Research Journal of Recent Sciences ISSN 2277-2502
Vol. **14(1),** 25-34, January **(2025)** *Res. J. Recent Sci.*

Exploring Effective Strategies for Phosphorus Removal from Wastewater: A Comprehensive Review of Chemical, Biological, and Physicochemical Methods

Kirti B. Zare[1] and Manisha Tanwer[2]
[1]Department of Chemical Engineering, Dr. D. Y. Patil Institute of Engineering, Management & Research & D. Y. Patil International University, Akurdi, Pune, Maharashtra, India
[2]Department of Chemistry, D.Y. Patil College of Engineering, Akurdi Pune, Maharashtra, India
kirti.zare@dypiemr.ac.in

Available online at: www.isca.in, www.isca.me
Received 10th September 2024, revised 26th Octomber 2024, accepted 29th November 2024

Abstract

Phosphate and ammonium are significant contributors to eutrophication in water bodies, originating mainly from wastewater. However, conventional methods for removing these nutrients in water treatment plants face considerable challenges. Additionally, the natural reservoir of phosphorus is finite and expected to be depleted within the next 50 to 100 years, highlighting the urgency of phosphorus recycling as a pressing issue. One promising avenue for phosphorus retrieval from effluent is through the sleet of crystalline struvite. Struvite, also identified as $MgNH_4PO_4{\cdot}6H_2O$*, presents an appealing solution for sustainable development. This method not only recovers valuable phosphorus but also mitigates environmental issues associated with excess phosphorus in wastewater. After precipitation, struvite serves as an effective fertilizer or a valuable resource for phosphorus recovery, supporting a circular economy and lessening reliance on conventional phosphorus sources. The effectiveness of struvite recovery hinges on achieving the appropriate super saturation of wastewater, which dictates the rate and extent of striate formation. In recent research, the stability domain of struvite in synthetic wastewater (SWW) was investigated, focusing on the kinetics of its spontaneous precipitation. This investigation involved aqueous solutions mimicking the composition of municipal wastewaters. By adjusting the concentrations of* Mg_2^+*,* NH_4^+*, and* $PO4_3^-$ *ions maintain a stoichiometric molar ratio of 1:1:1, varying degrees of super saturation with respect to struvite were achieved. Results indicate that phosphorus removal rates of up to 70% or higher can be attained through this method. However, there remains room for improvement, particularly in controlling the quality of struvite production. Efforts in refining this technique could enhance its efficiency and viability for widespread implementation in wastewater treatment processes.*

Keywords: Phosphate, Ammonium, Wastewater, Crystalline salt, Efficiency.

Introduction

The removal of phosphorus from wastewater is an essential process in protecting water bodies from eutrophication, a condition that leads to excessive algae growth and subsequent ecological imbalances. As phosphorus is a key nutrient in agricultural runoff and industrial effluents, its effective management in wastewater treatment is critical. This evaluation offers an in-depth survey of the numerous strategies employed for phosphorus removal, focusing on chemical, biological, and physicochemical methods. Chemical, sleet & thickening, widely adopted for their efficiency, while biological methods, including enhanced biological phosphorus removal (EBPR), offer sustainable solutions through microbial processes. Physicochemical methods, combining physical and chemical processes, provide additional flexibility in treatment approaches.

By synthesizing current research and advancements in these methods, this analysis objectives to present a wide-ranging overview of their effectiveness, challenges, and potential for optimization. The study also addresses the economic and environmental implications of each method, offering insights into how these strategies can be integrated into existing wastewater treatment infrastructures. Ultimately, this review seeks to guide future research and practical applications in the field, contributing to the expansion of extra supportable and active phosphorus removal knowledge.

This introduction sets the stage for a comprehensive review article by outlining the importance of phosphorus removal, summarizing the methods to be discussed, and highlighting the relevance of the review to both research and practical applications.

Over the past decade, the formation of MAP, usually discussed, has garnered considerable attention as an effective method for recovering nitrogen and phosphorus from wastewater. This process offers a sustainable alternative to traditional phosphate rock mining, which is currently the primary source of phosphorus for agricultural use.

Studies have demonstrated that struvite is just as effective as single and triple superphosphate fertilizers in providing phosphorus for crops.

However, several challenges, including technical, regulatory, and social factors, have hindered the widespread adoption of struvite as a fertilizer alternative. A notable technical issue is the small size of struvite crystals typically produced in crystallization processes.

Overview of methods: Chemical, Biological, and Physicochemical: Chemical methods for phosphorus removal typically involve the use of coagulants such as aluminum salts, iron salts, or lime. These methods are effective for removing dissolved phosphorus but may produce large volumes of sludge. This study examines the optimization of alum and ferric chloride dosing for phosphorus removal. It concludes that precise dosing can enhance phosphorus removal efficiency and minimize sludge production.

This paper investigates the optimization of alum and ferric chloride medicating for phosphorus exclusion, emphasizing the significance accurate dosing to improve efficiency and minimize sludge production[1]. Precipitation is a commonly employed chemical technique for phosphorus removal from wastewater. In this process, specific chemicals are added to react with dissolved phosphorus, forming solid precipitates. These precipitates are subsequently removed from the wastewater through sedimentation or filtration. This method is especially effective in lowering phosphorus concentrations to comply with regulatory standards.

Two of the most commonly used chemicals in the precipitation process are alum (aluminum sulfate) and ferric chloride. Alum, when added to wastewater, dissociates into aluminum ions (Al^{3+}), which react with phosphate ions ($PO_4{}^{3-}$) to form aluminum phosphate ($AlPO_4$), a solid precipitate that can be removed from the water. Ferric chloride operates similarly, dissociating into ferric ions (Fe^{3+}) that react with phosphate to form ferric phosphate ($FePO_4$). Both of these chemicals are effective in removing phosphorus, but they also come with specific advantages and disadvantages. The study compares various chemical precipitation methods, focusing on alum and ferric chloride. It provides insights into their performance, cost-effectiveness, and environmental impacts[2].

The precipitation process generally involves three steps: coagulation, flocculation, and sedimentation. During coagulation, the chemical (alum or ferric chloride) is added to the wastewater, where it dissociates into metal ions.

These metal ions then interact with the phosphate ions present in the water during the flocculation stage, forming insoluble metal-phosphate complexes. In the final sedimentation step, these precipitates aggregate into larger particles that settle out of the water, allowing for their removal through sedimentation or filtration. This mechanism is effective in reducing phosphorus levels in wastewater to very low concentrations.

One of the primary advantages of chemical precipitation remains its in height competence in removing dissolved phosphorus, repeatedly realizing stages under supervisory limits. The process is also relatively simple and can be easily implemented in existing wastewater treatment facilities without requiring significant modifications. Additionally, precipitation is versatile, working effectively across a wide range of wastewater compositions and also helping to remove other contaminants such as heavy metals. These benefits make chemical precipitation a reliable method for phosphorus removal.

However, the use of chemical precipitation also has notable drawbacks. One of the major disadvantages is the large volume of sludge that is generated, which requires subsequent treatment and disposal. This sludge management can lead to increased operational costs. Moreover, the cost of the chemicals themselves, along with the need for careful handling, particularly with corrosive agents like ferric chloride, can add to the overall expense of the process. Additionally, the introduction of these chemicals can lead to secondary pollution, such as increased sulfate levels from alum, which might necessitate further treatment. This review covers the mechanisms underlying phosphorus precipitation using alum and ferric chloride, discussing factors influencing the efficiency of the process and strategies for optimization[3].

Once dried, these fine crystals turn into a powder that is difficult to distribute using standard agricultural equipment because of its light weight. Although there have been some reports of producing larger struvite pellets through the agglomeration of smaller crystals, achieving this requires precise control over process conditions to maintain the correct super saturation ratio. Furthermore, the formation of struvite pellets is extremely reliant on the category and design reactor, which often necessitates high flow rates and, consequently, greater energy consumption.

Typically, creating struvite pellets is a more intricate process than producing struvite crystals. This study aimed to establish a technique for transforming fine struvite crystals into granular fertilizers suitable for agricultural use. The resulting struvite-based fertilizer was assessed for key characteristics, including pH, salt index, particle size distribution, and heavy metal content, with the findings compared to those of a commercial NPK fertilizer.

Wastewater management is a pressing environmental concern, and this review concentrates on research related to the elimination and retrieval of phosphorus and nitrogen from effluent via struvite representation. Effluent with elevated levels of phosphorus and nitrogen presents an excellent opportunity for struvite production.

Struvite, which contains substantial amounts nitrogen and magnesium, a viable another to rock phosphate for sustaining agricultural productivity. This review delves into the values then concepts of struvite nucleation and crystal development, along with the issues influencing struvite quality. Struvite forms when Mg^{2+}, NH_4^+, and PO_4^3- are present in equimolar concentrations under slightly alkaline conditions.

Adding a magnesium source is essential for fostering optimal conditions for the interaction between phosphate and magnesium. Due to the limited recycling and reuse of phosphorus, significant amounts are lost in waste streams from domestic and agro-industrial sectors.

In recent years, the cost of phosphorus-based fertilizers has increased significantly due to resource scarcity and the rising energy costs associated with phosphate rock mining. This economic pressure has spurred interest in recovering phosphorus from waste streams, presenting it as a contaminant-free, nutrient-rich mineral product.

Biological methods utilize microorganisms to remove phosphorus biologically, often through processes such as enhanced biological phosphorus removal (EBPR).This paper reviews the mechanisms underlying EBPR and discusses recent advances in microbial consortia engineering. It highlights the potential of integrating EBPR with other wastewater treatment processes to enhance overall performance[4].

Table-1: The percentage loss of N, P and K varies across waste sources, impacting nutrient availability and highlighting areas for improved recovery and recycling efforts[5].

Type of Waste	Nitrogen	Phosphorus	Potassium
Industries	7.98	9.84	14.15
Trade	5.55	3.98	5.98
Kitchen	14.15	25.64	27.56
Urine	64.624	42.64	51.64
Faces	6.94	21.26	8.97

Simultaneously, soils are becoming nutrient-depleted due to the extensive application of synthetic chemical fertilizers[6]. With phosphorus demand projected to rise by 1.5% annually, these resources could be depleted within 100 to 250 years[7].

They offerings detailed study and rapid of recent study about the custom modified carbon materials for managing orthophosphate in effluent. It explores various methodologies employed provides a thorough evaluation of the extreme capacities for phosphate adsorption. The review also examines how the incorporation of elements such as Ca, Mg, Al, La and Fe can enhance phosphate adsorption in carbon materials.

Furthermore, it discusses the detrimental effects of SO_4^{2-}, HCO_3-, humic acid (HA) and CO_3^{2-} on the removal of phosphate. The mechanisms involved in phosphates adsorption and the potential for using mCMs as fertilizers once adsorption saturation is achieved are systematically analyzed. Given their ability to adsorb phosphates, mCMs may play a significant role in promoting crop growth, improving effluent organization, addressing the reduction of orthophosphatemainstaycapitals[8].

It thoroughly examines key factors such as chemical characteristics, treatment techniques, challenges mire excerpt reuse, while also discussing advanced treatment technologies and best practices for enhancing resource recovery. The review identifies the environmental and resource conservation benefits of optimizing sludge reuse and outlines future research directions aimed at developing innovative treatment methods, improving economic and regulatory frameworks, and advancing the understanding of sludge properties[9].

Physicochemical methods often involve the use of adsorption, ion exchange, or membrane technologies. These methods are effective for polishing treated effluent to remove residual phosphorus. The paper reviews various advanced adsorbent materials, including biochar, metal oxides, and nanocomposites. It concludes that adsorbents with high specific surface areas and functional group modification show the most promise for efficient phosphorusremoval[10].

Struvite Sources of Components: Ammonium: In wastewater, ammonium levels are often difficult to quantify due to its formation during the degradation of nitrogenous materials. Urea breakdown is a key contributor, and in general, ammonium is found in excess compared to phosphorus and magnesium in wastewater.

Phosphorus: Phosphorus concentrations in human urine provide a useful measure for its recovery potential. In household wastewater, phosphorus primarily enters treatment plants as bioavailable, dissolved orthophosphate ions like H_2PO_4, HPO_4^{2-}, and PO_4^{3-}. While concentrations can fluctuate, a typical phosphorus level of around 10 mg/L is commonly observed[11-14].

Magnesium: Magnesium in wastewater streams can come from several sources. In areas with hard water, magnesium is more abundant. Additionally, treatment plants located near coastal areas may receive seawater, further contributing magnesium. Some plants use support materials in anaerobic digesters, which can also serve as magnesium sources by providing surface area for biomass to adhere to, thereby reducing its loss in the effluent. Struvite ($MgNH_4PO_4 \cdot 6H_2O$) precipitation offers a promising method for recovering phosphorus from municipal wastewater. The sweeping response for struvite development can be uttered as:

$Mg_2+ + NH_4+ + PO_4^{3-} + 6H_2O \rightarrow MgNH_4PO_4 \cdot 6H_2O$

Several physio-chemical factors influence struvite precipitation, including temperature, mixing energy, pH levels, the degree of supersaturating of Mg, NH_4, and PO_4^{3-}, and the presence of competing ions. Under favorable conditions, struvite can be extracted from various wastewater streams, such as raw sewage, landfill leachates, animal waste liquors, and supernatants or filtrates from anaerobic digesters.

The spontaneous formation of WWTPs has been widely documented, often resulting in scaling issues in plumbing and clogging of pumps. Anaerobic-based WWTPs have reported phosphorus recovery rates between 71% and 96% through struvite crystallization. However, spontaneous struvite formation is less common in small WWTPs, where it is not as thermodynamically favorable. Converting these smaller plants to anaerobic systems, which are more conducive to struvite formation, is typically not cost-effective. As a result, larger WWTPs have been the focus of most struvite recovery efforts, leaving smaller plants with fewer options for phosphorus recovery.

Struvite is a crystalline compound that forms when Mg, ammonium ion, then inorganic phosphates are present in identical grinder absorptions, escorted by $MgNH_4PO_4 \cdot 6H_2O$. It exhibits limited solubility in neutral to alkaline conditions, dissolving more readily in acidic environments. At 25°C, its solubility is measured at 0.018 g per 100 ml in water, 0.033 g per 100 ml in 0.0048 N HCl, and 0.178 g per 99.98 ml in 0.01 N HCl, with a solubility constant of $10^{13.26}$. Struvite crystallization generally occurs across a broad pH range, particularly in alkaline environments. As a lenient inorganic, struvite has a little precise significance and is resistant to being washed away by rain, making it a suitable fertilizer for use in flood-prone regions.

Struvite, a magnesium ammonium phosphates mineral, has garnered attention for its potential as a phosphorus-based fertilizer and its role in nutrient retrieval from effluent. This broadside explores the corporeal and biochemicalpossessions of struvite, including its crystallography, morphology, and thermal behavior, while emphasizing its significance in agricultural applications and phosphorus recovery processes.

The orthorhombic arrange mentstruvite comprises phosphates (PO_4^3) octahedra, distorted magnesium ($Mg\ (H_2O)_6^{2+)}$ octahedra, and ammonium (NH_4) groups that are interconnected through hydrogen bonds. These structural characteristics play a crucial role in its behavior in agricultural settings.

The morphology of struvite can vary significantly, often seen as compact clusters of fine crystals, irregular coarse structures, or elongated formations, with dimensions ranging from 15 μm to 3.5 mm. Munch and Barr reported observations from a pilot-scale magnesium ammonium phosphates (MAP) reactor that indicated the presence of smaller crystals compared to those from full-scale reactors in Japan. Kurita Water Industries noted that the average crystal size was measured at 2.0 ± 3.8 mm, with growth rates influenced. Notably, higher phosphorus concentrations (>200 mg/L) resulted in a mineral growing rate of 0.1733 mm per day, while lower concentrations (34–100 mg/L) exhibited a reduced rate of 0.061 mm per day.

Struvite comprises approximately 13% phosphorous, making it a viable phosphorous-based fertilizer. Additionally, it provides N (6%) and Mg (10%), enhancing its utility in soil amendment. The physical morphology of MAP crystals is commonly examined using SEM, while XRD is active ascertain chemical composition, matching crystal peaks with reference databases. Chemically, struvite is parsimoniously solvable underneath unbiased circumstances but demonstrates high solubility in acidic environments, remaining largely insoluble in alkaline circumstances. Its capability to increase soil pH makes it particularly beneficial for acidic soils. Research indicates that MAP-treated soils exhibit increased pH levels, contrasting with commercial nitrogen and phosphorous fertilizers that tend to lower pH[15].

Recent studies on the thermal properties of struvite reveal that its decomposition occurs below active infection situations, leading to the steady release of ammonia and partial transformation bobierrite when bubbled below 110°C for 24 hours. Scorching struvite in additional water facilitates the release of five aquatic particles, transforming it into the monohydrate form known as dittmarite. Notably, dittmarite comprises a developed phosphorous content (45.57% P_2O_5 or 19.9% P) compared to struvite, which has 28.9% P_2O_5 or 9.8% P.

Struvite holds substantial potential as a phosphorus-based fertilizer and for nutrient recovery. Understanding its crystallography, morphology, and thermal behavior is crucial for optimizing its applications in agriculture and wastewater management. Continued research is essential to uncover the economic feasibility of its transformation and to enhance its efficacy as a sustainable fertilizer option.

Struvite Chemistry: Struvite is classified as an orthophosphate mineral, comprising equivalent grinder attentions of Mg, ammonium ion, and orthophosphates. The over-all chemical formulary for struvite and its related reserves is represented as $AMPO_4 \cdot 6H_2O$. In this formula, "A" can denote either potassium (K) or ammonia (NH_3), while "M" refers to metals such as Mg, Co or Ni. This composition underscores the mineral's significance in both nutrient cycling and agricultural applications.

In its most common form, struvite exists as magnesium ammonium ion phosphates hex hydrate. It forms into an orthorhombic assembly, characterized by distinct conservative prisms that possess a quadrilateral base.

This unique crystallographic arrangement contributes to the mineral's physical properties and its behavior in soil environments[16].

Struvite's balanced composition of essential nutrients—magnesium, ammonium, and pH os pH ate—positions it as a promising candidate for use as a fertilizer. Its release of nutrients in a controlled manner can enhance soil fertility and promote sustainable agricultural practices. Furthermore, the mineral's ability to improve soil structure and increase nutrient retention makes it an advantageous addition to soil amendment strategies.

Struvite's classification as an orthophosphate's mineral, along with its chemical composition and unique crystallographic structure, highlights its importance in agriculture and nutrient recovery processes[17]. Continued research into its applications and benefits can further enhance its role as a sustainable fertilizer option. A summary of struvite's key chemical and physical properties can be found in Table-2.

Table-2: Struvite Properties[12].

Nature	Mineral Salt
Chemical Name	Phosphatehexa hydrate Magnesium ammonium
Formula	$MgNH_4PO_4.6H_2O$
Aspect	crystal White glowing
Structure	Orthorhombic
Mol. Wt.	245.423 g.mol−1
Sp. Gravity	1.7115

Crystal formation: Crystal development is a fundamental procedure that results in development of hard structures known as crystals. This process, though intricate, is widely applied in industrial settings to separate specific solid phases from mixtures. The crystallization process into key stages: nucleation and crystal growth. Nucleation marks initial formation of tiny crystal embryos from ions within a liquid or gaseous medium, primarily influenced by the reaction kinetics. Crystal growth, on the other hand, refers to the subsequent enlargement of these embryos as they approach equilibrium, with the final crystal size being dictated by the crystallization kinetics. In the case of struvite crystallization, achieving a supersaturating state is crucial to trigger the formation of the first crystals.

Nucleation and Nucleation Rate: Nucleation is the initial step in which ions of small crystal rudiments, occurs spontaneously in highly pure and heterogeneous nucleation, where crystals form due to impurities or foreign particles acting as a substrate. In wastewater, due to the presence of impurities, struvite tends to form via heterogeneous nucleation.

Crystal Growth: Following nucleation, crystal embryos grow into larger, detectable crystals. The growth rate is influenced by mass transfer processes, which involve the transportation of solutes from the surrounding solution to the crystal surface via diffusion, convection, or a combination of both. Additionally, surface integration mechanisms control how these materials are incorporated into the crystal lattice[18].

Factors Influencing Struvite Formation: Several factors contribute to the complexity of foreseeing and supervisory struvite nucleation and growing. These include initial state of the compounds, mass transmission among solid and liquid stages, reaction thermodynamics and kinetics, physical and naturallimits such as pH, supersaturating levels, intercourse vigor, malaise, and the occurrence of foreign ions.

pH One of the primary factors affecting struvite crystallization is the pH of the solution. It is closely related to solubility and supersaturating, which in turn influence the rate of struvite precipitation and the induction period. In wastewater treatment plants (WWTPs), struvite often precipitates due to increased pH levels, resulting from the removal of CO_2 from the solution.

Mixing Energy, the turbulence or mixing energy in the solution can affect struvite formation, particularly in areas where CO_2 is liberated, leading to an increase in pH. In environments with lower turbulence, struvite tends to form elongated crystals, while higher turbulence limits crystal growth and can lead to increased crystal breakage.

Materials and Methods

Laboratory-Scale Struvite Formation: To investigate struvite formation under controlled conditions, both synthetic and real wastewater were used to synthesize struvite. For the synthetic wastewater (MAPSyn), magnesium chloride, ammonium chloride, and potassium dihydrogen phosphates were combined in distilled water at a 1:1:1 molar ratio, with the pH kept between 8.5 and 9.0. The resulting crystals were then vacuum filtered, dried at ambient temperature, and analyzed using a light microscope Struvite Formation from Wastewater.

Struvite was also produced from anaerobic digestion effluent to simulate real-world conditions. In this process, phosphorus and magnesium were added to achieve the desired molar ratio of 1:1:1. The pH was similarly controlled between 8.5 and 9.0, and the formed crystals were harvested, filtered, and dried.

Struvite Precipitation Experiment: A simple experimental procedure was conducted to determine whether struvite formation occurred. A wastewater sample was mixed with magnesium chloride, stirred at high speed for rapid mixing, and then allowed to settle overnight. The precipitate formed was filtered, dried, and weighed to confirm the formation of struvite.

Effect of Magnesium Chloride Dosage: Experiments were conducted to determine the optimal dosage of magnesium chloride for struvite formation. Various concentrations of magnesium chloride were added to urine samples while keeping pH and temperature constant. The precipitate formed at different dosages was weighed to determine the most effective magnesium chloride concentration for struvite precipitation showed in Table-3.

Effect of pH on Struvite Precipitation: Impact of pH struvite formation studied by adjusting the pH of wastewater samples and observing the resulting precipitate. Experiment aimed towards recognize the optimal pH for effectual struvite precipitation in water showed in Table-4.

Effect of Temperature on Struvite Precipitation: Effect of temperature proceeding struvite formation was examined by conducting experiments at diverse temperatures while preserving continuous pH and magnesium chloride concentrations. The amount of precipitate formed at various temperatures was recorded to determine the optimal conditions for struvite precipitation.

Table-3: Amount of Struvite formed for different dosages of $MgCl_2$.

Exp. No.	Volume of wastewater (ml)	Initial pH	$MgCl_2$ added (ml)	Struvite formed	Final pH
1	40	7.88536	0	0.00985	8.98
2	40	7.9856	0.035	0.01145	8.99
3	40	7.8982	0.054	0.02312	8.94
4	40	7.8957	0.14	0.05445	8.95
5	40	7.894	0.254	0.0464	8.98
6	40	7.889	0.53	0.05865	8.82
7	40	7.459	0.754	0.05642	8.48
8	40	7.982	13	0.05246	8.95

Table-4: Amount of struvite formed for different pH values of wastewater.

Expt. No.	wastewater sample (ml)	added (in gm) $MgCl_2$	pH	formed of Struvite
1	30	0.1	8.53	0.052
2	30	0.1	8.6	0.054
3	30	0.1	8.76	0.048
4	30	0.1	8.93	0.063
5	30	0.1	9.2	0.75
6	30	0.1	9.46	0.94
7	30	0.1	9.7	0.123
8	30	0.1	9.98	0.147
9	30	0.1	10.2	0.182
10	30	0.1	10.33	0.17
11	30	0.1	10.5	0.12

Orthophosphate elimination from aqueous explanations has been investigated by means of various CSH materials derived from explosion heater slag and other sources. Giving to an explosion furnace slag-based BF-CSH adsorbent established a phosphates adsorption volume of 53.1 mg/g under normal situations (pH 7.0 and 25 °C), 73 times higher of untreated blast furnace slag. The enhanced performance of BF-CSH can be attributed to the abundance of Ca^{2+} ions in its structure, which show a strong affinity for phosphates. The adsorbent exhibited a phosphates elimination efficacy of 98.65–99.56% in replicated water (0.55–0.85 mmol/L phosphates concentration)[19].

They investigated a porous calcium silicate hydrate (CS-CSH) produced from carbide slag, which exhibited a surface area of 8.802m²/g and a pore volume of 0.024cm³/g. This material was synthesized at 150°C for 6 hours in an autoclave. The study demonstrated that CS-CSH could remove 14.79mg/g of phosphates after being reused nine times. Additionally, heating CS-CSH to 700°C improved its phosphates removal efficiency by 3.23mg/g. The research also indicated that adjusting the equilibrium pH between 5.3 and 10.2 could reduce the adverse effects of sulfate (SO_4^{2-}) and bicarbonate (HCO_3^-) on phosphates adsorption[20].

The primary mechanisms driving adsorption were identified as electrostatic attraction, ligand exchange, and Lewis's acid-base interactions in another study, they explored iron-modified nanofibers for treating low-concentration phosphorus in wastewater. They found that mixing 1.5 parts Fe $(OH)_3$ with 1 part carbon nanofibers (CNFs) and drying the blend with liquid nitrogen achieved a notable adsorption capacity of 11.45 mg/g showed variation in Table-5. The adsorbent retained around 80% of its initial capacity after 10 regeneration cycles using NaOH-based desorption.

Results and Discussion

For the struvite precipitation process, 0.5 grams of $MgCl_2$ was introduced into 90 milliliters of urine, leading. The mass resulting struvite precipitate was determined to be 0.182 grams.

Effect of $MgCl_2$ Concentration: Experiments were carried out at a steady pH of 8.53 and room temperature, revealing that the quantity of struvite produced rose progressively with the addition of $MgCl_2$, reaching a maximum yield at 0.1 grams, after which the formation stabilized. This increase up to 0.14 grams of $MgCl_2$ was due to the excess ammonia and phosphates in the wastewater relative to the amount of magnesium added. Once 0.14 grams of $MgCl_2$ was used, all available ammonia and phosphates in the wastewater were precipitated. As a result, adding more than 0.14 grams of $MgCl_2$ did not significantly change the amount of struvite formed showed in Figure-1.

Effect of pH: This study investigates the outcome of pH on formation of struvite during wastewater treatment processes. By maintaining a constant dosage of magnesium chloride ($MgCl_2$) at 0.15 g and varying the pH, the research explores the optimal conditions for struvite precipitation. This experiment aims to elucidate the relationship between pH levels and struvite formation, providing insights for optimizing wastewater treatment processes. The pH of the wastewater was systematically varied to assess its impact on struvite formation. The findings indicated a positive correlation between pH and struvite formation, with an increase in struvite precipitation observed as pH levels rose, reaching a peak at 10.26. Beyond this pH value, struvite formation began to decline, suggesting an optimal pH range for maximum precipitation. Figure-2 illustrates the percentage increase in struvite formation corresponding to the increasing pH levels in the wastewater, highlighting the importance of maintaining appropriate pH conditions for effective nutrient recovery.

The results demonstrate that pH is a critical factor influencing struvite formation, with optimal precipitation occurring at a pH of 10.26. Understanding this relationship can aid in enhancing the efficiency of wastewater treatment systems and maximizing nutrient recovery.

Table-5: The quantity of struvite produced at various wastewater temperatures can be determined by modeling the crystallization process under different thermal condition.

Expt. No.	Volume of wastewater	$MgCl_2$ added (g)	pH	Temperature	Struvite formed
1	30	0.1	8.53	10	0.02
2	30	0.1	8.53	20	0.032
3	30	0.1	8.53	25	0.043
4	30	0.1	8.53	30	0.052
5	30	0.1	8.53	35	0.054
6	30	0.1	8.53	40	0.049

Figure-2 Struvite formation is highly pH-dependent, with optimal crystallization occurring between pH 8.766 and 9.79 as this range maximizes the availability of magnesium, ammonium, and phosphate ions needed for crystal growth.

Effect of Temperature: This study examines effect of temperature on struvite formation in wastewater treatment processes. By maintaining a constant dosage of magnesium chloride ($MgCl_2$) at 0.125 grams and an initial pH of 8.536, the research investigates how variations in temperature influence the precipitation of struvite. Struvite, a valuable nutrient recovery product, is influenced by several factors, including temperature. This experiment aims to clarify the relationship between temperature and struvite formation, contributing to the optimization of wastewater treatment processes. Experiments were performed with a fixed dosage of $MgCl_2$ at 0.125 grams and an initial pH of 8.536. The temperature was systematically varied to observe its impact on the formation of struvite crystals. As the temperature augmented, a corresponding rise in the quantity of struvite precipitated was observed. This trend suggests that higher temperatures facilitate the formation of struvite, enhancing the precipitation process. Figure-3 illustrates the relationship between temperature and the percentage of struvite formation, providing a visual representation of how increasing temperature promotes struvite precipitation.

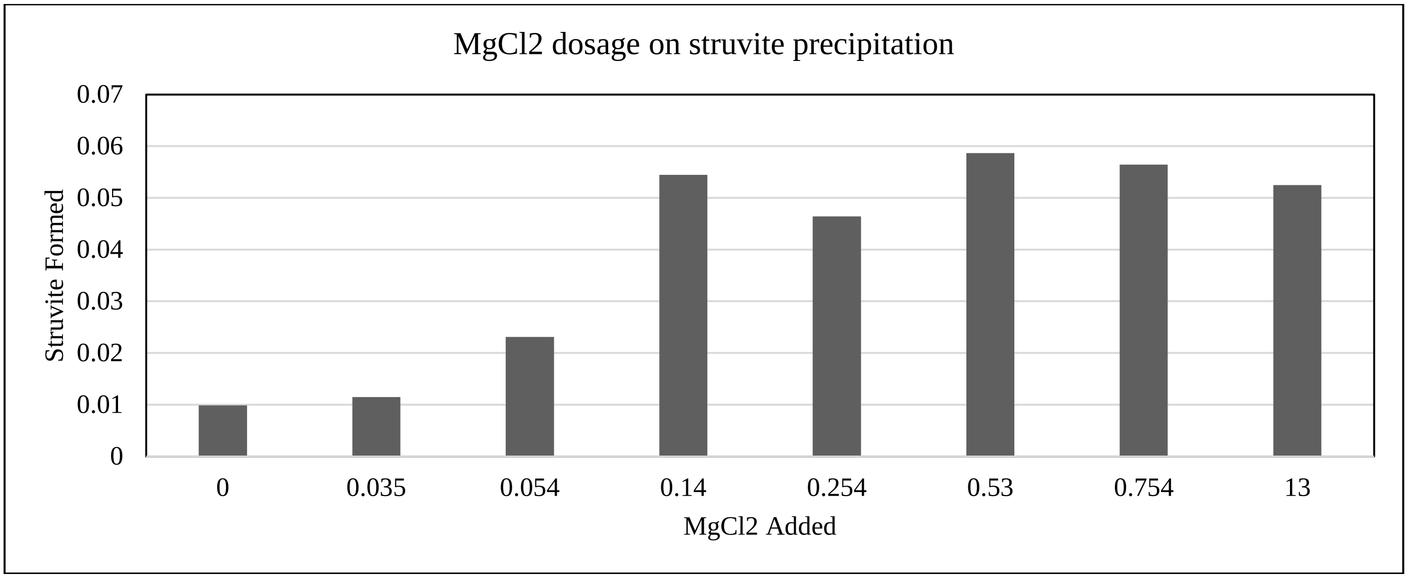

Figure-1: MgCl2 dosage on struvite precipitation.

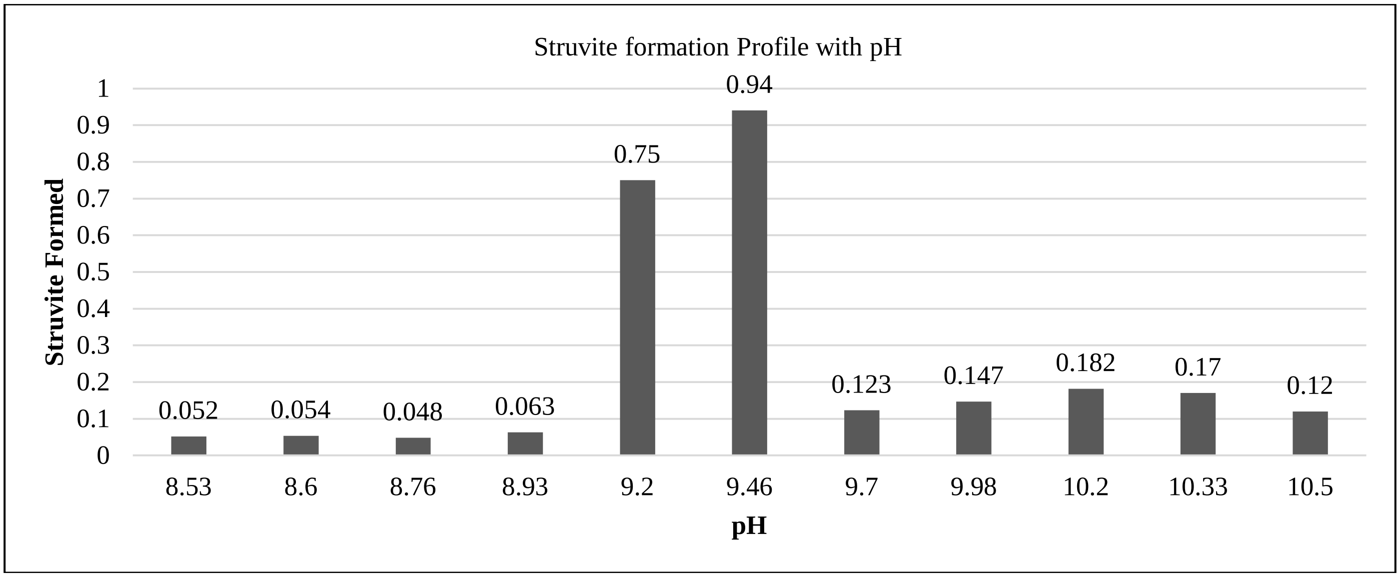

Figure-2: Struvite formation Profile with pH.

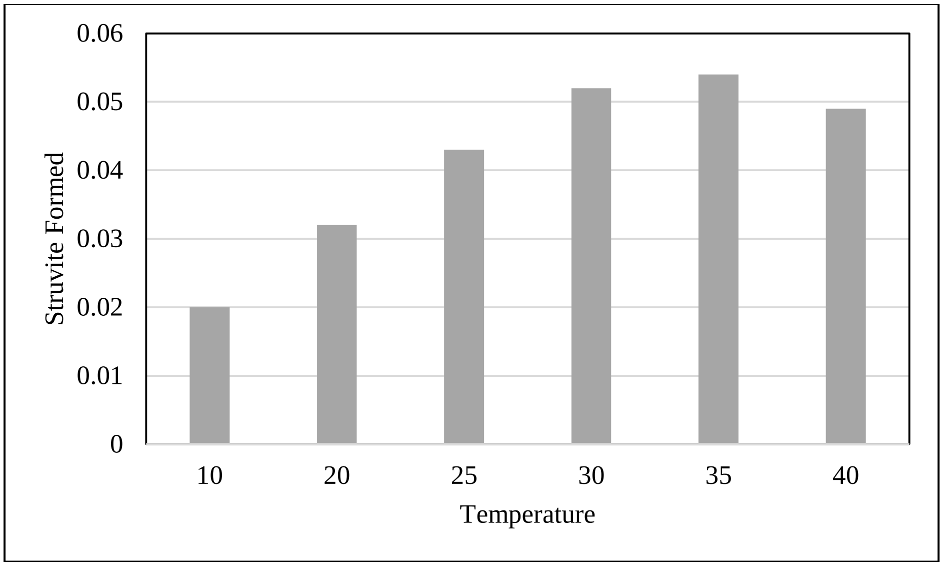

Figure-3: Upshot of temperature on struvite development.

The results highlight the status of temperature significant factor in struvite formation, with greater precipitation occurring at elevated temperatures. Understanding this relationship can inform strategies to improve nutrient recovery efficiency in wastewater treatment systems.

Conclusion

Despite the growing concern from researchers and scientists regarding the over-reliance on finite phosphorus rock reserves, there has been limited action from governments and policymakers to discourse this matter. One potential explanation to mitigate this dependence use of struvite-based fertilizers, which could serve as a partial substitute for traditional phosphorus-based fertilizers. In this study, the feasibility of utilizing struvite as a foundation for fertilizer production was thoroughly explored.

Struvite precipitation, a process that recovers phosphorus from wastewater, can be achieved by introducing magnesium sulfate as a source of magnesium. However, the efficiency and yield of struvite formation depend on optimizing several critical parameters, such as temperature, pH, and the dosage of magnesium chloride ($MgCl_2$). Fine-tuning these variables can significantly enhance the precipitation process, enabling a more effective recovery of struvite.

By adjusting the temperature, the solubility and crystal growth kinetics of struvite can be controlled. Lower temperatures may lead to slower crystal growth, while higher temperatures increase the solubility of struvite, which may hinder precipitation. pH, a major factor, directly influences the saturation state of the solution. Maintaining an ideal pH is crucial for promoting rapid and consistent crystal formation. Similarly, the concentration of magnesium chloride plays a vital role, as it determines the availability of magnesium ions necessary for struvite crystal formation. Finding the optimal $MgCl_2$ dosage ensures maximum precipitation efficiency, avoiding wastage while achieving high struvite yields.

This research underscores the potential of struvite as a sustainable and environmentally friendly alternative for phosphorus fertilizers, presenting a scalable solution that can help reduce the reliance on diminishing phosphate rock reserves. Through proper optimization of key parameters, struvite production can be made more efficient, further enhancing its viability as a fertilizer in the agricultural sector.

References

1. Zhang, M., Chi, Y., Li, S., Fu, C., Yuan, H., Wang, X., & Chen, F. (2022). Chemical phosphorus removal optimization from coating wastewater using iron–calcium salt. *Desalination and Water Treatment*, *264*, 164-171.

2. Maurer, M., & Boller, M. (1999). Modelling of phosphorus precipitation in wastewater treatment plants with enhanced biological phosphorus removal. *Water science and technology*, 39(1), 147-163.

3. Mohammed, S. A. M., & Shanshool, H. A. (2009). Phosphorus removal from water and wastewater by chemical precipitation using alum and calcium chloride. Iraqi Journal of Chemical and Petroleum Engineering, 10(2), 35–42. https://doi.org/10.31699/IJCPE.2009.2.7

4. Srivastava, G., Kapoor, A., & Ahmad, A. (2023). Improved biological phosphorus removal under low solid retention time regime in full-scale sequencing batch reactor. Sustainability. 15(7918), 1–22. https://doi.org/10.3390/su15107918

5. Giesen, A. (1999). Crystallization process enables environmentally friendly phosphate removal at low costs.

Environmental Technology, 20(7), 769–775. https://doi.org/10.1080/09593332008616873

6. Karak, T., & Bhattacharyya, P. (2010). Heavy metal accumulation in soil amended with roadside pond sediment and uptake by winter wheat. *The Scientific World Journal*, 10(17), 2314–2329. https://doi.org/10.1100/tsw.2010.220

7. Anderson, R., Brye, K. R., Greenlee, L., & Gbur, E. (2020). Chemically precipitated struvite dissolution dynamics over time in various soil textures. *Agricultural Sciences*, 11(6), 2–13. https://doi.org/10.4236/as.2020.116002

8. Bao, T., Damtie, M. M., Wang, C. Y., Chen, Z., Tao, Q., Wei, W., Cho, K., Yuan, P., Frost, R. L., & Ni, B.J. (2024). Comprehensive review of modified clay minerals for phosphate management and future prospects. *Science of the Total Environment,* 141425, 447(35), 1–22. https://doi.org/10.1016/j.scitotenv.2023.141425

9. Badawi, A. K., & Hassan, R. (2024). Optimizing sludge extract reuse from physio-chemical processes for zero-waste discharge A critical review. *Desalination and Water Treatment*, 319 (27), 1–14. https://doi.org/10.5004/dwt.2024.100527

10. Li, G., Zheng, B., Zhang, W., Liu, Q., Li, M., Zhang, H., & Zhang, H. (2024). Phosphate removal efficiency and life cycle assessment of different anode materials in electrocoagulation treatment of wastewater. *Sustainability*, 16(9), 3836, 1–25. https://doi.org/10.3390/su16093836

11. Rahman, M. M., Salleh, M. A. M., Rashid, U., Ahsan, A., Hossain, M. M., & Ra, C. S. (2014). Production of slow-release crystal fertilizer from wastewaters through struvite crystallization – A review. *Arabian Journal of Chemistry*, 7(17), 139–155. https://doi.org/10.1016/j.arabjc.2013.10.007

12. Battistoni, P., Fava, G., Pavan, P., Musacco, A., & Cecchi, F. (1997). Phosphate removal in anaerobic liquors by struvite crystallization without addition of chemicals: Preliminary results. *Water Research*, 31(11), 2925–2929. https://doi.org/10.1016/S0043-1354(97)00137-1

13. Kuwahara, Y., & Yamashita, H. (2017). Phosphate removal from aqueous solutions using calcium silicate hydrate prepared from blast furnace slag. *ISIJ International*, 57(9), 1657–1664. https://doi.org/10.2355/isijinternational.ISIJINT-2017-123

14. Fang, D., Huang, L., Fang, Z., Zhang, Q., Shen, Q., Li, Y., Xu, X., & Ji, F. (2018). Evaluation of porous calcium silicate hydrate derived from carbide slag for removing phosphates from wastewater. Chemical Engineering Journal, 354(27), 1–11. https://doi.org/10.1016/j.cej.2018.08.001

15. Luo, Y., Liu, M., Chen, Y., Wang, T., & Zhang, W. (2019). Preparation and regeneration of iron-modified nanofibers for low-concentration phosphorus-containing wastewater treatment. R. Soc. Open Sci, 6(9), 1–12. https://doi.org/10.1098/rsos.190764

16. Antunes, E., Jacob, M. V., Brodie, G., & Schneider, P. A. (2017). Isotherms, kinetics, and mechanism analysis of phosphorus recovery from aqueous solution by calcium-rich biochar produced from biosolids via microwave pyrolysis. *Journal of Environmental Chemical Engineering*, 6(1), 395–403.https://doi.org/10.1016/j.jece. 2017.12.011

17. Arshadi, M., Foroughifard, S., Etemad Gholtash, J., & Abbaspourrad, A. (2015). Preparation of iron nanoparticles-loaded Spondias purpurea seed waste as an excellent adsorbent for removal of phosphate from synthetic and natural waters. *Journal of Colloid and Interface Science*, 452(25), 69–77. https://doi.org/10.1016/ j.jcis.2015.04.025

18. Ma, Y., Dai, W., Zheng, P., Zheng, X., He, S., & Zhao, M. (2020). Iron scraps enhance simultaneous nitrogen and phosphorus removal in subsurface flow constructed wetlands. *Journal of Hazardous Materials*, 395(22), 12-26. https://doi.org/10.1016/j.jhazmat.2020.122612

19. Mackenzie, F. T., Ver, L. M., & Lerman, A. (2002). Century-scale nitrogen and phosphorus controls of the carbon cycle. *Chemical Geology*, 190(14), 13–32. https://doi.org/10.1016/S0009-2541(02)00108-0

20. McConville, J. R., Kvarnstrom, E., Jönsson, H., Karrman, E., & Johansson, M. (2017). Source separation: Challenges & opportunities for transition in the Swedish wastewater sector. *Resources, Conservation and Recycling*, 120(18), 144–156. https://doi.org/10.1016/ j.resconrec.2016.12.004