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Struvite in agriculture: A meta-analytical assessment of its effectiveness as a phosphorus source

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Abstract

Struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$), a slow-release phosphorus fertilizer obtained from wastewater, presents a sustainable solution to traditional phosphorus fertilizers in the context of increased phosphate rock depletion, increasing fertilizer prices and environmental problems attributed to phosphorus runoff. Its distinctive nutrient release pattern conforms to plant uptake behavior, minimizing nutrient loss and minimizing eutrophication threats. Struvite exhibits similar or better agronomic value compared to conventional fertilizers, particularly in acidic soils or when combined with sources of soluble phosphorus. Yet, large-scale application is hampered by technical issues such as costly recovery, inconsistent wastewater composition, requirement for pH adjustment and possible contaminants. Societal and regulatory constraints further restrict its scalability. Mitigating these limitations via optimized production processes, advanced formulations and enabling policy regimes could make struvite a linchpin in phosphorus circularity, driving sustainable agriculture and the international circular economy agenda.

Keywords: Struvite, Slow-release phosphorus fertilizer, wastewater nutrient recovery

Introduction

Phosphorus is a plant cell process and growth essential nutrient. Phosphorus fertilizers, along with other nutrients, have dramatically enhanced agricultural output in developed nations throughout the 20th century. It has also significantly contributed to widespread eutrophication issues (Dodds *et al.*, 2009) ^[9]. Traditional phosphorus fertilizers are produced from limited phosphate rock (PR) stocks. These quality phosphate rock reserves are dwindling, becoming increasingly costly and are geographically localized in a very limited number of countries (Reijnders, 2014) ^[29]. This is a cause for alarm regarding the availability and affordability of phosphorus fertilizers and posing food security risks on a global scale, particularly for nations with no indigenous phosphate rock deposits (Elser *et al.*, 2014) ^[13]. Severe reliance of agriculture on phosphate rock, as well as the speeding up of phosphorus runoff and eutrophication of fresh water and marine ecosystems, has increased interest in closing the phosphorus cycle by phosphorus recovery and recycling (Elser and Bennett, 2011) ^[12]. For instance, phosphorus recovered from various sources *i.e.* animal manures (Greaves *et al.*, 1999) ^[15], separately collected urine (Wilsenach *et al.*, 2007) ^[35] and municipal wastewater (Le Corre *et al.*, 2009) ^[21] can be transformed into efficient fertilizer products for agricultural application pending overcoming technical and financial barriers (Lederer *et al.*, 2014) ^[22]. Struvite ($\text{NH}_4\text{MgPO}_4 \cdot 6\text{H}_2\text{O}$) is the recovered phosphorus product which is simple to spread, with higher phosphorus content and can be manufactured with little contamination of heavy metal (Antonini *et al.* 2012) ^[3]. Struvite, a common wastewater treatment by-product, clogs pipes and creates a scale lines in the treatment plant facilities where pressure continuously changes (Jaffer *et al.* 2002) ^[19]. However, the issues can be prevented using manipulation of digestion process of the sludge to yield controlled struvite precipitation within specialized reactors (Baur, 2009) ^[4]. This has the effect of lowering the P concentrations in plant effluent that is released into watercourses and yields struvite granules which can be sold as a magnesium ammonium phosphate (MAP) fertilizer product for agro-use (Schauer *et al.* 2011; Hertzberger *et al.*, 2020) ^[30, 18].

Aside from the reduction in resource consumption, struvite also has possible efficiency

advantages and environmental advantages over traditional fertilizers due to its low solubility (Cabeza *et al.* 2011; Massey *et al.* 2009) [6, 24]. In contrast to typical mineral phosphorus fertilizers that are soluble and potentially cause high phosphorus levels in surface runoff when there is rainfall shortly after application, increasing the eutrophication of nearby water bodies (Hart *et al.* 2004) [17]. Struvite, being a less soluble "slow release" fertilizer, can theoretically offer a longer-lasting supply of P available for plant growth and development compared to the forms of immediately soluble P and therefore more in harmony with the plant's P requirement further along the growing season and facilitating its utilization efficiency (Withers *et al.* 2014) [36]. Reduced rate of dissolution of struvite could result in lower levels of fertilizer phosphorus being adsorbed onto particles of soil or lost to runoff. These benefits have the potential to be used to either improve the crop production or to facilitate reduced application levels of phosphorus without sacrificing or reducing yields but with few environmental impacts, and this would be beneficial economically for the agricultural sector as it goes toward future sustainable intensification.

Struvite Formation

Struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$) is a phosphorus compound that can precipitate from waste streams (Doyle & Parsons, 2002) [10] by raising the pH of the wastewater and keeping the molar ratio of PO_4^{3-} to Mg^{2+} at stoichiometric levels (Uysal and Kuru, 2013) [33]. A pH of 9.0 and a Mg^{2+} to PO_4^{3-} molar ratio of 1 were determined to be optimum for struvite precipitation from swine slurry in batch experiments (Cerrillo *et al.*, 2014) [7], while the same molar ratio at pH 9.5 was determined for precipitation of struvite from wastewater produced during potato (*Solanum tuberosum* L.) processing (Uysal and Kuru, 2013) [33]. Although struvite dissolution is most effective in acid conditions, its solubility is very low in water compared to other commonly applied phosphorus fertilizers. Solubility product constant of different samples of struvite that have been discussed in available literature is low, varying from 4.37×10^{-14} to 3.89×10^{-10} (Rahaman *et al.*, 2006) [27]. Nonetheless, struvite is a viable candidate for agricultural phosphorus fertilizers due to the result of the numerous abiotic and biotic soil processes that can aid in its dissolution, as discussed below:



Factors affecting struvite formation

pH: Ideal range for precipitation of struvite is 8.0–9.5. Higher pH favors struvite precipitation by reducing solubility.

Molar Ratios ($\text{Mg}^{2+}:\text{NH}_4^+:\text{PO}_4^{3-}$): Ideal ratio is 1:1:1; excess magnesium improves yield but increases cost.

Temperature: Moderate temperatures (25–35°C) support crystallization; too high or low can reduce efficiency.

Supersaturation: Drives nucleation and growth; higher super saturation yields finer crystals.

Mixing Intensity: Ensures uniform distribution but excessive mixing may inhibit crystal growth.

Seeding: Adding seed materials promotes faster and larger crystal formation.

Competing Ions: Calcium and carbonate can interfere, forming other precipitates like calcium phosphate.

Organic Matter & Impurities: May inhibit or alter crystal growth and purity.

Reactor Design & Retention Time: Affects contact time and crystal size; optimized designs enhance recovery.

Wastewater Composition: Varies by source; nutrient levels and contaminants impact struvite formation potential.

Technologies involved in struvite formation and recovery

1. **Fluidized Bed Reactor (FBR):** The most used method for regulating the crystallization of struvite. Encourages constant ion interaction and mixing. Yields larger and more pure crystals that are perfect for harvesting. Example: Ostara's PEARL® process.
2. **Stirred Tank Reactors (STR):** Continuous or batch reactors that are mechanically stirred. Excellent for small-scale and lab applications. Simple to use, but could produce uneven or smaller crystals.
3. **Airlift Reactor:** This device mixes and circulates air using air bubbles. Minimal use of energy. Well suited for biologically active systems.
4. **Crystallization in Pipe or Sludge Lines:** Struvite passively forms in digesters, dewatering units, or pipelines. Often considered a problem (scaling), but can be harnessed if controlled.
5. **Membrane crystallization** is a new technology that regulates ion transport and super saturation via membranes. It provides both selective recovery and high purity. More suited for specialized or high value applications.
6. **Electrochemical Precipitation:** This process releases magnesium ions or produces localized pH changes using electrodes. It can enhance the struvite formation without relying on external chemicals. Still in the early stages of development, primarily for specialized or research uses.
7. **Hybrid and Integrated Systems:** Integrate nutrient polishing procedures, membrane bioreactors (MBRs), or anaerobic digestion with struvite recovery. Boost overall operational effectiveness and nutrition management.
8. **Supporting Processes/Technologies**
 - Magnesium dosing systems (MgCl_2 , MgO , seawater, etc.).
 - pH control systems (NaOH , lime).
 - Solid-liquid separation units (centrifuge, sedimentation, filtration) for harvesting struvite.
 - Monitoring and control systems (sensors for pH, PO_4^{3-} , NH_4^+).

Applications of Struvite

1. **As a Slow-Release Fertilizer:** Struvite is primarily used in agriculture as a slow-release fertilizer for magnesium (Mg), nitrogen (N), and phosphorus (P). It reduces fertilizer runoff and leaching while increasing the efficiency of phosphorus usage. Particularly useful for long duration crops and in soils that range from acidic to neutral (Degryse *et al.*, 2017) [18].
2. **Recovery of Nutrients from Wastewater:** Recovered, especially anaerobic digestate, centrate, or urine, from wastewater treatment facilities (WWTPs). Minimizes operational problems such as equipment and pipeline scaling. It supports circular wastewater management's resource recovery objectives.
3. **Soil Remediation:** Struvite can be used to gradually supply necessary nutrients to deteriorated soils. In contaminated or nutrient-depleted soils, it increases fertility of soil and fosters microbial activity (Mehta *et al.*, 2015) [25].
4. **Use in Controlled-Release Fertilizer Coatings:** For intelligent nutrient delivery, struvite is either mixed with biodegradable polymers or utilized in granular formulations. Decreases the requirement for recurrent fertilizer applications and increases nitrogen utilization efficiency.

5. Potential/Future Industrial Applications: Materials engineering, ceramic precursors and flame retardants because of its thermal breakdown characteristic. High-purity phosphorus compound recovery is being investigated.

Struvite solubility

While the reported solubility is subject to variation depends on the source of the struvite, its purity and how the citrate solubility was measured. Struvite tends to have increased solubility in citrate tests as opposed to tests with pure water (Ostara Nutrient Recovery Technologies Inc., 2019; Rech *et al.*, 2019) ^[26, 28]. Research indicates that Ostara Inc.'s product, Crystal Green, has about 96% citrate-soluble and 4% water-soluble struvite (Ostara Nutrient Recovery Technologies Inc., 2019) ^[26]. Solubility in water is usually lower and limited to about 2–3% (Rech *et al.*, 2019) ^[28], while citrate solubility of struvite from swine manure, chicken litter, and municipal wastewater (Crystal Green) is found to be 18%, 28%, and 29%, respectively. The citrate solubility data indicate that plant-root-released organic acids are likely to be responsible for dissolving struvite.

pH and struvite particle size

It is evident and inverse that soil pH is related to the struvite response ratio, validating the hypothesis that acidic soils promote struvite dissolution, hence its availability to plants. In contrast to aboveground plant part phosphorus concentrations and uptake, the response ratios of aboveground biomass were less affected by soil pH. This suggests that pathways other than phosphorus source like soil test phosphorus (STP) were more important. As noticed in the case of phosphate rock (Margenot *et al.*, 2016; Szilas *et al.*, 2007; Hertzberger *et al.*, 2020) ^[23, 31, 18], extremely acidic soils are best for completely replacing traditional water-soluble phosphorus fertilizers with struvite. This is evidenced by results indicating that, at pH 4.5, aboveground biomass grown with struvite was equivalent to the aboveground biomass grown with traditional phosphorus fertilizers. In two soils, aerial wheat had greater phosphorus content and absorption when monoammonium phosphate granules were applied than when 3-mm struvite granules were applied. When struvite was ground to less than 0.15 mm, its phosphorus absorption equaled that of ground monoammonium phosphate. This shows that not just only the pH but also particle size affects dissolution of struvite (Achat *et al.*, 2014) ^[1].

Crop Responses to Struvite as a Phosphorus Fertilizer

Compared with conventional fertilizers like triple superphosphate or monoammonium phosphate, struvite demonstrated promising outcomes as a phosphorus fertilizer for a variety of crops and showed similar or superior nutrient uptake, growth, and yield. Its slow-release property guarantees a steady supply of P, Mg and N, which can improve the efficiency of nutrient usage, especially in crops with longer development cycles or in soils with moderate P availability. Struvite application equaled the efficacy of TSP and considerably increased maize biomass and grain yield as compared to control, particularly in P-deficient soils (Degryse *et al.*, 2017) ^[8]. The potential of struvite fertilizer for temperate cereals was highlighted by field studies that demonstrated improved P uptake and wheat production (Talboys *et al.*, 2016) ^[32]. As struvite releases nutrients slowly, experiments have revealed that it improves tomato plant growth and fruit yield compared to water-soluble fertilizers (Uysal *et al.*, 2014) ^[34]. Struvite's gradual release of P improves environmental sustainability by lowering losses through runoff and leaching.

Struvite granules were a slow-release P fertilizer

Utilizing slow-release phosphorus fertilizers represents a potential solution to encouraging more sustainable cropping systems, especially on low phosphorus fertility soils. These fertilizers can (a) lower the tendency for P fixation in soils and increase the recovery efficiency of fertilizer P, (b) lower the necessity for plants to spend large quantities of photosynthetic energy on phosphorus acquisition tactics like extensive root development, root exudation, or dependency on mycorrhizal association and (c) lower phosphorus losses by runoff soon after application (Hart *et al.*, 2004; Lambers *et al.*, 2008) ^[17, 20]. But commercially available struvite fertilizers as spreadable granules did not dissolve quite as quickly to provide phosphorus at the start of plant growth when applied directly on the seed. Nevertheless, in a 90-day pot test in which spring wheat was grown to grain maturity, struvite phosphorus uptake was as effective as from triple superphosphate (TSP). By day 36, only 9% of applied struvite had dissolved, while 26% had dissolved in the pots treated with struvite alone by the termination of the 90-day growing period (Ahmed *et al.*, 2015; Talboys *et al.*, 2016) ^[2, 32].

Struvite's effectiveness as a P fertilizer may be enhanced for crop species that exude organic acids in large quantities

Struvite dissolution tests showed that the presence of 1 mM of some organic acid anions greatly accelerated the struvite phosphorus dissolution rate and increased the equilibrium phosphorus concentration as well. Among the plant species tested, *Fagopyrum esculentum* (buckwheat) showed a far greater ability to take up phosphorus from struvite than *Triticum aestivum* (wheat), presumably because it exuded more organic acids (Zhang *et al.*, 2001) ^[37]. Of particular significance is the fact that even without stress, *F. esculentum* roots have been reported to excrete high levels of oxalic acid (Zheng *et al.*, 1998) ^[38], which was very effective in enhancing struvite solubility compared with the other organic acids that were used. Notably, no correlation of significance was observed between the dissolution rate of struvite and organic anion Mg^{2+} complex stability constants. This implies that the enhanced solubility is not as much about lowering Mg^{2+} concentration in the solution and perhaps is more due to direct surface interaction with struvite (Talboys *et al.*, 2016) ^[32].

Soil pH and NH_4^+ concentrations are unlikely to be detrimental to struvite P-fertilization

Reducing the pH increased the initial solubility of struvite; it had, however, very minimal effects on the ultimate equilibrium phosphorus concentration (Massey *et al.*, 2009; Bhuiyan *et al.*, 2007) ^[24, 5]. When applied together with highly soluble phosphorus fertilizer, the rate of early-stage dissolution of struvite becomes zero. This is due to the fact that the dissolved phosphorus concentration in the soil solution rapidly exceeds the level at which struvite starts to dissolve, up to a point where some of that phosphorus is taken away by processes including plant uptake, leaching, or fixation by soil particles. Thus, the major benefit of struvite in combination fertilizers is that it provides a continued release of phosphorus towards the end of the growing season after the soluble fertilizer's influence has worn off. Soil pH in such mixed treatments will not be critical. Substantiating this, Massey *et al.* (2009) ^[24] demonstrated that struvite was potent in moderately alkaline soils (pH 7.6), which suggested that pH does not play any prominent role in its overall efficacy during the growing season under normal agricultural conditions. Likewise, Achat *et al.* (2014) ^[1], in a set of

incubation experiments, concluded that soil pH had no significant effect on the efficacy of struvite. Conversely, the equilibrium phosphorus concentration was inhibited by the presence of ammonium (NH_4^+) in solution, as explored in studies of the impact of counter-ions on struvite dissolution.

Mixing struvite with soluble fertilizer P source (Struvite blend)

Mixing struvite with easily soluble phosphorus fertilizers can promote overall phosphorus recovery through offering immediate P availability for initial plant growth as well as prolonged P release from struvite to provide later-stage developmental support. In a 36-day pot trial where emphasis was placed on the early uptake of phosphorus, the benefits of blending struvite with DAP (diammonium phosphate) were well established. Struvite is considered to decrease phosphorus and nitrogen losses, and blending it with ammonium phosphate would serve to sustain soil P availability during the growing season. No large-scale field experiments have yet validated struvite's potential in lessening off-farm P losses (Margenot *et al.*, 2019) [23]. Three studies have investigated struvite with ammonium or superphosphates but did not include crop response data and were not considered for meta-analysis (Ahmed *et al.*, 2016; Guertal, 2015) [2, 16]. Wheat demonstrated greater P uptake when subjected to struvite-to-diammonium phosphate ratios of 20:80 and 10:90 under greenhouse trials in comparison to other blends (Talboys *et al.*, 2016) [32], in accordance with commercial guidelines to maintain struvite at below 35% in blends. Under acidic soil pH (pH 4.7), rock phosphate mixtures at 20% suppressed maize biomass through reduced P uptake (Franzini *et al.*, 2009) [14]. Since struvite P is usually more soluble in citrate than most phosphate rock P, struvite mixtures could be superior to phosphate rock.

Challenges and limitations in struvite formation and its use as a phosphorus fertilizer

1. Variability in Wastewater Composition

Particularly in municipal or industrial streams, wastewater's nutrient contents (Mg^{2+} , NH_4^+ , and PO_4^{3-}) are vary. Frequently lacks enough magnesium, necessitating external dosage, raising operating expenses. Competing ions, such as Ca^{2+} , CO_3^{2-} , might prevent struvite from crystallizing or result in undesirable precipitates, such as calcium phosphate

2. High pH Requirement

Struvite development requires pH of 8.0-9.5, which frequently involves chemical addition (such as lime or NaOH), raising expenses and influencing subsequent procedures. Overdosing may cause phosphate scale or magnesium hydroxide to precipitate.

3. Scaling and Operational Problems

In wastewater treatment facilities, unchecked struvite precipitation leads to scaling in digesters, pumps, and pipes. This can shorten the life of equipment and make maintenance more necessary.

4. Slow Dissolution Rate in Soils

Although struvite's slow dissolution makes it useful for controlled-release fertilization, it may restrict the short-term availability of phosphorus, particularly in low-acidity soils. Not the best for quickly correcting phosphorus-deficient soils (Degryse *et al.*, 2017; Talboys *et al.*, 2016) [8, 32].

5. Low Nitrogen to Phosphorus Ratio

Struvite contains nitrogen, but the N:P ratio (1:1) does not match many crop needs. To balance the delivery of nutrients, co-application with additional fertilizers could be necessary (Uysal *et al.*, 2014) [34].

6. Economic and Logistical Barriers

Recovery technologies (e.g., fluidized bed reactors) require high capital and operating costs. Commercial viability depends on regulatory incentives, fertilizer market prices, and scalability.

7. Contaminant Concerns

Depending on the source (e.g., sludge or urine), struvite may contain trace heavy metals or pharmaceuticals. Requires careful quality control to ensure safe agricultural use (Mehta *et al.*, 2015) [25].

8. Regulatory and Public Acceptance

Recovered waste-based fertilizers are frequently not adequately accommodated by fertilizer approval regulatory systems. Because it comes from wastewater, the public may have a bad opinion of it (Egle *et al.*, 2016) [11].

Future Prospects of Struvite as Phosphorus Fertilizer

Struvite has a lot of promise as a sustainable phosphorus fertilizer, particularly when considering the objectives of the circular economy, environmental preservation, and global phosphorus shortage. It is anticipated that future developments in recovery technology and cost-cutting measures will increase the viability of producing struvite from a variety of waste sources, including municipal, industrial, and agricultural waste. By providing value-added fertilizer products and stabilizing nutrient loads, struvite recovery can be integrated into the current wastewater treatment infrastructure, especially through sidestream and decentralized systems.

Agronomically speaking, struvite-based fertilizers may become more viable alternatives to traditional mineral fertilizers if they are customized to particular crop and soil conditions, perhaps by mixing them with sources of potassium or nitrogen. Furthermore, the creation of nanostructured struvite materials and coated or granulated formulations may enhance crop uptake and nutrient release profiles (Egle *et al.*, 2016; Talboys *et al.*, 2016) [11, 32].

In an effort to lessen reliance on artificial magnesium salts, there is also increased interest in alternative magnesium sources, such as saltwater, bittern, magnesite, and industrial by-products. The long-term field performance, soil-plant interactions, and environmental safety of struvite require more investigation, particularly with reference to pollutants of growing concern (e.g., heavy metals, pharmaceuticals).

Lastly, expanding the use of struvite will require public acceptance, policy backing, and inclusion in fertilizer regulations (such as the EU Fertilizing Products Regulation 2019/1009). With the right frameworks, struvite might play a significant role in resource-efficient, low-impact agriculture, bridging the gap between food production and waste management (Mehta *et al.*, 2015) [25].

Conclusion

Struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$) presents a sustainable and viable alternative to traditional phosphorus fertilizers, especially in terms of increasing pressure on finite phosphate rock reserves, growing fertilizer prices, and phosphorus-related environmental

degradation due to runoff. As a recovered wastewater-derived slow-release fertilizer, struvite minimizes nutrient loss to the environment while presenting a extended phosphorus release that closely matches the need of plant uptake. It has proved to be comparable or even superior performance compared to conventional fertilizers such as TSP and MAP, particularly in acidic soils or when blended with higher-solubility P sources. Its low solubility also minimizes the threat of eutrophication, and mixing it with quick-release fertilizers will provide phosphorus availability early in the season while prolonging nutrient release throughout the crop cycle.

Struvite's widespread use, despite its advantages, continues to be affected by a number of technical, economic, and societal challenges. High capital investment for recovery technology, variable compositions of wastewaters, and requirement of pH adjustment restrict its viability at scale. Additionally, the presence of contaminants in certain waste-derived struvite and limited regulatory and public acceptance make it more difficult to adopt. Future prospects will rest on maximizing production techniques, enhancing fertilizer formulation, and harmonizing regulatory environments to facilitate its adoption. With proper investment and policy backing, struvite has the potential to become a key part of circular phosphorus management and contributing to sustainable agriculture and supporting the global agenda for the circular economy.

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