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Struvite: Definition, Benefits, and Potential Application in Arkansas Agriculture

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Introduction

In recent years, increasing levels of phosphorus (P) and nitrogen (N) in waste streams causing eutrophication have gained global attention. Additionally, as phosphate is a nonrenewable resource, the price of rock phosphate, used in the production of fertilizer, is expected to increase as reserves are depleted. Consequently, it is important to consider options for the efficient use and preservation of existing phosphate resources. One potential solution may be the precipitation of P and N from liquid waste streams as the mineral struvite ($MgNH_4PO_4 \cdot 6H_2O$). For many years, struvite scaling has been a major problem for wastewater treatment plants (WWTPs). Recent interest in the development of technologies aimed at removing struvite from waste streams before struvite forms and accumulates in WWTP pipes may reduce labor and other costs associated with struvite removal, while also generating a valuable product for use in agricultural production.

Struvite is described as a slow-release P fertilizer that can contribute to crop productivity enhancement; therefore, application of struvite to nutrient-deficient agricultural lands could be of great benefit for Arkansas' agriculture. Preliminary field experiments have been conducted (Summer 2019) to evaluate the effects of electrochemically precipitated struvite (ECST), compared to other common P fertilizers [triple super phosphate (TSP), monoammonium phosphate (MAP), diammonium phosphate (DAP), rock phosphate, and a chemically precipitated struvite product (Crystal Green; CG)], on corn and soybean growth on a Calloway silt-loam soil (Fraglossudalfs) and on rice grown using a direct-seeded, delayed-flood production system on a Calhoun silt-loam soil (Glossaqualfs) with low soil-test P in eastern Arkansas. Preliminary field results demonstrate corn, soybean and rice yields were at least similar, and at times, greater from amendment with ECST than from other common, commercially available fertilizer-P sources and the CG struvite material. From an agronomic perspective, preliminary field results revealed that ECST could serve as an alternative fertilizer-P source for multiple row crops grown under field conditions. Economic analysis based on these preliminary results suggests that, in addition to being technically viable for crop production, ECST may also prove to be an economically viable fertilizer source, particularly as nonrenewable P stocks become scarce.

What is Struvite?

Struvite, the common name for magnesium (Mg^{2+}) ammonium (NH_4^+) phosphate hexahydrate ($MgNH_4PO_4 \cdot 6H_2O$; Johnston and Richards, 2003), is a high-value, slow-release, efficient fertilizer that can be recovered from both solid wastes, such as food, animal and human waste (Kataki et al., 2016; Farrow et al., 2017) and wastewaters, such as municipal, industrial and agricultural wastewaters (Westerman, 2009; Mayer et al., 2016). Equi-molar concentrations (1:1:1) of Mg^{2+}, NH_4^+ and PO_4^{3-} with alkaline pH and appropriate mixing are necessary to precipitate struvite as a solid (Rahaman et al., 2008). Struvite has a molecular weight of 245.43 g mol^{-1} and is readily soluble in acidic conditions, sparingly soluble at neutral conditions, but insoluble in alkaline conditions (Chirmuley, 1994).

Struvite fertilizer is granular, concentrated, non-sludgy, odorless, easy to handle, and free of traditional sludge-handling problems (Bouropoulos and Koutsoukos, 2000). Pure struvite as a fertilizer has a fertilizer grade of approximately 6-28-0 and contains approximately 16% MgO (Westerman, 2009). Generally, recovered struvite contains between 11 and 26% total P (Johnston and Richards, 2003) depending on the initial source and method of production, yet only about 0.02% is water-soluble (Negrea et al., 2010), while the remaining P is acid-soluble (Bridger et al., 1962), thus making struvite an ideal slow-release source of P for plants. Struvite is treated as P fertilizer although struvite is also an effective source of N and Mg.

Where is Struvite a Problem?

Over the years, struvite scaling, or deposits, are generally common in WWTPs, causing reductions in flow capacities in pipes and operational inefficiencies. The removal of struvite has generally been difficult and costly, with some estimates exceeding $100,000 for remediation of struvite scaling in mid-sized WWTPs (Ghosh et al., 2019; Forrest et al., 2008). Therefore, nutrient recovery as struvite, before struvite precipitates and accumulates in WWTP pipes and on equipment, would be a major relief in the wastewater treatment industry, where 80 to 90 of struvite can be recovered from wastewaters through struvite precipitation processes (Geerts et al., 2015). University of Arkansas researchers are currently experimenting with new technologies that have potential to remove P from wastewaters and generate energy, thus potentially reducing WWTP operational costs (related to struvite removal and electricity usage), while generating an additional income source, struvite for fertilizer.

Benefits of Struvite Removal from Waste Streams

Management of waste streams is a vital issue, with both sanitary and environmental concerns at the local and global levels. Recovery of nutrients in waste streams as struvite has much more to offer society than just the value-added end product. Eutrophication is a big environmental issue across the world today. Eutrophication can lead to severe economic, environmental and human health problems. Reduction in visibility in water bodies and odor problems from eutrophic algal blooms decrease property values in the surrounding area (Dodds et al., 2009). Wastewater treatment plants thus play an important role, as WWTPs are one of the main routes of non-diffuse P losses. The recovery of struvite in WWTPs can reduce operating costs by improving sludge dewatering, reducing biosolids volume, and preventing unwanted deposits in pipes. Removal of struvite from waste streams is a way to reduce eutrophication problems (Lee et al., 2007) and groundwater contamination from excess P and N. Sustainable P management should therefore focus on P recovery from waste streams. Recovery of struvite from waste streams can reduce offensive odors, which may impact property values in the neighboring areas to with eutrophic water bodies, and can reduce human health hazards originating from toxins released by eutrophic blue-green algae (cyanobacteria). Furthermore, struvite recovery from domestic wastewater could be an opportunity to generate local supplies of P fertilizers for crop production, create job opportunities and improve the economic status of the members of the local communities, and increase biodiversity in waterbodies due to mitigating eutrophication. Compared to land-applied biosolids as fertilizer, which can be problematic due to handling, odors and low nutrient concentrations, the concentrated nature of nutrients in struvite, coupled with easier handling and odorless nature, increase the value of struvite as a fertilizer. The positive impacts of wastewater-recovered struvite in the society can strengthen the economic, social and environmental aspects of sustainability.

Water quality degradation, as a result of P loading, can increase water scarcity, as polluted waters may be considered unfit for some specific types of human use (Davies and Simonovic, 2011). Water scarcity and pollution are closely connected to global food production, population, energy and economics, and may limit societal development if left unchecked (Simonovic, 2002). Removal of struvite from waste streams can reduce the problem of nutrient enrichment occurring at local and global scales, can improve drinking water quality for humans and animals and availability of water for various human uses, as well as the use of water bodies for recreation. In addition, treated wastewaters can be used for irrigation in agriculture. The understanding and optimization of the process of struvite removal from waste streams can enhance the sustainable development of society.

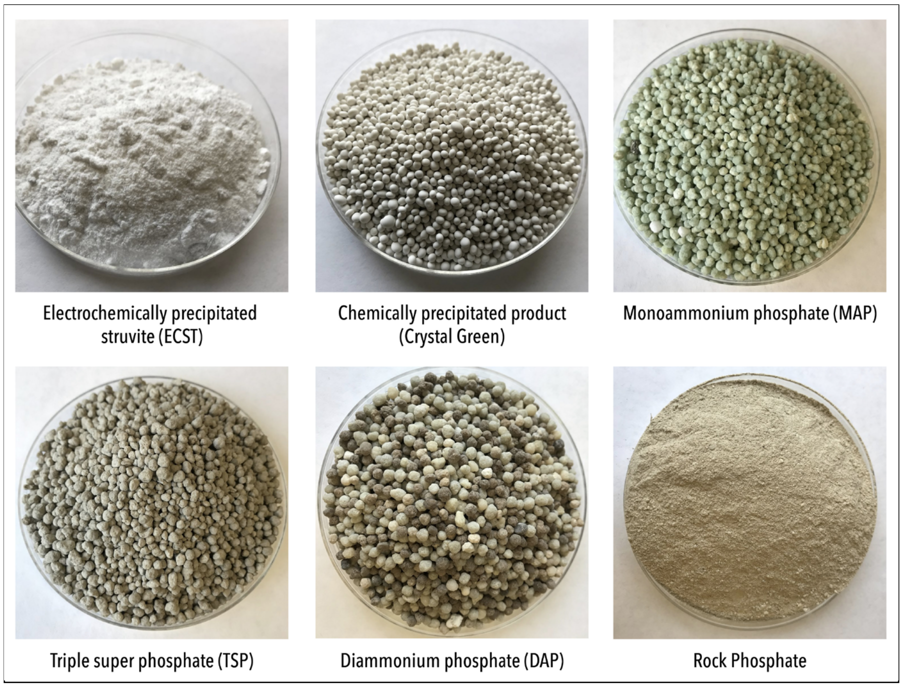

Figure 1. Fertilizer-phosphorus sources used in the field studies.

Potential Struvite Use in Arkansas Agriculture

Agriculture is the backbone of Arkansas' economy and is the largest sector, contributing about $21 billion in value added to Arkansas' economy each year. In 2018, over 7 million acres of crops were planted across Arkansas, with rice, corn and soybeans representing almost 75% of all harvested acres (English et al., 2019). As a slow-release P fertilizer, struvite can contribute to crop productivity enhancement, and struvite application to nutrient-deficient agricultural lands could be of great benefit. Food production is dependent on optimal P availability, and crop productivity would decline without sufficient fertilizer-P additions, often supplied by phosphate-rock-based fertilizers, resulting in decreasing revenue for the agricultural industry. The use of struvite could reduce dependence on the finite, nonrenewable resource of rock phosphate from which phosphate fertilizers are derived and ensure food security (Ashley et al., 2011). Many studies conducted in different parts of the world have reported similar effects of struvite as commercial fertilizers, such as TSP, MAP and DAP, on different crops, such as, corn, wheat and potato, in both alkaline and near-neutral to acidic soils (Johnston and Richards, 2003; Massey et al., 2009; Perez et al., 2009; Ackerman et al., 2013; Uysal and Kuru, 2015; Collins et al., 2016; Katanda et al., 2016). Although few studies have been conducted under field settings, particularly in the United States, the potential use of struvite in Arkansas' agriculture could be promising.

Agriculture production involves uncertainty, including uncertainty in input prices. Unexpected changes in fertilizer costs could cause financial challenges to producers, yet without optimal fertilizer inputs, there will likely be a decline in crop yields. The adoption of struvite as a nutrient source could slow, or even reverse, increasing rock-phosphate fertilizer prices, improve the economy of local and limited-resource farmers and ensure food security and community health (Cordell et al., 2009). Apart from its reported slow-release behavior, which provides a steady nutrient supply for plants and improves fertilizer-uptake efficiency, struvite could also be advantageous for soils and crops that require the input of Mg and N. Consequently, struvite could be a potential environmentally sustainable, renewable nutrient source for Arkansas agriculture.

Preliminary Field Results

Field experiments were conducted during Summer 2019 to evaluate the effects of ECST compared to other common fertilizer-P sources (TSP, MAP, DAP and rock phosphate) and Crystal Green on corn and soybean yields in a Calloway silt-loam soil (Aquic Fraglossudalfs) and on a pureline rice cultivar grown on a Calhoun silt-loam soil (Typic Glossaqualfs) with low soil-test P in eastern Arkansas. Fertilizer-P treatments were manually applied at a rate of 26.2 (corn), 39.3 (soybean), and 26.2 lbs P ac^{-1} (rice). Each fertilizer-P treatment plus an unamended control was replicated four times. Fertilizer-P sources were applied in their original form as either a pellet (MAP, DAP, TSP and Crystal Green), crystalline (ECST), or a powder (rock phosphate; Figure 1). For corn and soybean, fertilizer-P materials were surface-applied after planting. For rice, fertilizer-P materials were surface-applied and then incorporated prior to planting.

Table 1 summarizes results from preliminary field studies conducted to evaluate the effect of fertilizer-P sources on corn and soybean yields at the Cotton Branch Experimental Station (CBES) and on rice yield at the Pine Tree Research Station (PTRS). Yield results revealed significant differences ($P < 0.05$)

among fertilizer-P treatments for corn and rice. Corn yield from ESCT (211 bu ac^{-1}) was similar to that for TSP (187 bu ac^{-1}), but was approximately 1.2 times greater than corn yield from all other treatments. Corn yield from Crystal Green (182 bu ac^{-1}), TSP, DAP, MAP and rock phosphate did not differ from the unamended control (Table 1). Soybean yield did not differ ($P > 0.05$) among any fertilizer treatments. Results revealed that fertilizer-P application was not needed to maximize soybean yield at CBES despite soil-test-P suggesting a yield response should be expected.

Table 1. Summary of yield results from effect of fertilizer treatments for corn, soybean and rice from 2019 field studies at Cotton Branch Experimental Station (corn and soybean) and Pine Tree Research Station (rice). Means in a column with different letters are different at $P < 0.05$.

Fertilizer Treatment	Corn	Soybean	Rice
	bu ac^{-1}		
Triple super phosphate	187 ab	60 ab	232 a
Electrochemically precipitated struvite	211 a	67 a	228 ab
Diammonium phosphate	171 b	59 ab	226 ab
Monoammonium phosphate	178 b	61 ab	232 a
Crystal Green	182 b	60 ab	218 bc
Rock phosphate	166 b	60 ab	231 a
Unamended control	178 b	57 ab	213 c

† *Moisture contents were 15.5%, 13%, and 12% for corn, soybean and rice, respectively.*

Rice yield differed ($P < 0.05$) among fertilizer-P treatments. Rice yield from the ECST treatment (228 bu ac^{-1}) was similar to that of TSP, DAP, MAP and RP, all of which were on average 7.1% greater than the yield from the unamended control. Rice yield from Crystal Green (218 bu ac^{-1}) did not differ from that from the unamended control (Table 1).

In general, yield results from corn, soybean and rice showed that ECST was at least comparable, and at times superior, to other commercially available fertilizer-P sources for row-crop production. The slow-release mechanism of ECST likely aided in meeting the crops' P demand, thus resulting in greater yields.

Economics of Struvite as a Fertilizer P Source

While different treatments may not produce statistically different yields in fields, profitability of those treatments can still vary greatly as profits are based on actual costs and yields observed. Although the current market price of struvite fertilizer remains greater than many conventional fertilizer products, several factors must be considered in analyzing the overall economic viability of struvite. For example, the P and N content may vary among different phosphate products, thereby changing the amount of fertilizer needed to meet crop requirements. Figure 2 highlights the variation in the amount of phosphate and urea fertilizers needed to meet total fertilization rates of 26.2 lbs P ac^{-1} and 236 lbs N ac^{-1} for corn production in the studies described above. Consequently, a lower or greater price per unit of product may not directly relate to a lower/greater costs for fertilization.

A second factor to consider is the effect on yield. Although the overall costs for struvite fertilizer may be greater, an increase in average yield, as was shown in the preliminary studies described above, may be enough to offset the added cost of struvite use. Table 2 compares the total estimated net returns for corn, soybean and rice across various fertilizer treatments, only taking into account the cost of fertilizer. Using TSP as the primary point of comparison, applying ECST resulted in a 10.6% greater net return than TSP in corn and 2.4% greater net return in soybeans. However, in rice, estimated returns were 4.7% lower from ECST than from TSP. In the case of rice, MAP exhibited the best outcome with returns that were slightly greater (0.4%) than TSP.

Table 2. Estimated change in net returns per acre in relation to triple super phosphate (TSP). Net returns were based on average yields and total fertilizer costs of phosphorus and nitrogen.

Fertilizer Treatment	Corn	Soybean	Rice
	% change from TSP		
Triple super phosphate	-	-	-
Electrochemically precipitated struvite	10.6%	2.4%	-4.7%
Diammonium phosphate	-9.2%	1.7%	-1.7%
Monoammonium phosphate	-4.9%	3.2%	0.4%
Crystal Green	-13.0%	-20.3%	-12.2%
Rock Phosphate	-19.6%	-12.9%	-3.6%

Beyond the current cost of phosphate fertilizers, an additional factor to consider is the potential cost impact of future phosphate scarcity. As mineral phosphate resources continue to be depleted, the cost of mined rock phosphate is expected to rise, increasing the cost of conventional phosphate fertilizers and thus increasing the economic viability of struvite recovery (Anawar et al., 2019; de Boer et al., 2019). Investment

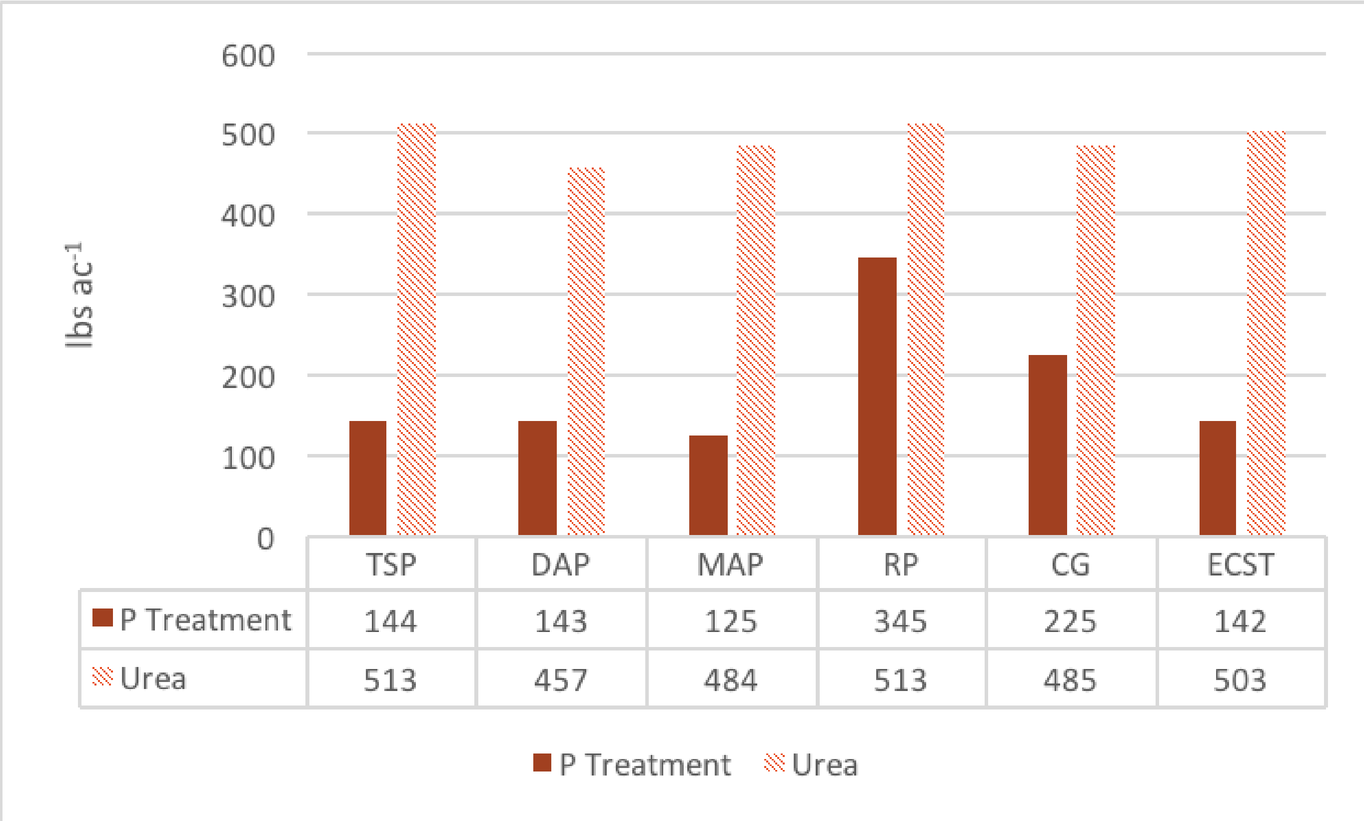

Figure 2. Amount of phosphorus (P) and nitrogen (N, as urea) fertilizer required to meet recommended fertilization rates of 26.2 lbs P ac^{-1} and 236 lbs N ac^{-1} across all treatments [triple super phosphate (TSP), diammonium phosphate (DAP), monoammonium phosphate (MAP), rock phosphate (RP), Crystal Green (CG), electrochemically precipitated struvite (ECST)] for corn grown in an experimental plot in Arkansas.

in struvite production in the U.S. could increase the country's self-sufficiency in phosphate fertilizer production and insulate producers from price shocks that may occur as a result of changes in global trade markets (Geissler et al., 2019).

Conclusions

Preliminary results appear to indicate that, from both an agronomic and economic perspective, ECST may show promise as an alternative fertilizer-P source for Arkansas row-crop producers, specifically when used in corn or rice production. While this fact sheet highlights ECST's potential in row crops, opportunities may also be recognized in other areas such as turf, ornamental and vegetable crop application (Min et al., 2019). Alternatively, as ECST products may be marketed as "environmentally friendly" or "green", this may allow producers to gain value by taking advantage of environmental premiums (Yetilmezsoy et al., 2017). Overall, electrochemical struvite precipitation from wastewater offers an alternative solution to the use of fertilizers derived from non-renewable phosphate reserves, while at the same time offsetting environmental consequences resulting from excess P and N through the capture and reuse of valuable resources.

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