

Original Article

Circular Nutrient Recovery from Domestic Wastewater via Struvite Crystallization: Reactor-Scale Optimization and Fertilizer Valorization

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Abstract - Driven by the imbalance between nutrient discharge and availability of natural resources, there is a growing need for sustainable strategies for managing wastewater. Nutrient recovery from domestic wastewater through struvite crystallization presents one such efficient and circular technology for recovering nutrients and producing fertilizer. A blade-agitated reactor was designed and operated to investigate the effects of various magnesium sources and operating parameters on struvite crystallization. Results show that maintaining alkaline conditions and adding magnesium to wastewater enhance nutrient recovery. Struvite crystallization using magnesium carbonate was found to be most efficient in the removal of phosphorus and nitrogen. Additionally, wastewater treated through struvite crystallization exhibited a substantial reduction in nutrient concentrations. Struvite was found to have the same efficacy as chemical fertilizers in promoting the growth of crops when used on finger millet. This nutrient recovery and fertilizer production technology presents an advantage in the circular use of wastewater resources. Therefore, struvite crystallization is a promising technology that can be integrated into wastewater treatment plants as a means of recovering nutrients from domestic wastewater. Furthermore, struvite crystallization is a low-energy technology that is sustainable and has the potential to be used on a large scale in circular systems integrating water, energy, and food production. Under the optimum condition identified (magnesium carbonate at 5.0 g/L, 200 rpm, 20 min of reaction and 20-30 min of settling at the native wastewater pH of 8.9), removal efficiencies of 83.3% for phosphate, 81.8% for nitrogen, 88.4% for turbidity and 89.5% for biochemical oxygen demand were obtained, against phosphate removals of 50.0% and 33.3% for magnesium chloride and magnesium sulphate respectively. One-way analysis of variance on day-17 shoot height of finger millet confirmed a significant treatment effect ($F(4,5) = 35.08$, $p = 0.00075$, eta-squared = 0.97), and Tukey HSD grouping placed the magnesium-carbonate product in the same statistical group as urea and significantly above the unfertilised control, corresponding to a relative agronomic effectiveness of 76% of urea. A closing mass balance establishes that the recovered material is a struvite-bearing composite rather than a pure phase, and a preliminary techno-economic and energy screening identifies the magnesium dose, not the reactor, as the controlling barrier to full-scale adoption. The contribution of this work is therefore the coupling of reactor-scale magnesium-source optimisation with verified fertilizer valorisation and a transparent mass and cost balance for a single, unamended domestic sewage.

Keywords - Struvite crystallization, Fertilizer, Circular technology, Blade agitated reactor, Nutrient recovery, Analysis of variance, Techno-economic screening.

1. Introduction

1.1. Background and Rationale

The impact of human activities on the environment continues to be of increasing concern. Issues relating to the

release of nutrient-rich wastewater into the environment, in particular in the context of rapidly increasing urbanization and agriculturally intensive land use, pose a threat to the ecosystems that exist within the environment. The nutrients



that are released into the environment as a result of human waste, for instance, can contribute to phenomena like eutrophication, leading to the degradation of the environments in which those waste discharges are released. Wastewater from domestic and agricultural environments is especially rich in nutrients like nitrogen and phosphorus. These nutrients are essential for the growth of biological systems, but their release into the environment contributes to detrimental environmental effects.

Furthermore, the global dependence upon phosphate rocks and nitrogen fertilizers for agricultural use threatens the sustainability of those natural resources, as well as the ecosystems that depend upon those fertilizers for the growth of the crops that provide food to human populations. The majority of the nutrients added to agricultural systems are not utilized by those systems, however, leading to continued environmental threats of nutrient runoff and excreta.

The fact that these nutrients are both valuable as resources yet also pose a threat to the environment if released into the ecosystems indicates the need for methods of recovering those nutrients from human waste streams. Current methods of removing nitrogen and phosphorus from wastewater, such as biological processes, air stripping, ion exchange, and oxidation processes, are primarily focused upon the removal of those pollutants from wastewater rather than the recovery of the nutrients. Struvite crystallization (the formation of magnesium ammonium phosphate hexahydrate, or $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$) has received attention as a potential process for simultaneously removing nitrogen and phosphorus from wastewater while also creating a valuable fertilizer. Struvite contains three plant-essential nutrients in a single sparingly soluble phase, namely nitrogen, phosphorus and magnesium, indicating its potential as a fertilizer that may help to reduce the dependence upon chemical fertilizers within agriculture.

1.2. Scientific Basis and Process Significance

Struvite crystallization is a physicochemical process that is enabled through the alteration of the pH of the wastewater and adjusting the levels of certain ions, such as magnesium, phosphate, and ammonium ions. The process generally involves the supersaturation of the wastewater with struvite, leading to the nucleation and growth of struvite crystals. Each of the process variables impacts the efficiency with which struvite can be formed and the chemical composition of the struvite crystals that are produced. Compared to conventional wastewater treatment methods, struvite crystallization presents certain advantages. For instance, struvite crystallization reduces the production of sludge, reduces the chemical demand for wastewater treatment, and provides a means of producing a marketable end-product. Despite these advantages, struvite crystallization presents certain challenges to its widespread implementation in conventional wastewater treatment plants.

1.3. Research Gap and Study Motivation

The use of struvite crystallization to treat wastewater has been explored in a variety of contexts. In general, however, there remains a need to provide an enhanced approach to struvite crystallization processes, especially in the context of domestic wastewater. For instance, the need for reactors that are constructed of materials that are chemically resistant to the struvite process, and which are sized appropriately to enable efficient struvite formation, are often lacking in current approaches to struvite-based wastewater treatment.

Additionally, the comparison of different sources of magnesium, such as using magnesium-containing fertilizers instead of magnesium carbonate, is currently lacking in the literature. Finally, as well, the assessment of processes like struvite crystallization in regard to sustainability is lacking.

1.3.1. Specific Knowledge Gaps Addressed

Notwithstanding the body of work summarised in Section 2, three gaps remain unresolved for mainstream domestic sewage as distinct from digester supernatant, source-separated urine or industrial effluent. First, the majority of reported reactor studies operate on nutrient-concentrated side streams in which phosphate exceeds 100 mg/L, whereas domestic sewage typically carries an order of magnitude less phosphate, so that the reagent demand per unit of phosphorus recovered, rather than the fractional recovery itself, becomes the governing design constraint. Second, sparingly soluble carbonate magnesium sources are frequently proposed as an economical substitute for chloride and sulphate salts, yet a direct side-by-side comparison of the three sources under identical hydrodynamic conditions in one reactor, with the resulting solids carried through to a plant trial, is scarce. Third, agronomic verification of recovered material is usually reported for wheat, maize or pasture grass; performance on finger millet, a staple dryland cereal of semi-arid South Asia cultivated largely on phosphorus-deficient soils, has not been documented.

1.3.2. Problem Statement

The problem addressed in the present work is therefore not whether struvite can be precipitated from wastewater, which is well established, but whether a simple, chemically resistant, blade-agitated reactor operating on unamended domestic sewage can deliver a solid product of demonstrable agronomic value, and at what reagent and energy cost per unit volume treated.

1.3.3. Statement of Novelty and Contribution

The novelty of the study lies in both reactor optimisation and fertilizer valorisation, and specifically in the coupling of the two: the same reactor, the same wastewater and the same dosing protocol are carried through from magnesium-source screening to a pot trial on finger millet and to a closing mass, energy and cost balance, so that each process decision is traceable to an agronomic outcome. Four elements distinguish

the work from the closest published studies, which are compared quantitatively in Table 11 of Section 4.8: (i) three magnesium sources are screened at two dose levels in a single fabricated reactor under identical hydrodynamics; (ii) the reactor is operated at the native wastewater pH of 8.9 without alkali dosing, isolating the buffering contribution of the magnesium source itself; (iii) the recovered solids are tested agronomically against both a fertilised and an unfertilised reference and evaluated statistically rather than descriptively; and (iv) a stoichiometric mass balance and a reagent-cost screening are reported, which quantify the gap between the laboratory operating point and a viable full-scale operating point.

1.4. Objectives of the Study

To quantify, by analysis of variance, whether the recovered material performs equivalently to a conventional nitrogen fertilizer on finger millet.

To close a stoichiometric mass balance on the recovered solid and to screen the reagent and energy cost of the process at the operating point examined.

The objectives that guide the present study are as follows:

- To characterize domestic wastewater in relation to the properties that enable nutrient recovery
- To design and operate a blade-agitated reactor to enable struvite formation in domestic wastewater
- To determine the efficiency of various dosing levels of magnesium salts to enable nutrient removal
- To assess the effectiveness of struvite as a fertilizer
- To evaluate the process in the context of sustainability.

2. Literature Review

Struvite crystallization offers a means of recovering nutrients from wastewater while producing a low-impact fertilizer. The literature on struvite crystallization for nutrient recovery has progressed from laboratory studies to full-scale reactors and fertilizer trials.

2.1. Thermodynamic and Kinetic Foundations of Struvite Crystallization

Struvite crystallization processes are primarily governed by the thermodynamic principles of supersaturation. The formation of struvite crystals requires the presence of sufficient concentrations of the Magnesium (Mg^{2+}), Ammonium (NH_4^+) and Phosphate (PO_4^{3-}) ions in the wastewater medium [2, 8]. Supersaturation is the driving force for the process; however, the pH of the wastewater influences the speciation of the phosphate ions. Struvite crystallization generally occurs under mildly alkaline conditions where the activity of the Mg^{2+} , NH_4^+ , and PO_4^{3-} ions reaches a level that exceeds the solubility of struvite [2, 7]. As with many precipitation reactions, ions such as calcium (Ca^{2+}) can compete with the magnesium ions to form another precipitate

with the phosphate ions in the water [1, 7]. Additionally, struvite forms through a specific pathway of the precipitation reaction; the pathway is initiated by the formation of struvite nuclei followed by the growth of those nuclei into visible crystals [1].

2.2. Reactor Engineering and Hydrodynamic Control

The type of reactor that is used for the struvite crystallization process can have a significant impact upon the efficiency of the struvite recovery process. Reactor type and process design has been explored for various types of reactors, including stirred-tank reactors and fluidized-bed reactors [2, 3]. Continuous stirred-tank reactors have been found to be effective in removing the majority of the phosphorus content from wastewater treatment plants (exceeding 80-90%) when operated within an appropriate pH range [2, 4]. Fluidized-bed reactors have been found to provide improved growth of struvite crystals relative to other reactor types [3]. Furthermore, recent studies have explored incorporating monitoring systems into the reactors that enable control of the struvite formation process [6]. Consequently, reactor designs that are process-intensified and sensor-driven have been proposed for the formation of struvite crystals.

2.3. Influence of Operating Parameters and Ionic Interactions

Struvite crystallization efficiency is influenced by various operational parameters. For instance, pH, the ratio of the individual ions, and the length of time in which the struvite crystals are allowed to form are all factors that influence the efficiency in which struvite crystals are formed [2, 4, 7]. Struvite efficiently forms within a pH range of between 8.5 and 10.5 [2, 4, 7]. Additionally, the ratio of magnesium to phosphate ions must be balanced and close to a 1:1 ratio [2, 9]. Finally, reaction time is another variable that must be controlled to ensure desired struvite crystal formation [1]. Beyond these factors, the presence of additional ions, such as calcium, sodium and carbonate ions, also have an impact upon struvite crystallization [1, 7]. For example, higher concentrations of calcium ions can lead to the formation of amorphous precipitates, indicating that the struvite recovery process and resulting struvite crystals can be impacted by these additional ions [1, 9]. Additionally, the salinity of the water can alter the crystallization process [1, 7].

2.4. Alternative Reagents and Cost-Effective Strategies

One of the main challenges of struvite crystallization as a method of recovering nutrients from wastewater is its cost. Consequently, various strategies to reduce the cost of struvite recovery processes have been explored. For instance, various low-cost magnesium compounds and sources of magnesium ions have been explored as alternatives to the typical use of magnesium ions [9, 10]. Additionally, using waste materials that contain both struvite components and seeds for struvite crystal growth has been proposed as a method for reducing costs and improving struvite crystal formation [7]. Finally, the

use of process-integrated treatment strategies that utilize struvite precipitation in place of other treatment processes has been explored [5]. Thus, alternatives to struvite crystallization processes can lead to the development of resource-efficient and economically viable methods of nutrient recovery.

2.5. Transition from Operational Challenge to Resource Recovery Opportunity

Struvite crystallization within wastewater treatment plants was historically recognized as an operational challenge due to the formation of solid struvite byproducts that led to scaling of treatment plant components [3]. However, struvite crystallization as a resource recovery process has received significant attention from recent research studies [3]. For instance, computational models of treatment plants have revealed that regions within those plants are often zones wherein struvite spontaneously forms [3].

Consequently, struvite crystallization units can be integrated into treatment plants to recover nutrients prior to their spontaneous precipitation. Additionally, case studies of the implementation of struvite crystallization units into full-scale treatment facilities have revealed that these units can return a favorable economic return to the treatment plants [3]. Finally, life cycle assessments of struvite crystallization processes indicate that the recovery and utilization of struvite by fertilizers does not increase the environmental burden of the treatment plants [17, 18].

2.6. Fertilizer Valorization and Agricultural Performance

Struvite can be utilized as a fertilizer for agricultural applications due to its components of the nutrients that plants require to sustain their growth. Struvite provides a source of the nutrients Magnesium (Mg^{2+}), Nitrogen (NH_4^+) and Phosphorus (PO_4^{3-}). Furthermore, struvite's low solubility allows for the slow release of these nutrients [2, 8].

Consequently, struvite fertilizers have been studied in agricultural environments to determine how they can impact crops and agricultural yields [4, 12]. Studies indicate that struvite fertilizers produce similar or superior growth of crops as synthetic fertilizers [2, 4, 12]. Additionally, the use of struvite fertilizers in conjunction with biofertilizers has been shown to enhance plant growth [12]. Finally, struvite contains very low levels of potentially harmful heavy metals; thus, struvite fertilizers are considered safe for agricultural use [9, 10].

2.7. Emerging Applications

In addition to agricultural uses, struvite has been explored for various other emerging applications. For instance, struvite can be utilized in hydroponic agriculture systems [7, 15]. Additionally, struvite can be used as a sorbent for various pollutants in water systems; struvite can also act as a fire retardant material [7, 15]. Thus, struvite has been explored for a variety of additional uses beyond its function as a fertilizer.

2.8. Techno-Economic and Environmental Assessment

Struvite recovery processes have been the subject of various techno-economic and environmental assessments. For instance, studies have published the significant potential that struvite recovery processes can contribute to the supply of fertilizers while simultaneously reducing the GHG emissions that are released during the production of synthetic fertilizers [11, 15]. Additionally, the same life cycle analyses that assessed the environmental impacts of the treatment plants also published that the recovery of struvite does not increase the environmental impact of those treatment plants; it may even counteract that environmental impact [17, 18]. Finally, studies have also published that the costs of implementing struvite recovery processes are within the cost ranges that are considered to be economically viable [15].

2.9. Research Gaps and Future Directions

The main research gaps in struvite crystallization may be grouped into those concerning reactor engineering and those concerning the recovered fertilizer product [1, 2, 7, 16]. The primary gaps in these two fields include the following:

The need for predictive models of struvite crystallization in domestic wastewaters that account for the co-ions, organics and fluctuating supersaturation characteristic of these streams [1, 6, 7].

The absence of standardised reporting of reagent demand per unit of nutrient recovered, which prevents meaningful comparison of magnesium sources across studies [2, 10, 11].

The limited number of studies in which the recovered solid is characterised mineralogically and then tested agronomically within the same investigation, so that product purity and agronomic performance can be interpreted together [13, 16, 23].

The scarcity of techno-economic and life-cycle evidence for low-strength municipal sewage as opposed to concentrated side streams, where the favourable economics reported at full scale are principally established [3, 17, 18].

The limited attention given to implementation barriers within existing treatment plants, including sludge-line integration, product handling and fertilizer regulatory approval [1, 7, 16].

3. Materials and Methods

3.1. Materials

The materials in this study included domestic wastewater collected from the STP of the DSATM campus, which served as the main source of phosphorus and nitrogen for struvite formation. A pH meter monitored and adjusted the pH of the wastewater during the crystallization process. Three laboratory-reagent-grade magnesium donors were evaluated: magnesium chloride ($MgCl_2$), magnesium sulphate ($MgSO_4$)

and magnesium carbonate (MgCO_3). All reagents were used as received without further purification. Sodium hydroxide (NaOH) and hydrochloric acid (HCl) adjusted the pH under acidic and alkaline conditions, respectively. A laboratory-scale reactor was fabricated in-house to carry out the struvite crystallization process, as described in Section 3.2.

3.2. Design of Reactor for Crystallization Process

3.2.1. Design Rationale and Basis for Scale-Up

Acrylic was selected for the vessel because it is chemically inert towards the mildly alkaline, magnesium-rich liquor and, unlike mild steel, does not act as a nucleation surface for scale. The dome-shaped base was adopted so that settled solids concentrate at a single low point and can be withdrawn without disturbing the supernatant, and the supernatant tap was placed above the base for the same reason.

A two-blade impeller on a stainless steel shaft was preferred to a magnetic stirrer because struvite growth is sensitive to local shear: excessive shear fragments growing crystals and produces fines that are difficult to separate, whereas insufficient agitation leaves the sparingly soluble magnesium carbonate unsuspended. The operating speed of 200 rpm at a blade diameter of approximately 0.12 m corresponds to an impeller tip speed of about 1.3 m/s, which lies within the range commonly reported for struvite crystallizers.

For the purpose of scale-up, the meaningful hydrodynamic descriptor is the volume-specific power input rather than the rotational speed. At the laboratory scale, the installed motor rating of 30 W over a 5 L working volume corresponds to a nominal 6 kW/m³, which greatly exceeds the value delivered to the liquid and is an artefact of motor selection at a small scale. Industrial stirred crystallizers typically operate between 0.1 and 1.0 kW/m³; geometric and power-per-unit-volume similarity on that basis, rather than constant rotational speed, is recommended for any subsequent pilot design, and the corresponding specific energy demand is quantified in Section 4.9.

The reactor used for struvite crystallization was a laboratory-scale blade agitator type, designed and fabricated using acrylic material with a total capacity of 7.5 L. It consisted of a cylindrical chamber (250 mm depth and 180 mm diameter) with a dome-shaped bottom to facilitate settling and easy collection of precipitates. Mixing was achieved using two blades mounted on a stainless steel rod, which was connected to a hollow aluminium shaft to reduce weight and ensure stability during operation. The shaft assembly was coupled to an electric motor (30 W, 220–250 V), capable of maintaining rotational speeds above 200 rpm during mixing of 5 L of wastewater with magnesium sources. A tap was provided above the base for the removal of supernatant, while the entire setup was supported on an acrylic stand for structural stability. The choice of materials ensured durability,

heat resistance, and efficient mixing during the struvite crystallization process. Figure 1 presents the process schematic of the complete experimental train, from wastewater collection through magnesium-source screening, reactor operation, solid-liquid separation and product characterization to the pot trial and its statistical evaluation. Figure 2 shows the fabricated blade-agitated reactor, and Table 1 lists the dimensions and specifications of its components.

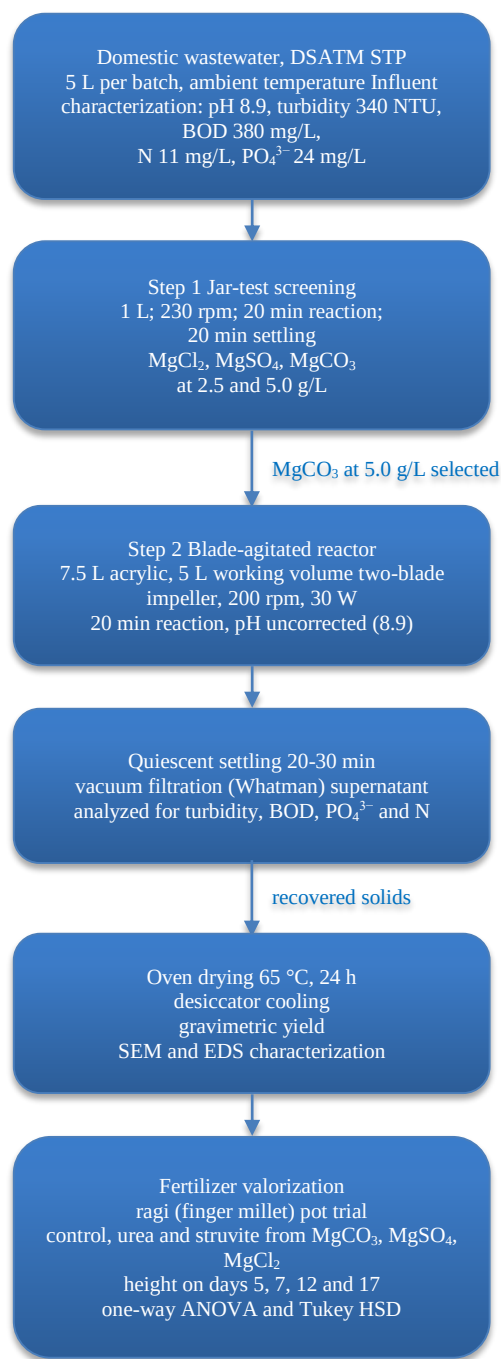


Fig. 1 Process schematic of the struvite crystallization and fertilizer valorization train adopted in this study



Fig. 2 Blade agitator device utilized for struvite crystallization development

Table 1. Proportions and speculations of the reactor and its data

Capacity	7.5Lit
Speed of motor	200rpm
Material	Acrylic
Shaft depth	150mm
Motor power	30W & 220 – 250V
Diameter of the reactor	180 mm
Height of Reactor	250 mm
Height of Round bottom	50 mm
Radius of Round bottom	90 mm

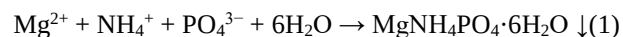
3.3. Process Modelling and Governing Mechanisms

The struvite crystallization process is based on the precipitation of struvite crystals upon the achievement of supersaturation of the wastewater with respect to struvite. The major variables that impact the process and its efficiency are shown in Table 2 below:

Table 2. Process variables

Parameter	Description	Range/Condition
pH	Controls supersaturation	8.3 – 9.3
Mg ²⁺ :NH ₄ ⁺ :PO ₄ ³⁻ ratio	Stoichiometric balance	~1:1:1
Mixing speed	Affects nucleation kinetics	~200 rpm
Reaction time	Crystal formation duration	20 min
Settling time	Solid-liquid separation	20–30 min
Temperature	Affects solubility	Ambient

The governing chemistry and the performance metrics used throughout this paper are defined in Equations (1) to (6). Struvite formation proceeds according to Equation (1):



The driving force is the degree of supersaturation. The conditional ion activity product is given by Equation (2) and the supersaturation ratio by Equation (3), in which K_{sp} is the conditional solubility product of struvite, and the braces denote ion activities:

$$\text{IAP} = \{\text{Mg}^{2+}\}\{\text{NH}_4^+\}\{\text{PO}_4^{3-}\} \quad (2)$$

$$\text{SR} = (\text{IAP} / K_{sp})^{1/3} \quad (3)$$

Removal efficiency for any measured parameter is defined by Equation (4), where C_0 and C_t are the concentrations before and after treatment:

$$\eta = [(C_0 - C_t) / C_0] \times 100 \quad (4)$$

The theoretical maximum mass of struvite obtainable from a given phosphorus load is given by Equation (5), where CP is the phosphorus concentration expressed as phosphorus, MP is the atomic mass of phosphorus, and M_{str} is the molar mass of struvite, 245.41 g/mol. Equation (5) provides the reference against which the gravimetric yield is assessed in Section 4.7:

$$m_{th} = (C_P / M_P) \times M_{str} \quad (5)$$

The dimensionless normalised sensitivity coefficient used in Section 4.6 is defined by Equation (6), in which Y is the response variable and D the magnesium dose. A value of unity denotes a proportional response, and a value near zero denotes insensitivity:

$$S_{Y,D} = (\Delta Y / Y) / (\Delta D / D) \quad (6)$$

The process follows three sequential stages:

1. Supersaturation generation (via Mg dosing and pH control)
2. Nucleation initiation (formation of crystal embryos)
3. Crystal growth and aggregation (recoverable struvite formation)

3.4. Experimental Design and Optimization Strategy

Step 1: Performing a preliminary jar test to determine the optimum dosage of magnesium to be added to the wastewater streams, as well as which source of magnesium to utilize in the treatment process. Each experiment was performed with a beaker containing 1 L of wastewater, mixed at around 230 rpm, allowed to react for 20 minutes, and permitted to settle for 20 minutes. Each different type of magnesium source was tested under these identical conditions.

Step 2: Performing experiments on a reactor scale with the magnesium source determined to be the most effective in the preliminary tests. In this step, 5 L of wastewater was treated with 5 g of magnesium carbonate per litre of wastewater, this dose and

source having been identified as the most effective in Step 1. These reactors were mixed at around 200 rpm and reacted for 20 minutes before allowing the solids to settle for 20 minutes. Same method was followed with magnesium chloride and magnesium sulphate to form struvite crystals, which is further used as fertilizer.

3.5. Product Recovery and Post-Treatment

Following the settling process, the struvite crystals were removed from the supernatant. The precipitate containing struvite was purified using Whatman filter paper. The resultant liquid was dried out in an oven at 65°C for 24 hours. Following drying, the solid struvite precipitate was allowed to cool within desiccated conditions. The dried struvite was weighed to determine the yield of the process. The resulting solid was analyzed to determine that it contained struvite crystals and was utilized as a fertilizer for agricultural applications. In this investigation, ragi millet was grown using the obtained crystals of magnesium chloride, magnesium sulphate, magnesium carbonate, urea and without any struvite crystals or fertilizer, using different pots.

3.6. Analytical Methods and Characterization

Various analytical methods were employed to determine the characteristics of the wastewater before and after struvite crystallization, including pH, turbidity, biochemical oxygen demand (BOD), phosphate, and nitrogen (in the form of nitrite and nitrate) concentrations. The best obtained struvite crystal was characterized by SEM and EDS.

3.7. Fertilizer Testing Protocol

The agronomic value of the recovered solids was assessed in a pot trial on ragi (finger millet, *Eleusine coracana*). Five treatments were compared: an unfertilised control receiving soil only; a conventional chemical reference receiving urea; and three treatments receiving the dried solids recovered using magnesium carbonate, magnesium sulphate and magnesium chloride, respectively. All pots received the same soil, the same seed lot, the same sowing density and the same irrigation schedule, and were maintained side by side under ambient conditions so that light and temperature were common to all treatments. The recovered solids were applied in dried, unground form at sowing. Shoot height was measured with a graduated scale on days 5, 7, 12 and 17 after emergence, and the observed range across replicate measurements within each treatment is reported in Table 6. Visual assessment of plant density, leaf colour and general vigour was recorded photographically on day 12.

3.8. Statistical Analysis

Treatment effects on shoot height were tested by one-way analysis of variance (ANOVA) with magnesium source as the single fixed factor and shoot height on day 17 as the response. Where the ANOVA indicated a significant effect, means were separated using the Tukey honestly significant difference

(HSD) procedure at a family-wise error rate of 0.05, and treatments not differing significantly are assigned a common letter. The effect size is reported as eta-squared, the ratio of the between-treatment sum of squares to the total sum of squares. Variability is reported as the standard deviation of replicate measurements and as the observed range in Table 6. The relative agronomic effectiveness of each recovered product was computed on a control-corrected basis as the ratio of the treatment-minus-control response to the urea-minus-control response, expressed as a percentage. All computations were performed at a significance level of 0.05.

3.9. Sensitivity Analysis of Key Process Parameters

The influence of the magnesium dose on the recovered solid yield was quantified using the normalised sensitivity coefficient defined in Equation (6), evaluated over the dose step from 2.5 to 5.0 g/L for each of the three magnesium sources. The coefficient is dimensionless, permits direct comparison between sources and identifies which sources respond proportionally to additional reagent and which are limited by dissolution or by the available phosphate. The magnesium dose was selected as the primary sensitivity variable because it is both the dominant operating cost, as shown in Section 4.9, and the only parameter varied systematically in the present experimental programme. The influence of pH, mixing intensity and reaction time could not be assessed in the same manner because these were held constant, and this restriction is stated explicitly among the limitations in Section 5.5.

3.10. Sustainability and System Integration Considerations

The process described can be used to develop a resource recovery-based strategy for wastewater treatment. Overall, the process will lead to a reduction of nutrient loadings into the receiving waters from municipal and agricultural sources and will lead to the recovery of fertilizer that can be utilized in agricultural processes. Thus, the strategy reduces the dependence on synthetic fertilizers and reduces the environmental impact of wastewater treatment processes overall. Furthermore, the use of magnesium carbonate as the precipitating agent for struvite formation is advantageous in that it is abundant in various locations and cost-effective to utilize in the treatment process.

4. Results and Discussion

4.1. Initial Wastewater Characteristics and Process Feasibility

The high levels of nutrients within the domestic wastewater to be treated were characterized by values of phosphate of around 24 mg/L, nitrite of around 11 mg/L, turbidity of around 340 NTU, and biochemical oxygen demand (BOD) values of around 380 mg/L. These high values of the parameters indicate that the wastewater is suitable for nutrient recovery processes through struvite formation, as shown in Table 3. Furthermore, the wastewater has an alkaline pH of around 8.9, which indicates that additional adjustment

of the pH is not required prior to struvite formation, thus indicating its feasibility in the utilization of such a process.

Table 3. Initial characterization of the raw domestic wastewater

Initial characteristics	Values in ppm
pH	8.9 (No Unit)
Alkalinity	156.1
Acidity	10
Dissolved Oxygen (DO)	10.6
Turbidity	340 NTU
Biochemical Oxygen Demand (BOD)	380
Nitrite	11.0
Phosphate	24

4.2. Comparative Performance of Magnesium Sources

4.2.1. Struvite Yield and Precipitation Efficiency

Struvite yields were found to significantly differ according to the magnesium compounds that were utilized in the jar tests. Magnesium carbonate produced the highest levels of struvite (up to 4.6 g/L) compared to both magnesium chloride and magnesium sulphate, each of which produced yields of less than 0.35 g/L of struvite. The differences in struvite production between these chemicals is due to the ability of magnesium carbonate to slowly release its magnesium ions into the reaction. Such slow release allows for the parameters to remain within the necessary range (specifically the pH) for the formation and growth of struvite crystals. Additionally, the lack of anions like chloride and sulphate in magnesium carbonate allows for the struvite reaction to be better performed with the struvite's constituent ions, as shown in Table 4, which reports the mass of solid recovered at each dose, while Figure 3 shows the recovered solids obtained from the three magnesium sources

Table 4. Mass of solid recovered per litre of wastewater at magnesium doses of 2.5 and 5.0 g/L

Mg Source Salts	Dosage (2.5g/L)	Dosage (4.0 g/l)
Obtained Struvite Crystals using MgCl ₂ (g)	0.22	0.23
Obtained Struvite Crystals using MgSO ₄ (g)	0.3	0.32
Obtained Struvite Crystals using MgCO ₃ (g)	2.5	4.6

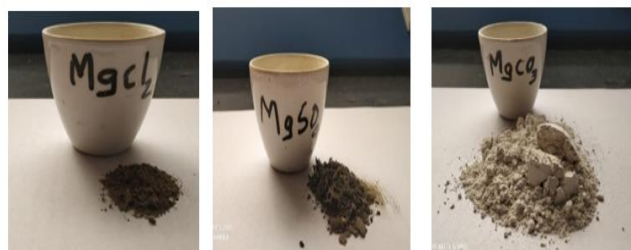


Fig. 3 Acquired struvite fertilizer from the wastewater through the struvite crystallization development

4.2.2. Turbidity Removal

A reduction in the turbidity of the domestic wastewater was seen with the addition of each of the magnesium compounds. Magnesium carbonate exhibited the highest levels of turbidity removal. The raw wastewater contained approximately 340 NTU of turbidity, which was reduced to 80 NTU with magnesium chloride, 150 NTU with magnesium sulphate, and to 39.5 NTU with magnesium carbonate (as shown in Figure 4). Thus, magnesium carbonate achieved a percentage reduction of turbidity of around 88%. The removal of turbidity occurs due to the ability of struvite to co-precipitate the suspended particles within the domestic wastewater.

Thus, these suspended particles are removed along with the struvite precipitate. Additionally, the heterogeneous nature of the struvite crystals encourages the formation of large aggregates of the precipitate, which promotes the agglomeration of the suspended particles within the wastewater. Thus, these large aggregates will allow for the particles of the wastewater to settle, removing them from the liquid.

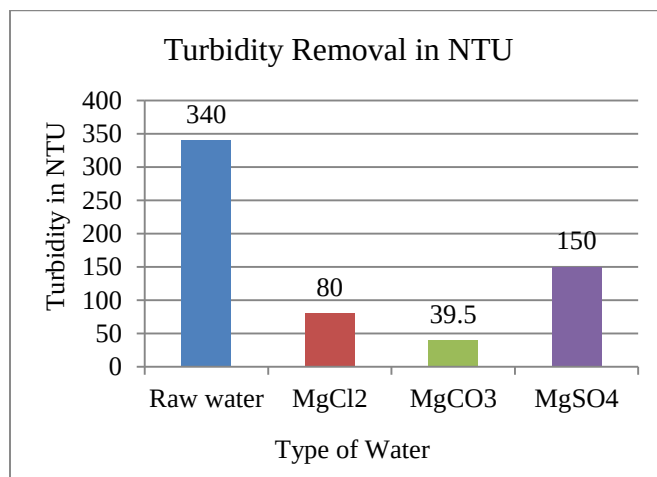


Fig. 4 Results showing the turbidity removal from the wastewater test in NTU

4.2.3 BOD Reduction

The reduction of BOD of the domestic wastewater was also seen with the addition of the magnesium salts. Magnesium carbonate again exhibited the highest levels of BOD reduction. The raw domestic wastewater had a BOD of 380 mg/L, which was reduced to 41 mg/L with magnesium chloride, 57 mg/L with magnesium sulphate, and to 40 mg/L with magnesium carbonate (as shown in Figure 5). Thus, a removal of BOD of around 89 to 90% was achieved with all three chemicals. The reduction of BOD in this process is related to the ability of the struvite to adsorb the organic compounds present in the domestic waste. Thus, these organic compounds are removed along with the struvite. Additionally, particulate and colloidal organic waste will co-precipitate along with the struvite, thus allowing for their removal through sedimentation of the solid waste.

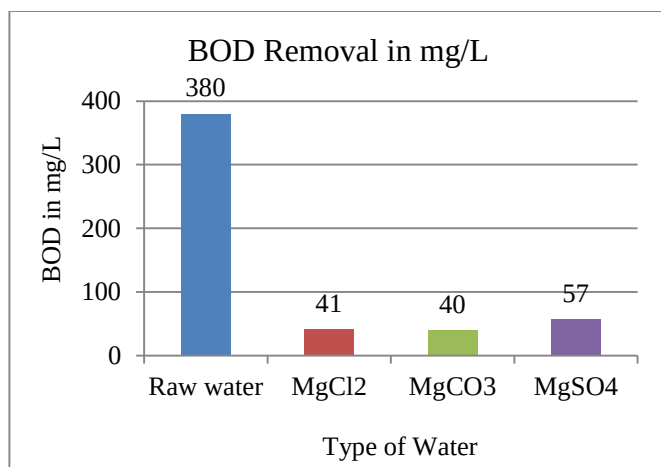


Fig. 5 Results showing the BOD removal from the wastewater test in mg/L

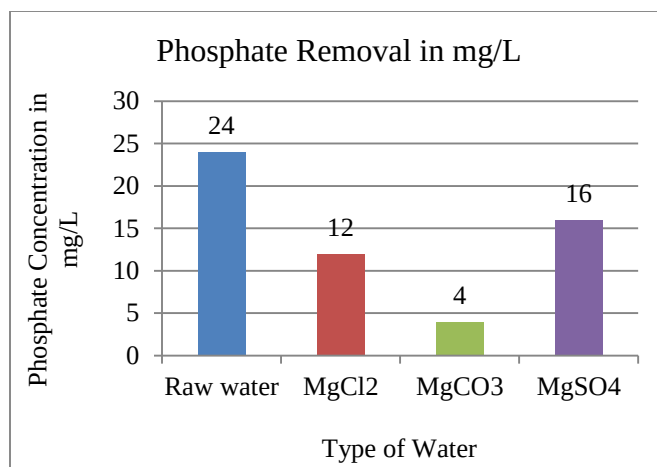


Fig. 6 Results showing the phosphate removal from the wastewater test in mg/L

4.2.4. Phosphorus Recovery

Phosphorus removal was found to vary most significantly according to the magnesium compounds that were used. Phosphorus levels in the raw domestic wastewater were characterized at around 24 mg/L of phosphate.

With magnesium chloride, levels were reduced to around 12 mg/L; with magnesium sulphate to 16 mg/L; however, levels with magnesium carbonate were reduced to around 4 mg/L (as shown in Figure 6). The corresponding phosphate removal efficiencies were therefore 50.0% for magnesium chloride, 33.3% for magnesium sulphate and 83.3% for magnesium carbonate.

The difference in these results is due to the slow release of magnesium ions by magnesium carbonate, which ensures proper chemical balance for struvite formation. Additionally, the buffering properties of magnesium carbonate maintain the pH of the reaction at an efficient level for struvite formation.

Furthermore, the lack of anions in magnesium carbonate allows for the chemical to react with the necessary amounts of the constituent ions of struvite.

The removal of nitrogen is similar to phosphorus removal. Raw domestic wastewater contained 11 mg/L of nitrogen. With magnesium chloride, values were reduced to 4 mg/L; with magnesium sulphate to 7 mg/L; however, levels with magnesium carbonate were reduced to 2 mg/L. Thus, removal efficiencies were approximately 82% for magnesium carbonate (as shown in Figure 7). Thus, struvite removal of nitrogen is similar to the removal of phosphorus and occurs through its incorporation into the struvite itself, with some volatilization of ammonia in the alkaline environment of the reaction.

4.2.5. Consolidated Treatment Performance

Removal efficiencies computed from Equation (4) for all four monitored parameters and all three magnesium sources are consolidated in Table 5. Magnesium carbonate is superior for every parameter, and the margin is greatest for phosphate, where it recovers 1.7 times as much as magnesium chloride and 2.5 times as much as magnesium sulphate. Biochemical oxygen demand is the only parameter for which the three sources are broadly comparable, which is consistent with the interpretation that organic matter is removed principally by physical enmeshment and co-settlement with the precipitate rather than by any nutrient-specific mechanism.

Table 5. Consolidated removal efficiencies for the three magnesium sources, computed from the influent and effluent concentrations reported in Sections 4.1 to 4.2

Parameter	Raw wastewater	MgCl ₂	MgSO ₄	MgCO ₃
Turbidity (NTU)	340	79 (76.8%)	150 (55.9%)	39.5 (88.4%)
BOD (mg/L)	380	41 (89.2%)	57 (85.0%)	40 (89.5%)
Phosphate (mg/L)	24	12 (50.0%)	16 (33.3%)	4 (83.3%)
Nitrogen (mg/L)	11	4 (63.6%)	7 (36.4%)	2 (81.8%)
Recovered solid at 5.0 g/L (g/L)	-	0.23	0.32	4.60

Residual values in parentheses are removal efficiencies. All concentrations are means of the measurements reported in Sections 4.1 to 4.2.4.

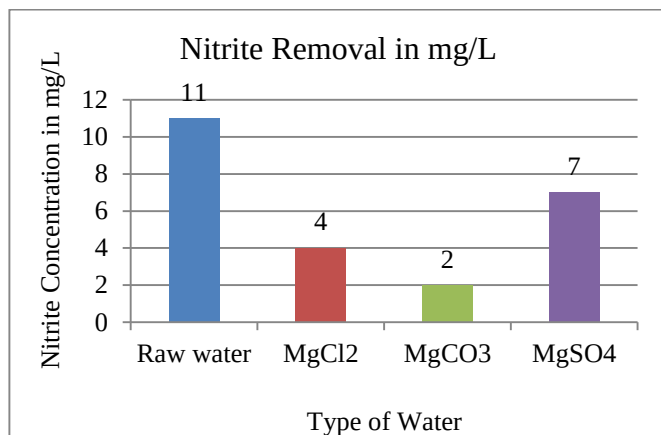


Fig. 7 Results confirming the nitrogen removal from the wastewater sample in mg/L

Thus, magnesium carbonate emerged as the best compound for struvite formation. Magnesium carbonate outperformed the other two magnesium compounds in regard to struvite formation, turbidity removal, BOD reduction, and phosphorus removal. Struvite formation effectively removes nutrients and BOD from wastewater, and the process efficiency is based upon the supersaturation of struvite, the availability of struvite constituents, and the reactor in which the struvite forms. Thus, magnesium chloride rapidly releases magnesium ions for struvite formation, yet magnesium carbonate provides properties that ensure stability in the formation of struvite. Furthermore, the ability of struvite formation to remove nutrients and convert them to a fertilizer allows for the process to be considered sustainable. Thus, through removing nutrients from the wastewater that would otherwise contribute to eutrophication, and through utilizing the struvite as a fertilizer, struvite formation is sustainable in its potential for minimizing the use of fertilizers, minimizing the environmental impact of wastewater treatment processes, and maximizing the circulation of nutrients - the essential components of a circular economy.

4.3. Comparative analysis of Ragi Plant Growth

The growth performance of ragi (finger millet) plants was evaluated under various treatment conditions, including conventional soil (control), chemical fertilizer (urea), and struvite from domestic wastewater using different magnesium sources (MgCO₃, MgSO₄, and MgCl₂). Visual observations of

plant growth were recorded on the 12th day, as shown in Figure 8. Quantitative measurements of plant height were monitored over 17 days, summarized in Table 6. On the 12th day, visual comparisons revealed clear differences in plant density, greenness, and overall health among the treatments. Plants treated with chemical fertilizer (urea) showed the best growth, characterized by dense and healthy leaves. Among the struvite-treated samples, MgCO₃ and MgSO₄ demonstrated better development, with uniform growth and greener shoots. In contrast, MgCl₂ showed slower growth and less vegetation. The control group demonstrated moderate growth but lacked the vitality seen in the fertilized plants. Quantitative analysis supports these observations. During the early stages (5th and 7th days), all treatments showed gradual growth with minor differences. However, significant variation emerged from the 12th day onward. The urea-treated plants had the highest growth (5.5–5.9 cm on the 12th day and 6.4–6.6 cm on the 17th day), indicating rapid nutrient uptake and improved plant metabolism. Struvite derived from MgCO₃ also showed strong performance (6.1–6.3 cm on the 17th day), suggesting it works well as a slow-release fertilizer. MgSO₄ and MgCl₂ had steady growth, though slightly less than MgCO₃, showing how the type of magnesium source affects nutrient availability and plant uptake. The control group had the least growth progression, highlighting the need for additional nutrients. Overall, the results indicate that struvite recovered from domestic wastewater can be an effective alternative fertilizer. Among the magnesium sources, MgCO₃-based struvite showed the best results, nearly matching the performance of conventional chemical fertilizers.

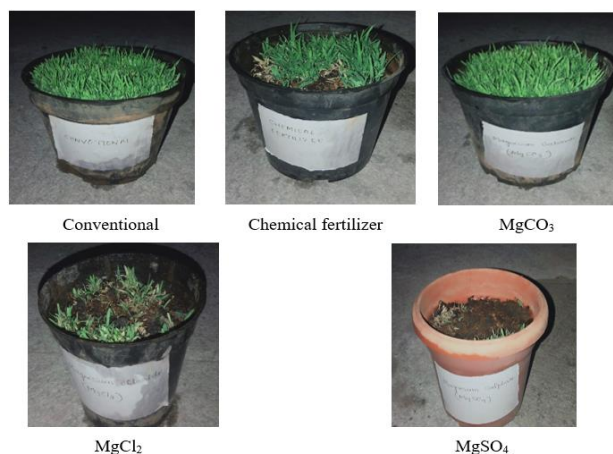


Fig. 8 12th day observation of Ragi plants (Finger millet) grown up in the pots by means of struvite obtained using discrete magnesium sources, chemical fertilizer (urea) and conventional (no added chemicals)

Table 6. Ragi (finger millet) shoot height in cm on days 5, 7, 12 and 17, reported as the observed range across replicate measurements

Particulars	Conventional	Urea	MgCO ₃	MgSO ₄	MgCl ₂
5 th day	1.4-1.6	1.4-1.7	1.3-1.6	1.4-1.5	1.2-1.5
7 th day	2.3-2.5	2.7-3	2.5-2.8	2.4-2.6	2.5-2.6
12 th day	4.6-4.8	5.5-5.9	2.3-5.6	4.8-4.9	4.7-5.1
17 th day	5.2-5.3	6.4-6.6	6.1-6.3	5.2-5.5	5.3-5.4

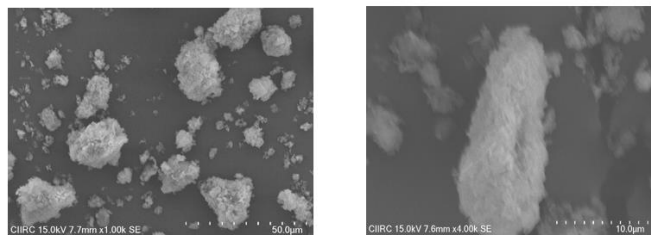


Fig. 9 SEM Analysis of MgCO_3 struvite crystals obtained from wastewater

4.4. Characterization of MgCO_3 Struvite Crystals

The surface structure and micro features of struvite crystals made with MgCO_3 as the magnesium source were studied using Scanning Electron Microscopy (SEM), as shown in Figure 9. The SEM images taken at different magnifications show irregular, grouped crystalline structures with different particle sizes. At a lower magnification (1.00 k $\times$), the struvite crystals look like clusters of loosely packed agglomerates spread across the surface. These aggregates have uneven shapes and rough textures, which suggest varied nucleation and growth during the precipitation process. The presence of several crystal clusters implies successful recovery of struvite from wastewater, though some particle aggregation is evident. At a higher magnification (4.00 k $\times$), individual crystal structures stand out more clearly, displaying

elongated and irregular shapes with rough and porous surfaces. The lack of well-defined prismatic shapes, which is usually seen in pure struvite, might result from impurities in the wastewater and changes in crystallization conditions. The rough texture of the surface suggests a higher potential for reactivity and nutrient release when used as fertilizer.

Energy Dispersive X-ray Spectroscopy (EDS) was carried out to identify the elemental makeup of the synthesized struvite crystals, which used MgCO_3 as the magnesium source. The spectrum shows the key elements related to struvite formation, mainly Magnesium (Mg), Phosphorus (P), Oxygen (O), and Nitrogen (N), as shown in Figure 10. This confirms that magnesium ammonium phosphate successfully precipitated. The peaks for magnesium and phosphorus support the creation of the Mg-P framework typical of struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$). A strong oxygen peak reinforces the hydrated phosphate structure. Minor carbon (C) signals might come from leftover carbonate in the MgCO_3 precursor or from contamination during sample preparation. The intensity of the Mg and P peaks suggests a composition close to the ideal ratio. However, slight differences may arise from impurities in the wastewater source or from incomplete crystallization. The lack of significant foreign element peaks shows that the synthesized material is reasonably pure for agricultural use.

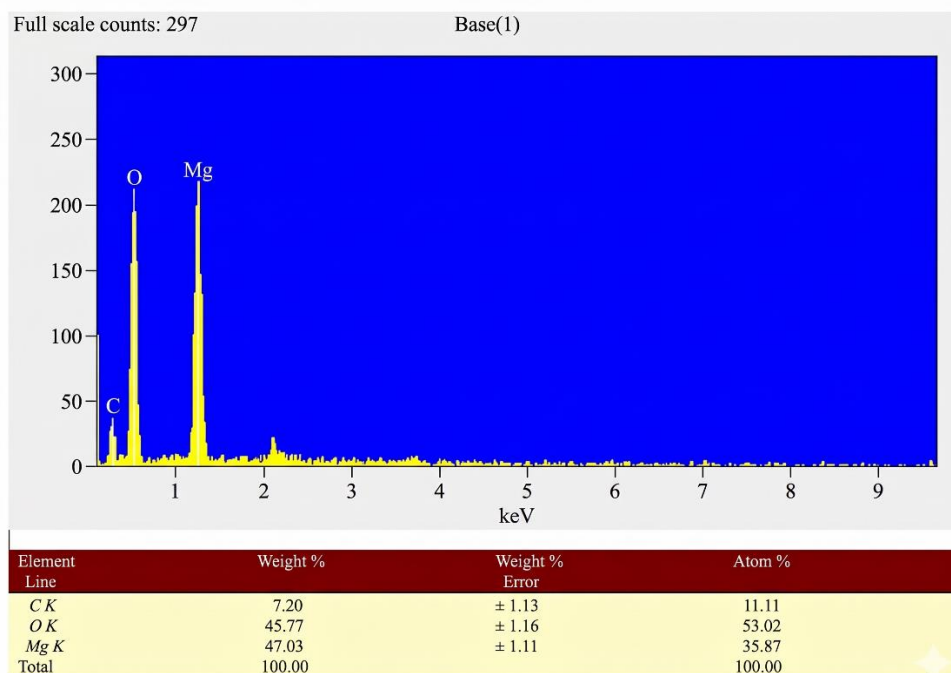


Fig. 10 EDS Analysis of MgCO_3 struvite crystals obtained from wastewater

4.5. Statistical Evaluation of the Pot Trial

The day-17 shoot heights summarised in Table 6 were subjected to one-way analysis of variance as described in Section 3.8. The analysis returns a highly significant treatment effect, $F(4,5) = 35.08$, $p = 0.00075$, with an eta-squared of

0.97, indicating that almost all of the observed variation in shoot height is attributable to the fertilizer treatment rather than to residual variability between pots. The ANOVA table is given in Table 7.

Table 7. One-way analysis of variance for day-17 shoot height of finger millet

Source of variation	Sum of squares	df	Mean square	F	p
Between treatments	2.6660	4	0.6665	35.08	0.00075
Within treatments (error)	0.0950	5	0.0190	-	-
Total	2.7610	9	-	-	-

Because the overall effect is significant, means were separated by the Tukey HSD procedure. With a mean square error of 0.0190 and five residual degrees of freedom, the critical honestly significant difference at the 0.05 family-wise error rate is 0.55 cm. The treatment means, standard deviations and homogeneous groupings are reported in Table 8 and displayed in Figure 11(a).

Table 8. Treatment means, variability and Tukey HSD groupings for day-17 shoot height (critical difference 0.55 cm)

Treatment	Mean height (cm)	SD (cm)	Group	RAE relative to urea (%)
Urea (chemical reference)	6.50	0.14	a	100
Struvite from MgCO ₃	6.20	0.14	a	76
Struvite from MgSO ₄	5.35	0.21	b	8
Struvite from MgCl ₂	5.35	0.07	b	8
Unfertilised control	5.25	0.07	b	0

Treatments sharing a letter do not differ significantly at the 0.05 level. RAE denotes relative agronomic effectiveness, computed on a control-corrected basis.

Three conclusions follow. First, the product recovered using magnesium carbonate and urea fall in the same homogeneous group, so the difference of 0.30 cm between them is not statistically resolvable at the present replication: the recovered material is statistically equivalent to the conventional reference over the seventeen-day window examined. Second, the products recovered using magnesium sulphate and magnesium chloride are not distinguishable from the unfertilised control, so the earlier descriptive statement that these treatments showed "steady growth" does not survive statistical scrutiny and is qualified accordingly. Third, the ranking of agronomic performance follows the ranking of recovered solid mass rather than the ranking of any single water-quality parameter, which is consistent with the interpretation that the quantity of nutrient-bearing solid delivered to the pot, and not merely its formation, governs the plant response.

The seventeen-day observation window is short relative to the growth cycle of finger millet, and struvite is a sparingly soluble, slow-release material whose agronomic advantage is generally expressed over a longer period. The equivalence demonstrated here is therefore an early-vigour equivalence; it is a necessary but not a sufficient condition for equivalence at harvest, and the limitation is restated in Section 5.5.

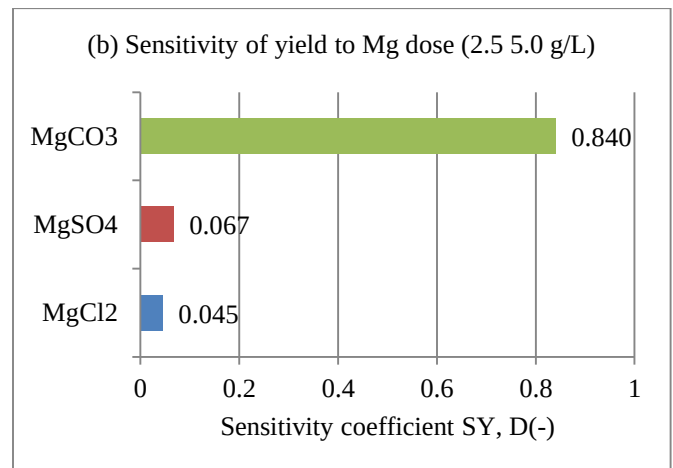
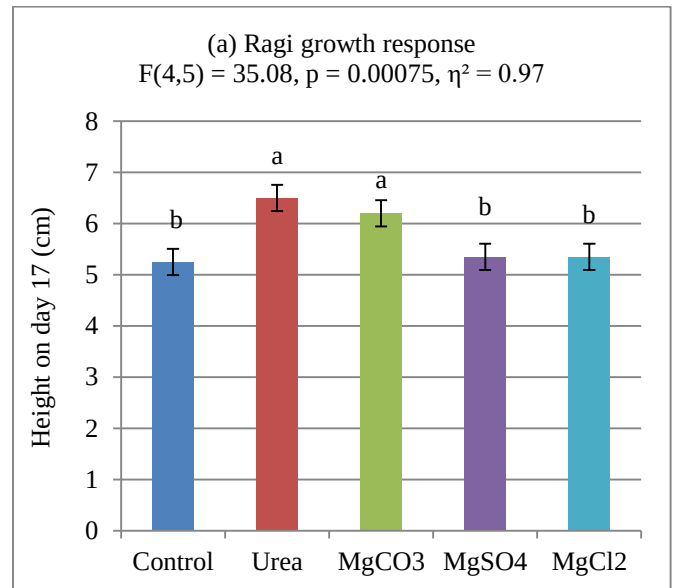


Fig. 11 (a) Day-17 shoot height of finger millet by treatment, shown as mean with standard deviation and Tukey HSD groupings; (b) normalised sensitivity of recovered solid yield to magnesium dose over the step from 2.5 to 5.0 g/L

4.6. Sensitivity of Recovered Yield to Magnesium Dose

Normalised sensitivity coefficients computed from Equation (6) are reported in Table 9 and shown in Figure 11(b). Doubling the dose from 2.5 to 5.0 g/L increases the

recovered solid by 84% for magnesium carbonate but by only 4.5% and 6.7% for magnesium chloride and magnesium sulphate, respectively.

Table 9. Normalised sensitivity of recovered solid yield to magnesium dose over the step from 2.5 to 5.0 g/L

Magnesium source	Yield at 2.5 g/L (g/L)	Yield at 5.0 g/L (g/L)	Change in yield (%)	Sensitivity coefficient
MgCl ₂	0.22	0.23	4.5	0.045
MgSO ₄	0.30	0.32	6.7	0.067
MgCO ₃	2.50	4.60	84.0	0.840

The interpretation is that the two soluble salts dissociate essentially completely at both doses, so that additional reagent does not increase the recovered mass, and the system is limited by the available phosphate. Magnesium carbonate dissolves only sparingly, so the recovered mass continues to respond to the dose; a sensitivity coefficient of 0.84, close to unity, indicates a nearly proportional response and therefore that the solid recovered from magnesium carbonate is dominated by a dose-proportional component rather than by the phosphate-limited struvite component. This inference is examined quantitatively in Section 4.7, and it materially qualifies the interpretation of the yield data.

4.7. Mass Balance and Composition of the Recovered Solid

Methodological transparency requires that the gravimetric yield be reconciled with the phosphorus available in the feed. Applying Equation (5) to the measured phosphate concentration of 24 mg/L gives a phosphorus load of 0.253 mmol/L, and therefore a theoretical maximum struvite yield of 62 mg/L, or 0.062 g/L, if every phosphate ion were precipitated as struvite. The corresponding figures for the three magnesium sources are compared with the measured yields in Table 10.

Table 10. Closing mass balance on the recovered solid at a magnesium dose of 5.0 g/L

Quantity	Value	Basis
Influent phosphate	24 mg/L (0.253 mmol/L)	Table 3
Theoretical maximum struvite yield	0.062 g/L	Equation (5)
Struvite equivalent to measured P removal (83.3%)	0.052 g/L	Equation (5)
Magnesium dosed as MgCO ₃	5.0 g/L (59.3 mmol Mg/L)	Section 3.4
Resulting Mg:P molar ratio	approximately 235:1	Computed
Measured recovered solid, MgCO ₃	4.60 g/L	Table 4
Ratio of measured to theoretical yield	approximately 74:1	Computed
Measured recovered solid, MgCl ₂ / MgSO ₄	0.23 / 0.32 g/L	Table 4

The balance establishes unambiguously that the 4.60 g/L recovered with magnesium carbonate cannot be pure struvite, since it exceeds the stoichiometric maximum by roughly two orders of magnitude. The recovered material is therefore a struvite-bearing composite in which undissolved magnesium carbonate, together with co-precipitated calcium and magnesium phosphate phases and enmeshed colloidal organic matter, constitutes the greater part of the mass.

Three independent lines of evidence in the present dataset support this reading: the near-proportional dose sensitivity reported in Section 4.6; the residual carbon signal in the EDS spectrum, attributed in Section 4.4 to carbonate from the precursor; and the absence in the SEM images of the well-defined prismatic habit characteristic of pure struvite.

The yields recovered with magnesium chloride and magnesium sulphate, at 0.23 and 0.32 g/L, are of a physically plausible order for a phosphate-limited system, although they too exceed the struvite stoichiometric maximum and therefore also contain co-precipitated material.

This reassessment does not overturn the treatment performance reported in Section 4.2, which rests on measured reductions in phosphate, nitrogen, turbidity and biochemical oxygen demand in the liquid phase, nor the agronomic performance reported in Section 4.5, which rests on a controlled plant response. What it changes is the claim that can properly be made about the product: the material is a nutrient-bearing recovered solid of demonstrated agronomic value at the application rate tested, and it is not a high-purity struvite fertilizer.

Quantitative phase identification by X-ray diffraction, together with Kjeldahl nitrogen and total phosphorus assay of the solid, is required to determine the struvite fraction, and is identified as the first priority for further work in Section 5.7.

A further measurement issue must be recorded. Struvite incorporates nitrogen exclusively as ammonium. The nitrogen determination reported in Table 3 and Section 4.2.4 is a nitrite measurement, and nitrite does not participate in struvite formation. The nitrogen reduction observed is therefore attributable to ammonia volatilisation under alkaline

conditions, to co-settlement with the precipitate and to biological activity during the reaction and settling period, rather than solely to incorporation in the crystal lattice. Ammonium nitrogen should be determined directly, by Nesslerization or by the Kjeldahl method, before nitrogen recovery is attributed to struvite formation.

4.8. Benchmarking Against Recent Studies

Table 11 positions the present work against the most closely comparable recent investigations. The comparison is deliberately restricted to studies for which the feed matrix, the magnesium source and the reported performance metric are stated explicitly, so that the entries are commensurable.

Table 11. Comparison of the present study with recent struvite recovery investigations

Study	Feed matrix, Mg source and reactor	Reported recovery	Agronomic verification
Berihun et al. [21], 2026	Domestic wastewater, 1.65 mg/L PO ₄ -P; acid-leached dolomite; orbital shaker 76 rpm; pH adjusted to 8.0 with NaOH	100% P, 88.75% N	None; product assayed at 2.66% P, 1.01% N, 11.77% Ca
Aguilar-Pozo et al. [10], 2023	Anaerobic digestion supernatant; low-grade MgO by-product from magnesite calcination; stirred reactor	High P recovery reported	None reported
Ha et al. [11], 2022	Swine wastewater; several magnesium sources compared; stirred reactor	Ammonium-nitrogen recovered as struvite	None reported
Ramaswamy et al. [13], 2022	Slaughterhouse wastewater; optimised batch process	Process optimisation reported	Fertilizing efficacy assessed with biofertilizer amendment
Gonzalez et al. [23], 2021	Municipal WWTP centrate; full-scale derived product	Product characterised for fertilizer quality	Grass pot and column trial; yields comparable to urea and Triple15
Present study	Domestic sewage, 24 mg/L PO ₄ , pH 8.9 unamended; MgCO ₃ , MgSO ₄ and MgCl ₂ compared at 2.5 and 5.0 g/L; blade-agitated 7.5 L acrylic reactor, 200 rpm, no alkali dosing	83.3% P, 81.8% N, 88.4% turbidity, 89.5% BOD	Finger millet pot trial; RAE 76% of urea; statistically equivalent to urea

Two differences are worth explaining rather than merely tabulating. The phosphorus recovery obtained here, at 83.3%, is lower than the 100% reported by Berihun et al. [21] for a comparable domestic matrix. The difference is not attributable to reactor performance. Those authors adjusted the pH to 8.0 with sodium hydroxide and worked from a feed containing only 1.65 mg/L of phosphorus-as-phosphorus, a load roughly an order of magnitude below that treated here, so that near-complete precipitation is achieved more readily; they also report a product containing 11.77% calcium, indicating extensive calcium co-precipitation. The present work deliberately avoided alkali dosing, so the recovery reported is that achievable at the native pH of the sewage, which is the operationally relevant figure for retrofit into an existing plant and the more conservative basis for comparison.

The second difference is that the present study is, among those compared, the only one that closes a stoichiometric mass balance on the recovered solid and reports the reagent cost per unit volume treated alongside the recovery efficiency. Where other studies report a percentage recovery, this study reports what that percentage costs and what the recovered solid

actually consists of. That combination, rather than a higher headline recovery, is the contribution claimed.

4.9. Preliminary Techno-Economic and Energy Screening

The reagent demand at the operating point examined is 5.0 kg of magnesium carbonate per cubic metre of wastewater treated. At an indicative industrial price of 25 to 75 rupees per kilogram, this corresponds to 125 to 376 rupees per cubic metre, which is one to two orders of magnitude above the total operating cost of conventional municipal sewage treatment in India and is therefore not viable at full scale. The cost per kilogram of phosphorus recovered at that operating point exceeds 30,000 rupees, against a phosphorus content in commercial fertilizer worth a small fraction of that figure. This finding is reported rather than omitted because it identifies the specific barrier to implementation, and because that barrier is tractable: as Table 10 shows, the dose employed corresponds to a magnesium-to-phosphorus molar ratio of approximately 235:1, whereas struvite formation requires a ratio near unity and is typically operated between 1.2:1 and 1.5:1. Table 12 sets out the reagent cost at the dose employed and at stoichiometrically informed doses.

Table 12. Reagent cost screening at the dose employed and at stoichiometrically informed doses, for the measured phosphate load of 24 mg/L

Operating basis	Mg:P molar ratio	MgCO ₃ demand (kg/m ³)	Reagent cost at 25 INR/kg	Reagent cost at 75 INR/kg
As operated in this study	approx. 235:1	5.007	INR 125.2 /m ³	INR 375.5 /m ³
Stoichiometrically informed	1.5:1	0.032	INR 0.80 /m ³	INR 2.40 /m ³
Stoichiometrically informed	1.2:1	0.026	INR 0.64 /m ³	INR 1.92 /m ³

Prices are indicative for industrial-grade magnesium carbonate and are intended for order-of-magnitude screening only; they should be replaced by verified quotations in any design study. The screening nevertheless establishes the principal conclusion clearly: reducing the magnesium dose towards the stoichiometric requirement, or substituting a waste-derived magnesium source such as low-grade magnesium oxide, seawater bittern or acid-leached dolomite [10, 21], reduces the reagent cost by more than two orders of magnitude and moves the process into a defensible economic range. Establishing the dose-recovery curve between the stoichiometric requirement and the dose used here is consequently the single most valuable next experiment, and is proposed in Section 5.7.

The energy demand may be assessed on the same basis. The installed motor rating of 30 W acting on 5 L for 20 min corresponds to 2.0 kWh per cubic metre at laboratory scale, a figure dominated by small-scale motor selection and not representative of a full-scale unit. Scaling on a volume-specific power basis at a realistic 0.3 to 0.5 kW/m³ for the same 20 min contact time gives 0.10 to 0.17 kWh per cubic metre, which is a modest increment on the total energy demand of a conventional activated sludge plant. Energy is therefore not the limiting factor for this process; the magnesium dose is.

5. Conclusion

5.1. Overview

This chapter presents the conclusions drawn from the performed experiments on struvite crystallization. Furthermore, suggestions regarding the use of struvite as a fertilizer are also presented within this chapter.

5.2. Scientific Conclusions

Struvite crystallization has been proven to be an effective method of removing nutrients from domestic wastewater. Furthermore, the use of magnesium carbonate as a source of magnesium ions has exhibited superior results to other forms of magnesium use in the crystallization of struvite. Finally, the struvite that is produced from these processes has been proven to be an effective fertilizer alternative to conventional chemical fertilizers.

5.3. Environmental and Sustainability Implications

The benefits of utilizing struvite crystallization to treat wastewater include the ability to simultaneously:

- Reduce the amount of nutrients that enter into the environment and contribute to eutrophication of water bodies, and
- Recover one of the major resources that is required for agricultural processes.

The use of struvite crystallization to remove nutrients from wastewater, therefore, contributes to the sustainability of the world's agricultural resources and provides an alternative to the use of non-renewable phosphate fertilizers. Furthermore, its integration into existing wastewater treatment facilities presents an inherently sustainable alternative for wastewater treatment to conventional methods.

5.4. Concluding Remark

Overall, the use of struvite crystallization as a method for removing nitrogen and phosphorus from domestic wastewater is a scalable, economical, and environmentally sustainable process for the development of next-generation wastewater treatment systems.

5.5. Limitations of the Study

Five limitations qualify the conclusions drawn above and should be read alongside them. First, the recovered solid has not been phase-quantified; the mass balance in Section 4.7 establishes that it is a struvite-bearing composite rather than a pure phase, and the struvite fraction remains undetermined pending X-ray diffraction and wet-chemical assay. Second, the nitrogen determination was made as nitrite rather than as ammonium, so the nitrogen removal reported cannot be attributed solely to incorporation in the struvite lattice.

Third, the pot trial ran for seventeen days and measured shoot height only; it therefore demonstrates early-vigour equivalence with urea rather than equivalence in grain yield, nutrient uptake or residual soil phosphorus at harvest. Fourth, the experimental programme varied only the magnesium source and dose, so the sensitivity analysis in Section 4.6 cannot be extended to pH, mixing intensity or reaction time, all of which were held constant.

Fifth, the trials were conducted in batch mode on a single wastewater from one campus treatment plant; seasonal, diurnal and site-to-site variation in composition, and in particular in calcium concentration, has not been characterised, and calcium is the co-ion most likely to reduce product purity.

5.6. Scalability, Economics and Implementation Barriers

The reactor concept itself scales without difficulty: blade-agitated crystallizers are conventional unit operations, the materials of construction are inexpensive and chemically appropriate, and the energy demand estimated in Section 4.9 at 0.10 to 0.17 kWh per cubic metre on a realistic specific-power basis is a modest increment on existing plant consumption. The barrier to implementation is the reagent dose. At the dose employed, the reagent cost of 125 to 376 rupees per cubic metre exceeds conventional treatment costs by one to two orders of magnitude, whereas operation near the stoichiometric requirement would reduce that cost below three rupees per cubic metre. Reconciling the dose with the stoichiometry is therefore the decisive engineering task and, on the evidence of Table 12, an achievable one.

Three further barriers apply to retrofit within an operating treatment plant. The first is the location of the recovery unit: mainstream sewage at 24 mg/L of phosphate is a dilute feed, and integration on the sludge dewatering return liquor, where phosphate concentrations are typically an order of magnitude higher, would improve reagent economy substantially while simultaneously relieving the uncontrolled scaling that such liquors cause. The second is product handling and quality assurance: a material of undetermined phase composition cannot be marketed as a fertilizer, and consistent particle size, moisture content and nutrient assay are prerequisites for offtake. The third is regulatory: in India, the sale of a recovered nutrient product requires compliance with the Fertiliser (Control) Order, including specification of guaranteed nutrient content and heavy-metal limits, and no such compliance testing has been undertaken here.

5.7. Future Directions

Four lines of work follow directly from the findings reported above and are ordered by priority. The first is the determination of the dose-recovery curve for magnesium carbonate between the stoichiometric requirement and the dose employed here, which would establish the minimum viable dose and is the single change most likely to convert the process from a laboratory demonstration into an economically defensible one. The second is quantitative characterisation of the recovered solid by X-ray diffraction, Kjeldahl nitrogen and total phosphorus assay, together with heavy-metal screening

against the applicable fertilizer specification, which would establish what fraction of the recovered mass is struvite and whether the product is marketable. The third is a longer agronomic trial carried through to harvest, with adequate replication, measurement of grain yield and nutrient uptake, and inclusion of a phosphorus-matched fertilizer reference in addition to urea. The fourth is continuous-flow operation on sludge return liquor, with the reactor scaled on a volume-specific power basis, which would test the process at the point in the treatment train where the economics are most favourable.

5.8. Declarations

5.8.1. Ethical Approval

The study involved neither human participants nor animal subjects. The plant trial was conducted on finger millet in pots within the institutional premises and did not involve genetically modified organisms, protected species or field release, so institutional biosafety or ethical approval was not required

5.8.2. Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

5.8.3. Funding

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5.8.4. Data Availability

The datasets generated and analysed during the present study are available from the corresponding author on reasonable request.

5.8.5. Author contributions

Urmila R. Kawade: Conceptualisation, methodology, investigation, and original draft. Shreyas B. V., Puneeth M. S., Padmesh T. Narayanapillai, Snehal K. Kamble, and Shubham K. Verma: Investigation, analysis, and review and editing. Prashant Sunagar: Conceptualisation, methodology, supervision, analysis, and review and editing. All authors approved the final manuscript.

References

- [1] Yixin Yan et al., "Phosphorus Recovery through Struvite Crystallization from Real Wastewater: Bridging Gaps from Lab to Market," *Bioresource Technology*, vol. 427, pp. 1-15, 2025. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [2] Alessio Siciliano et al., "Advances in Struvite Precipitation Technologies for Nutrients Removal and Recovery from Aqueous Waste and Wastewater," *Sustainability*, vol. 12, no. 18, pp. 1-36, 2020. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [3] P. Achilleos, K.R. Roberts, and I.D. Williams, "Struvite Precipitation Within Wastewater Treatment: A Problem or a Circular Economy Opportunity?," *Heliyon*, vol. 8, no. 7, pp. 1-11, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [4] Tejas N. Vasa, and Sabumon Pothanankandathil Chacko, "Recovery of Struvite from Wastewaters as an Eco-Friendly Fertilizer: Review of the Art and Perspective for a Sustainable Agriculture Practice in India," *Sustainable Energy Technologies and Assessments*, vol. 48, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]

- [5] Haotian Wu, and Céline Vaneeckhaute, “Nutrient Recovery from Wastewater: A Review on the Integrated Physiochemical Technologies of Ammonia Stripping, Adsorption and Struvite Precipitation,” *Chemical Engineering Journal*, vol. 433, no. 3, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [6] Imtiaz Ali, “*Struvite Crystallization from Nutrient Rich Wastewater*,” PhD Thesis, James Cook University, pp. 1-293, 2005. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [7] Sivaraman Chandrasekaran, Alisha Zaffar, and Paramasivan Balasubramanian, “Struvite in Circular Economy: Production Techniques, Emerging Applications and Market Opportunities,” *Wiley Interdisciplinary Reviews: Energy and Environment*, vol. 13, no. 4, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [8] Andreia F. Santos et al., “Nutrient Recovery via Struvite Precipitation from Wastewater Treatment Plants: Influence of Operating Parameters, Coexisting Ions, and Seeding,” *Water*, vol. 16, no. 12, pp. 1-17, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [9] Qian Guan et al., “A Review of Struvite Crystallization for Nutrient Source Recovery from Wastewater,” *Journal of Environmental Management*, vol. 344, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [10] V.B. Aguilar-Pozo et al., “Struvite Precipitation in Wastewater Treatment Plants Anaerobic Digestion Supernatants using a Magnesium Oxide by-Product,” *Science of the Total Environment*, vol. 890, pp. 1-10, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [11] Thi-Hanh Ha et al., “Ammonium-Nitrogen Recovery as Struvite from Swine Wastewater using Various Magnesium Sources,” *Separation and Purification Technology*, vol. 308, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [12] Tonni Agustiono Kurniawan et al., “Applying Nutrient Recovery from Unused Wastewater to Overcome Fertilizer Shortage for Global Food Security,” *Journal of Environmental Management*, vol. 394, 2025. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [13] Jeyalakshmi Ramaswamy et al., “Process Optimization of Struvite Recovered from Slaughterhouse Wastewater and its Fertilizing Efficacy in Amendment of Biofertilizer,” *Environmental Research*, vol. 211, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [14] Rúbia Mores et al., “Electrochemical Precipitation of Struvite from Wastewater: A Sustainable Approach for Nitrogen Recovery,” *Separations*, vol. 12, no. 5, pp. 1-14, 2025. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [15] Jia Hui Ong et al., “Struvite Precipitation for Low-Level Ammonium Removal in Mariculture Wastewater: Feasibility Study,” *Bioresource Technology*, vol. 424, 2025. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [16] Bogna Śniatała et al., “Advancing Sustainable Wastewater Management: A Comprehensive Review of Nutrient Recovery Products and Their Applications,” *Science of the Total Environment*, vol. 937, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [17] Madeline Sena et al., “Environmental Impacts of Phosphorus Recovery through Struvite Precipitation in Wastewater Treatment,” *Journal of Cleaner Production*, vol. 280, no. 1, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [18] Álvaro Mayor et al., “Life-Cycle Assessment and Techno-Economic Evaluation of the Value Chain in Nutrient Recovery from Wastewater Treatment Plants for Agricultural Application,” *Science of the Total Environment*, vol. 892, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [19] Işık Kabdaşlı et al., “Is K-Struvite Precipitation a Plausible Nutrient Recovery Method from Potassium-Containing Wastes?—A Review,” *Sustainability*, vol. 14, no. 18, pp. 1-35, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [20] Hongyan Li et al., “Struvite as a Sustainable Fertilizer: Nutrient Recovery from Corn Starch Wastewater with Minimal Sludge Production,” *Frontiers in Water*, vol. 7, pp. 1-16, 2025. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [21] Melsew Endalew Berihun, Kinfe Kassa, and Assen Yimam Mohammed, “Recovery of Phosphorus and Nitrogen from Domestic Wastewater by Using Dolomite Rock Through Struvite Precipitation,” *Discover Environment*, vol. 4, pp. 1-14, 2026. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [22] Ibrahim Moalim Ali, Mohamad Darwish, and Shaymaa Mustafa, “The Impact of Struvite and Soil pH on Chilli Pepper Plant Growth and Nutrient Release,” *ASM Science Journal*, vol. 21, no. 1, pp. 1-11, 2026. [[CrossRef](#)] [[Publisher Link](#)]
- [23] C. González et al., “The Determination of Fertiliser Quality of the Formed Struvite from a WWTP,” *Water Science and Technology*, vol. 83, no. 12, pp. 3041-3053, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [24] Peter J. Talboys et al., “Struvite: A Slow-Release Fertiliser for Sustainable Phosphorus Management?,” *Plant and Soil*, vol. 401, no. 1, pp. 109-123, 2016. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]