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Corn and Soybean Response to Wastewater-recycled Phosphorus Fertilizers

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ABSTRACT

The ability to recycle phosphorus (P) from wastewaters could provide a sustainable, continuous source of P that might also help protect surface water quality from P enrichment. The mineral struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$) is an understudied material that can be created from P-containing wastewater and has been shown to have agricultural fertilizer value. The objective of this study was to evaluate the effects of electrochemically precipitated struvite (ECST), chemically precipitated struvite (Crystal Green; CG), diammonium phosphate (DAP), monoammonium phosphate (MAP), rock phosphate (RP), and triple super phosphate (TSP) on corn (*Zea mays*) and soybean (*Glycine max*) response in a 79-day greenhouse pot study. The effects of fertilizer treatment (i.e., ECST, CG, TSP, MAP, DAP, RP, No P/+N, and No P/-N) on select plant and soil properties were evaluated separately by crop (i.e., soybean and corn). Results demonstrated that when a crop response to P fertilization was expected, there were differences in degree of plant response depending on fertilizer-P source. Although soybean plant properties were not, corn plant properties and corn and soybean elemental tissue concentrations differed ($P < 0.05$) among fertilizer amendments. Total corn dry matter from ECST did not differ from that from RP and TSP and was 1.2 times greater than that from CG. Belowground corn dry matter from ECST was 1.9 times greater than that from CG, TSP, DAP, No P/+N, and No P/-N. Corn cob-plus-husk dry matter from CG and ECST were similar. Corn belowground tissue P concentration from CG did not differ from that from DAP, TSP, and MAP and was 1.4 times larger than that from ECST. Corn cob-plus-husk tissue P concentration from ECST was similar to that from MAP and DAP and was 1.2 times larger than that from CG. Corn stem-plus-leaves tissue P concentration from ECST differed from that from all other treatments and was 1.8 times greater than that from the No P/+N control. Results generated from this study not only provide information on the understudied electrochemically precipitated struvite, but also further reasons why more research should be conducted on not only the implementation of struvite as a fertilizer-P source, but also struvite's potential impact on sustainable food production and the preservation of water resources.

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Introduction

Phosphorus (P) has been historically considered a non-renewable resource that is a crucial nutrient for all life and sustains worldwide food production (Ashley et al., 2011). Currently, 90% of the world's P supply is used to make P fertilizers (Cordell et al., 2009). Phosphorus is obtained by mining phosphate-containing rock, also called phosphorite or rock phosphate (RP), a sedimentary rock formed by marine deposits, where peak production has the potential to be reached in the next 50 years (Antonini et al., 2012; Cordell et al., 2009; Filippelli, 2011; Metson et al., 2016). Additionally, the limited RP reserves are concentrated in only a few countries, and declining quantities of RP will, in turn, lead to increasing prices of this non-renewable P resource (Talboys et al., 2015).

In 2016 alone, RP mining ranked fifth in overall production volume of non-energy minerals with 255 million metric tons (~ 281 million tons) globally (Geissler et al., 2018), and 27.1 million metric tons (~ 29.9 million tons) produced domestically (Jansinski and Kohler, 2016). Additionally, the United States (US) was the leading importer of RP with 1.59 million metric tons (~ 1.75 million tons) and had no RP exports in 2016 (Jansinski and Kohler, 2016). Furthermore, the energy requirement to mine and process RP is substantial, totaling 82,190 kJ/metric ton (70,670 Btu/ton), consuming 51,464 m³ (323,700 barrels) of oil, ~ 19.82 million m³ (0.7 billion ft³) of gas, ~ 5.3 million L (1.4 million gal) of gasoline, and 10.4 billion MJ (2,900 million kW) of electricity in 1997 (USDOE–EERE, 2002).

Concurrent with overall global population growth, it is estimated that by 2025 the demand for meat production will increase by 50% due to increasing populations of affluent, urban communities (Jarvie et al., 2015). Increased meat production will increase the demand for animal feed production by 42%, which also requires grain production to increase by 50% (Jarvie

et al., 2015). In order to meet these increasing demands, it is anticipated that the demand for P fertilizers will need to increase by 2.4 times greater than the levels in the year 2000 (Jarvie et al., 2015). Furthermore, after the peak P mining is reached, the quantity and quality of available P will begin to decline, likely having negative impacts that are severe and far-reaching. The combination of increasing preference for meat diets, global population growth, P demand, and P-fertilizer price with diminished quantity and quality of RP sources has the potential to cause severe effects on the world's food supply and the world's economic, political, and social relations (Jarvie et al., 2015; Johnston and Richards, 2003; Kataki et al., 2016; Metson et al., 2016; Talboys et al., 2015).

Another complicating factor is that the land-application of P fertilizer over decades has caused P to accumulate to large concentrations in many agricultural soils because the P requirement of most plants is actually quite low (Jarvie et al., 2015; Liu et al., 2012; Metson et al., 2016). Although P is a relatively abundant element in nature, P is one of the least readily available nutrients for plants. There are many forms in which P naturally exists; however, many are not able to be assimilated by plants because plants can only absorb P in an inorganic form that is dissolved in the soil solution (Ashley et al., 2011; Nascimento et al., 2018). One of the largest P pools within the soil is organic forms of P, which encompass 20 to 80% of the total soil P (Schachtman et al., 1998). Elemental P is chemically reactive, so P always exists as phosphate minerals within natural environments, where there are 170 different mineral-P forms that vary greatly in solubility (Schachtman et al., 1998).

Many soils also have widely varying chemical and physical characteristics that influence the solubility and forms of P minerals. Some soil characteristics that affect the solubility of P are the concentrations of aluminum (Al), calcium (Ca), and iron (Fe), the surface area and inherent

nature of soil particles, and the soil pH (Holford, 1997). The total P concentration within soil depends on the soil horizon, soil texture, land use/intensity, and age, ranging from 10¹ to 10³ g P/kg (Kruse et al., 2015). Due to the tendency of P to favor the solid phase and the generally low solubility of P compounds, the quantity of P within the soil solution, is always quite low (Sharma et al., 2013). Just 0.1% of the total P in an average soil is available to be assimilated by plants (Sharma et al., 2013). In addition, the concentration of dissolved, inorganic P in the soil solution hardly ever goes above 10 μM (Shen et al., 2011). Therefore, P is considered one of the most immobile and unavailable plant nutrients due to the rapid conversion of P to organic forms, adsorption by soil colloids, and the precipitation of P as solids (Holford, 1997; Schachtman et al., 1998). In turn, the low availability of P within in agricultural soils requires crop producers to take measures to deal with the nutrient issue.

Within agricultural settings, few soils are unfertilized and are able to release P at a rate that is needed to support ideal growth rates of many plant or crop species. Hence, most agriculture production systems require the input of P fertilizers to achieve optimal crop productivity (Massey et al., 2009; Metson et al., 2016; Schachtman et al., 1998; Talboys et al., 2015). Many conventional P fertilizers are readily soluble, but the plant-available P released from the applied P fertilizers is rapidly fixed and the quantity of plant-available P in the soil solution decreases over time as a result of these fixation reactions. Declining P levels during a planting season have the potential to create insufficient P levels later in the growing season. During later stages of crop development, the crop requires P in much more significant quantities than during earlier stages. Having insufficient P levels at critical points of crop development could hinder the development of seeds and fruits and impede desired crop yields. The quick immobilization of P causes crop producers to have to apply P fertilizers annually in order to

combat the problem of low P availability in most soils (Holford, 1997; Massey et al., 2009; Metson et al., 2016; Schachtman et al., 1998; Talboys et al., 2015).

The substantial amount of accumulated soil P from the excess land-application of P fertilizers leads to agricultural runoff in many locations that can contain large P concentrations (Massey et al., 2009; Metson et al., 2016; Talboys et al., 2015). Consequently, P has become a contaminant in many natural surface water sources from excess fertilizer application, agricultural runoff containing excessive amounts of soluble and sediment-bound P from agriculturally dominated watersheds, and also from wastewater discharge that contains excessive quantities of nutrients, namely P.

The US alone processes enormous quantities of wastewater. Wastewater treatment plants (WWTPs) treat wastewater to designated standards that are low enough so the environment can assimilate the water, and some nutrients, back into the natural water cycle. However, the total sum of wastewater released is too much for environments to naturally process due to the total quantity of nutrients contained in the wastewaters. For instance, there are over 14,000 WWTPs in the US that process 1,736 m³/s (458,603 gal/s) of wastewater, which equates to ~ 125 million m³/day (~ 33 billion gal/day; Hallas et al., 2019). The wastewaters that enter the WWTPs have a total P concentration range of 3 to 11 mg P/L (11.4 to 41.6 mg/gal; Hallas et al., 2019). If 7.5 mg P/L (28.4 mg/gal) was the average P concentration in all wastewaters, then the US WWTPs would approximately process 0.34 Tg P (374,786 t P) yearly (Hallas et al., 2019).

Excess P in surface waters has been linked to eutrophication and the creation of hypoxic zones in freshwater and coastal marine environments (Hallas et al., 2019; Jarvie et al., 2015; Liu et al., 2012; Metson et al., 2016). Phosphorus and nitrogen (N) are the two elements that are the most concerning with regards to eutrophication. Additionally, increased P levels, compared to

increased N levels, influence the scale of eutrophication even more so because P is the most-limiting macronutrient needed by phototrophs in aquatic environments (Anderson et al., 2002). For example, in 1965 Lake Erie received more than ~73 metric tons (80 tons) of phosphates daily, where just 400 g (0.88 lbs) of PO_4^{3-} supported the production of approximately 350 metric tons (386 tons) of algal slime (Sharma, 1999).

Eutrophication is a slow natural process that occurs over hundreds of years (Leng, 2009). Therefore, when human activities cause excess P to accumulate in marine and inland waterbodies, it causes accelerated plant and algal growth, leading to human-induced eutrophication, or cultural eutrophication (Anderson et al., 2002). Moreover, cultural eutrophication can happen in as fast as a decade and studies have suggested that, even if a freshwater lake is under optimal conditions, the rehabilitation process of a eutrophic lake could take 1000 years (Leng, 2009).

Eutrophication is a global issue and causes costly damage. By the year 2005, it was documented that there were 146 coastal marine dead zones globally from severe eutrophication, and 43 of them were located in the US (Carpenter, 2008). In 2009, almost 38% of the lakes in the US were experiencing eutrophic conditions (Carpenter, 2008; Leng, 2009). One of the dead zones in the US is inside the Gulf of Mexico, which is caused by the heavy nutrient load of the Mississippi River's discharge. By July 2017, the dead zone occupied 22,730 km^2 (8,776 mi^2) (Carpenter, 2008; USDC-NOAA, 2017). The US spends over \$2.2 billion annually to reverse the devastating effects of eutrophication and hypoxia. Hypoxia is the associated condition of low to no dissolved oxygen in the water from advanced eutrophication (Jarvie et al., 2015; Leng, 2009; Liu et al., 2012; Metson et al., 2016). The accelerating decline of RP reserves and the

degradation of aquatic ecosystem health are both daunting issues that are only going to continue to grow, but there could be a solution.

The mineral struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$) is currently being studied as a potential P fertilizer. Struvite is an efficient, slow-release P source that can be recovered as a crystalline precipitate through recycling P from a variety of wastewater sources (Rahman et al., 2014). Struvite has been considered a problem because struvite is an unintended by-product of the wastewater treatment process. Struvite can naturally precipitate on the inside of pipes in WWTPs in areas where there are rapid pressure changes and can lead to pipe clogs. However, these problems have been overcome through the controlled chemical precipitation of struvite via manipulated sludge digestion processes within specialized reactors (Talboys et al., 2015). The chemical precipitation of struvite involves an aqueous solution that contains ammonium (NH_4^+) and phosphate (PO_4^{3-}) and the addition of magnesium (Mg^{2+}) that combines to produce struvite in a crystalline, granular form (Jarvie et al., 2015; Kataki et al., 2016; Tansel et al., 2018). The addition of Mg^{2+} is necessary due to the fact that municipal, anthropogenic, and livestock wastewater typically contain low levels of Mg^{2+} ; thus, the addition of Mg^{2+} is required to optimize the precipitation process of struvite (Rahman et al., 2014). The controlled precipitation of struvite removes and recycles excess nutrients from wastewater, producing a potentially functional fertilizer for agriculture with an equal molar ratio of 1:1:1 of Mg^{2+} , NH_4^+ , and PO_4^{3-} (Jarvie et al., 2015; Kataki et al., 2016; Rahman et al., 2014; Tansel et al., 2018). Not only is struvite produced in a different way than conventional fertilizers, but struvite has also been shown to be a slow-release P source that is a result of struvite's low aqueous solubility (Talboys et al., 2015). Struvite may improve P-uptake efficiency by plants because the P-release rate

closely matches the timing of P need in some crops later in the growing season (Massey et al., 2009; Talboys et al., 2015).

Massive quantities of soybean (*Glycine max*) and corn (*Zea mays*) are produced in modern agriculture. It is estimated that, in 2019, the US alone will produce 353 Tg (13.9 billion bu; USDA-NASS, 2019b) of corn grain from a harvested land area of 33.2 million ha (82 million ac; USDA-NASS, 2019a). For soybeans, it is estimated that the US alone will produce 100 Tg (3.68 billion bu; USDA-NASS, 2019d) of soybean grain from a harvested land area of 30.7 million ha (75.9 million ac; USDA-NASS, 2019c) in 2019. In addition, corn and soybean are also crops that have been shown to have positive responses to struvite application (Thompson, 2013; Thompson et al., 2013). A 3-year-long, agricultural field study conducted in Iowa assessed the P availability of struvite in a corn-soybean rotation on a silt-loam, loam, and silty-clay soil that had very low to low initial soil-test P levels (Thompson, 2013). This study measured corn and soybean response by measuring the plant properties of aboveground plant tissue dry weight (DW), P concentration, and P uptake and also grain yield, grain moisture, P concentration, and P accumulation. The results of the corn- and soybean-response measurements that were made each year of the field study demonstrated that when struvite and the conventional-P fertilizer, triple superphosphate (TSP), were applied at similar P rates, the two fertilizer-P sources resulted in no differences in any of the plant property responses (Thompson, 2013). However, even though there were no treatment effects on plant properties, sometimes the plant properties of the corn treated with struvite were numerically greater (Thompson, 2013). Additionally, the corn grain measurements (i.e., grain yield, P concentration, and P accumulation) showed that the plant available-P of the applied struvite was repeatedly equivalent to, and sometimes even greater than TSP (Thompson, 2013). Researchers concluded that recovered P in the form of struvite had

similar or greater crop-P availability compared with TSP, a conventional inorganic P fertilizer (Thompson, 2013).

Another field study, also conducted in Iowa, compared the effects of struvite and TSP on the response of corn and soybean in a corn-soybean rotation on a silt-loam, loam, and silty-clay soil (Thompson et al., 2013). The field study was conducted over four years with the objective of providing more information on what the ideal P rate would be for optimal soybean and corn yields from soils with low soil-test P. There were seven different P rates that were applied in this experiment: 0, 28, 56, 84, 112, 168, and 280 kg P₂O₅/ha (0, 25, 50, 75, 100, 150, and 250 lbs P₂O₅/ac; Thompson et al., 2013). The field study demonstrated that the two largest rates of struvite not only increased initial corn dry weight, but also increased P uptake more than the same rates of P applied as TSP (Thompson et al., 2013). Both P sources produced similar large increases in corn grain yield and considerable residual effects on the yield of soybean grain from the P that was applied a year prior to the crop rotation. Results from the first and second years of the corn-soybean rotation study showed that there were no differences between the two P fertilizers and their effects on initial corn DW, P concentration, and P uptake, and also grain yield (Thompson et al., 2013). The results of the field study also demonstrated that P availability from struvite in a corn-soybean rotation was comparable to that of TSP (Thompson et al., 2013).

Struvite is an example of a wastewater-recycled P fertilizer that has the potential to be multi-beneficial. Struvite application is being seen as economically advantageous for not only crop producers, but also WWTPs. If struvite was applied as a P fertilizer, crop producers could potentially maintain optimal, or even increase, crop yields while reducing fertilizer application rates. Additionally, struvite application also has the potential to lower environmental impacts because struvite's slow-release characteristic could decrease the quantity of P that is lost in runoff

(Massey et al., 2009; Talboys et al., 2015). Additionally, the controlled chemical precipitation of struvite could stop WWTPs from having to deal with struvite-clogged pipes, thereby improving time, energy, treatment, and cost efficiencies and effectiveness while also reducing the P concentration in effluent (Jarvie et al., 2015; Kataki et al., 2016; Rahman et al., 2014; Tansel et al., 2018). Furthermore, if the removal and reuse of nutrients from wastewater was fully implemented on a national level, the US demand for RP could be reduced by 20% (Hallas et al., 2019). Recycling P from P-containing wastewaters into a P fertilizer, in general, could improve efficiencies and cost-effectiveness of agricultural systems and WWTPs (Talboys et al., 2015). Recycling P from the wastewater of WWTPs as struvite also can reduce energy consumption, dependence on RP, and eutrophication in surface waters from cleaner WWTP effluent, decreased P concentrations in runoff, and reduced fertilizer-P application rates (Massey et al., 2009; Metson et al., 2016; Talboys et al., 2015).

Phosphorus recycling is a necessary area of research for the sustainability of water resources, the environment, and global food production. However, little has been done to see whether a largescale application of struvite could reduce the current RP dependence and if there is a cost-effective way that struvite production and application could be practically implemented (Hug and Udert, 2013; Metson et al., 2016).

Justification

Soil or plant response to wastewater-recovered struvite from electrochemical precipitation methods has not been evaluated in any setting (i.e., laboratory, greenhouse, or the field). Consequently, more information is needed to determine if electrochemically precipitated

struvite is a viable fertilizer-P source for plants and how electrochemically precipitated struvite compares to other common, commercial fertilizer-P sources and chemically precipitated struvite.

Objectives and Hypotheses

In order to study and provide more information on the possible benefits of struvite as a fertilizer-P source, a greenhouse potted-plant experiment was conducted. The objective of the study was to assess corn and soybean response to P fertilization with two wastewater-recovered struvite sources (i.e., chemically precipitated and electrochemically precipitated) and to compare corn and soybean response to that produced by other commonly used P fertilizers in an agriculturally managed silt-loam soil.

Based on previous reports that plant dry weight (DW), grain yield, tissue P concentration, and P uptake and soil available P responded positively to the application of struvite and that the responses were equal to or greater than other conventional P fertilizers (Johnston and Richards, 2003; Kataki et al., 2016; Massey et al., 2009; Thompson, 2013; Thompson et al., 2013), it was hypothesized that corn and soybean plants amended with either struvite source would have an equal or even greater response (i.e., final plant height; stem-plus-leaves, pod/cob-plus-husk, aboveground, belowground, and total dry matter; and stem-plus-leaves, pod/cob-plus-husk, and belowground tissue P and Mg concentrations) to P fertilization than the plants that were treated with the conventional P fertilizers.

Materials and Methods

Soil Collection, Processing, and Initial Characterization

The soil used in this greenhouse study was a Captina silt-loam (fine-silty, siliceous, active, mesic Typic Fragiudults; Soil Survey Staff, 2017) that was collected from a field (36°05'47"N 94°09'58"W) at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR, that had been under cultivated soybean production for at least several years prior. Ten, 18.9-L (5 gal) buckets of soil were manually collected on 18 February 2019 from the top 10 to 15 cm (4 to 6 in) of several adjacent raised beds at the edge of the soybean field from within an area of approximately 2.8 m² (30 ft²; Figure 1). The specific field/soil was chosen because it was initially understood that the field had been agriculturally managed without large amounts of P-fertilizer inputs. On the day of collection, the soil was wet from recent rainfall and was partially frozen. The soil was transported to a greenhouse and was spread out onto tarps on the tops of benches to air-dry before further processing.

Five, random sub-samples of soil were collected while air-drying, oven-dried at 70°C (158°F) for 48 hours, mechanically ground, and sieved through a 2-mm mesh screen prior to soil physical and chemical property determinations. Soil pH and electrical conductivity (EC) were measured potentiometrically in a 2:1 water-volume-to-soil-mass slurry (Table 1). The soil organic matter (SOM) concentration was determined gravimetrically through weight-loss-on-ignition after 2 hours of combustion at 360°C (680°F) in a muffle furnace (Zhang and Wang, 2014; Table 1). Total soil N and carbon (C) were determined by high-temperature combustion with an Elementar VarioMAX CN analyzer (Elementar Americas Inc., Ronkonkoma, NY; Table 1). Select water-soluble and Mehlich-3 extractable (Tucker, 1992) elemental concentrations (i.e., P, K, Ca, Mg, S, Na, Fe, Mn, Zn, Cu, and B; Table 2) were determined following extraction in a 10:1 extractant volume to soil mass ratio. Digested and extracted solutions were analyzed by inductively coupled, argon-plasma, optical emissions spectrometry (ICAP-OES; Soltanpour et

al., 1996). Particle-size analyses were conducted using a modified 12-hr hydrometer method (Gee and Or, 2002) to determine sand, silt, and clay fractions and confirm the soil textural class (Table 3).

The soil was overturned and mixed periodically during the air-drying process until all of the soil was not visually wet anymore, which required approximately 11 days of drying at approximately 22.7°C (72.8°F). Air-dried soil was then manually pushed through an 8-mm sieve to remove unwanted debris (i.e., roots, old stems, and other organic material). Any large soil clods that hardened from air-drying were broken up using a mortar and pestle before being pushed through the sieve. Once all of the soil had been sieved, the sieved soil was again laid out to completely air-dry and was mixed periodically for several more days before being returned to the buckets for later use.

Fertilizer Treatments

To evaluate the effectiveness and plant response of P-containing, wastewater-recovered struvite compared to other common, commercially available P fertilizers, six P-fertilizer materials were included in this study (Table 4). The eight treatments evaluated in this study included: 1) an electrochemically precipitated struvite (ECST) material, 2) Crystal Green (CG), a chemically precipitated struvite material, 3) triple superphosphate (TSP), 4) monoammonium phosphate (MAP), 5) diammonium phosphate (DAP), 6) rock phosphate (RP), 7) an unamended control that did not have added P, but had added N (No P/+N), and 8) an unamended control without added P or N (No P/-N; Figure 2).

Since struvite can be produced by multiple techniques, this study included two different types of struvite material. Crystal Green is a chemically precipitated struvite material that was

produced from a large municipal wastewater treatment plant near Atlanta, GA. Crystal Green is commercially produced and sold by Ostara Nutrient Recovery Technologies Inc., a United Kingdom-based company that uses their Pearl and waste activated sludge stripping to remove internal phosphorus (WASSTRIP) technological processes to produce struvite granules with a diameter of approximately 2.5 to 3.0 mm (0.10 to 0.12 in; Talboys et al., 2015). The second struvite source was produced by researchers in the Department of Chemical Engineering at the University of Arkansas, Fayetteville, via electrochemical precipitation from synthetically made wastewater containing known concentrations of P and ammonium and magnesium-containing cathodes.

The quantity of P fertilizer that was used per treatment was based on the initial Mehlich-3 soil-test-P concentration, the recommended P-fertilization rate for soybean and corn was from the Arkansas soybean and corn production handbooks, respectively (Espinoza and Ross, 2008; Slaton et al., 2013), and the differential P concentrations of the six fertilizer materials such that an equivalent P application rate was used for all six fertilizer materials. The initial Mehlich-3 soil-test-P concentration for a full-season soybean production was already optimum and no phosphorus pentoxide (P_2O_5) was recommended for application (Slaton et al., 2013). Therefore, a wheat double-crop soybean production system with a soil-test-P value of 26-35 mg/kg was used to determine the P_2O_5 application rate, which was 56.0 kg P_2O_5 /ha (50 lbs P_2O_5 /ac), which equated to 24.4 kg P/ha (21.8 lbs P/ac; Slaton et al., 2013). The P_2O_5 recommendation for corn was 84.1 kg P_2O_5 /ha (75 lbs P_2O_5 /ac), which equated to 36.6 kg P/ha (32.7 lbs P/ac) for a yield goal of 11 Mg/ha (175 bu/ac; Espinoza and Ross, 2008). Furthermore, since each P fertilizer also had a different N concentration, the amount of N, in the form of urea (46% N), needed to be added to each fertilizer material with a N concentration lower than that of DAP (i.e., ECST, CG,

TSP, MAP, and RP; Table 4) was calculated such that an equivalent amount of N was also applied to all treatments (i.e., ECST, TSP, MAP, DAP, RP, and No P/+N control; Table 5; Table 6), except for the No P/-N control treatment, which received no P or N. The No P/+N control treatment received the equivalent amount of urea as the P fertilizer that required the largest amount of N input, which was RP (Table 5; Table 6). Both P and N amounts were prepared and combined in plastic bags prior to being applied. Though the geometry and appearance of the fertilizer materials differed, most were pellets (DAP, MAP, CG, urea, and TSP), one was crystalline (ECST), and one was powder (RP), the original, solid form of each fertilizer was used.

The experimental unit for this greenhouse study consisted of one pot containing one of each fertilizer treatment mixed with air-dried soil and a plant, either soybean or corn. Each fertilizer-plant treatment combination was replicated three times for a total of 48 pots.

Pot Preparation

Plastic, 6,435 cm³ (1.7 gal), injection-molded nursery containers (Item # CN-NCIM/600 series, Pro Cal, South Gate, CA) 21.3 cm (8.3 in) tall and 22.9 cm (9 in) in diameter were used for this study. The pots had six, 1.5 cm (0.6 in) diameter holes (i.e., raised notches) at the bottom to allow for free drainage of water, thus glass fiber filter paper (item # 454, 18.5-cm diameter, VWR International, Radnor, PA) was needed to cover the holes to prevent loss of soil. Seven different, approximately 1 cm (0.4 in) long, silts were cut into the outer perimeter of the filter paper such that the filter paper would fit around and on top of the raised notches at the bottom of the pots.

A uniform and consistent amount of soil to add to each pot was determined next. Air-dried soil was poured into one pot to a depth of 10.7 cm (4.2 in), then the soil was poured into a 3.8-L (1 gal) plastic bag. The plastic bag full of soil was then placed onto a pre-weighed tub, where the plastic bag and soil mass was recorded at 4,058 g (8.9 lbs). The remaining 47 soil masses were prepared by weighing out the same mass [$4,058 \pm 0.1$ g ($8.9 \pm 2.2 \times 10^{-4}$ lbs)] of air-dried soil into plastic bags.

The amount of P fertilizer and urea to add per pot were pre-weighed to ± 5 mg (1.8×10^{-4} oz) of the target weight (Table 5; Table 6). The P-fertilizer amounts were prepared first, followed by the urea amounts, and both N and P fertilizer amounts were placed together in a small plastic bag for later mixing with the soil. The ECST and RP amounts were placed in a small glass vial inside the plastic bag that contained the urea to keep the powderized fertilizers from sticking to the inside of the plastic bags.

The pots were prepared by premixing the soil and the fertilizers before the soil was added to the pots to simulate the common field practice of fertilizer incorporation by tillage. The glass fiber filter paper was placed at the bottom of the pot, then the soil-plus-prepared-fertilizer treatment mixture was transferred to a 7.6 L (2 gal) plastic bag for more thorough mixing. The soil-plus-prepared-fertilizer treatment mixture was then added to each respective pot.

Based on the particle-size analyses of initial soil sub-samples, the soil had 27% sand, 66% silt, and 7% clay, which confirmed the soil had a silt-loam texture (Table 3). The Soil Water Characteristics Program, which used multiple regression equations (Saxton et al., 1986), was used to estimate the soil's wilting point (6.7% v/v), field capacity (26.1% v/v) and saturated water contents (47.0% v/v), and estimated, undisturbed bulk density (1.41 g/cm³; Table 3). The estimated field capacity water content was necessary in order to wet each pot of soil to

approximately field capacity prior to planting soybean and corn seeds. Three sub-samples were taken from the leftover air-dried soil that was not used to fill the pots to determine the gravimetric water content of the air-dried soil. The masses of the three sub-samples were recorded before and after oven-drying at 70°C (158°F) for 48 hours. It was determined that the average gravimetric water content was 0.007 g/g, which equated to a volumetric water content of 0.011 cm³/cm³ using the estimated soil bulk density.

In order to bring the air-dried soil in each pot to field capacity (~ 26.1% v/v) initially, 684 mL (0.18 gal) of water was required. However, for purposes of re-wetting, the target volumetric water content (VWC) range was chosen between 24 and 26% (v/v) to make sure no free water drained from the bottom of the pots, potentially removing some of the added fertilizer nutrients. Water was applied to each pot by splitting up the total volume of water, measured out in a 1-L graduated cylinder, into two half increments. The first increment of water was poured onto the soil surface and the second increment was not added until all of the water from the first increment had infiltrated into the soil. All pots were initially watered in this manner. The following day, all 48 pots received an additional small volume of water [50 mL (0.01 gal)] before the seeds were planted. The additional volume of water was added to ensure that there was adequate moisture in the upper portion of the soil, as the previously added water likely had seeped lower into the pot and to adjust for any evaporation losses that occurred overnight. Three small indentions were made in the center of the pot in a triangle arrangement to a depth of approximately 3 cm (1.2 in). One seed was placed into each of the three indentions, followed by manually pinching the indentions closed to establish good soil-to-seed contact. The seed-planting process was repeated until all 24 soybean and 24 corn pots were seeded. After all seeds had been planted, the pots were randomized on a 1.5 m x 6.7 m (5.0 ft x 22.1 ft) greenhouse bench.

After about 10 days, once every pot had at least one seed germinate and emerge, the number of plants in each pot was cut back to one. The selection process regarding what plant was kept in the pot took into account visual assessment of plant vigor, including plant height, leaf color, leaf structure, and overall leaf health. If all plants in a pot appeared to have no differentiating features, the plant that was located closest to the center of the pot was kept. The plants that were removed were manually pinched at the base of the stem and gently pulled out, removing the plant with the roots still attached, and then brushing off any soil that remained on the roots back into the pot.

Pot Management

Three times a week, the VWC in the top 6 cm (2.4 in) of soil in three randomly selected pots of both corn and soybean was measured using a SM150 soil moisture meter (SM150T* soil moisture sensor attached to a HH150 Moisture Meter, Delta-T Devices, Cambridge, England, UK) to assess the volume of water needed to be added to return the soil in the pot to the target VWC range. The moisture content of each selected pot was checked first before any water was added, then increasing increments of water were added to pots until the upper 6 cm of soil had a VWC in the range of 24 to 26% (v/v), which was considered a well-watered or optimum soil moisture condition. After each increment of water was added, the soil VWC was not measured again until about 10 minutes after watering in order for the water to have sufficiently infiltrated into the soil. Once the target VWC was reached in the randomly selected pots, the total volume of water added to the selected corn or soybean pots was then applied to the remaining pots all at once by carefully pouring the water onto to soil surface such that no water would leak out of the bottom of the pot. As plants grew, increasing volumes of water were needed to be added to each

pot to replace water that had evaporated and transpired since the prior watering. All of the corn and soybean pots were periodically rearranged on top of the greenhouse bench throughout the 79-day growing period and experienced average high and low temperature of 29.5 and 21.7°C, respectively (85.1 and 71.1°F, respectively).

Despite efforts to carefully water each pot so that no water, and potentially applied fertilizer nutrients, leaked from the bottom of the pots, three soybean pots experienced minor leakage in the early weeks of the experiment. During the second week of the experiment, the greenhouse roof leaked from heavy rainfall, dripping rainwater into two soybean pots. The third soybean pot experienced minor leakage from added water that flowed down the side of the pot where the soil had settled and shrunk slightly away from the inside of the pot.

During the growing period, there were two insect infestations that required a total of four insecticide applications. The first insect problem was a minor thrips infestation that developed on the soybeans two to three weeks after the plants were trimmed down to one plant per pot. Consequently, a three-step pesticide application was implemented for both the soybean and corn plants. First, a 2.5 mL (0.5 tsp) dose of Marathon [1% active ingredient of imidacloprid, 1-((6-Chloro-3-pyridinyl) methyl)-N-nitro-2-imidazolidinimine, OHP Inc., Bluffton, SC] was applied to the base of the plant stems, which was followed by plant watering. Second, Conserve [11.6% active ingredient, spinosad, 2-((6-Deoxy-2, 3, 4-tri-O-methyl- α -L-mannopyranosyl) oxy)-13-((5-(dimethylamino) tetrahydro-6-methyl-2H-pyran-2-yl) oxy)-9-ethyl-2, 3, 3a, 5a, 5b, 6, 9, 10, 11, 12, 13, 14, 16a, 16b-tetradecahydro-14-methyl-1H-as-indaceno (3, 2-d) oxacyclododecin-7, 15-dione and 2-((6-Deoxy-2, 3, 4-tri-O-methyl- α -L-mannopyranosyl) oxy)-13-((5-(dimethylamino) tetrahydro-6-methyl-2H-pyran-2-yl) oxy)-9-ethyl-2, 3, 3a, 5a, 5b, 6, 9, 10, 11, 12, 13, 14, 16a, 16b-tetradecahydro-4, 14-dimethyl-1H-as-indaceno (3, 2-d) oxacyclododecin-7, 15-dione, Dow

AgroSciences, Indianapolis, IN] was sprayed at a concentration of 0.53 mL/L (2 mL/gal) on the leaves of the plants two weeks after the first Marathon application. Conserve was applied by spraying the tops and bottoms of the plant leaves until the solution had beaded.

The second insect problem was a minor infestation of spider mites on the corn and was discovered roughly five weeks after the plants were trimmed back to one plant per pot. Dealing with the spider mites called for a two-step pesticide application. The first part called for the same insecticide, Conserve, that was previously used for the second step of the thrips infestation. To deal with the third and final insecticide application for thrips, and the first insecticide application for the spider mites, Conserve was applied to both soybean and corn two weeks after the initial Conserve application. The Conserve was applied at the concentration of 1.6 mL/L (6 mL/gal x 2 gal), which was a greater concentration than the previous Conserve application and larger than the recommended amount for thrips on soybean. A larger concentration of Conserve was applied because the elevated dose was required for the spider mites on corn. The second insecticide application for the spider mites called for the use of M-pede (49% active ingredient, potassium salts of fatty acids, Dow AgroSciences, Indianapolis, IN), which was the fourth and final insecticide application and occurred two weeks after the last Conserve application. The applied M-pede had a concentration of 10.6 mL/L (40 mL/gal x 2 gal) and was applied in the same manner that the previous Conserve was applied. However, roughly four days after the M-pede was applied, visual inspection revealed that most of the soybean plants had experienced minor pesticide damage. The affected soybean plants ranged in damage severity. The leaves of the affected soybean plants first showed signs of necrosis, then the leaves began to curl up and shrivel on themselves and slowly fall off. The leaves that had fallen off and could be identified to

what plant they came from were picked up and stored in paper bags that were attached to the side of the pots for future accounting during dry matter measurements.

As the soybeans began to grow tall, they began to bend over and droop downward. In an attempt to counteract the soybean plants from drooping, bamboo (*Bambusa Shreb*) stakes were placed into the pots, roughly 2.5 to 5.0 cm (1 to 2 in) from the base of the soybean plant. String was used to gently tie the soybean stems to the bamboo stakes at two to three different places along the soybean stem with the hope the plant would grow up and around the stakes.

Nitrogen, in the form of urea (46% N), was applied to all the corn P-fertilizer treatments (i.e., ECST, CG, TSP, MAP, DAP, RP, and No P/+N control), excluding the No P/-N control treatment, on 5 June 2019, 40 days after planting, as the recommended mid-season N application at a field-equivalent rate of 266 kg N/ha (237 lbs/ac) for a corn yield goal of ~ 13.8 Mg/ha (~ 220 bu/ac) grown on a silt-loam soil (Espinoza and Ross, 2008). After accounting for the initial N added to each pot with the P fertilizer, the additional amount of urea added to each pot averaged $1,494 \pm 5$ mg/pot (0.05 oz $\pm 1.8 \times 10^{-4}$ oz), which equated to 687 mg N/pot (0.02 oz). Urea was manually sprinkled around the base of the corn plants, followed by re-watering to return the soil to the target moisture content.

Plant Measurements

Plant heights of both soybean and corn were recorded starting three weeks after planting. The corn plant heights were recorded to the nearest centimeter by first using a meter stick, then eventually a tape measure, from the base of the stem to the highest point on the plant where the plant naturally rested. The plant heights were recorded until the 11th week, or the 77th day of the experiment (12 July 2019; Figure 3; Figure 4), three days before the plants were destructively

sampled. The soybeans were measured the same way as the corn until the soybeans began to droop. If a soybean plant was drooping down during a plant measurement, the stem was manually straightened by holding just under the top of the stem where there was branching of new leaves from the main stem, and was measured to the nearest centimeter using a meter stick or a measuring tape from the base of the stem to the highest point when held straight.

Pot Deconstruction

The experiment was terminated on the 79th day, 15 July 2019. Prior to deconstructing each corn pot, each corn plant was examined to see whether the plant had the beginning development of a second cob. Whether there was a second cob or not was determined by feeling and squeezing the husk to see if there was any cob formation on the inside and was recorded. Afterward, the corn pots were deconstructed first by removing the corn cob(s) with the husk attached. The stem-plus-leaves portion of the aboveground plant material was then collected. Roughly 15 to 30 cm (6 to 12 in) of the stem was left in order to facilitate measurement of the basal stem diameter. The remaining plant portions and soil were then removed from the pot by placing the pot into a plastic tub, where pressure was then applied along the outer surface of the pot until the soil and plant were loose enough to be removed. The basal stem diameter was then measured with a calipers ~ 1 cm (0.4 in) above the first node on the corn stem. After the basal stem diameter was recorded, the rest of the stem was cut at the soil surface and collected. The soil was then separated from the roots by manually applying pressure on the outer circumference of the soil until the main root mass separated from the soil. While roots were being separated from the soil and collected, any remnants of the glass fiber filter paper that was placed at the bottom of the pot at the beginning of the experiment was removed and discarded. The root

masses were then dunked repeatedly in an 18.9-L (5 gal) bucket of tap water and massaged until the remaining soil had been removed from the root masses. The clean roots were then manually squeezed to remove excess water and collected. Soil removed from the individual pots was put into 7.6-L (2 gal) plastic bag for later micro-root removal and further processing. Soybean pots were deconstructed in the same manner as the corn pots were.

Each pot had pods or cobs, aboveground (i.e., stem-plus-leaves) and belowground (i.e., roots) plant material, and soil retained for further processing and final chemical analyses. Soil from each pot was poured into a 2-mm sieve inside a plastic tub and was sieved to remove the micro-roots that remained. The micro-roots were washed and gently massaged in an 18.9-L bucket of tap water until they were clean of any attached soil. The sieved soil was then placed back in the plastic bag for further processing.

All plant tissue material was oven-dried at 66.6°C (151.9°F) for five days and weighed for dry matter determinations. Additionally, after drying, the number of soybean pods in each sample was recorded. There were five different dry matter portions that were determined per plant that were be used for statistical analyses: stem-plus-leaves dry matter (SLDM), cob(s)-plus-husk/pods dry matter (CHDM/PDM), belowground dry matter (BGDM), aboveground dry matter [i.e., stem-plus-leaves plus cob(s)-plus-husk/pods (AGDM)], and total dry matter [i.e., stem-plus-leaves plus cob(s)-plus-husk/pods plus belowground; (TDM)].

Sub-samples of the various plant tissue were mechanically ground and sieved to 6 mm (0.24 in) then were ground again to 2 mm (0.08 in). Plant tissue samples were chemically analyzed to determine total tissue N by high-temperature combustion (Elementar VarioMAX CN analyzer, Elementar Americas Inc., Ronkonkoma, NY) and total tissue P, Mg, K, Ca, and Fe

concentrations by acid digestion (USEPA, 1996) followed by analysis by ICAP-OES (Soltanpour et al., 1996).

Soil Measurements

After the micro-roots had been removed by sieving through a 2-mm mesh screen, the soil was mixed, and five sub-samples were collected and combined for one final soil sample per pot. Soil sub-samples were oven-dried for 48 hours at 70°C (158°F) then sieved again to 2 mm. Oven-dried soil sub-samples were analyzed for total soil N by high-temperature combustion with Elementar VarioMAX CN analyzer (Elementar Americas Inc., Ronkonkoma, NY) and water-soluble and Mehlich-3 extractable (Tucker, 1992) P, Mg, K, Ca, and Fe concentrations following extraction and analysis by ICAP-OES (Soltanpour et al., 1996) as previously described.

Statistical Analyses

Based on a completely random experimental design, a one-factor analysis of variance (ANOVA) was conducted with SAS 9.4 (SAS Institute, Inc., Cary, NC) using the PROC GLIMMIX procedure to evaluate the effect of the fertilizer treatment (i.e., ECST, CG, TSP, MAP, DAP, RP, No P/+N, and No P/-N) on plant [i.e., final plant height; stem diameter; stem-plus-leaves dry matter; cob(s)-plus-husk/pod dry matter; aboveground, belowground, and total dry matter; and total tissue N, P, Mg, K, Ca, and Fe concentration and uptake for roots, stems-plus-leaves, and cob(s)-plus-husk/pods] and soil chemical properties [i.e., final pH, electrical conductivity, total N, and Mehlich-3 extractable and water-soluble soil P, Mg, K, Ca, and Fe

concentrations) separately by crop (i.e., soybean and corn). Treatment means were separated by least significant difference (LSD) at the alpha level of 0.05. Significance was judged at $P < 0.05$.

Results and Discussion

Soybean Response

Plant Properties

The initial soil-test P concentration was already optimal for soybean (Slaton et al., 2013), thus no plant response was expected. All measured soybean plant properties (i.e., FPH, SD, SLDM, PDM, BGDM, AGDM, and TDM) were unaffected ($P > 0.05$) by fertilizer treatment (Table 7). Soybean final plant height ranged from 107 cm from CG, DAP, and RP to 122 cm from TSP and averaged 108 cm across all treatments (Table 7). Soybean stem diameter ranged from 6.5 mm from DAP to 8.5 mm from CG and averaged 7.2 mm across all treatments (Table 7). Soybean stem-plus-leaves dry matter ranged from 19.1 g from RP to 23.4 g from CG and averaged 20.5 g across all treatments (Table 7). Soybean pod dry matter ranged from 4.2 g from CG to 7.9 g from ECST and averaged 6.4 g across all treatments (Table 7). Soybean belowground dry matter ranged from 6.9 g from MAP to 8.1 g from ECST and averaged 7.8 g across all treatments (Table 7). Soybean aboveground dry matter ranged from 26.1 g from RP to 28.0 g from ECST and averaged 27.0 g across all treatments (Table 7). Similar to soybean belowground dry matter, total dry matter ranged from 33.5 g from MAP to 36.1 g from ECST and averaged 34.4 g across all treatments (Table 7). The lack of a P-fertilizer effect on soybean plant response was likely related to the initial soil-test P concentration (Table 2) already in the

optimal range for soybean production on a silt-loam soil (Slaton et al., 2013), thus minimal to no soybean response was expected.

Tissue Properties

Even though the initial soil-test P concentration was already optimal for soybean (Slaton et al., 2013), thus no yield response was expected, and all soybean plant properties (i.e., FPH, SD, SLDM, PDM, BGDM, AGDM, and TDM) were unaffected by fertilizer treatments (Table 7), soybean belowground (Table 8), pod (Table 9), and stem-plus-leaves (Table 10) tissue P concentrations all differed ($P < 0.05$) among P-fertilizer treatments.

Soybean belowground tissue P concentration was numerically largest from MAP, which did not differ from that in the TSP treatment (Table 8). Soybean belowground tissue P concentration was numerically smallest from the No P/-N control, which was similar to that in the No P/+N control (Table 8). Soybean belowground tissue P concentration from both struvite treatments (ECST and CG) were also similar to each other (Table 8). Soybean belowground tissue P concentration from ECST did not differ from that in the TSP and DAP treatments and the belowground tissue P concentration in the CG did not differ from that in the RP treatment (Table 8). The belowground tissue P concentration from TSP and MAP, which did not differ, was 1.4 times larger than that from both control treatments (No P/-N and No P/+N; Table 8) on account of both control treatments receiving no P input (Table 8).

All other reported soybean belowground tissue elemental concentrations (i.e., N, Mg, K, Ca, and Fe) did not differ ($P > 0.05$) among fertilizer treatments (Table 8). Soybean belowground tissue N concentration ranged from 23.3 g/kg from CG to 25.7 g/kg from TSP and averaged 24.7 g/kg across all treatments (Table 8). Soybean belowground tissue Mg concentration ranged from

1.8 g/kg from the No P/-N control to 2.1 g/kg from DAP and averaged 1.9 g/kg across all treatments (Table 8). Soybean belowground tissue K concentration ranged from 6.8 g/kg from CG to 9.0 g/kg from MAP and averaged 7.9 g/kg across all treatments (Table 8). Soybean belowground tissue Ca concentration ranged from 7.6 g/kg from MAP to 9.9 g/kg from the No P/+N control and averaged 8.3 g/kg across all treatments (Table 8). Soybean belowground tissue Fe concentration ranged from 1684 mg/kg from RP to 3483 mg/kg from CG and averaged 2229 mg/kg across all treatments (Table 8). None of the reported soybean belowground tissue elemental concentrations (i.e., N, Mg, K, Ca, and Fe) were numerically largest from ECST (Table 8). The struvite treatment CG was numerically larger than that from ECST among soybean belowground tissue Ca and Fe concentrations (Table 8). However, the CG struvite source had two of the numerically lowest soybean belowground tissue elemental concentrations (i.e., N and K; Table 8).

Soybean pod tissue P concentration was numerically largest from MAP, which did not differ from that in the ECST and DAP treatments (Table 9). Soybean pod tissue P concentration was numerically smallest from RP, which was similar to that in the No P/+N and No P/-N control treatments (Table 9). Soybean pod tissue P concentration from both struvite treatments (ECST and CG) were similar to one another and both also did not differ from that in the TSP and DAP treatments (Table 9). The pod tissue P concentration from ECST, MAP, and DAP, which did not differ, was 1.3 times larger than that from RP and both control treatments (No P/-N and No P/+N), which did not differ (Table 9). Despite being in the powder form, P contained in RP is virtually unavailable for plant uptake in the short-term after application due to the low solubility of RP (Table 9; Kumari and Phogat, 2008), thus the similar behavior of RP to both No-P control treatments is reasonable. The calcium carbonate (CaCO_3) fraction of RP is more soluble than the

phosphate (PO_4^{2-}) portion and, when Ca^{2+} is released into the soil solution, the pH increases on the surface of RP particles, further decreasing the solubility of PO_4^{2-} (Kumari and Phogat, 2008).

All other reported soybean pod tissue elemental concentrations (i.e., N, Mg, K, Ca, and Fe) did not differ ($P > 0.05$) among fertilizer treatments (Table 9). Soybean pod tissue N concentration ranged from 28.8 g/kg from both controls (No P/+N and No P/-N) to 31.8 g/kg from MAP and averaged 30.3 g/kg across all treatments (Table 9). Soybean pod tissue Mg concentration ranged from 2.6 g/kg from RP to 3.0 g/kg from ECST and averaged 2.9 g/kg across all treatments (Table 9). Soybean pod tissue K concentration ranged from 21.5 g/kg from RP to 23.9 g/kg from MAP and averaged 23.1 g/kg across all treatments (Table 9). Soybean pod tissue Ca concentration ranged from 8.3 g/kg from RP to 9.6 g/kg from the No P/+N control and averaged 8.8 g/kg across all treatments (Table 9). Soybean pod tissue Fe concentration ranged from 36.5 mg/kg from RP to 44.2 mg/kg from TSP and averaged 40.9 mg/kg across all treatments (Table 9).

Five of the six reported soybean pod tissue elemental concentrations (i.e., P, Mg, K, Ca, and Fe) were numerically lowest from RP (Table 9). Three of the six reported soybean pod tissue elemental concentrations (i.e., N, P, and K) were numerically largest from MAP (Table 9). Only Mg in the ECST treatment produced the numerically largest concentration in the soybean pod tissue between the two struvite sources (Table 9). The ECST material had a crystalline form and had the second largest Mg concentration behind CG (Table 4), which allowed for Mg to be more readily available for plant uptake and translocation to the soybean pods than the CG material.

Soybean stem-plus-leaves tissue P concentration was numerically largest from MAP, which did not differ from that in the ECST, CG, TSP, and DAP treatments (Table 10). Stem-plus-leaves tissue P concentration was numerically smallest in the RP and the No P/-N control

treatments, which both were similar to each other and also to that in No P/+N control (Table 10). Stem-plus-leaves tissue P concentration from both struvite treatments (ECST and CG) were similar to one another and were almost numerically identical (Table 10). The stem-plus-leaves tissue P concentration in the ECST, CG, TSP, MAP, and DAP, which did not differ, was 1.4 times larger than that in the RP and the No P/+N and No P/-N control treatments, which did not differ (Table 10). Similar to the explanation for pod tissue P concentration differences, stem-plus-leaves tissue P concentration from RP was similar to both control treatments (No P/+N and No P/-N) and was smaller than that from ECST, CG, TSP, MAP, and DAP was due to the P from RP being relatively unavailable for plant uptake and translocation in the plants due to low solubility of P in RP (Table 10; Kumari and Phogat, 2008).

Similar to P, stem-plus-leaves tissue Mg concentrations also differed ($P < 0.05$) among P-fertilizer treatments (Table 10). Soybean stem-plus-leaves tissue Mg concentration was numerically largest from ECST, which did not differ from that in the CG, TSP, and MAP treatments (Table 10). Stem-plus-leaves tissue Mg concentration was numerically smallest from RP, which was similar to that in the DAP and No P/+N and No P/-N control treatments (Table 10). Similar to P, both soybean stem-plus-leaves tissue Mg concentrations from ECST and CG were similar to each other, while the stem-plus-leaves tissue Mg concentration from CG was also similar to that in the TSP, MAP, DAP, and No P/-N control treatments (Table 10). The stem-plus-leaves tissue Mg concentration of the ECST, CG, TSP, and MAP treatments, which did not differ, was 1.2 times larger than that of RP (Table 10) due to RP having the lowest Mg concentration among all fertilizer-P sources (i.e., ECST, CG, TSP, MAP, and DAP; Table 4).

All remaining reported soybean stem-plus-leaves tissue elemental concentrations (i.e., N, K, Ca, and Fe) did not differ ($P > 0.05$) among fertilizer treatments (Table 10). Soybean stem-

plus-leaves tissue N concentrations ranged from 26.9 g/kg from RP to 31.4 g/kg from CG and averaged 29.1 g/kg across all treatments (Table 10). Soybean stem-plus-leaves tissue K concentrations ranged from 13.0 g/kg from ECST to 15.2 g/kg from CG and averaged 13.9 g/kg across all treatments (Table 10). Soybean stem-plus-leaves tissue Ca concentrations ranged from 14.8 g/kg from RP to 17.6 g/kg from ECST and averaged 16.1 g/kg across all treatments (Table 10). Soybean stem-plus-leaves tissue Fe concentrations ranged from 50.2 mg/kg from RP to 65.0 mg/kg from the No P/+N control and averaged 57.3 mg/kg across all treatments (Table 10).

Four of the six reported soybean stem-plus-leaves tissue elemental concentrations (i.e., N, Mg, K, and Ca) were at least numerically largest from either struvite material (ECST and CG; Table 10). The ECST treatment had the numerical largest soybean stem-plus-leaves tissue Mg and Ca concentrations, while the CG material had the numerical largest soybean stem-plus-leaves N and K concentrations (Table 10). In addition, similar to pod tissue, the RP treatment had the numerical lowest concentration for five of the six reported soybean stem-plus-leaves tissue elemental concentrations (i.e., N, P, Mg, Ca, and Fe; Table 10).

In 11 out of 18 reported soybean tissue elemental concentrations [i.e., soybean belowground tissue N, P, Mg, and K concentrations (Table 8); pod tissue N, P, Mg, and K concentrations (Table 9); and stem-plus-leaves tissue P, Mg, and Ca concentrations (Table 10)], the ECST treatment had a numerically larger concentration than from the CG struvite treatment. The ECST material had a crystalline physical form, which allowed for likely greater reactivity, while CG was in a pelletized physical form when they were applied, which likely slowed the dissolution of the CG material to some degree, resulting in at least numerically lower tissue concentrations from CG than from ECST. The crystalline form possesses a substantially larger surface area to react with the soil and water than the pellet form, which could have allowed for

increased concentrations of plant-available nutrients that could have been taken up and translocated to various regions of the plant.

Soil Property Changes

With the exclusion of final soybean water-soluble soil P and Mehlich-3 soil P, Mg, and Fe concentrations, all measured final soybean soil chemical properties [i.e., pH, electrical conductivity (EC), total N (TN) and water-soluble Mg, K, Ca, and Fe and Mehlich-3 K, and Ca] were unaffected ($P > 0.05$) by fertilizer treatment (Table 11). Soybean water-soluble soil P concentration was numerically largest from TSP and the No P/+N control treatments, which did not differ from each other or differ from that in the ECST, CG, MAP, and DAP treatments (Table 11). Water-soluble soil P concentration was numerically smallest from the No P/-N control, which did not differ from that in the RP treatment (Table 11). Water-soluble soil P concentration was also similar between the two struvite treatments (ECST and CG; Table 11). The soybean water-soluble soil P concentration in the ECST, CG, TSP, MAP, DAP, and the No P/+N control treatments, which did not differ, was 1.4 times larger than that in the RP and the No P/-N control treatments, which did not differ (Table 11). Similar to the explanation for soybean pod and stem-plus-leaves tissue P, the P in RP was relatively unavailable for plant uptake because of low solubility despite the increased surface area for reactions from the powdered form (Table 11; Kumari and Phogat, 2008).

Soybean Mehlich-3 soil P concentration, which was roughly 100 times greater in concentration than the water-soluble soil P concentration, was numerically largest from the CG, TSP, and DAP treatments, which did not differ from each other and did not differ from that in the ECST and MAP treatments (Table 11). Mehlich-3 soil P concentration was numerically

smallest from both control treatments (No P/+N and No P/-N), which both were similar to that in the RP treatment (Table 11). Mehlich-3 soil P concentration in both struvite treatments (ECST and CG) did not differ from each other (Table 11). The Mehlich-3 soil P concentration in the ECST, CG, TSP, MAP, and DAP treatments, which did not differ, was 1.3 times larger than that in the RP and both control (No P/+N and No P/-N) treatments, which did not differ (Table 11), likely due to the low solubility of RP and (Kumari and Phogat, 2008) and the lack of P inputs in both control treatments (Table 5).

The Soybean Mehlich-3 soil Mg concentration, which was roughly 2500 times greater in concentration than the water-soluble soil Mg concentration, after soybeans were grown was 1.4 times larger in the CG treatment than in all other treatments (i.e., ECST, TSP, MAP, DAP, RP, No P/+N, and No P/-N), which did not differ (Table 11) likely due to CG having the largest Mg concentration among the fertilizers (Table 4) and the slow-release nature of the pelletize CG material (Talboys et al., 2015). The CG struvite material was also the only fertilizer that did not fully dissolve and could still be visually seen in the soil at the end of the experiment. Mehlich-3 soil Mg concentration was numerically smallest from that in the No P/+N control treatment, which was similar to that in the ECST, TSP, MAP, DAP, RP, and No P/-N control treatments (Table 11). The Mehlich-3 soil Mg concentration in the CG struvite treatment was 1.3 times greater than that in the ECST struvite treatment (Table 11).

Mehlich-3 soil Fe concentration, which was roughly 760 times greater than the water-soluble soil Fe concentrations, was numerically largest from TSP, which was similar to that in the MAP, DAP, and RP treatments (Table 11). Mehlich-3 soil Fe concentration was numerically smallest from the No P/+N control, which did not differ from that in the ECST, CG, and No P/-N control treatments (Table 11). Mehlich-3 soil Fe concentration in both struvite treatments (ECST

and CG) was similar to one another and both were similar to both control treatments (No P/+N and No P/-N) and also to that in the MAP, DAP, and RP treatments (Table 11).

No other measured soybean soil chemical properties differed among P-fertilizer treatments following soybean growth. Soil pH ranged from 7.2 in the ECST, MAP and DAP to 7.3 in the CG, TSP, and both control (No P/+N and No P/-N) treatments and averaged 7.26 across all treatments (Table 11). Soil EC ranged from 0.13 dS/m from RP to 0.15 dS/m from DAP and averaged 0.14 dS/m across all treatments (Table 11). Total soil N ranged from 0.7 g/kg from ECST, RP, and the No P/-N control to 0.8 g/kg from CG, TSP, MAP, DAP, and the No P/+N control and averaged 0.76 g/kg across all treatments (Table 11). The measured soybean water-soluble soil Mg concentrations for all fertilizer treatments were less than the detection limit (dl) of 0.01 mg/kg (Table 11). Water-soluble soil K concentrations ranged from 0.15 mg/kg from ECST to 0.33 mg/kg from DAP and averaged 0.25 mg/kg across all treatments (Table 11). Water-soluble soil Ca concentrations ranged from 6.5 mg/kg from ECST to 7.5 mg/kg from DAP and averaged 7.16 mg/kg across all treatments (Table 11). Water-soluble soil Fe concentrations ranged from 0.12 mg/kg from CG and the No P/-N control to 0.21 mg/kg from the No P/+N control treatment and averaged 0.15 mg/kg across all treatments (Table 11).

Mehlich-3 soil K concentrations, which were roughly 280 times greater than water-soluble soil K concentrations, ranged from 69 mg/kg from ECST and the No P/+N control treatments to 72 mg/kg from RP and averaged 70 mg/kg across all treatments (Table 11).

Mehlich-3 soil Ca concentrations, which were roughly 145 times greater than water-soluble soil Ca concentrations, ranged from 1097 mg/kg from the No P/+N control to 1123 mg/kg from CG and averaged 1110 mg/kg across all treatments (Table 11).

With the exclusion of soil pH and TN and water-soluble soil Mg concentrations, CG had numerically larger magnitudes for eight of the 10 measured soybean soil chemical properties (i.e., EC, water-soluble P, K, and Ca, and Mehlich-3 P, Mg, K, Ca, and Fe) than the ECST struvite material after soybeans were grown (Table 11). The numerically lower soil concentrations from ECST than CG (Table 11) correlated to how 11 of the 18 reported soybean tissue properties [i.e., soybean belowground tissue N, P, Mg, and K concentrations (Table 8); pod tissue N, P, Mg, and K concentrations (Table 9); and stem-plus-leaves tissue P, Mg, and Ca concentrations (Table 10)] had numerically larger concentrations from the ECST than the CG treatment. Furthermore, the numerically lower soil concentrations from ECST than CG (Table 11) and how the majority of the reported soybean tissue properties had numerically larger concentrations from ECST than CG, also correlated to how five of the seven measured soybean plant properties (i.e., FPH, PDM, BGDM, AGDM, and TDM) were numerically greater for ECST than that in the CG treatment (Table 7).

A possible explanation for why CG was numerically larger than ECST in eight of the 10 measured soil chemical properties was likely related to the physical form of both fertilizers. Even though both struvite sources (ECST and CG) may have slow-release characteristics (Talboys et al., 2015), as evidenced by the low water-soluble P concentrations, ECST was in a crystalline form and CG was in a pellet form. Crystalline forms of fertilizers possess substantially larger surface areas for reactions with the soil, water, and plant roots than pelletized forms, which could have allowed for increased plant availability and readily transferable forms of nutrients for plant uptake. In addition, the struvite fertilizer CG was the only material that did not fully degrade and some pellets were still observed in the soil by the end of the experiment. Results are also in agreement with how the ECST material had numerically larger elemental concentrations in 11

out of 18 reported soybean tissue elemental concentrations [i.e., soybean belowground tissue N, P, Mg, and K concentrations (Table 9); pod tissue N, P, Mg, and K concentrations (Table 8); and stem-plus-leaves tissue P, Mg, and Ca concentrations (Table 10)] than that from the CG material. In addition, the ECST was created from synthetic wastewater without any post-processing of the material, while CG was created from real wastewater and post-processing consisted of pelletization to facilitate transport and spreading of the material in field-scale settings. These preparation differences likely contributed to the slower-release behavior of the CG compared to the ECST material, as evidenced by the mostly numeric differences in tissue compared to final soil concentrations of several nutrients.

Corn Response

Plant Properties

In contrast to the soybean plant responses and with the exception for stem diameter, all measured corn plant properties (i.e., FPH, SLDM, CHDM, BGDM, AGDM, and TDM) differed ($P < 0.05$) among P-fertilizer treatments (Table 12). Final plant height was numerically largest from TSP, which did not differ from that in the CG, MAP, DAP, RP, and No P/+N control treatments (Table 12). Final plant height was numerically smallest from the No P/-N control treatment, which did not differ from that in the ECST treatment (Table 12). Final plant height was also similar between the two struvite treatments (ECST and CG; Table 12). Final plant height from TSP was 1.2 times larger than that in the No P/-N control treatment (Table 12).

Similar to final plant height, corn stem-plus-leaves dry matter was numerically largest from TSP, which did not differ from that in the DAP, ECST, RP, MAP, and No P/+N control treatments (Table 12). Stem-plus-leaves dry matter from the No P/-N control treatment was

numerically smallest among all treatments (i.e., ECST, CG, TSP, MAP, DAP, RP, and the No P/+N control; Table 12). Stem-plus-leaves dry matter from the two struvite treatments (ECST and CG) did not differ from each other and both were similar to that from the RP, MAP, and No P/+N control treatments (Table 12). The mean stem-plus-leaves dry matter from TSP and DAP, which did not differ, was 1.3 times larger than that from the No P/-N control treatment (Table 12).

Corn cob-plus-husk dry matter was numerically largest from CG, which was similar to that in the ECST treatment, and both did not differ from that in the TSP, MAP, RP, DAP, and No P/+N control treatments (Table 12). Cob-plus-husk dry matter from the No P/-N control treatment was numerically smallest among all treatments (i.e., ECST, CG, TSP, MAP, DAP, RP, and No P/+N control; Table 12). The cob-plus-husk dry matter from the ECST, CG, TSP, MAP, DAP, RP, and the No P/+N control treatments, which did not differ, was 3.9 times larger than that from the No P/-N control treatment (Table 12).

Belowground corn dry matter was numerically largest from ECST, which did not differ from that in the RP treatment (Table 12). Belowground corn dry matter was numerically smallest from the No P/-N control, which did not differ from that in the MAP, TSP, DAP, CG, and No P/+N control treatments (Table 12). Belowground corn dry matter from both struvite treatments (ECST and CG) differed from each other and CG did not differ from TSP, MAP, DAP, and both control treatments (No P/+N and No P/-N; Table 12). Additionally, belowground corn dry matter from the ECST treatment was 2.0 times greater than that from CG and ECST was also 1.9 times greater than that from the CG, TSP, DAP, and both control (No P/+N and No P/-N) treatments, which did not differ (Table 12).

Similar to final plant height and stem-plus-leaves dry matter, corn aboveground dry matter was numerically largest from TSP, which did not differ from that in the DAP, RP, MAP, and CG treatments (Table 12). Aboveground corn dry matter from the No P/-N control treatment was numerically smallest among all treatments (i.e., ECST, CG, TSP, MAP, DAP, RP, and the No P/+N control; Table 12). Aboveground corn dry matter from the two struvite treatments (ECST and CG) did not differ from one other and aboveground corn dry matter from ECST also did not differ from that in the MAP, DAP, RP, and the No P/+N control treatments. Aboveground corn dry matter from CG was also similar to that from TSP, MAP, DAP, RP, and the No P/+N control treatment (Table 12). Mean aboveground corn dry matter from CG, TSP, MAP, DAP, and RP, which did not differ, was 1.6 times larger than that from the No P/-N control treatment (Table 12).

Similar to belowground dry matter, total corn dry matter was numerically largest from ECST, which did not differ from that in the RP and TSP treatments (Table 12). Total corn dry matter from the No P/-N control treatment was numerically smallest among all treatments (i.e., ECST, CG, TSP, MAP, DAP, RP, and the No P/+N control; Table 12). Total corn dry matter from CG was also similar to that from TSP, MAP, DAP, and No P/+N control treatments (Table 12). Total corn dry matter from ECST was 1.2 times greater than that from CG (Table 12). The total corn dry matter from ECST, TSP, and RP, which did not differ, was 1.6 times greater than that from the No P/-N control treatment (Table 12). In contrast to the other measured corn properties, corn stem diameter was unaffected ($P > 0.05$) by fertilizer-P treatments, which ranged from 9.6 from MAP to 10.6 mm from the No P/+N control and averaged 10.0 mm across all treatments (Table 12).

There are two possible explanation for why the ECST and RP treatments resulted in the numerically largest belowground and total corn dry matter. First, both the ECST and RP materials were in a powder form when applied, respectively, whereas all other fertilizer-P materials were applied as pellets. Fertilizers in a powderized physical form possess substantially larger surface areas to react with the soil and water than fertilizers in pellet forms. Secondly, it was previously stated that the RP treatment potentially resulted in the numerical lowest for soybean pod (Table 9), stem-plus-leaves tissue P (Table 10), and soybean water-soluble soil P concentrations (Table 11) because of the low solubility of RP (Kumari and Phogat, 2008). However, RP treatment in corn pots could have been solubilized more so than in soybean pots due to corn releasing organic acids within the rhizosphere, thus decreasing soil pH (Oburger et al., 2010). Therefore, the ECST and RP treatments could have resulted in the top two numerically largest belowground and total corn dry matter due to ECST and RP being in crystalline/powder forms and RP being solubilized from root-excreted organic acids, which could have allowed for increased concentrations of plant-available P and N to increase dry matter production in the various plant parts (Oburger et al., 2010).

Tissue Properties

In contrast to soybean tissue response, 12 of the 18 reported corn tissue elemental concentrations [i.e., corn belowground tissue N, P, K, and Ca concentrations (Table 13); cob-plus-husk tissue N, P, and Ca concentrations (Table 14); and stem-plus-leaves tissue N, P, Mg, K and Ca concentrations (Table 15)] differed ($P < 0.05$) among P-fertilizer treatments. Of the six elements measured (i.e., N, P, Mg, K, Ca, and Fe) in the three tissue samples collected (i.e.,

belowground, cob-plus-husk, and stem-plus-leaves), all but Ca and Fe are considered mobile in plants (Goldy, 2013).

With the exclusion of corn belowground tissue Mg and Fe, all reported corn belowground tissue elemental concentrations (i.e., N, P, K, and Ca) differed ($P < 0.05$) among fertilizer-P treatments (Table 13). Except for Ca and Fe, the elements of N, P, Mg, and K are considered mobile in plants (Goldy, 2013). Corn belowground tissue N concentration was numerically largest from CG, which did not differ from that in the TSP, MAP, DAP, RP, and the No P/+N control treatments (Table 13). The lack of a significant treatment effect on belowground tissue N concentration was likely due to uniform total N rate that all treatments, except for the No P/-N control, received (Table 6), which indicates that fertilizer-P source did not affect N uptake when P was added in equivalent amounts across all treatments. Belowground tissue N concentration was numerically smallest from the No P/-N control, which differed from all other treatments (i.e., ECST, CG, TSP, MAP, DAP, RP, and No P/+N control; Table 13). Belowground tissue N concentration from CG was 1.4 times greater than that from the ECST treatment (Table 13). Since the plants grown in both struvite treatments received almost the same amount of urea to even out the total applied N rate (Table 6), the difference in belowground N tissue concentration from CG to ECST could possibly be explained by the difference in the physical structures of the two struvite materials. The crystalline structure of ECST had a considerably larger surface areas to react with the soil and water than the pelletized CG. The difference in surface area potentially allowed for more rapid dissolution of the ECST material and movement away from the active root zone in the pots, whereas the slower dissolution of the CG material kept the N closer to the active root zone longer for greater plant availability. Belowground tissue N concentration from ECST did not differ from that in the TSP, MAP, RP and the No P/+N control treatments (Table

13). The mean belowground tissue N concentration from CG and DAP, which did not differ, was 2.4 times larger than that from the No P/-N control treatment and belowground tissue N concentration from ECST was 1.7 times larger than that from the No P/-N control treatment (Table 13).

Corn belowground tissue P concentration was numerically largest from CG and DAP, which both did not differ from that in the TSP and MAP treatments (Table 13). Belowground tissue P concentration was numerically smallest from the No P/-N control treatment, which was similar to that in the ECST, RP, and the No P/+N control treatments (Table 13). Furthermore, similar to N, corn belowground tissue P concentrations from CG was 1.4 times larger than that from the ECST treatment (Table 13). Similar to N, slower dissolution of the CG pellet material may have kept the P in the active root zone, whereas more rapid dissolution of the crystalline ECST material may have allowed P to move away from the active root zone in the pot and become somewhat less available to active roots. The mean belowground tissue P concentration from CG, TSP, MAP, and DAP, which did not differ, was 1.4 times greater than that from ECST, RP, and both control (No P/+N and No P/-N) treatments, which did not differ (Table 13).

Corn belowground tissue K concentration was numerically largest from the No P/-N control, which differed from all other treatments (i.e., ECST, CG, TSP, MAP, DAP, RP, and No P/+N control; Table 13). Belowground tissue K concentration was numerically smallest from the No P/+N control, which was similar to the ECST and RP treatments (Table 13). It has been reported that the addition of N increases K uptake (Armstrong, 1998; Aulakh and Malhi, 2005). Therefore, it is unclear why the No P/-N control produced the numerical largest and why the No P/+N control produced the numerical lowest corn belowground tissue K concentration. Belowground tissue K concentrations from CG was 1.4 times larger than that from the ECST

treatment (Table 13). Similar to the reasoning for N and P, the difference in the physical structure of the two struvite fertilizers to affect dissolution rates could explain greater K uptake in the roots from CG than from ECST. Additionally, belowground tissue K concentration from CG did not differ from that in the TSP, MAP, and DAP treatments and belowground tissue K concentration from ECST was similar to that in the No P/-N control, TSP, MAP, RP, and DAP treatments (Table 13). Belowground tissue K concentration from the No P/-N control treatment was 2.4 times larger than that from the No P/+N control treatment, and belowground tissue K concentration from CG was 1.6 times larger than that from the No P/+N control treatment (Table 13).

Corn belowground tissue Ca concentration was numerically largest from RP, which did not differ from that in the CG, TSP, MAP, and the No P/+N control treatments (Table 13). Belowground tissue Ca concentration was numerically smallest from the No P/-N control, which differed from all other treatments (i.e., ECST, CG, TSP, MAP, DAP, RP, and No P/+N control; Table 13). Unlike N, P, and K, belowground tissue Ca concentrations from both struvite treatments (ECST and CG) were similar, and both also did not differ from that in the TSP, MAP, DAP, and the No P/-N control treatments (Table 13). The belowground tissue Ca concentration from RP was 1.8 and 3.8 times larger than that from ECST and DAP, which did not differ, and that from the No P/-N control, respectively (Table 13).

In contrast to the other measured corn belowground tissue elemental concentrations, corn belowground tissue Mg and Fe concentrations were unaffected ($P > 0.05$) by fertilizer-P treatments (Table 13). Corn belowground tissue Mg concentration ranged from 0.81 g/kg from the No P/+N control to 1.16 g/kg from CG, averaging 0.93 g/kg across all treatments (Table 13). Corn belowground tissue Fe concentration, which was 138 times greater in concentration than

corn stem-plus-leaves tissue Fe concentration, ranged from 2597 mg/kg from CG to 9067 mg/kg from RP and averaged 4850 mg/kg across all treatments (Table 13). Only corn belowground tissue N, P, and Mg concentrations were largest from the CG treatment (Table 13). Additionally, besides corn belowground tissue Fe concentration, the CG struvite material resulted in at least 1.3 to 1.4 times numerically larger tissue elemental concentrations in all reported corn belowground tissue elemental concentrations (i.e., N, P, Mg, K, and Ca) than ECST (Table 13).

The reported corn cob-plus-husk tissue N, P, and K concentrations differed ($P < 0.05$) among P-fertilizer treatments (Table 14). Cob-plus-husk tissue N concentration was numerically largest from MAP, which did not differ from that in the ECST, CG, TSP, DAP, RP, and the No P/+N control treatments (Table 14). Cob-plus-husk tissue N concentration was numerically smallest from the No P/-N control, which differed from all other treatments (i.e., ECST, CG, TSP, MAP, DAP, RP, and No P/+N control; Table 14). Additionally, cob-plus-husk tissue N concentration from both struvite treatments (ECST and CG) were similar to each other (Table 14). The cob-plus-husk tissue N concentration from ECST, CG, TSP, DAP, RP, and the No P/+N control, which did not differ, was 1.4 times larger than that from the No P/-N control treatment (Table 14).

Corn cob-plus-husk tissue P concentration was numerically largest from ECST, which did not differ from that in the MAP, DAP, and the No P/-N control treatments (Table 14). Cob-plus-husk tissue P concentration was numerically smallest from the No P/+N control, which was similar to the CG, TSP and RP treatments (Table 14). Cob-plus-husk tissue P concentrations from ECST was 1.2 times larger than that from CG (Table 14). The ECST-P was derived from a synthetic rather than an actual wastewater like the CG-P was. It is possible that the CG-P had additional associated compounds or complexes that rendered the P somewhat less mobile once in

the plant than the relatively cleaner ECST-P. Cob-plus-husk tissue P concentration from CG did not differ from that in the TSP, MAP, DAP, RP, and the No P/+N and No P/-N control treatments (Table 14). The cob-plus-husk tissue P concentration from ECST was 1.4 times larger than that from the No P/+N control treatment (Table 14).

Corn cob-plus-husk tissue Ca concentration was numerically largest from MAP, which did not differ from that in the ECST, CG, TSP, DAP, RP, and the No P/+N control treatments (Table 14). Cob-plus-husk tissue Ca concentration was numerically smallest from the No P/-N control, which differed from all other treatments (i.e., ECST, CG, TSP, MAP, DAP, RP, and No P/+N control; Table 14). Cob-plus-husk tissue Ca concentrations from both struvite treatments (CG and ECST) did not differ from each other (Table 14). Additionally, the cob-plus-husk tissue Ca concentration from ECST, CG, TSP, MAP, DAP, RP, and the No P/+N control, which did not differ, was 7.1 times larger than that from the No P/-N control treatment (Table 14).

In contrast to the other measured corn cob-plus-husk tissue elemental concentrations (i.e., N, P, and Ca), cob-plus-husk tissue Mg, K, and Fe concentrations were unaffected ($P > 0.05$) by fertilizer-P treatments (Table 14). Corn cob-plus-husk tissue Mg concentration ranged from 1.0 g/kg from the No P/-N control to 1.2 g/kg from CG and averaged 1.1 g/kg across all treatments (Table 14). Corn cob-plus-husk tissue K concentration ranged from 8.6 g/kg from CG to 9.4 g/kg from ECST and averaged 9.0 g/kg across all treatments (Table 14). Corn cob-plus-husk tissue Fe concentration ranged from 6.6 mg/kg from CG to 47.2 mg/kg from RP and averaged 20.9 mg/kg across all treatments (Table 14). Additionally, in four of the six measured corn cob-plus-husk tissue elemental concentrations (i.e., N, P, K, and Fe), the ECST treatment was at least numerically larger than that from the CG treatment (Table 14).

Corn stem-plus-leaves tissue N concentration was numerically largest from CG, which did not differ from that in the ECST, DAP, and RP treatments (Table 15). Corn stem-plus-leaves tissue N concentration was numerically smallest from the No P/-N control, which differed from all other treatments (i.e., ECST, CG, TSP, MAP, DAP, RP, and No P/+N control; Table 15). Stem-plus-leaves tissue N concentration from ECST was similar to that from the CG, RP, DAP, and MAP treatments (Table 15). The mean stem-plus-leaves tissue N concentration from ECST, CG, DAP, and RP, which did not differ, was 3.1 times larger than that from the No P/-N control treatment (Table 15).

Corn stem-plus-leaves tissue P concentration was numerically largest from ECST, which differed from all other treatments (i.e., CG, TSP, MAP, DAP, RP, No P/+N control, and No P/-N control; Table 15). Stem-plus-leaves tissue P concentration was numerically smallest from the No P/+N control, which differed from all other treatments (i.e., ECST, CG, TSP, MAP, DAP, RP, and No P/-N control; Table 15). Stem-plus-leaves tissue P concentration from both struvite treatments (ECST and CG) differed from one another and the stem-plus-leaves tissue P concentration from CG was similar to that from the TSP, MAP, DAP, and the No P/-N control treatments (Table 15). The mean stem-plus-leaves tissue P concentration from ECST was 1.2 times greater than that from the CG treatment and also 1.8 times greater than that from the No P/+N control treatment (Table 15). The stem-plus-leaves tissue P concentration mean from CG, TSP, MAP, DAP, and the No P/-N control, which did not differ, was 1.5 times larger than that from the No P/+N control treatment (Table 15).

Corn stem-plus-leaves tissue Mg concentration was numerically largest from ECST, which did not differ from that in the other struvite treatment (CG) and RP (Table 15). Stem-plus-leaves tissue Mg concentration was numerically smallest from the No P/-N control, which

differed from all other treatments (i.e., ECST, CG, TSP, MAP, DAP, RP, and No P/+N control; Table 15). Similar to P, corn stem-plus-leaves tissue Mg concentration from CG was similar to that in the ECST and RP treatments (Table 15). The mean stem-plus-leaves tissue Mg concentration from ECST, CG, and RP, which did not differ, was 1.8 times larger than that from the No P/-N control treatment (Table 15).

Corn stem-plus-leaves tissue K concentration was numerically largest from the No P/-N control, which differed from all other treatments (i.e., ECST, CG, TSP, MAP, DAP, RP, and No P/+N control; Table 15). Stem-plus-leaves tissue K concentration was numerically smallest from TSP, which was similar to that from MAP and the No P/+N control treatments (Table 15). Similar to Mg, corn stem-plus-leaves tissue K concentration from ECST was similar to that in CG and RP (Table 15). Corn stem-plus-leaves tissue K concentration from CG was also similar to that from MAP, DAP, RP, and the No P/+N control treatments (Table 15). The corn stem-plus-leaves tissue K concentration mean from the No P/-N control treatment was 1.4 times larger than that from the TSP treatment (Table 15).

Corn stem-plus-leaves tissue Ca concentration was numerically largest from CG, which did not differ from that in the ECST and RP treatments (Table 15). Stem-plus-leaves tissue Ca concentration was numerically smallest from the No P/-N control, which differed from all other treatments (i.e., ECST, CG, TSP, MAP, DAP, RP, and No P/+N control; Table 15). Additionally, stem-plus-leaves tissue Ca concentrations from both struvite treatments (CG and ECST) were similar to each other, and both were also similar to that from RP (Table 15). Corn stem-plus-leaves tissue Ca concentration from ECST, CG, and RP, which did not differ, was 2.8 times larger than that from the No P/-N control treatment (Table 15).

In contrast to the other measured corn stem-plus-leaves tissue elemental concentrations, corn stem-plus-leaves tissue Fe concentration was unaffected ($P > 0.05$) by fertilizer-P treatments (Table 15). Corn stem-plus-leaves tissue Fe concentrations ranged from 25.2 mg/kg from the No P/-N control to 46.7 mg/kg from CG and averaged 35.1 mg/kg across all treatments (Table 15). Additionally, both struvite materials (CG and ECST) were within the top three numerically largest for all of the reported corn stem-plus-leaves tissue elemental concentrations (i.e., N, P, Mg, K, Ca, and Fe; Table 15).

Similar to the current study, Thompson (2013) conducted a 3-year-long, agricultural field study that assessed the P availability of struvite in a corn-soybean rotation on a silt-loam, loam, and silty-clay soil that had very low to low initial soil-test P levels and measured various plant properties (i.e., aboveground plant tissue dry weight, P concentration, P uptake, and grain yield, grain moisture, grain-P concentration, and P accumulation). Thompson (2013) concluded that not only did both struvite sources (ECST and CG) have similar treatment effects on corn plant properties (i.e., aboveground plant tissue dry matter and P concentration), but also at times resulted in plant properties that were numerically greater than that of the common, conventional P-fertilizer, TSP. Corn aboveground tissue dry matter from TSP was numerically greatest and differed from ECST, however, total dry matter from ECST was the numerically greatest and was similar to that from TSP (Table 12). Although aboveground tissue dry matter from CG was numerically greater than from ECST and did not differ from TSP, aboveground tissue dry matter from CG was still numerically less than from TSP (Table 12). For corn stem-plus-leaves tissue P concentration, both struvite sources (ECST and CG) were numerically greater than that from TSP (Table 15). Corn stem-plus-leaves tissue P concentration from ECST was not only the numerically greatest but was also 1.2 times greater than that from the TSP treatment (Table 15).

Corn stem-plus-leaves tissue P concentration from CG was numerically greater but did not differ from that from the TSP treatment (Table 15).

Although yield was not measured in this study due to terminating the study before the corn plants reached full maturity, cob-plus-husk (Table 14) and stem-plus-leaves tissue P concentrations (Table 15) from ECST were greater than that from CG and TSP, which suggests that corn yields would have been at least similar, and perhaps greater, from ECST than yields from CG and/or TSP.

The larger aboveground tissue-P concentration [i.e., cob-plus-husk (Table 14) and stem-plus-leaves (Table 15)] for ECST than from CG or TSP, coupled with the lower belowground tissue P concentration (Table 13) from ECST than from CG or TSP suggests that the P from ECST was more mobile in the plant than the P from CG or TSP. The relatively greater purity of the ECST material than that of the CG or TSP material may have contributed to mobility differences as well as could have led to slightly different forms of P that were taken up by the plant roots from the various fertilizer-P sources. The CG material had a greater organic fraction than that of ECST, which could have played a role as well in differential P mobility in the plant.

Both struvite sources (ECST and CG) had a combined total of 12 of the 18 corn tissue elemental concentrations that were at least numerically largest [i.e., corn belowground tissue N, P, and Mg concentrations (Table 13); cob-plus-husk tissue P, Mg, and K concentrations (Table 14); and stem-plus-leaves tissue N, P, K, Mg, Ca, and Fe concentrations (Table 15)] among the other fertilizer-P sources. Furthermore, of the 12 numerically largest values of the corn tissue elemental concentrations that were from either of the struvite sources (ECST and CG), seven were from CG [i.e., corn belowground tissue N, P, and Mg concentrations (Table 13); cob-plus-husk tissue Mg concentrations (Table 14); and stem-plus-leaves tissue N, Ca, and Fe

concentrations (Table 15)]. Only two of the 18 corn tissue elemental concentrations [i.e., belowground tissue Ca (Table 13) and cob-plus-husk tissue Fe concentrations (Table 14)] did the TSP treatment result in at least a numerically larger value than either of the struvite treatments (ECST and CG). Additionally, in contrast to the reported soybean tissue elemental concentrations, in 10 out of 18 of the reported tissue elemental concentrations [i.e., corn belowground tissue N, Mg, K, and Ca concentrations (Table 13); cob-plus-husk tissue Mg and Ca concentrations (Table 14); and stem-plus-leaves tissue N, Ca, and Fe concentrations (Table 15)], the CG struvite had at least a numerically larger treatment mean than ECST.

Soil Property Changes

Similar to the final soil chemical properties from growing soybeans, only the measured final corn soil concentrations of water-soluble soil P and Mehlich-3 soil P and Mg concentrations differed ($P < 0.05$) among P-fertilizer treatments (Table 16) after growing corn. Corn water-soluble soil P concentration was numerically largest from TSP and MAP treatments, which both did not differ from that in the ECST, CG, and DAP treatments (Table 16). Corn Water-soluble soil P concentration was numerically smallest from RP, which did not differ from that in the No P/+N control (Table 16). Water-soluble soil P concentration was also similar between the two struvite treatments (ECST and CG; Table 16). The water-soluble soil P concentration from ECST, CG, TSP, MAP, and DAP, which did not differ, was 1.7 times larger than that from RP and the No P/+N control, which did not differ (Table 16).

Similar to final soybean soil concentrations, corn Mehlich-3 soil P concentration was less than 100 times greater in concentration than corn water-soluble soil P concentration (Table 16). Corn Mehlich-3 soil P concentration was numerically largest from DAP, which did not differ

from that in the ECST, MAP, and TSP treatments (Table 16). Mehlich-3 soil P concentration was numerically smallest from RP, which was similar to that in the No P/+N control treatment (Table 16). Mehlich-3 soil P concentrations from ECST was 1.1 times larger than that from the CG treatment (Table 16). Mehlich-3 soil P concentration from ECST did not differ from that in the TSP, MAP, and DAP treatments, and the Mehlich-3 soil P concentration from CG differed from all other treatments (i.e., ECST, TSP, MAP, DAP, RP, No P/+N control, and No P/-N control; Table 16). Mehlich-3 soil P concentration from ECST, TSP, MAP, and DAP, which did not differ, was 1.5 times greater than that from RP and the No P/+N control, which did not differ (Table 16). Mehlich-3 soil P concentration from CG was also 1.3 times greater than that from RP and the No P/+N control treatments, which did not differ (Table 16).

Corn Mehlich-3 soil Mg concentration was numerically largest from CG and the No P/-N control treatments, which both differed from all other fertilizer-P treatments (ECST, TSP, MAP, DAP, RP, and No P/+N control; Table 16). A possible explanation for why CG and the No P/-N control, had the largest corn Mehlich-3 soil Mg concentration may have been due to the CG treatment receiving the largest Mg input, which was not controlled across all treatments. Furthermore, the No P/-N control treatment had the largest Mehlich-3 soil Ca concentration of all corn fertilizer-P treatments (i.e., ECST, CG, TSP, MAP, DAP, RP, and No P/+N control; Table 16), where it has been reported that large concentrations of soil Ca can inhibit root uptake of Mg (Guo et al., 2016; Yan and Hou, 2018), thus keeping more Mg in the soil. Mehlich-3 soil Mg concentration was numerically smallest from RP, which did not differ from that in the TSP treatment (Table 16). Mehlich-3 soil Mg concentration from CG was 1.1 times greater than that from the ECST treatment (Table 16). The Mehlich-3 soil Mg concentration from CG and the No P/-N control, which did not differ, was 1.4 times larger than that from the RP treatment (Table

16). In addition, Mehlich-3 soil Mg soil concentration from ECST was 1.2 times greater than that from the RP treatment (Table 16).

All remaining measured final soil chemical properties (i.e., pH, EC, total N and water-soluble Mg, K, Ca, and Fe and Mehlich-3 K, CA, and Fe) after corn was grown did not differ ($P > 0.05$) among fertilizer-P treatments (Table 16). Soil pH ranged from 7.3 from ECST to 7.4 from all other P-fertilizer treatments (i.e., CG, TSP, MAP, DAP, RP, No P/+N control, and No P/-N control) and averaged 7.39 across all treatments (Table 16). Similar to soil EC after soybean growth, soil EC ranged from 0.12 dS/m from RP to 0.14 dS/m from ECST and averaged 0.13 dS/m across all treatments (Table 16). Total N was 0.8 g/kg for all fertilizer-P treatments (Table 16).

Similar to water-soluble soil Mg concentrations after soybeans were grown, water-soluble soil Mg concentrations after corn was grown were less than the detection limit of 0.01 mg/kg (Table 16). Water-soluble soil K concentrations ranged from 0.16 mg/kg from RP to 0.46 mg/kg from the No P/-N control and averaged 0.27 mg/kg across all treatments (Table 16). Water-soluble soil Ca concentrations ranged from 7.5 mg/kg from RP and the No P/-N control to 7.9 mg/kg from TSP and averaged 7.7 mg/kg across all treatments (Table 16). Water-soluble soil Fe concentrations ranged from 0.13 mg/kg from MAP to 0.19 mg/kg from TSP and averaged 0.16 mg/kg across all treatments (Table 16). Mehlich-3 soil K concentrations, which were roughly 230 times larger than water-soluble soil K concentrations, ranged from 61 mg/kg from RP to 70 mg/kg from the No P/-N control and averaged 64 mg/kg across all treatments (Table 16). Mehlich-3 soil Ca concentrations, which were roughly 148 times greater than water-soluble soil Ca concentrations, ranged from 1127 mg/kg from MAP to 1175 mg/kg from the No P/-N control and averaged 1145 mg/kg across all treatments (Table 16). Mehlich-3 soil Fe

concentrations, which were over 700 times greater than water-soluble soil Fe concentrations, ranged from 106 mg/kg from the No P/-N control to 114 mg/kg from ECST and averaged 110 mg/kg across all treatments (Table 16).

In contrast to the reported final soil chemical properties after soybeans were grown, and with the exclusion of final soil pH, total N, and water-soluble soil Mg concentration after corn was grown, eight of the 10 remaining soil chemical properties (i.e., EC, water-soluble soil P, K, and Fe, and Mehlich-3 soil P, K, Ca, and Fe concentrations; Table 16) were at least numerically larger from ECST than the CG struvite material. The at least numerically lower nutrient concentrations in the soil from CG than ECST (Table 16) correlated with 10 of the 18 reported corn tissue properties [i.e., corn belowground tissue N, Mg, K, and Ca concentrations (Table 13); cob-plus-husk tissue Mg and Ca concentrations (Table 14); and stem-plus-leaves tissue N, Ca, and Fe concentrations (Table 15)] that had at least numerically larger elemental concentrations from CG than ECST. However, the numerically lower nutrient concentrations in the soil from CG than ECST (Table 16) did not correlate to how ECST had greater concentrations than CG for four of the seven of the measured corn plant properties [i.e., SD, SLDM, BGDM, and TDM (Table 12)].

Thompson (2013) also concluded that, within a corn-soybean rotation, recovered P as struvite resulted in an equivalent or greater plant available-P concentration than TSP. Water-soluble and Mehlich-3 soil P concentrations, after corn was grown, from ECST were numerically lower than that from TSP, but did not differ significantly (Table 16). Water-soluble soil P concentration from CG was also numerically lower from that in the TSP treatment but did not differ significantly (Table 16). Mehlich-3 soil P concentration from CG was lower than that from TSP (Table 16).

Implications

Results generated from this study regarding struvite's potential benefits provide further reasons why more research should be conducted on not only the implementation of struvite as a fertilizer-P source, but also struvite's potential impact on sustainable food production and the preservation of water resources (Massey et al., 2009; Metson et al., 2016; Talboys et al., 2015). If further research concludes that the hypothesized benefits of the controlled precipitation and application of struvite are accurate, this substance, once-considered a useless problematic by-product (i.e., pipe-clogging struvite; Talboys et al., 2015), could result in multi-beneficial effects that are far reaching (Massey et al., 2009; Talboys et al., 2015).

Recycling P from P-containing wastewaters into struvite has the potential to reduce global food production's dependence on RP, therefore increasing food security (Hallas et al., 2019) and also reducing energy consumption. Furthermore, the intentional precipitation of struvite can also be beneficial for WWTPs and individual agricultural producers (Massey et al., 2009; Talboys et al., 2015). Struvite precipitation in WWTPs can improve cost, time, energy, and treatment efficiencies and effectiveness of WWTPs, while also reducing the P concentration in effluent (Jarvie et al., 2015; Kataki et al., 2016; Rahman et al., 2014; Tansel et al., 2018). Additionally, agricultural producers benefit by the use of struvite as P fertilizer because struvite application has the potential to maintain or even improve crop yields and decrease fertilizer-P application rates due to struvite's slow-release characteristics (Massey et al., 2009; Talboys et al., 2015). Recycling P from P-containing wastewaters into struvite has the potential to reduce eutrophication in surface waters due to cleaner WWTP effluent, decreased fertilizer-P

application rates, and decreased P concentrations in runoff (Massey et al., 2009; Metson et al., 2016; Talboys et al., 2015).

Conclusions

Plant and/or soil response to wastewater-recovered struvite from electrochemical precipitation methods has not been assessed in any setting (i.e., the laboratory, greenhouse, or the field). As a result, more information is required to determine whether ECST is a viable fertilizer-P source for plants and how ECST compares to other common, commercial fertilizer-P sources and chemically precipitated struvite. Consequently, the objective of this greenhouse study was to evaluate the corn and soybean response to P fertilization with two wastewater-recovered struvite sources (ECST and chemically precipitated CG) and compare their response to other commonly used P fertilizers (i.e., TSP, MAP, DAP, and RP) in an agriculturally managed silt-loam soil. It was hypothesized that corn and soybean would have an equal or even greater response (i.e., final plant height; stem-plus-leaves, pod/cob-plus-husk, aboveground, belowground, and total dry matter; and stem-plus-leaves, pod/cob-plus-husk, and belowground tissue P and Mg concentrations) to P fertilization with either struvite source than plants that were treated with other common fertilizer-P sources.

Since the initial Mehlich-3-soil-test-P-concentration was already optimal for a full-season soybean production system (Slaton et al., 2013), there was no expectation of a soybean plant response to P fertilization. Therefore, the results demonstrated that, when crop response to P fertilization was expected, there were differences in degree of plant response depending on fertilizer-P source. Both struvite treatments, ECST and CG, had at least similar plant (i.e., dry matter and elemental tissue concentrations) and soil responses in both corn and soybean pots to

several other commonly used fertilizer-P sources (i.e., TSP, MAP, DAP, and RP). In some cases, the ECST treatments had an even larger positive effect on plant properties than most of the other fertilizer-P treatments. These results provide more useful information on how wastewater-recycled nutrients such as struvite, in crystalline (ECST) or pelletized (CG) form, perform as compared to other common, commercially available P fertilizers. However, more research is still required in order to verify the large potential benefits of not only using struvite as a recycled-P fertilizer, but P recovery from wastewater as an alternative approach to improve wastewater quality and provide sustainable source of fertilizer-P for further agricultural production.

Acknowledgments

I would like to thank the University of Arkansas Honors College for supporting this study with an Honors College research grant. Thanks also to Dr. Trent Roberts for providing the corn seeds and Dr. Leandro Mozzoni for providing the soybean seeds used in this study. Thank you to my mentor and professor, Dr. Kristofor Brye, whose sagacity and wisdom have been not only been essential in the success of this research, but also in my success as an individual. Dr. Brye has been a part of every step of this study and I am grateful for his continuous support, mentorship, and teachings. I would also like to state my appreciation to my committee members, Dr. David Miller and Dr. Lisa Wood, for their help and judgment. Thank you to the Rosen Alternative Pest Control Center facility manager, Jessica Kivett, for her help and assistance during the duration of the greenhouse stage of this research. Lastly, an immense thank you to Ryder Anderson, Tyler Durre, Sam Park, Tatum Simms, Shelby Lebeau, and Ryan Greenfield, whose advice and help were instrumental in the completion of this study.

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Table 1. Summary of initial total nitrogen (N), carbon (C), and soil organic matter (SOM) concentration, pH, and electrical conductivity (EC) of the soil used in the greenhouse pot experiment.

Chemical Property	Mean (\pm standard error)
Total N (%)	0.06 (< 0.01)
Total C (%)	0.62 (0.02)
SOM (%)	1.44 (0.02)
pH	7.3 (0.1)
EC (dS/m)	0.099 (< 0.01)

Table 2. Summary of initial water-soluble and Mehlich-3 soil concentrations of select elements (i.e., P, K, Ca, Mg, S, Na, Fe, Mn, Zn, Cu, and B).

Element	Water-soluble	Mehlich-3
	Mean (\pm standard error)	Mean (\pm standard error)
	mg/kg	
P	4.3 (0.1)	34 (1.0)
K	35 (3.4)	144 (9.2)
Ca	54 (1.0)	1136 (10)
Mg	dl†	33 (1.5)
S	4.7 (0.1)	7.3 (0.1)
Na	2.6 (0.2)	24 (0.4)
Fe	3.2 (0.3)	102 (2.5)
Mn	1.2 (0.3)	370 (16)
Zn	0.3 (0.03)	1.3 (0.02)
Cu	0.05 (< 0.01)	1.3 (0.03)
B	0.04 (< 0.01)	0.5 (0.01)

† Elemental concentration was less than the detection limit (dl) of 0.02 mg/kg.

Table 3. Summary of soil textural and water retention physical properties (i.e., soil textural class, percent sand, silt, and clay, and estimated wilting point, field capacity, saturated water contents, and undisturbed bulk density).

Physical Property	Mean (\pm standard error)
Soil textural class	Silt loam
Sand (%)	27 (1.0)
Silt (%)	66 (1.0)
Clay (%)	7 (0.2)
Estimated wilting point (% v/v)	6.7†
Estimated field capacity (% v/v)	26.1†
Estimated saturated water content (% v/v)	47†
Estimated undisturbed bulk density (g/cm ³)	1.41†

† Soil water contents and undisturbed bulk density were estimated using measured sand, clay, and soil organic matter concentrations (Saxton et al., 1986).

Table 4. Summary of the fertilizer grade and nitrogen (N), phosphorus (P), and magnesium (Mg) concentrations of each fertilizer-nutrient source used in the greenhouse pot experiment (i.e., ECST, CG, TSP, MAP, DAP, RP, and urea).

Fertilizer	Fertilizer Grade	Nutrient Concentration (%)		
		N	P	Mg
ECST [†]	9-52-0	9.3	22.8	5.7
CG	6-27-0	5.7	11.7	8.3
TSP	0-41-0	0.0	18.2	0.6
MAP	11-48-0	11.0	20.9	1.5
DAP	18-42-0	18.1	18.3	0.7
RP	0-17-0	0.0	7.6	0.3
Urea	46-0-0	46.0	0.0	0.0

[†] Electrochemically precipitated struvite (ECST), Crystal Green (CG), triple superphosphate (TSP), monoammonium phosphate (MAP), diammonium phosphate (DAP), and rock phosphate (RP).

Table 5. Summary of target phosphorus (P) fertilizer amounts and total urea-nitrogen (N) inputs per pot and actual mean P fertilizer and urea inputs per pot for each treatment (ECST, CG, TSP, MAP, DAP, RP, No P/+N, and No P/-N) for the soybean.

Treatment	Fertilizer Inputs - Soybean			
	P Fertilizer		Urea	
	Target Weight (mg/pot)	Mean Weight (mg/pot)	Target Weight (mg/pot)	Mean Weight (mg/pot)
ECST [†]	320.8	320.7	92.7	92.9
CG	626.5	626.9	79.4	79.6
TSP	401.4	401.2	157.1	157.0
MAP	349.5	350.0	76.0	77.0
DAP	399.2	399.7	0.0	0.0
RP	961.1	962.2	156.4	156.5
No P/+N	0.0	0.0	157.3	157.0
No P/-N	0.0	0.0	0.0	0.0

[†] Electrochemically precipitated struvite (ECST), Crystal Green (CG), triple superphosphate (TSP), monoammonium phosphate (MAP), diammonium phosphate (DAP), rock phosphate (RP), unamended control that did not have added P, but had added N (No P/+N), and unamended control without added P or N (No P/-N)

Table 6. Summary of target phosphorus (P) fertilizer amounts and total urea-nitrogen (N) inputs per pot and actual mean P fertilizer and urea inputs per pot for each treatment (ECST, CG, TSP, MAP, DAP, RP, No P/+N, and No P/-N) for the corn.

Treatment	Fertilizer Inputs - Corn			
	P Fertilizer		Urea	
	Target Weight (mg/pot)	Mean Weight (mg/pot)	Target Weight (mg/pot)	Mean Weight (mg/pot)
ECST [†]	481.2	481.9	1633.7	1634.2
CG	939.7	939.3	1613.7	1613.3
TSP	602.0	603.6	1730.3	1728.3
MAP	524.3	522.8	1608.6	1609.4
DAP	598.7	597.8	1494.6	1495.7
RP	1441.7	1442.3	1729.2	1727.8
No P/+N	0.0	0.0	1730.6	1731.4
No P/-N	0.0	0.0	0.0	0.0

[†] Electrochemically precipitated struvite (ECST), Crystal Green (CG), triple superphosphate (TSP), monoammonium phosphate (MAP), diammonium phosphate (DAP), rock phosphate (RP), unamended control that did not have added P, but had added N (No P/+N), and unamended control without added P or N (No P/-N).

Table 7. Summary of the effects of fertilizer amendment (ECST, CG, TSP, MAP, DAP, RP, No P/+N, and No P/-N) on select soybean plant properties [i.e., final plant height (FPH), stem diameter (SD), stem-plus-leaves dry matter (SLDM), pod dry matter (PDM), belowground dry matter (BGDM), aboveground dry matter (AGDM), and total dry matter (TDM)].

Treatment	Plant Properties - Soybean						
	FPH (cm)	SD (mm)	SLDM (g)	PDM (g)	BGDM (g)	AGDM (g)	TDM (g)
ECST†	108a††	7.5a	19.8a	7.9a	8.1a	28.0a	36.1a
CG	107a	8.5a	23.4a	4.2a	7.5a	27.6a	35.2a
TSP	122a	7.1a	21.5a	5.4a	7.0a	27.1a	33.9a
MAP	112a	6.9a	19.9a	6.7a	6.9a	26.7a	33.5a
DAP	107a	6.5a	19.8a	7.1a	7.7a	27.0a	34.6a
RP	107a	6.9a	19.1a	7.0a	7.4a	26.1a	33.6a
No P/+N	121a	7.7a	20.9a	6.4a	7.1a	27.3a	34.5a
No P/-N	115a	6.7a	19.9a	6.4a	7.5a	26.3a	33.8a
<i>P</i> -value	0.5*	0.17	0.25	0.45	0.97	0.62	0.85
Overall mean	108	7.2	20.5	6.4	7.8	27.0	34.4

† Electrochemically precipitated struvite (ECST), Crystal Green (CG), triple superphosphate (TSP), monoammonium phosphate (MAP), diammonium phosphate (DAP), rock phosphate (RP), unamended control that did not have added P, but had added N (No P/+N), and unamended control without added P or N (No P/-N).

†† Means in a column with different letters are different at $P < 0.05$.

* Bolded values are significant at $P < 0.05$

Table 8. Summary of the effects of fertilizer amendment (ECST, CG, TSP, MAP, DAP, RP, No P/+N, and No P/-N) on soybean belowground tissue elemental concentrations of select elements (N, P, Mg, K, CA, and Fe).

Treatment	Soybean Belowground Tissue Elemental Concentrations					
	N	P	Mg	K	Ca	Fe
	g/kg					mg/kg
ECST†	25.4a††	1.8bc	2.0a	7.7a	7.8a	2051a
CG	23.4a	1.7cd	1.9a	6.9a	8.2a	3483a
TSP	25.8a	2.0ab	1.9a	8.9a	8.4a	1727a
MAP	25.5a	2.1a	1.9a	9.0a	7.6a	1701a
DAP	23.9a	1.9b	2.1a	7.8a	8.6a	2089a
RP	25.5a	1.7de	2.0a	8.6a	8.0a	1684a
No P/+N	23.4a	1.5ef	1.9a	7.3a	9.9a	2345a
No P/-N	25.0a	1.5f	1.8a	7.2a	7.8a	2749a
<i>P</i> -value	0.09	< 0.01*	0.62	0.11	0.32	0.52
Overall mean	24.7	–	2.1	7.9	8.3	2229

† Electrochemically precipitated struvite (ECST), Crystal Green (CG), triple superphosphate (TSP), monoammonium phosphate (MAP), diammonium phosphate (DAP), rock phosphate (RP), unamended control that did not have added P, but had added N (No P/+N), and unamended control without added P or N (No P/-N).

†† Means in a column with different letters are different at $P < 0.05$.

* Bolded values are significant at $P < 0.05$.

Table 9. Summary of the effects of fertilizer amendment (ECST, CG, TSP, MAP, DAP, RP, No P/+N, and No P/-N) on soybean pod tissue elemental concentrations of select elements (N, P, Mg, K, CA, and Fe).

Treatment	Soybean Pod Tissue Elemental Concentrations					
	N	P	Mg	K	Ca	Fe
	g/kg					mg/kg
ECST†	31.3a††	3.3ab	3.0a	23.8a	8.7a	40.7a
CG	30.1a	3.1b	3.0a	23.8a	9.0a	42.8a
TSP	30.0a	3.2b	3.0a	23.5a	9.1a	44.2a
MAP	31.8a	3.6a	2.9a	23.9a	8.5a	42.5a
DAP	31.5a	3.3ab	2.8a	22.9a	8.6a	42.3a
RP	30.1a	2.6c	2.6a	21.5a	8.3a	36.5a
No P/+N	28.8a	2.7c	2.9a	22.6a	9.6a	38.8a
No P/-N	28.8a	2.7c	2.8a	22.6a	8.7a	39.5a
<i>P</i> -value	0.17	< 0.01*	0.09	0.07	0.09	0.76
Overall mean	30.3	–	2.9	23.1	8.8	40.9

† Electrochemically precipitated struvite (ECST), Crystal Green (CG), triple superphosphate (TSP), monoammonium phosphate (MAP), diammonium phosphate (DAP), rock phosphate (RP), unamended control that did not have added P, but had added N (No P/+N), and unamended control without added P or N (No P/-N).

†† Means in a column with different letters are different at $P < 0.05$.

* Bolded values are significant at $P < 0.05$.

Table 10. Summary of the effects of fertilizer amendment (ECST, CG, TSP, MAP, DAP, RP, No P/+N, and No P/-N) on soybean stem-plus-leaves tissue elemental concentrations of select elements (N, P, Mg, K, CA, and Fe).

Treatment	Soybean Stem-plus-Leaves Tissue Elemental Concentrations					
	N	P	Mg	K	Ca	Fe
	g/kg					mg/kg
ECST†	29.6a††	2.0a	2.9a	13.0a	17.6a	55.7a
CG	31.4a	2.0a	2.8ab	15.2a	16.0a	63.0a
TSP	29.2a	2.1a	2.6abc	14.0a	15.7a	55.0a
MAP	29.7a	2.3a	2.7ab	14.8a	17.0a	56.4a
DAP	30.4a	2.0a	2.5bcd	13.1a	16.5a	57.0a
RP	27.0a	1.5b	2.3d	13.3a	14.8a	50.3a
No P/+N	29.0a	1.6b	2.5bcd	14.0a	16.1a	65.0a
No P/-N	27.0a	1.5b	2.3cd	13.7a	15.4a	56.7a
<i>P</i> -value	0.33	< 0.01 *	0.01	0.42	0.13	0.83
Overall mean	29.1	–	–	13.9	16.1	57.3

† Electrochemically precipitated struvite (ECST), Crystal Green (CG), triple superphosphate (TSP), monoammonium phosphate (MAP), diammonium phosphate (DAP), rock phosphate (RP), unamended control that did not have added P, but had added N (No P/+N), and unamended control without added P or N (No P/-N).

†† Means in a column with different letters are different at $P < 0.05$.

* Bolded values are significant at $P < 0.05$.

Table 11. Summary of the effects of fertilizer amendment (ECST, CG, TSP, MAP, DAP, RP, No P/+N, and No P/-N) on select soil chemical properties [final soil pH, electrical conductivity (EC), and total nitrogen (TN)] and water-soluble and Mehlich-3 elemental concentrations of select elements (P, Mg, K, CA, and Fe) following soybean growth.

Treatment	Soil Chemical Properties - Soybean												
	pH	EC (dS/m)	TN (g/kg)	Water-soluble					Mehlich-3				
				P	Mg	K	Ca	Fe	P	Mg	K	Ca	Fe
				mg/kg									
ECST†	7.2a	0.14a	0.7a	0.37a††	dl*	0.15a	6.5a	0.14a	37a	26b	69a	1105a	112cb
CG	7.3a	0.14a	0.8a	0.40a	dl	0.28a	7.3a	0.12a	40a	33a	70a	1128a	113cb
TSP	7.3a	0.14a	0.8a	0.42a	dl	0.25a	7.4a	0.15a	40a	24b	70a	1119a	117a
MAP	7.2a	0.14a	0.8a	0.40a	dl	0.22a	7.2a	0.13a	39a	24b	70a	1101a	114ab
DAP	7.2a	0.15a	0.8a	0.41a	dl	0.33a	7.5a	0.15a	40a	24b	70a	1107a	114ab
RP	7.3a	0.13a	0.7a	0.29b	dl	0.29a	7.0a	0.14a	31b	24b	72a	1107a	111ab
No P/+N	7.3a	0.15a	0.8a	0.42a	dl	0.23a	7.1a	0.21a	29b	23b	69a	1097a	110c
No P/-N	7.3a	0.14a	0.7a	0.28b	dl	0.25a	7.3a	0.12a	29b	25b	70a	1115a	112cb
<i>P</i> -value	0.12	0.85	0.77	< 0.01 **	1.0	0.69	0.72	0.54	< 0.01	< 0.01	0.97	0.73	0.02
Overall mean	7.26	0.14	0.76	–	–	0.25	7.16	0.12	–	–	70	1110	–

† Electrochemically precipitated struvite (ECST), Crystal Green (CG), triple superphosphate (TSP), monoammonium phosphate (MAP), diammonium phosphate (DAP), rock phosphate (RP), unamended control that did not have added P, but had added N (No P/+N), and unamended control without added P or N (No P/-N).

†† Means in a column with different letters are different at $P < 0.05$.

* Elemental concentration was less than the detection limit (dl) of 0.01 mg/kg.

** Bolded values are significant at $P < 0.05$.

Table 12. Summary of the effects of fertilizer amendment (ECST, CG, TSP, MAP, DAP, RP, No P/+N, and No P/-N) on select corn plant properties [i.e., final plant height (FPH), stem diameter (SD), stem-plus-leaves dry matter (SLDM), cob-plus-husk dry matter (CHDM), belowground dry matter (BGDM), aboveground dry matter (AGDM), and total dry matter (TDM)].

Treatment	Plant Properties - Corn						
	FPH (cm)	SD (mm)	SLDM (g)	CHDM (g)	BGDM (g)	AGDM (g)	TDM (g)
ECST†	191bc††	10.0a	35.8ab	11.1a	28.7a	46.9b	75.7a
CG	193ab	9.8a	33.8b	13.4a	14.1c	47.5ab	61.6c
TSP	211a	9.8a	37.7a	13.2a	15.4c	51.0a	66.4abc
MAP	209ab	9.6a	35.5ab	12.4a	16.6bc	48.0ab	64.6bc
DAP	205ab	9.9a	36.7a	11.6a	15.1c	48.3ab	63.4bc
RP	200ab	10.2a	35.8ab	12.3a	24.9ab	48.1ab	73.1ab
No P/+N	204ab	10.6a	35.4ab	11.9a	15.3c	47.4b	62.6bc
No P/-N	176c	9.9a	27.7c	3.14b	13.9c	29.8c	43.8d
<i>P</i> -value	0.01*	0.4	< 0.01	< 0.01	0.03	< 0.01	< 0.01
Overall mean	–	10.0	–	–	–	–	–

† Electrochemically precipitated struvite (ECST), Crystal Green (CG), triple superphosphate (TSP), monoammonium phosphate (MAP), diammonium phosphate (DAP), rock phosphate (RP), unamended control that did not have added P, but had added N (No P/+N), and unamended control without added P or N (No P/-N).

†† Means in a column with different letters are different at $P < 0.05$.

* Bolded values are significant at $P < 0.05$.

Table 13. Summary of the effects of fertilizer amendment (ECST, CG, TSP, MAP, DAP, RP, No P/+N, and No P/-N) on corn belowground tissue elemental concentrations of select elements (N, P, Mg, K, CA, and Fe).

Treatment	Corn Belowground Tissue Elemental Concentrations					
	N	P	Mg	K	Ca	Fe
	g/kg					mg/kg
ECST†	11.8b††	0.9b	0.87a	5.0cde	8.1b	5240a
CG	16.8a	1.3a	1.16a	7.0b	10.2ab	2597a
TSP	15.7ab	1.2a	0.97a	6.8bcd	11.0ab	3492a
MAP	14.9ab	1.1a	0.98a	6.7bcd	9.2ab	3656a
DAP	16.3a	1.3a	0.94a	6.9bc	8.9b	3043a
RP	13.4ab	0.8b	0.85a	4.9de	15.5a	9067a
No P/+N	15.3ab	0.9b	0.81a	4.5e	10.3ab	6354a
No P/-N	6.8c	0.8b	0.87a	11.0a	4.1c	5348a
<i>P</i> -value	< 0.01*	< 0.01	0.19	< 0.01	< 0.01	0.17
Overall mean	–	–	0.93	–	–	4850

† Electrochemically precipitated struvite (ECST), Crystal Green (CG), triple superphosphate (TSP), monoammonium phosphate (MAP), diammonium phosphate (DAP), rock phosphate (RP), unamended control that did not have added P, but had added N (No P/+N), and unamended control without added P or N (No P/-N).

†† Means in a column with different letters are different at $P < 0.05$.

* Bolded values are significant at $P < 0.05$.

Table 14. Summary of the effects of fertilizer amendment (ECST, CG, TSP, MAP, DAP, RP, No P/+N, and No P/-N) on corn cob-plus-husk elemental concentrations of select elements (N, P, Mg, K, CA, and Fe).

Treatment	Corn Cob-plus-Husk Tissue Elemental Concentrations					
	N	P	Mg	K	Ca	Fe
	g/kg					mg/kg
ECST†	14.7a††	2.7a	1.1a	9.4a	0.15a	14.5a
CG	13.9a	2.3bcd	1.2a	8.6a	0.18a	6.6a
TSP	13.4a	2.3bcd	1.1a	9.1a	0.09a	17.0a
MAP	14.8a	2.5ab	1.1a	8.8a	0.19a	17.3a
DAP	14.1a	2.5ab	1.1a	9.2a	0.14a	19.7a
RP	13.7a	2.1cd	1.1a	8.8a	0.11a	47.2a
No P/+N	13.8a	2.0d	1.1a	9.0a	0.13a	25.5a
No P/-N	10.0b	2.4abc	1.0a	8.8a	0.02b	19.3a
<i>P</i> -value	< 0.01*	0.01	0.27	0.79	< 0.01	0.60
Overall mean	–	–	1.1	9.0	–	20.9

† Electrochemically precipitated struvite (ECST), Crystal Green (CG), triple superphosphate (TSP), monoammonium phosphate (MAP), diammonium phosphate (DAP), rock phosphate (RP), unamended control that did not have added P, but had added N (No P/+N), and unamended control without added P or N (No P/-N).

†† Means in a column with different letters are different at $P < 0.05$.

* Bolded values are significant at $P < 0.05$.

Table 15. Summary of the effects of fertilizer amendment (ECST, CG, TSP, MAP, DAP, RP, No P/+N, and No P/-N) on corn stem-plus-leaves tissue elemental concentrations of select elements (N, P, Mg, K, CA, and Fe).

Treatment	Corn Stem-plus-Leaves Tissue Elemental Concentrations					
	N	P	Mg	K	Ca	Fe
	g/kg					mg/kg
ECST†	14.4ab††	1.6a	2.2a	10.9b	5.3a	39.9a
CG	15.2a	1.4b	2.2a	10.1bc	5.5a	46.5a
TSP	12.2d	1.3bc	1.9b	8.8d	4.4b	34.0a
MAP	13.5bdc	1.3b	1.7b	9.3dc	4.6b	34.4a
DAP	13.9abc	1.4b	1.9b	9.7c	4.7b	32.1a
RP	14.0abc	1.2c	2.1a	10.0bc	5.4a	36.3a
No P/+N	12.7dc	0.9d	1.8b	9.3dc	4.6b	32.5a
No P/-N	4.7e	1.4b	1.2c	12.3a	1.9c	25.2a
<i>P</i> -value	< 0.01*	< 0.01	< 0.01	< 0.01	< 0.01	0.20
Overall mean	–	–	–	–	–	35.1

† Electrochemically precipitated struvite (ECST), Crystal Green (CG), triple superphosphate (TSP), monoammonium phosphate (MAP), diammonium phosphate (DAP), rock phosphate (RP), unamended control that did not have added P, but had added N (No P/+N), and unamended control without added P or N (No P/-N).

†† Means in a column with different letters are different at $P < 0.05$.

* Bolded values are significant at $P < 0.05$.

Table 16. Summary of the effects of fertilizer amendment (ECST, CG, TSP, MAP, DAP, RP, No P/+N, and No P/-N) on select soil chemical properties [final soil pH, electrical conductivity (EC), and total nitrogen (TN)] and water-soluble and Mehlich-3 elemental concentrations of select elements (P, Mg, K, CA, and Fe) following corn growth.

Treatment	Soil Chemical Properties - Corn												
	pH	EC (dS/m)	TN (g/kg)	Water-soluble					Mehlich-3				
				P	Mg	K	Ca	Fe	P	Mg	K	Ca	Fe
				mg/kg									
ECST†	7.3a	0.14a	0.8a	0.44a††	dl*	0.24a	7.7a	0.16a	41a	28b	65a	1144a	114a
CG	7.4a	0.13a	0.8a	0.42a	dl	0.20a	7.7a	0.14a	36b	31a	62a	1130a	111a
TSP	7.4a	0.13a	0.8a	0.48a	dl	0.28a	7.9a	0.19a	42a	23cd	63a	1159a	112a
MAP	7.4a	0.13a	0.8a	0.48a	dl	0.24a	7.8a	0.13a	42a	25c	62a	1127a	110a
DAP	7.4a	0.13a	0.8a	0.45a	dl	0.30a	7.8a	0.17a	43a	24c	65a	1165a	112a
RP	7.4a	0.12a	0.8a	0.26c	dl	0.16a	7.5a	0.14a	28d	22d	61a	1128a	109a
No P/+N	7.4a	0.13a	0.8a	0.28c	dl	0.31a	7.8a	0.16a	29d	24c	65a	1133a	109a
No P/-N	7.4a	0.13a	0.8a	0.33b	dl	0.46a	7.5a	0.16a	32c	31a	70a	1175a	106a
<i>P</i> -value	0.74	0.59	0.06	< 0.01**	1.0	0.84	0.97	0.70	< 0.01	< 0.01	0.07	0.25	0.18
Overall mean	7.39	0.13	0.8	–		0.27	7.7	0.16	–	–	64	1145	110

† Electrochemically precipitated struvite (ECST), Crystal Green (CG), triple superphosphate (TSP), monoammonium phosphate (MAP), diammonium phosphate (DAP), rock phosphate (RP), unamended control that did not have added P, but had added N (No P/+N), and unamended control without added P or N (No P/-N).

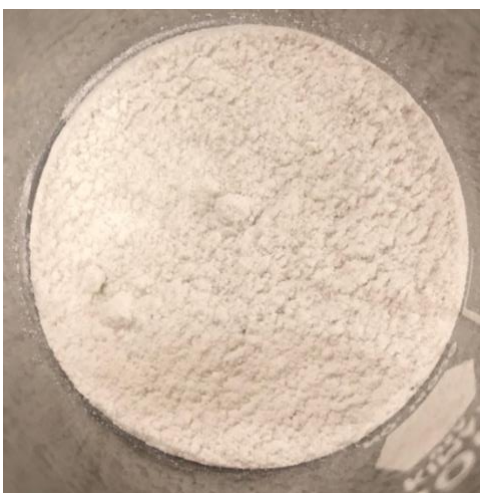
†† Means in a column with different letters are different at $P < 0.05$.

* Elemental concentration was less than the detection limit (dl) of 0.01 mg/kg.

** Bolded values are significant at $P < 0.05$.



Figure 1. Site of soil collection at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR (36°05'47"N 94°09'58"W).



(a)



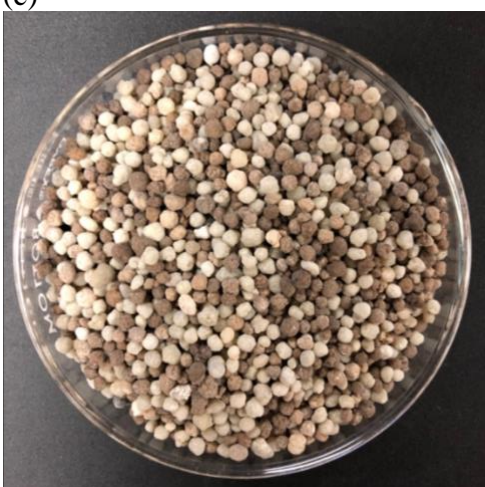
(b)



(c)



(d)



(e)



(f)

Figure 2. Physical appearance of electrochemically precipitated struvite (a), Crystal Green struvite (b), triple superphosphate (c), monoammonium phosphate (d), diammonium phosphate (e), and rock phosphate (f).



Figure 3. First repetition of soybean fertilizer treatments at 2 (top), 6 (middle), and 11 (bottom) weeks after planting. Treatment order (left to right): 1) unamended control without added P or N (No P/-N), 2) unamended control that did not have added P, but had added N (No P/+N), 3) triple superphosphate (TSP), 4) monoammonium phosphate (MAP), 5) diammonium phosphate (DAP), 6) rock phosphate (RP), 7) Crystal Green (CG), and 8) electrochemically precipitated struvite (ECST).



Figure 4. First repetition of corn fertilizer treatments at 2 (top), 6 (middle), and 11 (bottom) weeks after planting. Treatment order (left to right): 1) unamended control without added P or N (No P/-N), 2) unamended control that did not have added P, but had added N (No P/+N), 3) triple superphosphate (TSP), 4) monoammonium phosphate (MAP), 5) diammonium phosphate (DAP), 6) rock phosphate (RP), 7) Crystal Green (CG), and 8) electrochemically precipitated struvite (ECST).