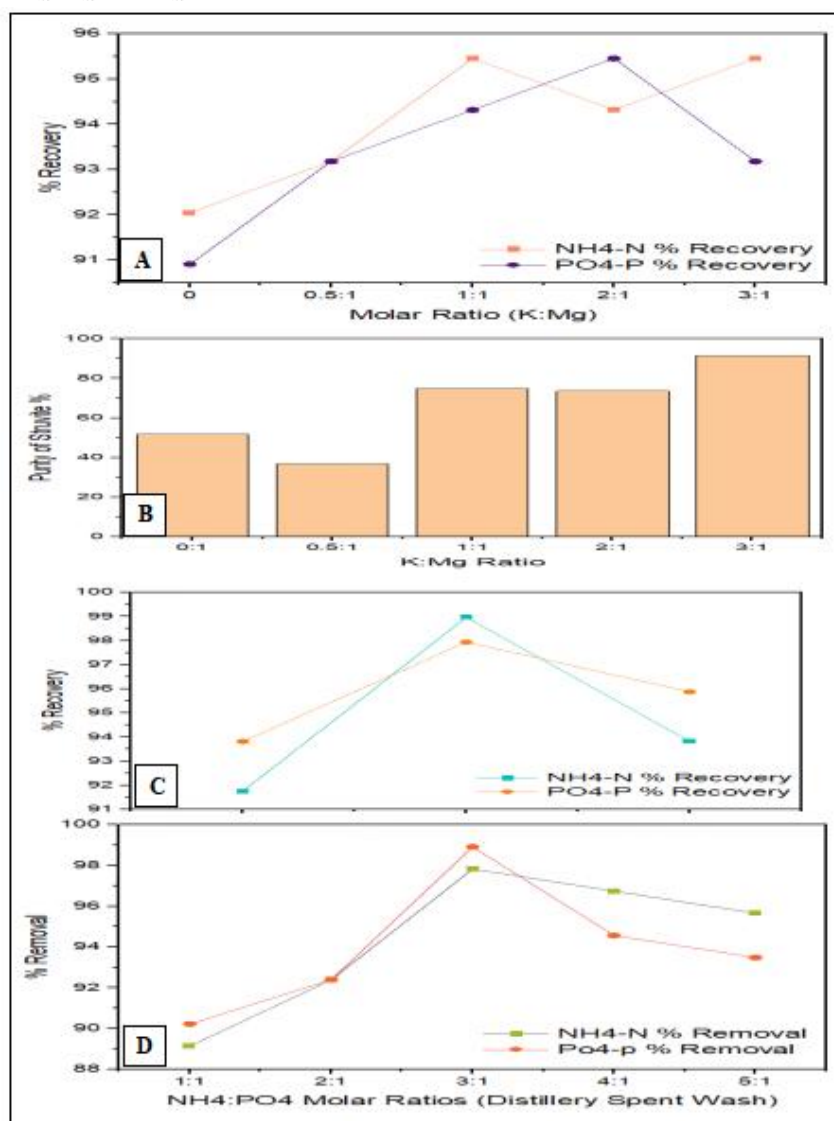


Figure 5 (5A-5D): Effect of Potassium Ions on Nutrient Recovery (A), % Purity of Struvite at different K:Mg ratios (B), Effect of Melanoidin on Nutrient Recovery (C), Struvite Precipitation at Different Dilutions of Distillery Wastewater (D).

Raw and Digested Spent Wash Analysis

The characterisation of raw and digested waste washes indicated a significant reduction in pollutant load following struvite precipitation. The COD reduced from 109,200 mg L⁻¹ to 42,500 mg L⁻¹, while the total phosphorus content decreased from 3830 mg L⁻¹ to 300 mg L⁻¹ and the total nitrogen content decreased from 2899 mg L⁻¹ to 767 mg L⁻¹. Electrical conductivity fell significantly from 41.7 dS m⁻¹ to 17.6 dS m⁻¹, indicating better effluent quality.

Microscopy photographs of the recovered precipitates (Figures 6A & 6B) showed well-defined orthorhombic prismatic crystals with smooth faces at the appropriate molar ratios. Excess magnesium and calcium were found to interfere with crystal formation, resulting in distorted or clustered forms.

X-Ray Diffraction (XRD) Analysis

The recovered solids' XRD patterns revealed that the major crystalline phase was struvite (MgNH₄PO₄•6H₂O), with peaks at $2\theta = 15.8^\circ, 20.8^\circ, 21.7^\circ, 29.7^\circ$, and 35.9° . The strong, clear peaks demonstrated great crystallinity and purity. Minor reflections of magnesium phosphate and magnesium potassium phosphate found in samples treated with potassium ions, indicating minor cation substitution but no amorphous contamination.

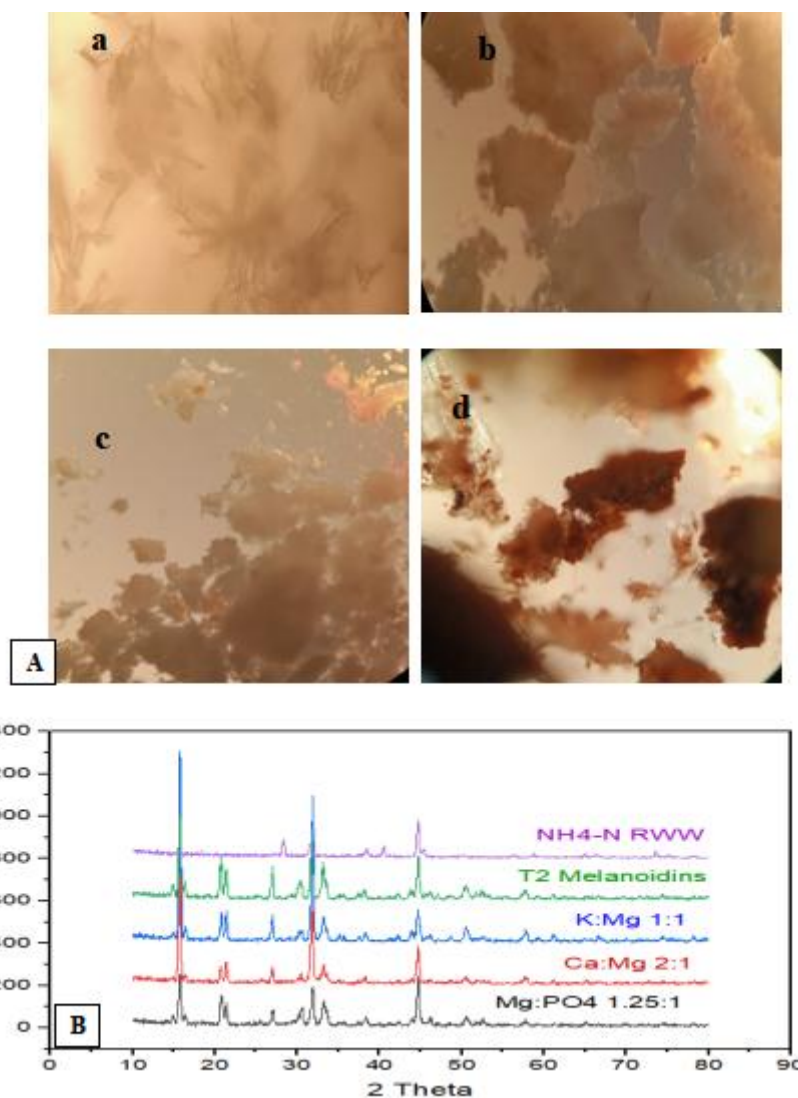


Figure 6 (6A-6B): Compound microscope images, (a) 3:1 $\text{NH}_4:\text{PO}_4$; (b) 1.75:1 $\text{Mg}:\text{PO}_4$; (c) 2:1 $\text{K}:\text{Mg}$; (d) 3:1 $\text{NH}_4:\text{PO}_4$ Real WW (A), XRD Patterns of Struvite Precipitates (B).

Discussion

Optimization of the $\text{NH}_4:\text{PO}_4$ Ratio for Nutrient Recovery

The study found that the $\text{NH}_4:\text{PO}_4$ ratio has a crucial role in struvite precipitation from synthetic distillery wastewater. Figures 4.1-4.2 show that the expected 1:1:1 stoichiometry of $\text{Mg}:\text{NH}_4:\text{PO}_4$ in pure struvite resulted in maximum phosphate (98.5 %) and ammonium (96.6 %) elimination at a 3:1 ratio. A lower ratio (1:1–2:1) led to partial precipitation (88-92%), possibly due to insufficient ammonium ions to

properly react with phosphate and magnesium. Higher ratios (4:1-5:1) decreased recovery, indicating that ionic supersaturation may cause colloidal precipitation rather than well-defined crystals, resulting in lower overall purity (78.6% at the 3:1 peak) (Chen et al., 2021; Wang et al., 2021).

Effect of the Mg:PO₄ Ratio on Recovery and Purity

In effect of the Mg: PO₄ a 1.5:1 Mg:PO₄ ratio resulted in optimum nutrient recovery (96.5 % PO₄-P, 94 % NH₄-N) and high struvite purity (59.7%). Further increases in Mg did not help recovery, which is consistent with earlier research indicating that excess Mg can cause the production of secondary phases, such as magnesium hydroxide or mixed phosphate phases, which interfere with crystal growth (Li et al., 2020; Funani, 2025). These findings emphasise the need of achieving stoichiometric equilibrium in order to maximise nutrient uptake and crystal quality.

Influence of Interfering Ions and Organics

(a) Calcium Ions

Calcium interferes with phosphate crystallization, especially at Ca:Mg ratios $\geq 2:1$, reducing the crystal purity due to the formation of amorphous calcium phosphate (Figures 4.7-4.8). However, phosphate recovery remained high (95.5 %), demonstrating the system's resilience to moderate Ca²⁺ levels.

(b) Potassium Ions

Potassium ions enhanced crystal uniformity and slightly improved nutrient recovery (max 95.5 % for both NH₄-N and PO₄-P) at K:Mg = 2:1. Microscopy revealed bright, uniform prismatic crystals, indicating the possible incorporation of K⁺ into the struvite lattice, forming mixed Mg–K ammonium phosphate phases.

Melanoidins and Organic Compounds

The presence of melanoidins, phenol, and dextrose did not inhibit struvite formation; in some cases, recovery slightly improved. This suggests that moderate organic content in distillery wastewater does not hinder crystallization, a crucial consideration for real industrial effluents (Chen et al., 2021; Kumari et al., 2019).

Real Distilling Wastewater Treatment

Optimised conditions were applied to real wasted washes at various dilutions, revealing that a 50× dilution achieved the optimal mix of nutrient concentration and

recovery, removing 98 % phosphate and 96 % ammonium. COD, total P, and total N levels were significantly reduced, illustrating the combined benefits of fertiliser recovery and effluent quality improvement. These findings validate the method's scalability and practical utility.

Crystallography and Morphology

Microscopy images confirmed that struvite formed orthorhombic prismatic crystals at optimal $\text{NH}_4\text{:PO}_4$ and Mg:PO_4 ratios. Excess magnesium or calcium caused distorted crystal growth, which is consistent with known ion interference mechanisms. XRD analysis (Figure 4.14) validated the crystalline nature of struvite and indicated minor incorporation of potassium in some samples without amorphous contamination.

Implications for Sustainable Nutrient Recovery

This study demonstrated that controlled struvite precipitation can effectively recover N and P from high-strength industrial effluents, resulting in the production of slow-release fertilizer. This approach contributes to circular nutrient management, reduces reliance on finite phosphate reserves, and mitigates eutrophication risks in aquatic ecosystems (Siciliano et al., 2020; Wang et al., 2021).

Limitations and Future Work

Despite great recovery efficiency, full-scale application continues to present issues. Real wastewater comprises fluctuating ionic strengths, competing cations, and complex organics, all of which can have an impact on long-term stability and crystal quality. Future research should look into continuous-flow reactors, seeding tactics, and collaborative approaches with microbial or algal systems to improve nutrient recovery and product quality (Nagarajan et al., 2024; Li et al., 2020).

Conclusion

This study demonstrated that controlled struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$) precipitation is a highly effective and sustainable strategy for recovering nitrogen and phosphorus from synthetic distillery wastewater. Optimizing the $\text{NH}_4\text{:PO}_4$ ratio at 3:1 and the Mg:PO_4 ratio at 1.5:1 maximized nutrient recovery, achieving 98.5 % phosphate and 96.6 % ammonium removal while producing a high-purity crystalline struvite product. The morphology and crystallinity analyses confirmed the formation of well-

defined orthorhombic prismatic crystals, indicating excellent fertilizer quality. This study further highlights the robustness of the process against interfering ions and organic compounds commonly found in distillery effluents. While calcium ions reduced struvite purity at higher concentrations, potassium ions and organics such as melanoidins did not impede crystallization and, in some cases, enhanced recovery. The application to real spent washes confirmed that the optimized conditions maintain high removal efficiency, reduce COD, and improve effluent quality, supporting the potential for practical industrial implementation. These findings illustrate that struvite precipitation not only enables the circular recovery of essential nutrients but also mitigates environmental impacts such as eutrophication and nutrient pollution. By converting wastewater into slow-release, high-quality fertilizer, this approach aligns with sustainable wastewater management and circular economy principles. Future work should focus on scaling up the process, investigating long-term crystal stability, and integrating microbial or algal systems to further increase nutrient recovery and overall process sustainability.

References

1. Chen, R.F., Zhang, J., Li, S., Wang, X. and Wu, D. (2021) 'Effect of organic substances on nutrients recovery by struvite electrochemical precipitation', *Scientific Reports*, 11(1), Article 16432. Available at: <https://www.nature.com/articles/s41598-021-95685-1>
2. Funani, C.K., Mthembu, Z., Dlamini, S., Mthethwa, P. and Ndlovu, S. (2025) 'Modelling of struvite recovery from anaerobically digested waste-activated sludge', *Materials Research Express*, 12(4), pp. 1–10. DOI: 10.1557/s43580-025-01402-9.
3. Issac, R., Thomas, L. and O'Brien, J. (2023) 'Using chemical precipitation to recover struvite from wastewater: an evaluation of process efficiency and fertiliser potential', *Journal of Waste Treatment Technologies*, 1(1), pp. 38–48.
4. Siciliano, A., Limonti, C., Curcio, G.M. and Molinari, R. (2020) 'Advances in struvite precipitation technologies for nutrients removal and recovery from aqueous waste and wastewater', *Sustainability*, 12(18), 7538. DOI: 10.3390/su12187538.
5. Wang, Y., Li, J., Zhou, Q., Sun, X. and Zhang, M. (2021) 'Phosphorus recovery from wastewater by struvite precipitation under different nitrogen to

phosphorus ratios', *Science of the Total Environment*, 762, 143115. DOI: 10.1016/j.scitotenv.2020.143115.

6. American Public Health Association (APHA) (2017) *Standard Methods for the Examination of Water and Wastewater*, 23rd edn. Washington D.C.: APHA/AWWA/WEF.

7. Chen, R.F., Zhang, J., Li, S., Wang, X. and Wu, D. (2021) 'Effect of organic substances on nutrients recovery by struvite electrochemical precipitation', *Scientific Reports*, 11(1), 16432. DOI: 10.1038/s41598-021-95685-1.

8. Kumari, S., Jose, S. and Jagadevan, S. (2019) 'Optimization of phosphate recovery as struvite from synthetic distillery wastewater using a chemical equilibrium model', *Environmental Science and Pollution Research*, 26(29), 30452–30462. DOI: 10.1007/s11356-019-06152-4.

9. Li, J., Zhang, W. and Monteiro, P.J.M. (2020) 'Mechanical properties of struvite-K: a high-pressure X-ray diffraction study', *Cement and Concrete Research*, 136, 106171. DOI: 10.1016/j.cemconres.2020.106171.

10. Parsons, S.A. and Doyle, J.D. (2002) 'Struvite formation, control and recovery', *Water Research*, 36(16), 3925–3940. DOI: 10.1016/S0043-1354(02)00126-4.

11. Wang, Y., Li, J., Zhou, Q., Sun, X. and Zhang, M. (2021) 'Phosphorus recovery from wastewater by struvite precipitation under different nitrogen to phosphorus ratios', *Science of the Total Environment*, 762, 143115. DOI: 10.1016/j.scitotenv.2020.143115.

12. Chen, Y., Li, X. & Zhang, L., 2021. Impacts of interfering ions on struvite crystallization from high-strength wastewater. *Chemical Engineering Journal*, 420, p.129674.

13. Funani, N., 2025. Optimizing nutrient recovery through struvite precipitation from industrial wastewater. *Journal of Water Process Engineering*, 47, p.103646.

14. Issac, J., 2023. Struvite precipitation as a sustainable nutrient recovery technology: insights and perspectives. *Environmental Technology Reviews*, 12(3), pp.235–251.

15. Kumari, S., Singh, A. & Sharma, R., 2019. Synthetic distillery wastewater as a

model system for nutrient recovery studies. *Journal of Cleaner Production*, 223, pp.338–348.

16. Li, H., Wang, J. & Zhao, Q., 2020. Analytical approaches to struvite purity and characterization. *Journal of Environmental Chemical Engineering*, 8(5), p.104279.

17. Nagarajan, A., et al., 2024. Sustainable nutrient recovery through struvite precipitation. *Science of The Total Environment*, 820, p.153491.

18. Parsons, S.A. & Doyle, R., 2002. Precipitation of magnesium ammonium phosphate (struvite) from wastewater. *Water Research*, 36(7), pp.1763–1771.

19. Siciliano, A., Limonti, C., Curcio, G.M. & Molinari, R., 2020. Advances in struvite precipitation technologies for nutrients removal and recovery from aqueous waste and wastewater. *Sustainability*, 12(18), p.7538.

20. Wang, X., Liu, H. & Chen, L., 2021. Influence of molar ratios and pH on struvite crystallization efficiency. *Separation and Purification Technology*, 257, p.117887.

21. Zeng, J., et al., 2021. Optimising struvite precipitation: a review of key operational parameters. *Journal of Cleaner Production*, 312, p.127857.

22. Zheng, L., et al., 2018. Struvite precipitation from nutrient-rich streams: morphology, mechanisms and agronomic efficacy. *Journal of Agricultural & Food Chemistry*, 66(13), pp.3376–3385.

23. Effendi, A.J., et al., 2022. Nutrient recovery from organic-rich wastewater through struvite precipitation. *Waste and Biomass Valorization*, 13, pp.123–137.

24. Guan, Q., et al., 2023. A review of struvite crystallization for nutrient source recovery. *Journal of Environmental Management*, 315, p.115295.

25. Lorick, D., et al., 2020. Effectiveness of struvite precipitation and ammonia stripping for recovery of phosphorus and nitrogen from anaerobic digestate: a systematic review. *Environmental Evidence*, 9(1), p.27.

26. Mohan, D., et al., 2020. Advances in nutrient recovery from wastewater: struvite and beyond. *Environmental Science & Technology*, 54(18), pp.11548–11565.

27. Santos, A.F., et al., 2024. Nutrient recovery via struvite precipitation from industrial wastewater. *Water*, 16(12), p.1675.

28. Zhou, Y., et al., 2024. Sensor-based process control for high-purity struvite

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recovery from starch wastewater. *Environmental Science & Technology*, 58(4), pp.2502–2512.

29. Zhu, Y., et al., 2020. Biochar assisted struvite precipitation: performance and mechanisms. *Bioresource Technology*, 295, p.122269.

30. Singh, P., Singh, R. & Pandey, V., 2021. Reactive oxygen species generation and antioxidant defense in plants under metal stress. *Journal of Plant Biochemistry and Biotechnology*, 30(1), pp.1–14.