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Original Research

Potential of Struvite Recovery from Compost Leachate Using Multistage Processes

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Abstract: Leachates produced from composting activities often contain high levels of ammonium and phosphate. If left untreated, these compounds can pollute water bodies, but at the same time they also represent nutrients that could be recovered and reused. This study explored the possibility of transforming composting leachate into struvite, a slow-release fertilizer, by applying sequential recovery processes. Initial characterization of the leachate showed high concentrations of phosphate (1179.8 mg/L) and ammonium (312.5 mg/L), while magnesium was almost absent (0.017 mg/L), confirming the need for external Mg addition. A series of experiments and PHREEQC simulations were carried out to examine the influence of magnesium sources ($MgCl_2$ and MgO), pH adjustment, molar ratios, and mixing conditions. The results showed that $MgCl_2$ consistently enhanced nutrient removal compared with MgO, with the best outcomes occurring around pH 9 for ammonium and pH 10 for phosphate. Increasing the Mg dosing ratio to 5:1:1 further improved precipitation, while controlled mixing (fast followed by slow) supported crystal formation. The presence of struvite crystals confirmed the effectiveness of the process. These findings suggest that composting leachate, which is often considered problematic waste, can be converted into a valuable product while reducing environmental risks.

1. INTRODUCTION

Composting is a widely practiced method for managing organic waste and converting biodegradable materials into stable humus-like compost that can enhance soil fertility. Despite these benefits, composting processes also generate a significant amount of leachate, a dark and odorous liquid that often contains high levels of organic matter, ammonium, phosphate, and various dissolved ions (Priyambada, Widianarko, Sasongko, & Puspita, 2021). If left untreated, this leachate may pose serious environmental problems, including surface water eutrophication, groundwater contamination, and indirect greenhouse gas emissions, when infiltrated into anaerobic environments (Puspita, Budihardjo, & Samadikun, 2024). Nitrogen and phosphorus are particularly concerning, as ammonium (NH_4^+) can lead to toxic effects on aquatic ecosystems and contribute to nitrate pollution through nitrification, while phosphate (PO_4^{3-}) acts as a limiting nutrient for algal growth and is a major driver of eutrophication in lakes and rivers. However, the same compounds that create environmental hazards represent a valuable resource for agriculture. In the context of phosphorus scarcity and the rising costs of chemical fertilizers, leachate streams with high nutrient concentrations could be reimagined as raw materials for nutrient recovery rather than as pollutants requiring disposal (Ramadan, Fajar, & Puspita, 2024).

One of the most promising approaches for nutrient recovery from wastewater and similar effluents is the crystallization of struvite (magnesium ammonium phosphate hexahydrate, $MgNH_4PO_4 \cdot 6H_2O$). Struvite is a sparingly soluble crystalline compound that precipitates when magnesium, ammonium, and phosphate ions are present at sufficient concentrations under alkaline conditions. Research on struvite crystallization has gained momentum over the past two decades because of its dual role in both wastewater treatment and resource recovery. On the one hand, struvite formation reduces the concentrations of ammonium and phosphate in effluents, mitigating risks of eutrophication. However, the recovered crystals can be directly applied as slow-release fertilizers, providing agronomic benefits such as gradual nutrient release and reduced leaching losses compared to conventional soluble fertilizers. Therefore, struvite recovery has been studied in a wide range of systems, including municipal wastewater treatment plants, anaerobic digestate supernatants, livestock manure effluents, landfill leachates, and various industrial wastewaters (Petal Battistoni, Fava, Pavan, Musacco, & Cecchi, 1997; Doyle & Parsons, 2002; Kabdaslı, Tünay, Öztürk, Yılmaz, & Arıkan, 2000; Le Corre, Valsami-Jones, Hobbs, & Parsons, 2009; Rahman et al., 2014; Yetilmezsoy & Sapci-Zengin, 2009). Beyond pollution control, the recovery of phosphorus as struvite also contributes to the broader sustainability agenda, as phosphorus is a finite, non-renewable resource concentrated in a few geographic regions and is subject to long-term depletion risks (Cordell, Drangert, & White, 2009).

However, the formation of struvite is influenced by multiple operational factors that require careful optimization. Among these, the pH is considered the most critical. Numerous studies have reported that struvite crystallization is most favorable under alkaline conditions, generally between pH 8 and 10.5 (Bhuiyan, Mavinic, & Beckie, 2007). At lower pH, phosphate is predominantly present as $H_2PO_4^-$ or HPO_4^{2-}, limiting the availability of PO_4^{3-} ions necessary for precipitation, whereas excessively high pH values can encourage the formation of competing salts, particularly calcium phosphates, that reduce struvite purity. The choice of the magnesium source is another decisive factor. Magnesium chloride ($MgCl_2$) is often used in laboratory studies because of its high solubility and reliable release of Mg^{2+} ions, which promotes rapid precipitation. Magnesium oxide (MgO), while less soluble, is cheaper and provides a slower release of magnesium, which, in some contexts, may improve crystal growth. Other alternatives, such as seawater, bittern, and industrial byproducts, have also been explored as cost-effective Mg sources (Doyle, Oldring, Churchley, Price, & Parsons, 2003; Hutnik et al., 2013; Münch & Barr, 2001; Ye et al., 2011). The stoichiometric ratio of magnesium to ammonium and phosphate is theoretically 1:1:1; however, in practice, excess magnesium dosing is frequently applied to overcome losses due to competing reactions and to ensure high recovery efficiencies (Thomas, 2007).

Hydrodynamics also plays a vital role in crystallization. Struvite formation begins with supersaturation, followed by nucleation and crystal growth, all of which are strongly affected by mixing intensity. Rapid mixing promotes homogeneity and enhances nucleation; however, excessive turbulence can break crystals or prevent them from growing to a size suitable for recovery. Conversely, gentle slow mixing provides favorable conditions for crystal aggregation and settling. Several studies have therefore recommended a two-step mixing regime—rapid mixing to initiate nucleation, followed by slow mixing to encourage growth and settling—as the most effective strategy (Wang, Burken, Zhang, & Surampalli, 2005). In addition, the reaction time and sedimentation period determine the extent to which equilibrium is approached, with longer retention times generally improving recovery but also increasing operational costs. Finally, the presence of competing ions, such as calcium, potassium, and sodium, as well as high levels of suspended solids or organic matter, can interfere with the crystallization pathway by either substituting in the crystal lattice or sequestering phosphate and magnesium into alternative compounds (Paolo Battistoni, De Angelis, Pavan, Prisciandaro, & Cecchi, 2001).

Although a large body of work has investigated struvite recovery from sewage sludge liquors, digester supernatants, and livestock effluents, the application of this technique to leachate composting remains relatively underexplored. Composting leachate is a particularly challenging medium because of its highly variable composition, elevated suspended solids content, and fluctuating pH. Mizuta et al. have shown that composting leachate can indeed support struvite precipitation, yet the recovery efficiency is strongly dependent on operating conditions, and the outcomes are less predictable than in digester or sewage liquors. Unlike more homogeneous wastewaters, composting leachate is influenced by multiple factors, including feedstock composition, composting temperature, and retention time, which affect both the nutrient content and interfering compounds. These challenges underline the need for systematic studies to determine how struvite recovery can be optimized, specifically for composting leachate streams.

The present study addresses this gap by investigating the potential production of struvite fertilizer from composting leachate through a sequential recovery process. This research combines geochemical modeling using PHREEQC with laboratory-scale experiments to examine the effects of the magnesium source, pH, molar ratios, and mixing conditions on struvite formation. Magnesium chloride and magnesium oxide were selected as representative soluble and sparingly soluble Mg sources, respectively, while the pH was varied between 6 and 11 to capture the full precipitation window. The molar ratio of Mg:NH_3:PO_4 was systematically increased from 1:1:1 to 5:1:1, and sequential mixing regimes, consisting of rapid followed by slow agitation, were tested to replicate practical treatment conditions. The reaction times and sedimentation periods were extended to 48 h to examine the kinetics of precipitation. By linking simulation and experiment, this study identifies the operational windows that maximize ammonium and phosphate recovery while producing visible struvite crystals.

The novelty of this study lies in the following three aspects. First, it applies a sequential mixing framework to composting leachate, which is a strategy that has rarely been explored for this particular waste stream. Second, it compares two distinct Mg sources under identical conditions, providing insights into their relative effectiveness in a complex leachate matrix. Third, it integrates PHREEQC simulations with experimental validation, offering both predictive and empirical perspectives on the formation of struvite. By addressing these aspects, this study contributes to a better understanding of nutrient recovery from composting leachate and highlights the potential of transforming an environmentally problematic waste stream into a valuable slow-release fertilizer resource.

2. MATERIALS AND METHODS

2.1 Data Collection and Characterization

Leachate samples were obtained from a composting facility and stored under cool and dark conditions prior to analysis. Standardized laboratory protocols were used following the APHA 24th edition. The parameters measured included pH, ammonium (NH_4^+), phosphate (PO_4^{3-}), magnesium (Mg^{2+}), total suspended solids (TSS), and selected major ions (Na, K, Ca, and Si). Measurements were performed in duplicate to ensure reproducibility. Initial results showed that the leachate was highly enriched in phosphate (1179.8 mg/L) and ammonium (312.5 mg/L) but almost devoid of magnesium (0.017 mg/L), confirming the necessity of Mg supplementation to enable struvite crystallization.

2.2 Experimental Framework

The study design combined thermodynamic modeling with bench-scale jar tests. This dual approach has been widely adopted in struvite research to first predict the precipitation conditions and then validate them experimentally. The geochemical software PHREEQC was used to simulate leachate composition under varying pH conditions (6–11) and magnesium addition. Simulations were performed using the measured initial concentrations of major ions (NH_4^+, PO_4^{3-}, Mg^{2+}, Ca^{2+}, K^+, Na^+, Si, and F) as input parameters, and the thermodynamic database provided in PHREEQC was used to calculate aqueous speciation and mineral saturation indices (SI). Two magnesium sources ($MgCl_2$ (aqueous) and MgO (solid)) were modeled to examine the solubility differences and to estimate the saturation index (SI) of struvite as well as potential competing mineral phases (e.g., calcium phosphate phases) under different pH scenarios. The SI values were used to identify the pH range at which struvite precipitation was thermodynamically favorable (SI > 0) and to evaluate potential competition from other mineral species. Based on the modeling results, laboratory trials were conducted in beakers with controlled mixing regimes. Each run consisted of a rapid-mix phase at 158 rpm for 1 h followed by a slow-mix phase at 30–75 rpm for 1 h. This sequential mixing setup reflects the common practice in struvite studies, where fast mixing promotes supersaturation and nucleation, and slow mixing allows crystal growth. Because the natural Mg concentration was insufficient, external Mg was added. Molar ratios of Mg:NH_4:PO_4 were varied systematically from 1:1:1 to 5:1:1. The pH of the leachate was adjusted using NaOH or HCl prior to the addition of Mg. The experimental design was guided by the simulation outputs, particularly the predicted struvite saturation window and the influence of magnesium availability on supersaturation. Screening experiments confirmed optimum precipitation near pH 9 for ammonium and pH 10 for phosphate. The mixing times were varied between 20 and 60 min, while sedimentation was extended from 20 to 48 h. This approach enabled the analysis of reaction kinetics and establishment of equilibrium conditions.

2.3 Data Analysis

The ammonium and phosphate removal efficiencies were calculated from the difference between the initial and residual concentrations using the following equation:

Removal efficiency (%) = (C_0-C_t)/C_0 x100% (1)

Where C_0 is the initial concentration and C_t is the concentration after treatment. The concentrations were determined spectrophotometrically. Kinetic data were analyzed by plotting the removal efficiency against sedimentation time and fitting regression models. Linear regression was applied as a descriptive tool to illustrate the overall temporal trend of nutrient removal, rather than to represent a mechanistic kinetic model of struvite crystallization. Optimal conditions were identified by comparing Mg sources, pH levels, molar ratios, and mixing regimes. Because struvite precipitation is governed by non-linear processes including nucleation, crystal growth, aggregation, and diffusion-controlled mechanisms, the regression analysis was intended to provide comparative trend evaluation only. More advanced kinetic modeling was beyond the scope of the present study and is recommended for future work.

3. RESULTS AND DISCUSSION

3.1. Preliminary characterization of composting leachate

Preliminary analysis of the composting leachate revealed a challenging nutrient-rich matrix. The leachate exhibited an acidic pH of 5.8, high concentrations of phosphate (1179.8 mg/L) and ammonium (312.5 mg/L), and negligible levels of magnesium (0.017 mg/L). In addition, high suspended solids (TSS 8105 mg/L), potassium (5255 mg/L), sodium (217.4 mg/L), calcium (136.3 mg/L), and silica (1146 mg/L) were detected, along with fluoride (583 mg/L). This profile confirmed that leachate is both a pollution concern and a potential nutrient source. The low magnesium concentration indicated that external Mg addition would be indispensable to induce struvite precipitation, while the presence of competing cations, such as potassium and calcium, could interfere with crystallization. The relatively high calcium concentration (136.3 mg/L) is particularly important, as Ca^{2+} can compete with Mg^{2+} for phosphate and promote the formation of calcium phosphate phases (e.g., amorphous Ca–phosphate or hydroxyapatite), thereby reducing phosphate availability for struvite formation. The extremely high potassium concentration (5255 mg/L) increases the ionic strength of the solution, which may reduce ion activity coefficients and consequently lower the effective supersaturation required for struvite nucleation. Although K^+ does not directly participate in struvite formation, elevated ionic strength can influence crystallization kinetics and precipitation efficiency. Silica (1146 mg/L) may also contribute to interference, as dissolved silicate species can interact with Mg^{2+} and potentially form magnesium–silicate complexes, reducing the free Mg^{2+} fraction available for reaction with ammonium and phosphate. Similarly, the presence of fluoride (583 mg/L) under alkaline conditions may lead to partial formation of MgF_2 or other magnesium–fluoride species, further decreasing magnesium availability. The very high TSS concentration (8105 mg/L) suggests that heterogeneous nucleation and adsorption phenomena are likely to occur. Suspended particles can adsorb phosphate or magnesium ions and may either promote localized nucleation or hinder crystal growth by trapping fine precipitates, thereby affecting sedimentation efficiency. These combined matrix effects help explain the need for excess magnesium dosing and careful pH control observed in subsequent experiments. Similar characteristics have been observed in leachates from organic waste treatment, where nutrient recovery requires chemical supplementation and careful process control (Doyle & Parsons, 2002; Le Corre et al., 2009).

Table 1. Preliminary Test

Parameter	**Value**	**Units**
pH	5.8	
Phosphate (PO_4)	1179.8	mg/L
Ammonia (NH_4)	312.5	mg/L
Total Suspended Solid (TSS)	8105.0	mg/L
Silica (Si)	1146.0	mg/L
Natrium (Na)	217.4	mg/L
Calsium (Ca)	136.3	mg/L
Potassium (K)	5255.0	mg/L
Magnesium (Mg)	0.017	mg/L
Fluoride (F)	583.0	mg/L

3.2 Stoichiometric Analysis and Mass Balance Consideration

The initial nutrient concentrations were converted into molar units to evaluate the stoichiometric feasibility of struvite formation. Ammonium (312.5 mg/L) corresponds to 17.36 mmol/L, while phosphate (1179.8 mg/L) corresponds to 12.42 mmol/L. Because struvite crystallizes according to a 1:1:1 molar ratio (Mg^{2+}:NH_4^+:PO_4^{3-}), phosphate was identified as the limiting reactant under the initial conditions. Based on this stoichiometry, the maximum theoretical struvite formation was 12.42 mmol/L, equivalent to approximately 3043 mg/L of $MgNH_4PO_4 \cdot 6H_2O$. This indicates that, even with sufficient magnesium supplementation, complete ammonium removal was not theoretically achievable because ammonium was present in excess relative to phosphate. The experimental results showing incomplete phosphate recovery suggest that matrix effects, including high calcium (136.3 mg/L), elevated potassium (5255 mg/L), and high suspended solids (8105 mg/L), likely reduced the effective availability of phosphate for struvite precipitation. These competing interactions explain why the observed removal efficiencies were lower than the theoretical maximum.

3.3 Effect of magnesium source and pH

The first set of experiments compared $MgCl_2$ and MgO as magnesium sources across a pH range of 6–11. The results demonstrated that $MgCl_2$ consistently outperformed MgO in nutrient removal. For ammonium, the greatest reduction was achieved at pH 9, whereas the phosphate removal peaked at pH 10. Under optimized conditions (pH 10 and Mg:NH_4:PO_4 molar ratio of 5:1:1 using $MgCl_2$), phosphate removal exceeded 70%, while ammonium removal approached nearly 60%. The lower performance of MgO can be attributed to its limited solubility, which releases Mg^{2+} ions at a slower rate, thus delaying nucleation and crystal growth. In contrast, $MgCl_2$ provided an immediate and high concentration of soluble magnesium, enabling rapid supersaturation and precipitation. The dependence on pH observed here is in line with established findings that struvite crystallization is strongly influenced by solution chemistry (Petal Battistoni et al., 1997). At near-neutral pH (6–7), little precipitation occurred, as the availability of PO_4^{3-} ions was restricted. Under highly alkaline conditions (>10.5), the competing precipitation of calcium phosphate and amorphous phosphate species may explain the decline in the removal efficiency. Thus, pH 9–10 can be considered the optimal window for struvite precipitation in composting leachate, which is consistent with previous studies on wastewater and digestates (Kabdaslı et al., 2000; Yetilmezsoy & Sapci-Zengin, 2009).

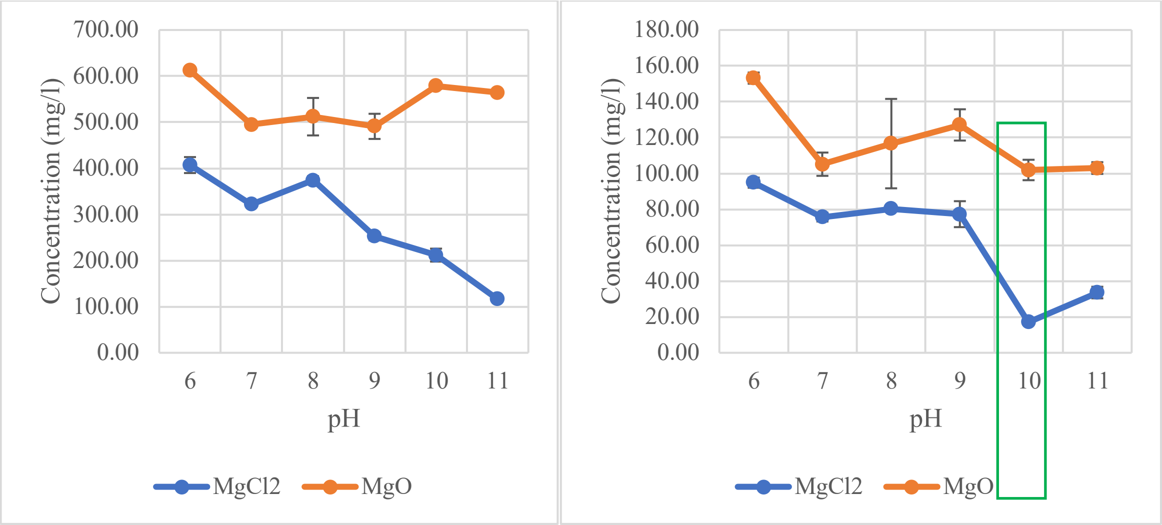


Fig 1. Effect of magnesium source and pH on ammonia and phospate reduction.

3.4 Influence of $Mg:NH_4:PO_4$ molar ratios

Following the identification of pH optima, the molar ratio of $Mg:NH_4:PO_4$ was varied between 1:1:1 and 5:1:1. A clear trend was observed: increasing the Mg dosage enhanced nutrient removal, with the most significant improvement between the 1:1:1 and 3:1:1 ratios. At ratios beyond 3:1:1, the incremental benefit was smaller, though maximum removal was reached at 5:1:1. Ammonium removal increased from ~25% at 1:1:1 to nearly 60% at 5:1:1, whereas phosphate removal increased from ~40% to >70%. To better represent resource recovery performance beyond percentage removal, phosphorus recovery was estimated based on the initial phosphate concentration (1179.8 mg/L). At >70% phosphate removal, approximately 826 mg/L of PO_4^{3-} was recovered from solution. Assuming complete conversion of removed phosphate into struvite ($MgNH_4PO_4\cdot 6H_2O$), the theoretical struvite yield corresponds to approximately 2.1 g/L, based on stoichiometric conversion (MW struvite = 245 g/mol; MW PO_4^{3-} = 95 g/mol). This estimation indicates that the process not only reduces nutrient concentrations but also produces a potentially recoverable solid product in the gram-per-liter range. The calculated crystallization yield relative to the theoretical maximum (based on the limiting phosphate concentration) suggests that a substantial fraction of recoverable phosphorus can be converted into solid form under optimized conditions. These findings are consistent with the principle that excess Mg is often required to overcome interference in complex wastewater (Rahman et al., 2014). Composting leachate with its high concentrations of calcium, potassium, and suspended solids likely sequestered some of the added magnesium, reducing the fraction available for struvite formation. Calcium can preferentially bind phosphate to form Ca–phosphate phases, while fluoride and silicate species may partially complex with Mg^{2+}, thereby decreasing the effective free magnesium concentration in solution. In addition, elevated ionic strength caused by high potassium levels may reduce ion activities and lower the effective supersaturation required for nucleation. Therefore, the observed need for overstoichiometric Mg dosing can be interpreted as compensation for these competing reactions and activity corrections rather than simple deviation from ideal stoichiometry. Excess Mg addition ensured that sufficient Mg^{2+} remained available for reaction with NH_4^+ and PO_4^{3-}. Similar requirements for overstoichiometric dosing have been reported for digester liquors (Cordell et al., 2009), landfill leachates (Bhuiyan et al., 2007), and animal manure effluents (Münch & Barr, 2001).

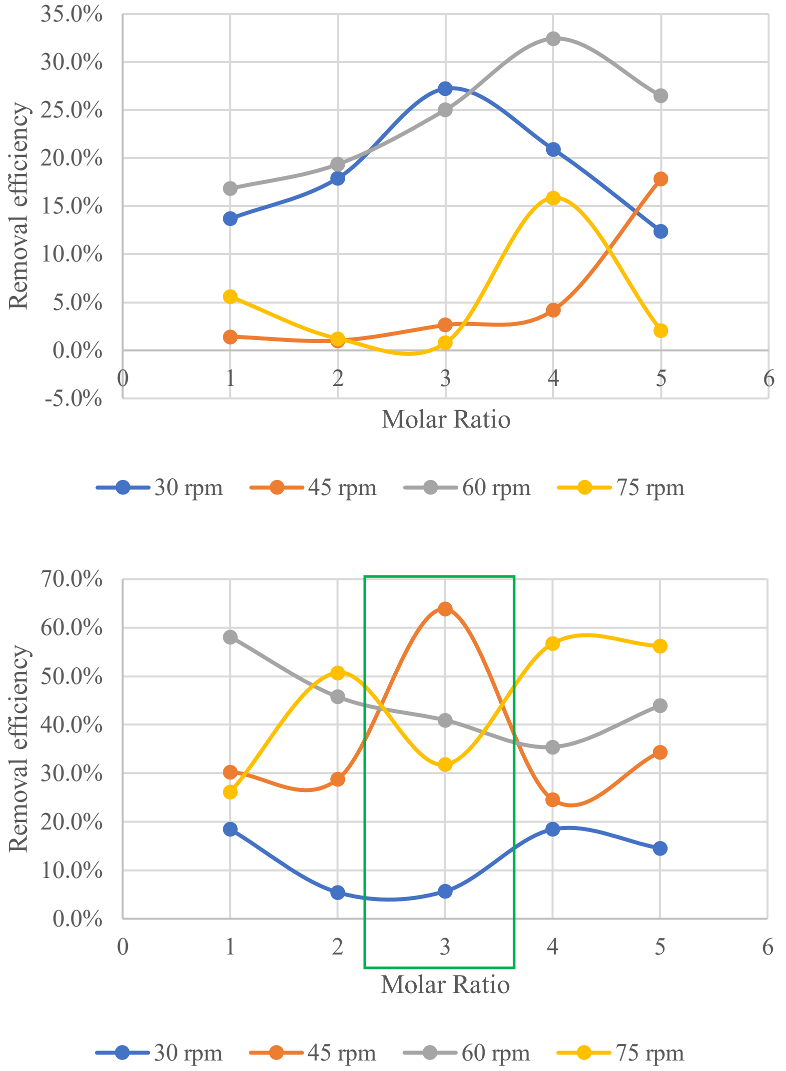
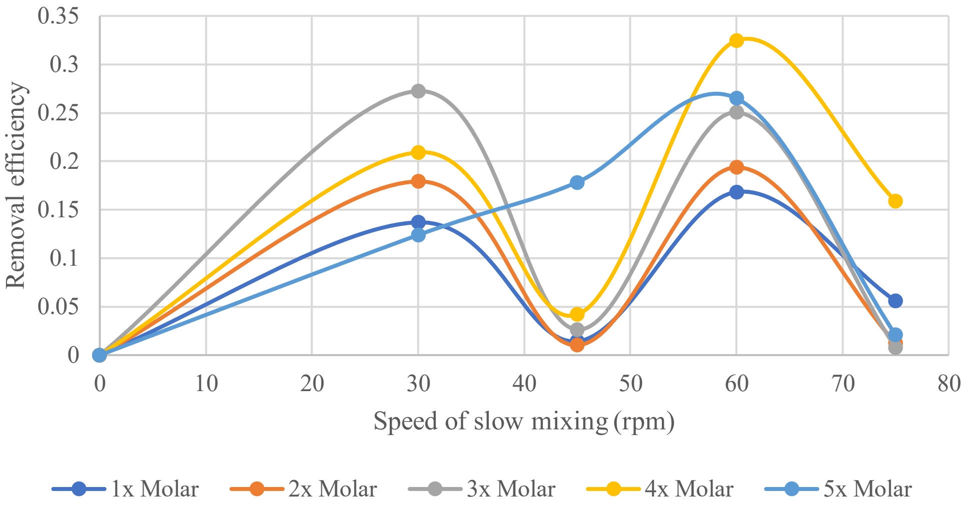


Fig 2. Influence of molar ratio on ammonia and phospate removal efficiency.

3.5 Effect of mixing regime

The sequential mixing approach, rapid mixing (158 rpm) followed by slow mixing, was evaluated by varying the slow-mix speed from 30 rpm to 75 rpm. The results showed that moderate agitation (approximately 60 rpm) provided the best balance between ammonium and phosphate removal. At very low speeds (30 rpm), the crystal nucleation and aggregation were insufficient, resulting in poor recovery. At very high speeds (75 rpm), shear forces likely disrupted crystal growth and resuspended fine particles, leading to a lower sedimentation efficiency.

This behavior underscores the importance of hydrodynamic control during crystallization. Previous studies have shown that rapid mixing promotes homogeneous nucleation, whereas gentle slow mixing supports crystal growth and aggregation into recoverable particles (Hutnik et al., 2013; Ye et al., 2011). The optimum at 60 rpm observed here mirrors similar results in engineered reactors, where overly vigorous mixing reduced the struvite particle size and increased washout (Doyle et al., 2003). From an operational perspective, optimizing mixing intensity is also relevant for process efficiency, as excessive agitation may increase energy consumption without proportionally improving nutrient recovery. Therefore, moderate mixing conditions not only enhanced precipitation performance but may also contribute to more practical and energy-efficient implementation at larger scale. Thus, sequential mixing is a promising operational strategy for leachate composting, enabling both nucleation and growth in a controlled manner.



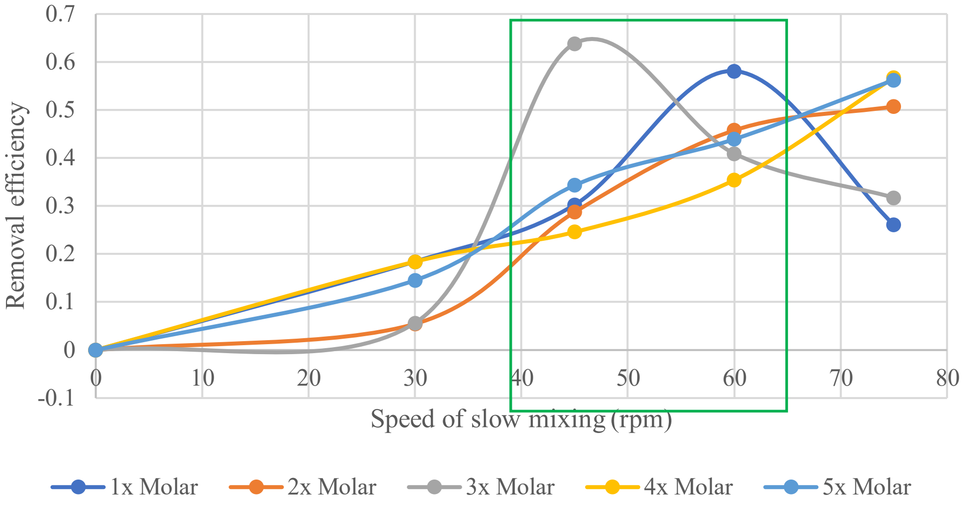


Fig 3. Influence of mixing regime on ammonia and phospate removal efficiency.

3.6 Influence of mixing and sedimentation times

The mixing time was varied between 20 and 60 min, while sedimentation was extended to 48 h to investigate the precipitation kinetics. The results demonstrated that most nutrient removal occurred within the first 30 min of slow mixing, with diminishing improvements beyond this duration. Sedimentation tests revealed that the removal efficiency increased steadily over time, reaching equilibrium after approximately 24–36 h. The ammonium and phosphate removal efficiencies approached 65 and 75%, respectively, after extended sedimentation. The kinetic profiles suggest that struvite crystallization in composting leachate follows a two-stage process: rapid initial nucleation and growth, followed by slower aggregation and settling. Regression analysis of the removal versus sedimentation time yielded moderate correlations ($R^2 \approx 0.36–0.40$), reflecting the complexity of the leachate matrix and the competing processes involved. These results align with kinetic studies of struvite formation in other wastewaters, which also reported rapid early stage precipitation followed by a slower approach to equilibrium (Thomas, 2007; Wang et al., 2005).

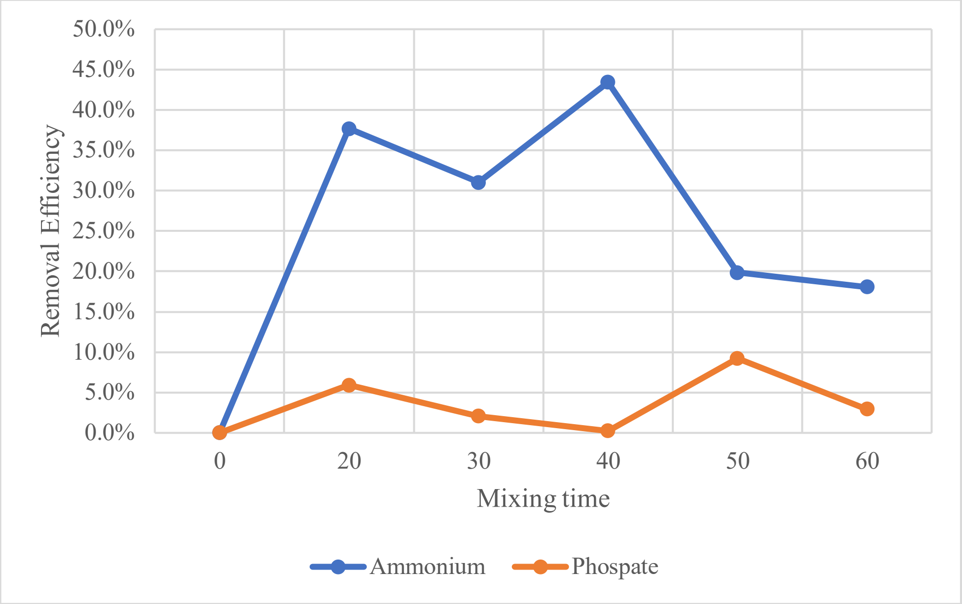


Fig 4. Influence of mixing and sedimentation times on ammonia and phospate removal efficiency.

3.7 Kinetic rate of ammonia and phospate precipitation

The choice of the magnesium source played an important role. $MgCl_2$ resulted in higher removal efficiencies than MgO, and pH strongly influenced the outcome. The most effective nutrient reduction occurred at pH 9 for ammonium and pH 10 for phosphate. Adjusting the molar ratio showed a clear trend: higher Mg input promoted more complete precipitation, with significant improvement from 1:1:1 to 5:1:1. The kinetic study investigated how the removal efficiency of ammonium and phosphate evolved with increasing sedimentation time (0–3000 min, ~ 2 days). It should be noted that the kinetic experiment was conducted under fixed operational parameters and did not necessarily represent the globally optimized pH and molar ratio. As shown in Figure 5, both ammonium and phosphate exhibited a positive trend with longer sedimentation times, indicating that struvite crystallization and settling continued gradually over time.

For ammonium, the removal efficiency increased from ~40% during the initial measurement to nearly 70% after 3000 min. The linear regression equation ($y = 0.0001x + 0.3589$, $R^2 = 0.3584$) was applied as a descriptive approximation of the overall trend rather than as a mechanistic kinetic model. The relatively low R^2 value indicates that ammonium removal does not follow a strictly linear pattern and that precipitation kinetics are governed by more complex processes, including nucleation, crystal growth, aggregation, and diffusion limitations. Phosphate removal followed a similar but slower trend, increasing from ~20% at early times to ~35% after 3000 min. The regression ($y = 7E–05x + 0.2026$, $R^2 = 0.4029$) likewise served only as a simplified representation of the temporal trend. Given the presence of competing ions such as calcium and potassium, as well as high suspended solids, phosphate precipitation is likely influenced by multi-phase reactions and surface-mediated processes rather than a single linear kinetic pathway. This lower value does not contradict the >70% phosphate removal reported under optimized conditions; rather, it reflects the specific operational settings applied during the kinetic experiment.

The R^2 values (0.36 for ammonium and 0.40 for phosphate) indicated only a moderate fit to a linear model, suggesting that the kinetics may not be strictly linear. In reality, struvite precipitation often follows a two-phase process: a rapid nucleation and growth stage within the first hour, followed by a slower approach to equilibrium as the supersaturation declines. The scatter at shorter times reflected this rapid initial drop, after which a slower linear trend dominated. Overall, the kinetic results highlighted that ammonium removal proceeded more effectively than phosphate removal under the tested conditions. This imbalance is consistent with previous studies showing that phosphate recovery is often more sensitive to competing ions and pH fluctuations. Although sedimentation was monitored up to 24–48 h to evaluate equilibrium behavior under batch conditions, this extended settling time was intended for mechanistic observation rather than to represent a practical hydraulic retention time (HRT) for full-scale operation. In engineered struvite reactors, shorter retention times can be achieved through enhanced mixing, seeding, fluidized-bed configurations, sludge recirculation, or improved solid–liquid separation systems. Nonetheless, the gradual increase in both removal efficiencies with time suggests that allowing sufficient contact and settling time improves recovery performance. Future research should focus on reactor design optimization to reduce HRT while maintaining high supersaturation and efficient crystal harvesting, thereby improving the practical applicability of the process. Future studies should also apply more appropriate kinetic models (e.g., pseudo-first-order, pseudo-second-order, or diffusion-controlled models) to better describe the crystallization mechanism in complex leachate matrices.

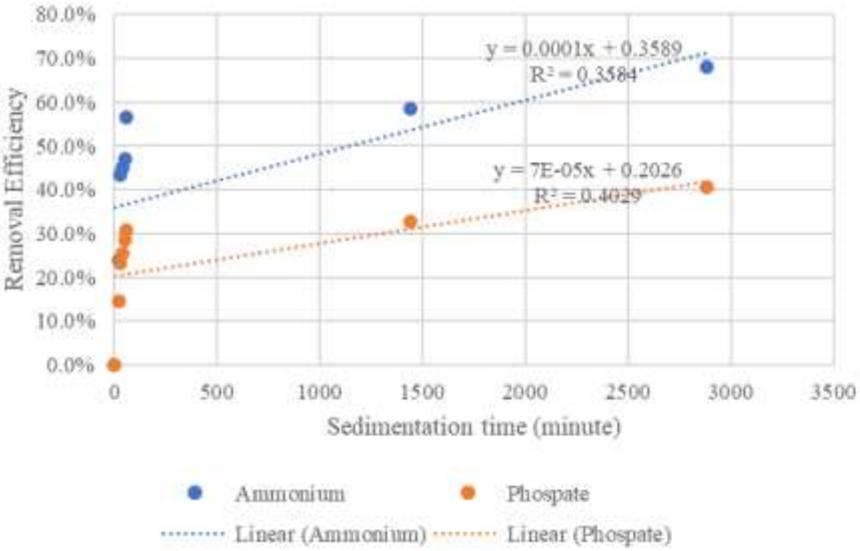


Fig 5. Kinetic rate of ammonia and phospate precipitation.

3.8 Visual confirmation of struvite

The microscopic examination of the precipitates confirmed the formation of crystalline struvite. The recovered solids displayed a typical white needle-like crystal morphology associated with struvite, providing qualitative evidence that the sequential recovery strategy successfully produced the target compounds. The confirmation of crystalline products is critical, as competing salts, such as amorphous calcium phosphate, can also form under similar conditions. Therefore, the visual confirmation strengthens the conclusion that the observed nutrient removal was predominantly due to struvite precipitation. Mixing intensity also affected the results; moderately slow mixing (around 60 rpm) provided a balance between promoting particle collisions and avoiding re-dispersion. Extending the mixing time led to better precipitation, although the effect leveled off after a certain period. Kinetic analysis suggested that both ammonium and phosphate removal followed a predictable precipitation pattern (Fig. 5) and visual inspection confirmed the formation of struvite crystals (Fig. 6).

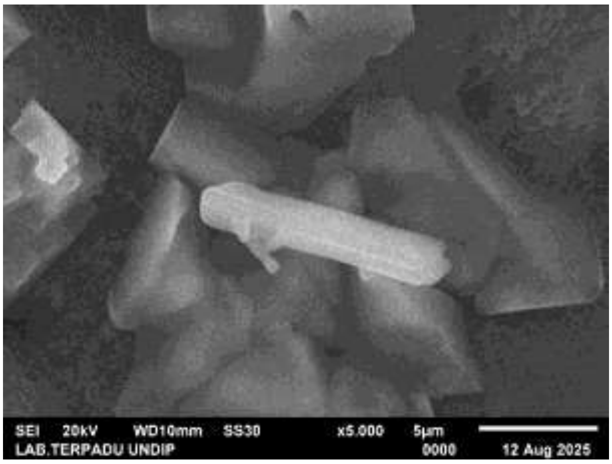


Fig 6. Struvite crystal formation.

3.9 Implications for nutrient recovery from composting leachate

The results of this study demonstrate that composting leachate, often regarded solely as problematic waste, can be transformed into a resource through sequential struvite recovery. By applying $MgCl_2$ supplementation, controlling the pH within 9–10, and adopting sequential mixing at moderate slow-mix speeds, significant recovery of ammonium and phosphate was achieved. The production of crystalline struvite highlights the potential for converting nutrient pollution into agricultural input, aligning with the principles of waste valorisation and circular economy.

Compared with previous work on sewage sludge liquors and digestates, the recovery efficiencies achieved in this study were somewhat lower. This outcome reflects the complexity of the composting leachate with higher suspended solids and competing ions. Nonetheless, the ability to recover more than 60% ammonium and 70% phosphate under optimized conditions is a promising outcome, particularly given that compost leachate has been underutilized in nutrient recovery research. Mizuta et al. similarly reported that struvite recovery from composting leachate is feasible but requires careful control of conditions. The present study adds to the literature by providing a detailed analysis of the Mg source, mixing regimes, and kinetics, offering practical guidance for potential scale-up.

Although laboratory results are encouraging, several limitations should be noted. First, the high suspended solid content of composting leachate may require pre-treatment to enhance recovery efficiency and reduce interference. Second, the reliance on chemical Mg sources such as $MgCl_2$ may limit economic feasibility unless supplemented with low-cost alternatives such as seawater or industrial by-products. In particular, while increasing the Mg:NH_4:PO_4 ratio to 5:1:1 improved phosphate recovery, the incremental benefit beyond 3:1:1 was comparatively smaller, suggesting diminishing returns relative to magnesium input. This indicates that optimization at lower overstoichiometric ratios may offer a more practical balance between nutrient recovery efficiency and chemical consumption. Furthermore, residual magnesium concentrations were not quantified in this study, and therefore the extent of unreacted Mg remaining in solution could not be assessed. Excess Mg dosing may lead to higher operational costs and potential downstream impacts if not recovered or reused. Future studies should therefore evaluate magnesium utilization efficiency (e.g., recovery per mol Mg added) and incorporate cost-performance analysis to determine the most economically viable dosing strategy. Third, the experiments were performed at the bench scale, and scale-up challenges such as reactor design, continuous operation, and handling of sludge-like precipitates remain to be addressed. Therefore, future research should focus on integrating struvite recovery with leachate management systems at composting facilities, exploring the use of alternative magnesium sources, and evaluating the agronomic performance of the recovered struvite as fertilizer. Techno-economic assessments are also essential to determine the practicality of implementing such recovery systems at full scale. Comprehensive techno-economic assessments are essential to determine the practicality and sustainability of implementing high Mg dosing strategies at full scale.

4. CONCLUSIONS

This study demonstrated the potential of composting leachate as a nutrient-rich feedstock for struvite precipitation, offering the dual benefit of pollution control and fertilizer production. The initial characterization revealed extremely high concentrations of ammonium (312.5 mg/L) and phosphate (1179.8 mg/L), but almost negligible magnesium, confirming the necessity of external Mg supplementation. Stoichiometric analysis indicated that phosphate (12.42 mmol/L) was the limiting reactant relative to ammonium (17.36 mmol/L), meaning that complete ammonium removal was theoretically constrained by phosphate availability. Despite the challenging matrix characterized by high suspended solids, interfering cations, and acidic pH, the sequential recovery strategy proved effective in achieving measurable nutrient removal and the formation of needle-like crystalline precipitates consistent with struvite morphology. However, because no advanced mineralogical characterization (e.g., XRD, FTIR, or SEM-EDS) was performed, the identity of the precipitated phase should be interpreted as indicative rather than conclusively confirmed as pure struvite. The presence of competing ions such as calcium suggests that mixed or calcium-phosphate phases may also have formed under certain conditions. The results clearly showed that the choice of magnesium source and pH were decisive factors. $MgCl_2$ consistently outperformed MgO because of its higher solubility, enabling immediate availability of Mg^{2+} for crystallization. Optimum nutrient recovery occurred at pH 9 for ammonium and pH 10 for phosphate, consistent with prior literature on struvite solubility, but highlighting the narrow operational window required for compost leachate. When the molar ratios were varied, a strong dose–response relationship was observed, with excess Mg addition (≥3:1:1) necessary to overcome competition from other ions and to push the system toward higher supersaturation. Under optimized conditions (pH 10 and $Mg:NH_4:PO_4 = 5:1:1$ using $MgCl_2$), phosphate removal exceeded 70%, demonstrating the feasibility of high recovery when operational parameters were carefully controlled. Mixing-regime experiments confirmed the importance of hydrodynamics. A sequential approach of rapid mixing followed by moderately slow mixing (approximately 60 rpm) provided the best balance between nucleation and crystal growth. At very low mixing speeds, limited nucleation reduced recovery, whereas at very high speeds, crystal breakage and re-suspension diminished the sedimentation efficiency. Similarly, the reaction time and sedimentation studies revealed a two-stage kinetic process: rapid initial removal within the first 30 min, followed by slower aggregation and settling over 24–36 h. In the kinetic experiment conducted under fixed operational parameters, ammonium removal reached nearly 70% after 48 h of sedimentation, while phosphate removal reached approximately 35%. This lower phosphate value reflects the specific experimental conditions applied during kinetic evaluation and does not contradict the higher removal observed under optimized settings. Ammonium removal reached nearly 70% after 48 h of sedimentation, while phosphate removal was lower at approximately 35%, reflecting the stronger sensitivity of phosphate recovery to matrix interferences. The kinetic results underline that ammonium removal was more efficient than phosphate removal under the tested conditions, a finding consistent with previous studies in which phosphate recovery was suppressed by competing ions such as calcium and potassium. Regression fits yielded modest R^2 values, indicating that more advanced kinetic models are required to fully capture the complexity of crystallization in such heterogeneous matrices. Nevertheless, the gradual increase in the recovery efficiency with time suggests that extended sedimentation could be a practical operational strategy for improving performance. Future studies should incorporate detailed solid-phase characterization and purity analysis to confirm mineral composition and evaluate the agronomic suitability of the recovered product.

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