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Wastewater-recycled struvite as a phosphorus source in a wheat–soybean double-crop production system in eastern Arkansas

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Abstract

Fertilizer-phosphorus (P) sources are mainly derived from rock phosphate (RP), which is a finite, actively mined resource. With growing human populations globally, alternative P sources are vitally important to ensure future food security. Precipitation of the mineral struvite ($MgNH_4PO_4{\cdot}6H_2O$) from wastewater could be a potential alternative fertilizer-P option from crop production. The objective of this study was to evaluate the effects of chemically precipitated struvite (CPST), compared with triple superphosphate (TSP) and an unamended control (UC) treatment, and irrigation (irrigated and non-irrigated/dryland) on above- (dry matter, yield, and tissue-N, -P, and -Mg concentrations and uptake) and belowground (root tissue N, P, and Mg concentrations) soybean [*Glycine max* (L.) Merr.] and wheat (*Triticum aestivum* L.) response in a wheat–soybean, double-crop production system on a silt-loam soil (Aquic Fraglossudalfs) in eastern Arkansas. Soybean aboveground and wheat belowground Mg concentrations were 1.1 and 1.2 times, respectively, greater ($p < .05$) from CPST than from TSP, while soybean belowground Mg and wheat stem P concentrations were similar between CPST and TSP. Wheat stem Mg and belowground N concentrations were 1.1 times greater ($p < .05$) from TSP than from CPST. Soybean seed P and Mg concentrations were 1.2 and 1.1 times, respectively, greater ($p < .05$) under irrigated than under dryland management. Results substantiate the use of CPST as a potential alternative fertilizer-P and -Mg source on a silt-loam soil for crop production. Using wastewater-recovered nutrients in a production-scale setting may offset the need for energy-intensive commercial fertilizers to supply essential plant nutrients.

Abbreviations: ANOVA, analysis of variance; CPST, chemically precipitated struvite; DAP, diammonium phosphate; DM, dry matter; ICAPS, inductively coupled, argon-plasma spectrometry; MAP, monoammonium phosphate; M3, Mehlich-3; RP, rock phosphate; TC, total carbon; TN, total nitrogen; TSP, triple superphosphate; UC, unamended control; WWTP, wastewater treatment plant.

1 | INTRODUCTION

Core Ideas

- Plant response to chemically precipitated struvite has not been evaluated in a double-crop production system.
- A 2-yr, wheat–soybean, double-crop production system study was conducted on a silt-loam P-deficient soil.
- Struvite response by soybean and wheat did not differ from triple superphosphate.
- Struvite recovered from wastewater may be a viable fertilizer-P option for wheat and soybean.

Phosphorus (P) is an essential nutrient for plant growth and agricultural production. Following nitrogen (N), P is the most-limiting nutrient in crop production. Currently, rock phosphate (RP) is the most essential, finite resource for the production of synthetic fertilizer-P sources, but RP reserves are unevenly distributed (Cordell et al., 2009). The prospect of P depletion threatens sustainable global food production. However, recovery of the mineral struvite ($MgNH_4PO_4$ $6H_2O$) from various wastewaters that contain P and N is gaining interest as an alternative P source (Bouwman et al., 2005; Metson et al., 2016).

Struvite recovery from wastewater is a new trend because of the reduction in the potential risk of surface water eutrophication of the receiving water bodies and meeting the stringent P removal requirements for wastewater disposal, which have become stricter in recent years (De-Bashan & Bashan, 2004). Struvite is a crystalline material that possesses equal molar concentrations of magnesium (Mg^{2+}), ammonium ($NH_4{}^+$), and phosphate ($PO_4{}^{3-}$) (Johnston & Richards, 2003; Schoumans et al., 2015). Over the years, the spontaneous deposition of struvite has been recorded in pipes of many wastewater treatment plants (WWTPs), which can be problematic (De-Bashan & Bashan, 2004; Doyle et al., 2003). Therefore, the recovery of struvite at the right place in WWTP processes has become an attractive option for WWTPs (Parsons et al., 2001) and can potentially be used as fertilizer-nutrient source in agricultural production.

Various methods have been used to recover struvite from wastewater such as biological, chemical, and electrochemical precipitation (De-Bashan & Bashan, 2004; Huang et al., 2016). In particular, chemical P recovery technology can recover 10–80% of P in wastewaters (De-Bashan & Bashan, 2004). In addition to reducing the P load to surface receiving waters after being processed in a WWTP, struvite has been shown to be a slow-release fertilizer that could provide a longer-term source of P than P fertilizers derived from RP. Struvite's slow-release characteristic could be more beneficial for plant growth than more readily soluble fertilizer-P sources, such as triple superphosphate (TSP), monoammonium phosphate (MAP), and diammonium phosphate (DAP), thus limiting fixation on soil particles, more closely matching the timing of plants' P need later in the growing season and improving P-uptake efficiency by plants (Talboys et al., 2015; Withers et al., 2014).

Similar plant growth or tissue-P uptake characteristics have been reported in many studies comparing struvite to other common fertilizer-P sources (Ghosh et al., 1996; Gonzalez-Ponce et al., 2009; Johnston & Richards, 2003; Li & Zhao, 2003; Kern et al., 2008; Massey et al., 2009; Omidire et al., 2021; Thompson, 2013). In contrast to the reported similarities, other studies have shown reduced plant response with struvite fertilization (Ackerman et al., 2013; Degryse et al., 2017; Everaert et al., 2017; Ganrot et al., 2007; Talboys et al., 2015). Thus, discrepancy exists regarding struvite's potential usefulness as an alternative fertilizer-P source for production-scale agriculture. One major reason is that most struvite evaluations have been conducted as greenhouse potted-plant studies, which could overestimate struvite suitability for crop growth (Hertzberger et al., 2020), thus field evaluations of struvite suitability are critically necessary and most meaningful.

Thompson (2013) conducted a 3-yr field trial in a corn (*Zea mays* L.)–soybean (*Glycine max* L.) rotation to evaluate P availability in corn fiber processing-derived struvite compared with TSP in three soils (silt loam [Typic Endoaquolls], loam [Aquic Pachic Hapludolls], and silty clay [Typic Endoaquolls]) in Iowa using 0, 12, 24, 36, 48, 72, and 120 kg P ha^{-1} of struvite and TSP. Results showed that P uptake was similar, and occasionally greater, with struvite, and there was no difference in soybean or corn grown with struvite compared with TSP at a similar applied-P rate, thus it was concluded that recovered struvite had at least comparable crop-growth performance to TSP (Thompson, 2013). Omidire et al. (2021) recently investigated the effects of MAP, DAP, TSP, RP, and two struvite sources (i.e., a chemically precipitated struvite [CPST] and electrochemically precipitated struvite) on annual rice (*Oryza sativa* L.) growth and productivity on a silt-loam soil (Typic Glossaqualfs) in eastern Arkansas and reported numerous similarities in rice properties between the struvite materials and the other commonly used fertilizer-P sources.

In addition to rice, soybean is an important economic crop that requires P for optimum production. Soybean has a large harvest index when it comes to P. Soybean plants need P during vegetative growth early in the season, but the demand for P is greatest during pod and seed development, where more than 60% of P ends up in the pods and seeds (Usherwood, 1998). For each 67 kg of soybean seed harvested per hectare, approximately 1.1 kg ha^{-1} of P_2O_5 are removed from the soil (Slaton et al., 2013), thus soil P must be replenished periodically. To assure adequate soybean yields, most producers also irrigate when needed during the growing season (Bajaj et al., 2008). In contrast, when water is unavailable or the implementation of irrigation is too costly, producers will practice dryland production, in which the only source of water to the crop is rainfall. However, the lack of available water or water-stressed conditions can limit plant biomass production and productivity or reduce yield from extended dry conditions. Consequently, irrigation is essential to producing adequate yields to recoup economic investments, particularly in a wheat (*Triticum aestivum* L.)–soybean, double-crop system.

Similar to soybean, wheat is another major row crop grown in the United States. Phosphorus increases wheat seedling vigor and is critical for proper tiller formation and development. Phosphorus fertilizer is best applied shortly before or after wheat is planted and preferably no later than Feekes stage 3, before tiller formation (Roberts & Slaton, 2014). Wheat grain removes about 80% of the aboveground plant P, while the remainder of the P is contained in the wheat straw (Roberts & Slaton, 2014).

Double-cropping wheat after soybean is a common production system in the lower Mississippi River delta region, particularly in Arkansas (USDA-NASS, 2020). In eastern Arkansas, the common agronomic management practices that producers adopt for the wheat–soybean system consist of N fertilization usually applied in the early spring for optimal wheat production followed by residue burning and conventional tillage after wheat harvest with furrow irrigation of the subsequent soybean crop as needed throughout the growing season (Brye et al., 2018). Double-crop systems provide pest control benefits in addition to increased revenue from the winter cash crop, which could serve as a second annual cash crop (Kyei-Boahen & Shang, 2006; Thomason et al., 2017). Another important agronomic characteristic of eastern Arkansas is the substantial nutrient, namely P, imbalance that exists throughout much of the region (Slaton et al., 2004), which further substantiates the importance of P fertilization for optimal crop productivity.

Many studies have examined struvite effectiveness as a fertilizer-P source for different plant types and crops in the greenhouse, but few studies have been conducted evaluating wastewater-recovered struvite in row crops under field conditions. Therefore, the objective of this study was to evaluate the effects of fertilizer-P source (CPST and TSP) and irrigation (irrigated and non-irrigated) on above- (dry matter, yield, and tissue-N, -P, and -Mg concentrations and uptake) and belowground (root tissue N, P, and Mg concentrations) soybean and wheat properties over 2 yr in a wheat–soybean, double-crop production system on a silt-loam soil in eastern Arkansas.

It was hypothesized that soybean amended with CPST at the same P rate as TSP would have at least similar aboveground dry matter and P and N uptake, but greater above- and belowground tissue Mg concentrations than P fertilization with the TSP. Yield, aboveground dry matter, aboveground nutrient uptake, aboveground and belowground tissue P, N, and Mg concentrations of soybean were also expected to be greater under irrigated than under dryland production. In addition, it was hypothesized that soybean grown in Year 1 would have similar yield, aboveground dry matter, aboveground nutrient uptake, aboveground and belowground tissue P, N, and Mg concentrations compared with that in Year 2. It was hypothesized that there would be no difference in aboveground and total wheat dry matter or wheat yield when amended with CPST compared with TSP. Aboveground and belowground wheat tissue P and N concentrations, and aboveground wheat P and N uptake were also expected to be similar between TSP and CPST fertilization, while aboveground and belowground wheat tissue Mg concentrations were expected to be greater from CPST than from TSP fertilization because of the greater Mg concentration in the chemical composition of CPST.

2 | MATERIALS AND METHODS

2.1 | Site description and history

This field study was initiated in June 2018 at the Lon Mann Cotton Branch Experiment Station (CBES) near Marianna, AR (34°44'1.40″ N; 90°45'48.23″ W). The study site was located in major land resource area 134, Southern Mississippi Valley Loess (Brye et al., 2013). The soil throughout the 0.56-ha study area was mapped as a Calloway silt loam (fine-silty, mixed, active, thermic Aquic Fraglossudalfs; Soil Survey Staff, 2015). Calloway soils have a surface layer of dark brown to brown silt loam with a subsoil of light brownish-gray silt loam and are derived from loess parent materials (NRCS, 2020). The top 10 cm of the soil profile is silt-loam textured and comprised of 16% sand, 73% silt, and 11% clay (Brye et al., 2006).

This field study was established in two large, interior border areas of a long-term, wheat–soybean, double-crop field study that was initiated in Fall 2001 (Figure 1). For the 6 yr prior to Fall 2001, the cropping system was a conventionally tilled soybean monoculture (Cordell et al., 2007). The long-term study was established to examine the effects of several field treatment combinations, including wheat residue levels (high and low, achieved with differential N fertilization), wheat residue burning and nonburning, and conventional tillage and no-tillage, on long-term trends in soybean growth and productivity and near-surface soil properties.

Starting in November 2001, and for every fall thereafter usually between late October and mid-November, a ‘Coker’ wheat cultivar was drill-seeded throughout the study area with a 19-cm row spacing at a rate of 168 kg seed ha^{-1} (Norman et al., 2016; Brye et al., 2018). Each year, wheat was harvested

FIGURE 1 Aerial view of the plot arrangement in the irrigated and dryland/non-irrigated portion of the study area for a wheat–soybean system in eastern Arkansas. The north direction is toward the top of the image. Individual plots dimensions are 6.1-m long × 3-m wide

in late May to early June. For safety purposes, four tiers of 12 plots each associated with the long-term study were separated with ∼12-m wide alley ways to prevent the fire from escaping control and burning unintended areas when imposing the residue-burning treatment each year. The burn alleys were always conventionally tilled by multiple passes with a tandem disc each year immediately after wheat harvest to serve as the fire break.

Between 2002 and 2013, a soybean cultivar (Maturity Group 4 to 5) with glyphosate resistance was drill-seeded with a row spacing of 19 cm by early to late June each year. Between 2014 and 2016, a Liberty-Link, ‘Armor’ soybean cultivar (Maturity Group 4 to 5) was drill-seeded in the study area to mitigate large weed pressure that had developed throughout the study area. The whole study area was uniformly tractor-sprayed with herbicides usually twice after soybean had been established each year to control weeds. For the first three soybean growing seasons, soybeans in the whole study area were grown with periodic furrow irrigation. From 2005 on, the study area was split into two halves, one half maintaining furrow irrigation, while the other half of the study area was converted to dryland soybean production with no additional irrigation (Brye et al., 2018).

The current field study, initiated in 2018, was consequently established in the large burn alleys of the long-term study, which had been consistently managed since 2001 with conventional tillage, no residue burning, no N, P, or K fertilization, and with the same wheat and soybean cultivars planted, managed, and harvested each year as were used for the long-term study. The current study had 12 plots established in a burn alley that received furrow irrigation since 2002, while 12 plots were established in a burn alley that received furrow irrigation from 2002 through 2004, then no irrigation (i.e., dryland) from 2005 thereafter (Figure 1).

The study area is characterized by a humid temperate climate, with 30-yr (i.e., 1981 to 2010) mean monthly air temperatures ranging from 0.6˚C in January to 32.3˚C in July (NOAA, 2021). The 30-yr mean annual air temperature and precipitation throughout the study area are 16.6˚C and 128.4 cm, respectively (NOAA, 2021).

2.2 | Field treatments and experimental layout

The two experimental factors evaluated in the current field study were irrigation and fertilizer-P source. Out of practical necessity, each irrigation treatment (i.e., furrow-irrigated and dryland) was a strip across different parts of the study area, separated by a levee that was established each year, and was replicated twice with adjacent strips (Figure 1). The

TABLE 1 Summary of the phosphorus (P), total nitrogen (N), and magnesium (Mg) concentrations, pH, and measured fertilizer grade for the chemically precipitated struvite (CPST) and triple superphosphate (TSP) fertilizer-P materials used in this wheat–soybean study in eastern Arkansas

Fertilizer-P source	Nutrient concentration P	N	Mg	pH	Measured fertilizer grade
	%	%	%		
CPST	11.7 (0.2)	5.7 (0.2)	8.3 (0.2)	8.77 (0.13)	6-27-0
TSP	18.2 (0.4)	< 0.1 (< 0.1)	0.6 (< 0.1)	2.42 (0.02)	0-42-0

Note. Means (± standard error) are reported (*n* = 5).

fertilizer-P-source factor, which consisted of three treatments, CPST, TSP, and an unamended control (UC), was replicated twice within each adjacent irrigation strip for a total of four replications of each fertilizer-P source under each irrigation treatments (Figure 1). Both irrigation and fertilizer-P source were evaluated field factors for each of the two soybean crops, but only fertilizer-P source was the field factor evaluated for the single wheat crop, as the irrigation treatment used for soybean was not maintained for the wheat crop. The CPST fertilizer-P source was created by chemical precipitation of raw wastewater from a wastewater treatment plant near Atlanta, GA, which is marketed and sold under the trade name Crystal Green by Ostara Nutrient Recovery Technologies, Inc. (Vancouver, Canada).

Although Omidire et al. (2021) recently evaluated CPST and TSP effects on annual flood-irrigated rice growth in a silt-loam soil in eastern Arkansas and measured similar plant properties, the current study was conducted on a different soil, at a different location, with different crops, and using different water management practices. Consequently, the current study represents unique and novel field research compared with the recent research in rice reported in Omidire et al. (2021).

2.3 | Fertilizer-P source analyses

Five replicates of pelletized CPST and TSP were prepared for chemical characterization. A 1:2 (mass/volume) fertilizer-to-water ratio paste was prepared to measure pH of the two fertilizer materials. High-temperature combustion was used to determine total N (TN) concentration using a VarioMax CN analyzer (Elementar Americas). To determine total-recoverable nutrient concentrations (i.e., P and Mg), a strong-acid digest was conducted (USEPA, 1996) and the resulting extracts were analyzed using inductively coupled, argon-plasma spectrometry (ICAPS). Table 1 summarizes the resulting chemical composition of the two fertilizer materials.

2.4 | Field management

In 2018, new plots were established in the burn alleys of the long-term, double-crop study, where P had not been applied since prior to Fall 2001. A total of 24 field plots (Figure 1), 6.1-m long × 3.1-m wide, were established after conventional tillage, which consisted of three passes with a tandem disc to a 5- to 10-cm depth followed by three passes with a field cultivator to break up soil clods and soften the seed bed. On 9 June 2018, Progeny 5414 LLS, a LibertyLink, Maturity Group 5.4, soybean were planted at a rate of 101 kg seed ha^{-1} (i.e., ~370,650 seed ha^{-1}; Ross et al., 2021) with 19-cm row spacing and approximately 10 cm between plants in a row. Dual II Magnum (1.17 L ha^{-1}; Syngenta, Greensboro, NC; 2-chloro-N-[2-ethyl-6-methylphenyl]-N-[{2S}−1-methoxy propan-2-yl] acetamide) and the Liberty (2.3 L ha^{-1}; Bayer CropScience, Research Triangle Park, NC; azanium, 2-amino-4-[hydroxy{methyl}phosphoryl] butanoate) herbicides were tractor-sprayer-applied twice after soybean planting to control weeds, such as Palmer amaranth (*Amaranthus palmeri* S.) and perennial ryegrass (*Lolium perenne* L.). Four days after soybean planting in 2018 (13 June), fertilizer P in the form of CPST and TSP was manually applied at 44 kg P ha^{-1} and incorporated by light, manual raking. Nitrogen was not balanced among fertilizer-P sources for the spring fertilizer-P application for soybean on account of the low N concentration in CPST (Table 1) and soybean being an N-fixing legume. Bifenthrin (0.37 L ha^{-1}; Control Solutions Inc, Pasadena, TX; [2-methyl-3-phenylphenyl]methyl 3-[{Z}−2-chloro-3,3,3-trifluoroprop-1-enyl]−2,2-dimethylcyclopropane-1-carboxylate) was tractor-sprayer-applied once during the soybean growing season to control insects. Twelve plots were temporarily flood-irrigated on a flat surface as needed approximately three times each year for the soybean crop, while the other 12 plots were non-irrigated (i.e., dryland soybean production). Soybeans were harvested with a plot combine on 30 October, 2018. All soybean seed harvested from a 5.7-m long × 1.9-m wide plot area was collected and bagged.

Following soybean harvest, without any additional field manipulations, winter wheat (USG 3895) was drill-seeded on 20 Nov. 2018 at 168.1 kg seed ha^{-1} with 19-cm row spacing. On 23 Nov. 2018, Finesse (0.035 kg ha^{-1}; DuPont, Wilmington, DE; 1-(2-chlorophenyl)sulfonyl-3-(4-methoxy-6-methyl-1,3,5-triazin-2-yl)-urea) and RoundUp (3.5 L ha^{-1}; Bayer CropScience; 2-(phosphonomethylamino) acetate, propan-2-ylazanium) were sprayed once for weed control. The winter wheat crop was rain-fed only without irrigation. Fertilizer P in the form of CPST and TSP was manually surface-applied 8 d after planting (28 November) at 44 kg P ha^{-1} and incorporated by light, manual raking. Nitrogen was not balanced among fertilizer-P sources for the fall fertilizer-P application for wheat on account of optimal fertilizer-N additions being applied at the recommended spring split-application timing, as described below. On 27 Feb. 2019, Axial (1.17 L ha^{-1}; Syngenta; [8-{2,6-diethyl-4-methylphenyl}−7-oxo-1,2,4,5-tetrahydropyrazolo {1,2-d} {1,4,5} oxadiazepin-9-yl] 2,2-dimethylpropanoate) and on 20 Mar. 2019 Harmony Extra (1.75 L ha^{-1}; DuPont; methyl 3-[{4-methoxy-6-methyl-1,3,5-triazin-2-yl}carbamoylsulfamoyl]thiophene-2-carboxylate;methyl 2-[{(4-methoxy-6-methyl-1,3,5-triazin-2-yl)-methylcarbamoyl}sulfamoyl]benzoate) were sprayed twice for weed control. Nitrogen, in the form of uncoated urea (460 g N kg^{-1}), was hand-applied at 56 kg N ha^{-1} on 17 Mar. 2019, and an additional split application was hand-applied at 56 kg N ha^{-1} approximately 1 mo later on 12 Apr. 2019 to all 24 plots. Because of a severe herbicide-resistant ryegrass infestation, wheat could not be combine-harvested at maturity in 2019. After individual wheat plant samples were collected, as described below, wheat and ryegrass in all plots were mowed with a rotary mower and conventionally tilled with five passes of a tandem disk to a 5-to-10-cm depth followed by five passes with a field cultivator to prepare the plots for subsequent soybean planting.

Following wheat termination, mowing, and tillage, soybean (Pioneer 46A70L) were drill-seeded on 12 June 2019 at a rate of 134.5 kg seed ha^{-1} (~370,650 seed ha^{-1}; Ross et al., 2021) with 19-cm row spacing and approximately 10 cm between plants in a row. Liberty (2.3 L ha^{-1}) was tractor-sprayer-applied twice (14 June and 13 July 2019) and Dual II Magnum (1.17 L ha^{-1}) was sprayed once to control weeds 2 d after soybean planting. Fertilizer P was manually applied to the same plots as in 2018 at 44 kg P ha^{-1} again and incorporated by light, manual raking on 13 June 2019. As in 2018, N was not balanced among fertilizer-P sources for the spring 2019 fertilizer-P application. Intrepid Edge (0.37 L ha^{-1}; Dow AgroSciences,; N'-tert-butyl-N'-[3,5-dimethylbenzoyl]−3-methoxy-2-methylbenzohydrazide) and Acephate 97UP (1.12 kg ha^{-1}; United Phosphorus; O,S-dimethyl acetyl phosphoramidothioate2) were tractor-sprayer-applied on 29 Aug. 2019 to control insects. Soybeans were harvested with a plot combine on 23 Oct. 2019. All soybean seed harvested from a 5.5-m long × 1.9-m wide plot area was collected and bagged.

Soybean seed samples from 2018 and 2019 were air-dried at approximately 25°C for 14 d. A subsample of air-dried seed from individual plots was oven-dried at 70°C for 48 h to determine oven-dried soybean seed yield per plot, which was subsequently adjusted to 130 g kg^{-1} (13%) moisture for yield reporting each year.

2.5 | Soil sampling and analyses

On 20 Apr. 2018, prior to soybean planting, soil samples were collected in all plots from the top 10 cm. Samples were oven-dried for 48 h at 70°C, mechanically crushed, and sieved through a 2-mm mesh screen. A potentiometer was used to measure electrical conductivity (EC) and soil pH with a mass/volume (1:2) soil-to-water ratio paste (Brye et al., 2004; Sikora & Kissel, 2014). Soil organic matter (SOM) concentration was measured by weight-loss-ignition in a muffle furnace for 2 h at 360°C (Zhang & Wang, 2014). High-temperature combustion was used to measure TN and total carbon (TC) concentrations using a VarioMax CN analyzer (Provin, 2014). Extractable soil nutrient (i.e., P, K, Ca, Mg, S, Na, Fe, Mn, Zn, Cu, and B) concentrations were measured by ICAPS (Soltanpour et al., 1996) following Mehlich-3 (M3) extraction in a 1:10 (mass:volume) soil/extractant solution ratio (Zhang et al., 2014).

2.6 | Fertilizer-P application rate determination

The amount of fertilizer-P material applied to both soybean and wheat crops, in the forms of CPST and TSP, was based on (a) the initial M3 soil-test P concentration prior to planting the first of two consecutive, summer soybean crops, (b) the recommended fertilizer-P rate for soybean (44 kg P ha^{-1}; Slaton et al., 2013) and wheat (44 kg P ha^{-1}; Roberts & Slaton, 2014) production on a silt-loam soil in Arkansas, and (c) the measured, total-recoverable P concentrations of the two fertilizer materials (Table 1). Based on soil sampling on 20 April, 2018, after all plots were established, but before soybean planting, mean M3 soil-test P was 24.8 mg kg^{-1} (standard error [SE] = 0.7) in the top 10 cm, which was in the low category for irrigated soybean production on a silt-loam soil in eastern Arkansas (Slaton et al., 2013; Roberts & Slaton, 2014), therefore a plant response was expected from the addition of fertilizer P for both soybean and wheat.

2.7 | Plant sampling and analyses

On 15 Oct. 2018 and 13 Oct. 2019, when soybeans achieved Reproductive Stage 7 (i.e., initial maturity; Popp et al., 2016), three soybean plants were randomly collected per plot for above- and belowground nutrient assessment. Each plant was collected from approximately the top 15 cm using a hand trowel. Plant roots were vigorously shaken and washed in tap water to remove attached soil particles. Aboveground biomass was separated from the roots by cutting each plant at the point on the stem where the soil surface was at. The three above- and belowground replications were combined for one sample per plot. In 2018 and 2019, above- and belowground soybean tissue samples were oven-dried for 7 d at 55˚C. Based on the combined area of the three collected plants, dry matter per unit area was calculated only for the total aboveground plant biomass.

Above- and belowground dry matter subsamples were mechanically pulverized and passed through a 2-mm mesh screen for chemical analyses. A subsample of oven-dried seed from the 2019 soybean harvest was also mechanically pulverized for chemical analyses. Total C and TN concentrations were measured by high-temperature combustion. Total tissue-P and -Mg concentrations were measured using ICAPS following strong-acid digestion (Soltanpour et al., 1996). Aboveground P, N, and Mg uptake (kg ha^{-1}) were calculated from aboveground dry matter and measured total P, N, and Mg concentrations.

On 4 June 2019, at physiological maturity, eight random wheat plants were manually collected per plot for above- and belowground nutrient assessment using the same sampling procedures as described above for soybean. The aboveground wheat samples were further separated into heads and stems. Wheat root, stem, and head samples were oven-dried at approximately 55˚C for 7 d. Wheat heads and stems were weighed to determine head and stem dry matter, respectively. Total aboveground wheat dry matter was obtained by the addition of head and stem dry matter. For chemical analyses, subsamples of dried roots, stems, and heads were ground and sieved to ≤2 mm. Total N and total P and Mg were determined using the same procedures as described above for soybean tissue samples. Head and stem P, N, and Mg uptake were calculated from the head and stem dry matter and the respective total tissue nutrient (P, N, and Mg) concentrations. Since a combine-harvest could not be performed in 2019 for wheat, an estimate of wheat yield on an area basis was calculated from the individual plant samples collected. To estimate wheat seed yield, seeds were assumed to constitute 90% (R. E. Mason, personal communication, 11 Dec. 2019) of the wheat head mass. The wheat head dry mass of the eight wheat samples collected was multiplied by the fraction of the seed-to-wheat-head mass fraction (0.90) and divided by area represented by the eight individual wheat plants that were collected in the field, where the result was scaled to kg ha^{-1} and reported at a grain moisture content of 120 g kg^{-1} (12%) moisture.

2.8 | Statistical analyses

Based on a split-plot experimental design, the effects of fertilizer-P source (CPST, TSP, and UC), irrigation (furrow-irrigated and dryland/non-irrigated), and their interaction on initial soil properties (soil EC and pH; M3 extractable soil P, Mg, K, S, Ca, Na, Zn, Fe, Mn, Cu, and B; and SOM, TN, and TC concentrations) prior to any fertilizer-P addition were evaluated by a two-factor analysis of variance (ANOVA) in SAS (version 9.4, SAS Institute) using the PROC GLIMMIX procedure. The whole-plot factor was irrigation, and the split-plot factor was fertilizer-P source. A gamma distribution was used for soil EC, pH, and M3 extractable soil nutrient concentration data, while a beta distribution was used for SOM, TN, and TC concentration data because these properties were expressed as percentages.

Based on a split-split-plot experimental design, a three-factor ANOVA was conducted using the PROC GLIMMIX procedure in SAS to evaluate the effects of year (2018 and 2019), irrigation, fertilizer-P treatment, and their interactions on soybean aboveground dry matter (DM); above- and belowground tissue-N, -P, and -Mg concentrations; aboveground tissue-N, -P, and -Mg uptake; and yield. The whole-plot factor was year, the split-plot factor was irrigation, and the split-split-plot factor was fertilizer-P treatment. A gamma distribution was used for the aboveground soybean DM, aboveground N, P, and Mg tissue uptake, and yield data, while a beta distribution was used for the above- and belowground tissue-N, -P, and -Mg concentration data, as these concentrations were expressed as percentages.

Based on a split-plot experimental design, a two-factor ANOVA was conducted in SAS using the PROC GLIMMIX procedure to evaluate the effects of irrigation, fertilizer-P treatment, and their interaction on seed-N, -P, and -Mg concentration and uptake from the 2019 soybean seed samples. The whole-plot factor was irrigation, and the split-plot factor was fertilizer-P treatment. A beta distribution was used for seed-N, -P, and -Mg concentrations, while a gamma distribution was used for seed-N, -P, and -Mg uptakes.

Based on a completely random design, a one-factor ANOVA using the PROC GLIMMIX procedure in SAS was conducted to evaluate the effects of fertilizer-P treatment on wheat head, stem, and total DM; seed-head and stem-N, -P, and -Mg concentration and uptake; belowground tissue-N, -P, and -Mg concentrations; and estimated wheat yield. A gamma distribution was used for head, stem, and total DM; seed-head and stem-N, -P, and -Mg uptake; and yield data. A beta distribution was used for seed-head and stem-P, -N, and -Mg concentration and belowground tissue-P, -N, and -Mg concentrations. For all analyses, $p < .05$ was used to judge significance. Least significant difference was used to separate mean, when appropriate, at the 0.05 level.

3 | RESULTS AND DISCUSSION

3.1 | Initial soil properties

Although conducted in border areas of a long-term field study that began in 2001, but was consistently annually managed, it was still necessary to assess the degree of soil property

TABLE 2 Analysis of variance summary of the effects of pre-assigned fertilizer-phosphorus source and irrigation treatments and their interaction on initial soil properties in the top 10 cm from 2018 in a wheat–soybean production system in eastern Arkansas

Soil properties	**Source of variation** **Fertilizer**	 **Irrigation**	 **Irrigation × fertilizer**
	p		
pH	0.61	**<0.01**[a]	0.69
Electrical conductivity	0.35	0.27	0.13
Phosphorus	0.69	0.18	0.73
Potassium	0.70	**<0.01**	0.84
Calcium	0.11	0.22	0.93
Magnesium	0.13	**<0.01**	0.47
Sulfur	0.77	0.09	0.65
Sodium	0.79	**<0.01**	0.25
Iron	0.59	0.49	0.38
Manganese	0.85	0.09	0.51
Zinc	0.55	0.22	0.61
Copper	0.65	0.77	0.89
Boron	0.64	**<0.01**	0.64
Total nitrogen	0.25	0.11	0.05
Total carbon	0.31	0.06	0.12
Soil organic matter	0.71	0.94	0.90

[a] Bolded values were considered significant at $p < .05$.

TABLE 3 Summary of the effects of irrigation on initial soil properties in the top 10 cm from 2018 in a wheat–soybean production system in eastern Arkansas

Soil properties	**Irrigated**	**Dryland**	**Overall mean**
pH	6.9 a[a]	6.5 b	–
Electrical conductivity (dS m^{-1})	0.120 a	0.110 a	0.115
Extractable nutrients (mg kg^{-1})			
Phosphorus	23.5 a	25.9 a	24.7
Potassium	46.9 b	61.5 a	–
Calcium	1,353 a	1,421 a	1387
Magnesium	385 a	311 b	–
Sulfur	9.7 a	8.9 a	9.3
Sodium	17.7 a	12.6 b	–
Iron	210 a	217 a	214
Manganese	198 a	172 a	185
Zinc	1.3 a	1.5 a	1.4
Copper	1.6 a	1.6 a	1.6
Boron	0.1 a	0.0 b	–
Total nitrogen (%)	0.1 a	0.1 a	0.1
Total carbon (%)	1.1 a	0.9 a	1.0
Soil organic matter (%)	2.3 a	2.3 a	2.3

[a] Means in a row with different letters are different at $p < .05$.

uniformity prior to establishing fertilizer-P treatments for the current study. Little to no inherent spatial soil property variation attributable to the pre-assigned fertilizer-P treatments was expected on account of the consistent annual management of the larger studies' border areas. However, the annual irrigation treatment for the summer soybean crop had been imposed annually since 2005, thus some soil property variation due to the differential irrigation methods was expected.

As expected, no measured soil property in the top 10 cm differed among pre-assigned fertilizer-P treatments ($p > .05$; Table 2). Consequently, the near-surface soil properties among all plots that received the fertilizer-P treatments were considered uniform in Year 1 of this study (2018). In contrast, initial soil pH, extractable soil K, Mg, Na, and B differed between irrigation treatments ($p < .01$), while EC, extractable soil P, Ca, S, Mn, Zn, Fe, and Cu, and TC, TN, and SOM concentrations were unaffected by irrigation treatment ($p > .05$; Table 2). Initial soil pH was 1.1 times greater in the irrigated than in the slightly more acidic dryland area (Table 3). Similar to soil pH, initial extractable soil Mg, Na, and B were 1.2, 1.4, and 0.1 times, respectively, greater in the irrigated than in the dryland area (Table 3). However, initial soil K was 1.3 times lower in the irrigated than in the dryland area (Table 3). Alkaline groundwater (Amuri et al., 2008) was used for annual furrow-irrigation of the summer soybean crop, thus causing the soil to become enriched with base-forming cations, such as Mg and Na, in the irrigated area, resulting in the more alkaline pH in the top 10 cm. Lower initial soil K under irrigated conditions was likely due to greater leaching as a result of increased available water from furrow-irrigation compared with only being rain-fed under dryland conditions. Table 3 also summarizes the mean magnitudes for all initial soil properties that were unaffected by the pre-assigned irrigation treatment. With no differences in initial soil properties in the top 10 cm among pre-assigned fertilizer-P treatments, any subsequent measured plant response differences were assumed to have been the result of the actual fertilizer-P treatments rather than any inherent differences that existed prior to fertilizer-P additions.

3.2 | Soybean response

Despite an expected yield response from fertilizer-P treatment because the initial soil-test P concentration was low for optimal soybean production (Slaton et al., 2013), soybean aboveground DM and seed yield were unaffected by fertilizer-P treatment and irrigation ($p > .05$) but differed between years ($p < .01$; Table 4). Soybean aboveground DM and seed yield were unaffected by fertilizer-P treatment likely due to the large P-adsorption ability of the soil. The presence of

TABLE 4 Summary of the effects of irrigation (I), fertilizer-P source (Fert), year (Yr), and their interactions on soybean plant properties for 2018 and 2019 in a wheat–soybean production system in eastern Arkansas

	Source of variation						
Plant properties[a]	**I**	**Fert**	**I × Fert**	**Yr**	**I × Yr**	**Fert × Yr**	**I × Fert × Yr**
	p						
AGDM	0.44	0.83	0.08	**<0.01**	0.16	0.53	0.95
Yield	0.80	0.73	0.72	**<0.01**	0.11	0.43	0.63
AGPC	0.17	0.19	0.20	**<0.01**	0.27	0.91	0.71
AGNC	0.97	0.54	0.60	**0.03**	0.63	0.67	0.69
AGMgC	0.69	**<0.01**[b]	0.39	0.31	0.49	0.55	0.84
BGPC	0.03	0.48	0.86	<0.01	**<0.01**	0.36	0.72
BGNC	0.25	0.28	0.69	<0.01	**0.01**	0.99	0.60
BGMgC	0.20	**0.03**	0.56	<0.01	**<0.01**	0.32	0.55
AGPU	0.12	0.58	0.30	0.85	**0.03**	0.72	0.59
AGNU	0.39	0.84	0.28	0.09	0.07	0.92	0.61
AGMgU	0.76	0.26	0.07	0.08	0.15	0.49	0.99

[a] Aboveground dry matter (AGDM); aboveground tissue P (AGPC), N (AGNC), and Mg. (AGMgC) concentration; belowground tissue P (BGPC), N (BGNC), and Mg (BGMgC). concentration; aboveground P (AGPU), N (AGNU), and Mg (AGMgU) uptake.

[b] Bolded values were considered significant at $p < .05$.

TABLE 5 Summary of the effect of year on aboveground dry matter (AGDM), yield, and aboveground tissue phosphorus (P) and nitrogen (N) concentrations for soybean in 2018 and 2019 in the wheat–soybean study in eastern Arkansas

Year	**AGDM**	**Yield**	**P**	**N**
	kg ha		%	
2018	15,439 a[a]	2,119 b	0.3 b	3.1 b
2019	11,619 b	2,951 a	0.4 a	3.4 a

[a] Means in a column with different letters are different at $p < .05$.

secondary minerals such as Fe, available in large concentrations in the top 10 cm of the slightly acidic soil (Table 3), and/or clay content in the study area likely adsorbed P released from both fast-dissolving TSP and slow-dissolving CPST, thus the P released from both fertilizers becomes similarly unavailable for plant uptake. Results of this study were similar to that reported by Ylagan et al. (2020) in a 79-d greenhouse pot study, where soybean aboveground DM and yield were reported to be unaffected by eight fertilizer-P treatments including CPST, TSP, and no P/–N (control) in a Captina silt loam (Typic Fragiudults) with an optimum soil-test P for soybean. In a similar study, but using corn, Ylagan et al. (2020) also reported that corn aboveground DM from CPST did not differ from TSP and corn aboveground DM from both fertilizers was at least 1.6 times greater than that from control.

Averaged across irrigation and fertilizer-P treatments, soybean aboveground DM was 1.3 times more in 2018 than the following year (2019; Table 5). However, soybean seed yield was 1.4 times greater in 2019 than in 2018 when averaged across irrigation and fertilizer-P treatments (Table 5). Soybean seed yield response in 2019 was likely due to differences in precipitation, particularly earlier in the growing season in June and July 2019, which were more than 2.3 and 5.3 times, respectively, and 2.1 times greater in October 2019 than in similar months in 2018 (Figure 2a). Increased rainfall in 2019 likely reduced soil pH, which promoted nutrient dissolution and availability earlier to set yield limits. However, the decreased rainfall in August and September 2019, which represented 97 and 5%, respectively, of the rainfall in the same months in 2018, likely caused reduction in soybean aboveground DM in 2019 (Figure 2a). In September 2019, soybeans were at the R6 growth stage with full seed and an already set yield limit, thus the dramatic relative reduction in rainfall may have only affected aboveground DM (Figure 2a). In addition, the cumulative effects of the three P fertilization events for soybean and wheat in 2018 and soybean in 2019 cannot be underestimated, as there was likely carry-over P from 2018 that had not become plant available in 2018 or early 2019 that benefited soybean yield in 2019. However, differences in soybean yield may also be attributed to the different cultivars grown each year, as soybean yields are closely related to genetic potential (Scaboo et al., 2010).

Similar to yield and DM, aboveground soybean tissue-P and -N concentrations were unaffected by fertilizer-P treatment and irrigation ($p > .05$) but differed between years ($p < .03$; Table 4). Averaged across irrigation and fertilizer-P treatments, aboveground soybean tissue-P and -N concentrations were 1.3 and 1.1 times, respectively, greater in 2019 than in the previous year (2018; Table 5). Total rainfall during the 5-mo soybean growing season in 2019 was more than 1.3 and

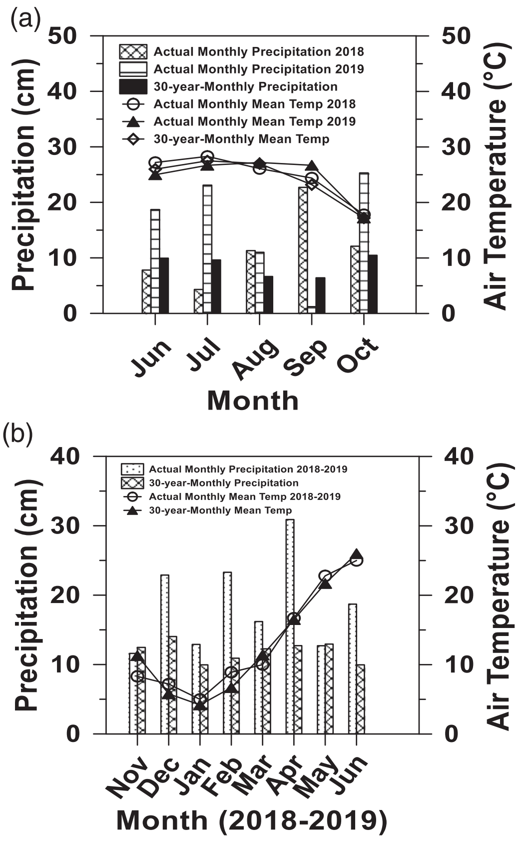

FIGURE 2 Monthly precipitation and air temperature and the 30-yr (1981 to 2010) monthly precipitation and air temperature during the 5-mo soybean growing season in 2018 and 2019 (a) and during the 8-mo wheat growing season in 2019 (b) at the Cotton Branch Experiment Station near Marianna, AR

TABLE 6 Summary of the effects of fertilizer-phosphorus (P) treatment (i.e., chemically precipitated struvite [CPST], triple superphosphate [TSP], and unamended control [UC]) on above- and belowground tissue-Mg concentration for soybean in 2018 and 2019 in a wheat–soybean production system in eastern Arkansas

Fertilizer-P treatment	Aboveground Mg	Belowground Mg
	%	
CPST	0.49 a[a]	0.11 ab
TSP	0.45 b	0.10 b
UC	0.43 b	0.12 a

[a] Means in a column with different letters are different at $p < .05$.

1.8 times greater than that in 2018 and 30-yr mean rainfall, respectively (Figure 2a). In August and September 2018 and 2019, soybeans were at Reproductive Stage 3 (beginning pod) to Reproductive Stage 6 (full seed), the period which most of the P is directed into the seeds because the demand for P is greatest during pod and seed development (Usherwood, 1998). Mean air temperature in August and September 2019 were slightly greater than similar months in 2018 (Figure 2a). Greater aboveground tissue-P and -N concentrations in 2019 than in 2018 was likely due to the warmer air temperature and above-normal precipitation in 2019, which likely created more ideal conditions that enhanced soil organic matter mineralization, dissolution of adsorbed P, and greater P diffusion into the plant than in 2018.

Similar to the current result, Ylagan et al. (2020) showed no difference in corn tissue-P concentration between TSP, CPST, and an unamended control for the stem plus leaves. However, soybean tissue-P concentration for the stem plus leaves from TSP did not differ from CPST, and both were more than 1.3 times greater than that from the unamended control (Ylagan et al., 2020). Corn tissue-N concentration for stem plus leaves was also more than 1.2 and 3.2 times greater from CPST than from TSP and the unamended control, respectively (Ylagan et al., 2020).

In contrast to P and N, aboveground soybean tissue-Mg concentration differed ($p < .01$) among fertilizer-P sources but was unaffected by irrigation and year ($p > .05$; Table 4). Averaged across irrigation treatments and years, aboveground soybean tissue-Mg concentration was 1.1 times greater from CPST than from TSP or the unamended control, which did not differ (Table 6). The greater aboveground tissue Mg concentration from CPST was expected due to the composition and dissolution of the struvite, with an initial Mg concentration more than 13.8 times greater than that in TSP (Table 1). The slower dissolution of CPST likely kept the Mg closer to the actively growing soybean root zone longer for greater plant availability. Magnesium is the central atom in chlorophyll molecules and aids in the activation of many plant enzymes. Addition of CPST to Mg-deficient soils could be a source of Mg to help improve plant growth and health.

In a 4.5-mo field experiment in the Netherlands, Gell et al. (2011) examined the effects of blackwater- and human urine-derived struvite materials compared with TSP and a control on corn response grown in a P-deficient, acidic sandy loam Andisol (pH = 4.5). Similar to soybean aboveground Mg concentration results of the current study, Gell et al. (2011) reported that blackwater-derived struvite increased Mg concentrations by 28% in corn aboveground tissue compared with TSP and the control. However, Ylagan et al. (2020) reported similar soybean tissue-Mg concentration in the stem plus leaves from CPST and TSP, but both were more than 1.1 times greater than that from the control. Ylagan et al. (2020) also reported that corn tissue Mg concentration in the stem plus leaves was at least 1.1 and 1.8 times greater from CPST than from TSP and the control, respectively.

In contrast to aboveground tissue concentrations, belowground soybean tissue-P, -N, and -Mg concentrations differed between irrigation treatments across years ($p < .01$; Table 4). Soybean belowground tissue P concentration was largest under irrigated management in 2018 (0.11% P) among all treatment combinations and 2.2 times greater than under irrigated management in 2019 (0.05% P), which was

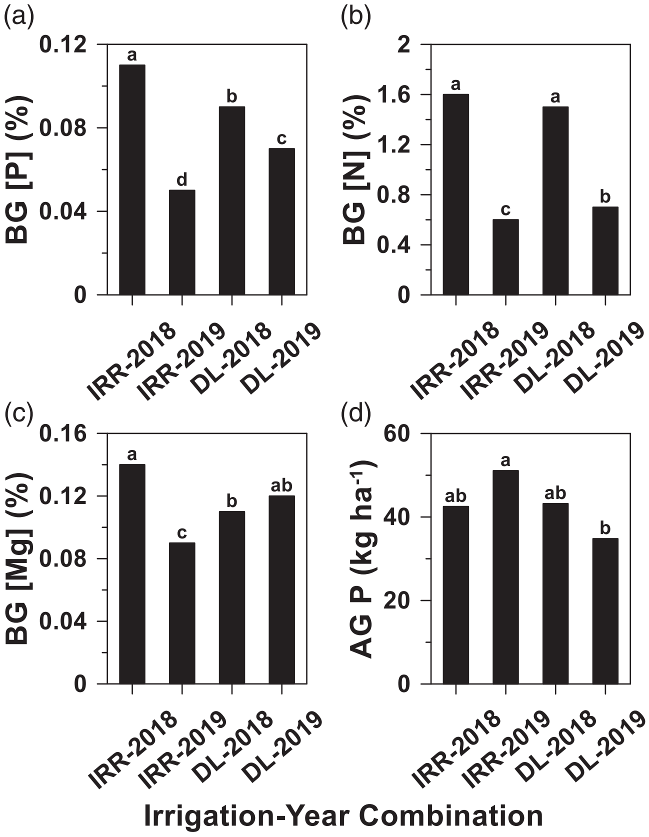

FIGURE 3 Interaction effect between irrigation [irrigated (IRR) and dryland (DL)] and year (2018 and 2019) treatment combination on soybean belowground tissue phosphorus (BG [P]) (a), nitrogen (BG [N]) (b), and magnesium concentrations (BG [Mg]) (c), and aboveground P uptake (AG P) (d) for a wheat–soybean production system in eastern Arkansas

smallest among all treatment combinations (Figure 3a). Soybean belowground tissue P concentration was also more than 1.2 times greater under dryland management in 2018 (0.09% P) than under dryland management in 2019 (0.07% P), both of which were at least 1.4 times greater than under irrigated management in 2019 (Figure 3a).

Soybean belowground tissue N concentration was more than 2.2 times greater from the irrigated and dryland managements in 2018, which did not differ, than from dryland management in 2019 and were more than 2.5 times greater than from irrigated management in 2019 (Figure 3b). Similar to tissue P, soybean belowground tissue N concentration was more than 2.6 times greater under irrigated management (1.6% N) in 2018 than under irrigated management (0.6% N) in 2019 (Figure 3b), while that from dryland management (1.5% N) in 2018 was also more than 2.1 times greater than that from dryland management (0.7% N) in 2019 (Figure 3b).

Similar to tissue N and P, belowground soybean tissue-Mg concentration was more than 1.5 times greater under irrigated management (0.14% Mg) in 2018 than under irrigated management (0.09% Mg) in 2019, which was lowest among all treatment combinations (Figure 3c). However, unlike tissue N and P, belowground soybean tissue-Mg concentration under dryland management in 2019 did not differ from that under dryland managements in 2018 (Figure 3c).

In October 2019, rainfall was numerically largest (25.3 cm) compared with all other months comprising the 5-mo soybean growing season in 2018, 2019, and 30-yr monthly means (Figure 2a). Soybean already reached an initial maturity stage in October 2019, when the demand for P, N, and Mg in the pods and seeds had been maximized, thus resulting in a reduction in the aboveground nutrient demand at this period. A possible explanation for lower belowground P, N, and Mg concentrations under irrigated and dryland managements in 2019 than in 2018 could be that some portion of P, N, and Mg in the soil solution was lost to leaching below the root zone from the above-normal precipitation, particularly in October 2019 (Figure 2a). Though the present study showed that belowground soybean tissue-P concentration was unaffected by fertilizer-P treatment, Ylagan et al. (2020) showed that belowground soybean tissue-P concentration was at least 1.1 and 1.3 times greater from TSP than from CPST and an unamended control, respectively.

Similar to aboveground tissue Mg, soybean belowground tissue Mg concentration differed among fertilizer-P treatments (p = .03; Table 4). Averaged across irrigation treatments and years, belowground tissue-Mg concentration was 1.2 times greater in the unamended control than from TSP, while that from CPST was intermediate and similar to both the unamended control and TSP (Table 6). Though aboveground soybean tissue-Mg concentration was similar between TSP and the unamended control, belowground tissue-Mg concentration was greater from the unamended control than from TSP likely due to the low Mg concentration in TSP (Table 1) and the large initial, background soil-Mg concentration (Table 3) that may not have become completely plant-available during plant nutrient uptake.

In contrast to aboveground tissue-P concentration, aboveground soybean P uptake was unaffected ($p > .05$) by fertilizer-P treatment but differed between irrigation treatments across years (p = .03; Table 4). Aboveground soybean P uptake was numerically largest under irrigated management in 2019 (51 kg ha^{-1}) and numerically lowest under dryland management in 2019 (35 kg ha^{-1}; Figure 3d). Unlike belowground soybean tissue-P, -N, and -Mg, aboveground soybean P uptake under irrigated management in 2018 (42 kg ha^{-1}) was similar to that under irrigated management in 2019 (Figure 3d). Similarly, aboveground soybean P uptake under dryland management in 2018 (43 kg ha^{-1}) was similar to that under dryland management in 2019 (Figure 3d). The alkaline groundwater used in the irrigated area likely increased soil pH at least slightly that enhanced P dissolution from secondary compounds and facilitated P diffusion and uptake into the plant when needed, causing greater

TABLE 7 Summary of the effects of irrigation, fertilizer-phosphorus (P) source, and their interactions on seed-P, -nitrogen (N), and -magnesium (Mg) concentrations and uptake for soybean in 2019 in a wheat–soybean production system in eastern Arkansas

	Source of variation		
Plant properties	**Irrigation**	**Fertilizer**	**Irrigation × fertilizer**
		p	
Seed P concentration	**<0.01**[a]	0.26	0.86
Seed N concentration	0.71	0.28	0.35
Seed Mg concentration	**<0.01**	0.22	0.45
Seed P uptake	0.57	0.52	0.49
Seed N uptake	0.52	0.82	0.90
Seed Mg uptake	0.43	0.68	0.54

[a] Bolded values were considered significant at $p < .05$.

soybean aboveground P uptake than under dryland conditions in 2019. Though results of the current study showed no fertilizer effect on soybean aboveground P uptake, in a 2-yr pot experiment, Cabeza et al. (2011) reported similar shoot-P uptake of corn grown with struvite derived from sewage treatment compared with TSP in an acidic sandy and pH-neutral loamy soil.

In contrast to tissue-Mg and -N concentrations and tissue-P uptake, aboveground soybean N and Mg uptake were similar between fertilizer-P or irrigation treatments ($p > .05$; Table 4) and averaged 436 and 62.6 kg ha^{-1}, respectively, across all treatments. The lack of a significant effect from the fertilizer or irrigation treatment on soybean aboveground N uptake was likely because soybean provided sufficient N through N fixation (Salvagiotti et al., 2008) uniformly across all treatments. Mastrodomenico and Purcell (2012) reported that N fixation could supply up to 90% of the total N required by the soybean plant. Nutrient uptake and portioning are a function of aboveground tissue nutrient concentration and aboveground DM (Bender et al., 2015). A soybean with a large aboveground tissue Mg concentration will not always result in a large aboveground Mg uptake. Though aboveground soybean tissue-Mg concentration differed among fertilizer-P sources, there was no fertilizer effect on soybean aboveground DM to produce an effect on aboveground Mg uptake.

In 2019, neither soybean seed P, N, or Mg concentrations were affected by fertilizer-P treatments ($p > .05$; Table 7). However, in 2019, soybean seed P and Mg concentrations differed between irrigation treatments ($p < .01$), whereas seed N concentration was also unaffected by irrigation ($p > .05$; Table 7) and averaged 6.7% N across all treatments. Averaged across fertilizer-P treatments, soybean seed P and Mg concentrations were 1.2 and 1.1 times, respectively, greater under irrigated (0.7% P and 0.31% Mg) than under dryland management (0.6% P and 0.29% Mg). The alkaline groundwater used for irrigation likely increased soil pH enough to enhanced P dissolution of iron phosphates and facilitated P diffusion into soybean roots, causing greater soybean seed P concentrations. Magnesium was present in groundwater used for irrigation (Amuri et al., 2008; Slaton et al., 2013), which was easily plant-available and taken up by soybean plants resulting in greater soybean seed Mg concentrations under irrigation than dryland conditions.

In 2019, neither soybean seed P, N, or Mg uptake were affected by fertilizer-P or irrigation treatments ($p > .05$; Table 7) and averaged 20, 199, and 9 kg ha^{-1}, respectively, across all treatments. Soybean seed P, N, or Mg uptake were likely unaffected by irrigation treatments due to the above-normal, growing-season rainfall in 2019 negated the effect of irrigation treatment as soybeans under both irrigated and dryland management likely received ample water from rainfall. However, the fertilizer-P sources have different solubilities and compositions, thus it stands to reason that the soybean's ability to fix N could have outperformed the slow-release mechanism of CPST, which had greater N and Mg in its chemical composition than TSP (Table 1). The lack of significant fertilizer treatment effect on soybean seed P uptake was likely that the soil had large P-adsorption ability such that, over a period of time, the P released from both fast-dissolving TSP and slow-dissolving CPST was not available for substantial vegetative uptake. A large proportion of released P from dissolving P fertilizers was likely rendered unavailable for plant uptake due to P binding to clays and/or Fe precipitation to form secondary minerals. Collectively, and similar to conclusions from Omidire et al. (2021) in rice, results showed that CPST had no substantial negative effects on soybean growth and productivity compared with TSP, thus supporting CPST as a potential alternative fertilizer-P option for large-scale soybean production in a wheat–soybean double-crop system.

3.3 | Wheat response

In 2019, wheat head, stem, and total DM; yield, seed-head-P, -N, and -Mg concentrations and uptake; stem N concentration; belowground P concentration; and stem P, N, and Mg uptake did not differ among fertilizer-P treatments ($p > .05$; Table 8). Averaged across fertilizer-P treatments, Table 8 summarizes mean values of wheat head, stem, and total DM; yield, seed-head-P, -N, and -Mg concentrations and uptake; stem-N concentration; belowground-P concentration; and stem-P, -N, and -Mg uptake. Though a wheat yield response was expected because the initial soil-test P concentration was low for optimal wheat production (Roberts & Slaton, 2014), P likely still limited wheat growth and productivity.

The overall mean precipitation and air temperature during the 8-mo wheat growing season across 2018 and 2019 was more than 1.5 and 1.0 times greater than the 30-yr mean

TABLE 8 Summary of the effects of fertilizer-phosphorus (P) source on seed head, stem and total dry matter, grain yield, seed-head P, nitrogen (N), and magnesium (Mg) concentrations, stem-P, -N, and -Mg concentrations, belowground P, N, and Mg concentrations, and seed-head- and stem-P, -N, and -Mg uptake for wheat in 2019 in a wheat–soybean production system in eastern Arkansas

Wheat properties	Fertilizer-P source	CPST	TSP	UC	Overall mean
	p				
Head dry matter (kg ha^{-1})	0.37	339 a	445 a	371 a	385
Stem dry matter (kg ha^{-1})	0.45	461 a	536 a	524 a	507
Total dry matter (kg ha^{-1})	0.41	800 a	979 a	893 a	891
Yield (kg ha^{-1})	0.38	2180 a	1926 a	1659 a	1922
Seed-head P concentration (%)	0.37	0.36 a	0.37 a	0.34 a	0.36
Seed-head N concentration (%)	0.08	1.68 a	1.81 a	1.69 a	1.73
Seed-head Mg concentration (%)	0.58	0.15 a	0.15 a	0.14 a	0.15
Stem P concentration (%)	**0.04**[a]	0.08 a	0.08 a	0.06 b	–
Stem N concentration (%)	0.21	0.55 a	0.61 a	0.53 a	0.56
Stem Mg concentration (%)	**<0.01**	0.10 b	0.11 a	0.10 b	–
Belowground P concentration (%)	0.07	0.13 a	0.12 a	0.10 a	0.12
Belowground N concentration (%)	**0.03**	0.77 b	0.88 a	0.76 b	–
Belowground Mg concentration (%)	**<0.01**	0.12 a	0.10 b	0.09 c	–
Seed-head P uptake (kg ha^{-1})	0.23	1.20 a	1.64 a	1.29 a	1.38
Seed-head N uptake (kg ha^{-1})	0.24	5.62 a	7.73 a	6.21 a	6.52
Seed-head Mg uptake (kg ha^{-1})	0.22	0.49 a	0.67 a	0.53 a	0.56
Stem P uptake (kg ha^{-1})	0.16	0.36 a	0.39 a	0.28 a	0.34
Stem N uptake (kg ha^{-1})	0.32	2.52 a	3.22 a	2.74 a	2.83
Stem Mg uptake (kg ha^{-1})	0.54	0.47 a	0.57 a	0.52 a	0.52

[a] Bolded values were considered significant at $p < .05$.

(Figure 2b). Thus, there are two possible explanations for why fertilizer treatments did not affect aboveground wheat properties. First, greater air temperature and above-normal precipitation during the wheat growing season in 2018/2019 likely created a favorable condition for the mineralization of SOM, allowing increased concentrations of plant-available P and N to increase DM production in various plant parts and yield in all plots. Secondly, the entire field was affected by ryegrass, which likely robbed wheat plants of nutrients released from the fertilizer-P sources and any carryover N from the previous soybean crop. Soybean residue generally contains a low C:N ratio (15 to 41:1; Green & Blackmer, 1995), which allows rapid mineralization of soybean residue-N and enhanced mineralization of SOM. The mineralization of previous soybean residue-N provides one of the rotational benefits for wheat following a soybean crop (Green & Blackmer, 1995).

In contrast to results of the current study, Rech et al. (2019) reported that wheat shoot DM and root-P concentration differed among TSP and three struvite sources, including CPST, in a greenhouse experiment. Wheat shoot DM from TSP was at least 21 and 41% greater than that from each of three struvite materials and the control, respectively (Rech et al., 2019). Rech et al. (2019) also reported that wheat total P uptake from TSP was 23 and 51% greater than that from CPST and the control, respectively, but was similar between the other two struvite sources and TSP. Rech et al. (2019) added that wheat root-P concentration was similar between the three struvite sources and TSP but was greater from all fertilizer-P sources than the control. Similar to results of the current study, Gell et al. (2011) reported that corn DM and P uptake did not differ among TSP, struvite, and an unamended control.

In contrast to the above wheat properties, wheat stem P and Mg and belowground N and Mg concentrations differed among fertilizer-P treatments in 2019 ($p < .04$; Table 8). Wheat stem P concentration was more than 1.4 times greater from the two fertilized treatments, which did not differ, than from the unamended control (Table 8). Though the two fertilizer-P sources were not expected to behave the same due to differential solubilities, it is plausible that the slow-release mechanism of CPST provided just enough P when wheat P demand occurred to match the available P from the faster-dissolving TSP. There could also have been some carry-over P from CPST applied that had not become plant available for the prior soybean crop but may have become available to benefit wheat-P demand. Similar results were confirmed by Ylagan et al. (2020) in soybean tissue-P concentration in the stem plus leaves, which was similar between CPST and TSP, and both fertilizers resulted in tissue-P concentrations in the stem plus leaves that were more than 1.3 times greater than that from the unamended control.

Unlike stem P, in 2019, wheat stem Mg concentration was 1.1 times greater from TSP than from CPST and the unamended control, which did not differ (Table 8). Similar to stem Mg, in 2019, wheat belowground N concentration was more than 1.1 times greater from TSP than from CPST and the unamended control, which did not differ (Table 8). Greater wheat stem Mg concentration from TSP was not expected due to the lower initial Mg concentration in the TSP fertilizer compared with that in CPST (Table 1). However, the greater stem Mg concentration from TSP was likely related to greater TSP dissolution, which would have increased cations in the soil solution, including Mg, coupled with the slow-release CPST characteristics that likely limited plant-available Mg and N concentrations.

In contrast to belowground N, in 2019, wheat belowground Mg concentration was more than 1.2 times greater from CPST than both TSP and the unamended control, while that from TSP was also 1.1 times greater than from the unamended control (Table 8). A greater belowground tissue Mg concentration was expected from CPST due to the Mg-containing composition of the struvite material (Table 1). Because wheat stem Mg concentration was lower than that from TSP, but the root Mg concentration was greater than that from TSP, it is plausible that the form of Mg once in the plant from CPST was less translocatable in the plant than that from TSP, perhaps due to chelation from organic compounds. Results from the current study agreed with reports from Gell et al. (2011) that struvite application could be a source of Mg in crop production. Furthermore, similar to soybean and rice (Omidire et al., 2021), collective results showed that CPST had no substantial negative effects on wheat growth and productivity compared with TSP, thus supporting CPST as a potential fertilizer-P option for large-scale wheat production in a wheat–soybean double-crop system.

3.4 | Environmental and agronomic implications

Struvite recovery from different types of wastewaters, such as industrial wastewater (El Diwani et al., 2007), swine wastewater (Suzuki et al., 2007; Rahman et al., 2011), municipal landfill leachate (Kim et al., 2007), sewage sludge (Munch & Barr, 2001), and agro-industrial wastes (Moerman et al., 2009), has attracted interest from agribusiness, environmentalists, and the wastewater treatment industry. The slow-release nature of struvite helps to reduce fertilizer-P application rate and can maintain or improve crop yield, making struvite beneficial to agricultural producers (Talboys et al., 2015). Furthermore, recycling P from P-containing wastewaters to create struvite in the wastewater treatment industry may improve energy use and reduce labor and other costs associated with struvite removal (Doyle & Parsons, 2002), while also generating a valuable product for use in agricultural production.

As a potentially attractive source of P in agriculture due to its slow-release characteristic (Talboys et al., 2015), wastewater-recovered struvite use in the environment could also help reduce the potential risk of surface water eutrophication and groundwater contamination (Tian et al., 2017) due to cleaner effluent from WWTP and from less surface P lost via runoff (Metson et al., 2016). Application of struvite in crop production is also a potential source of N and Mg, which could provide a potential reduction in cost of N fertilizers applied and help in soils deficient in Mg. However, when struvite is used in large amount over a long-term application, close monitoring of the soil Ca/Mg ratio would be important through soil testing to avoid any unintended, negative effects on plant growth.

Alternatively, wastewater-recovered struvite may enhance the sustainability of global crop production for the growing world population as the remaining quantities of RP are mined for the production of phosphate fertilizers. Therefore, more field tests of struvite application in row-crop agriculture are warranted and may represent a major step toward increasing sustainable food production system across the globe.

4 | CONCLUSIONS

Results from a 2-yr field study in a wheat–soybean, double-crop production system on a silt-loam soil in eastern Arkansas showed that CPST provided similar soybean and wheat yields and aboveground DM to TSP, but neither fertilizer significantly increased yield compared with the unamended control meaning that some other factor, or combination of factors, limited soybean and wheat growth. In addition, CPST provided similar wheat stem P and soybean belowground Mg concentrations, lower belowground N and stem Mg concentrations in wheat, greater belowground Mg concentration in wheat, and greater aboveground Mg concentration in soybean compared with TSP. Despite some lower tissue concentrations from CPST compared with TSP, differences were relatively small and likely had no major negative effects on soybean or wheat growth and productivity. Results also showed soybean seed P and Mg concentrations differed between irrigation treatments, which emphasized the significant role of the presence of sufficient water for soil nutrient distribution and plant nutrient uptake during crop production. Though N and Mg were not completely balanced across fertilizer-P treatments for either the soybean or wheat crops, this study demonstrated that wastewater-recovered struvite may be a viable, alternative fertilizer-P option in upland, row-crop agricultural production. Future research is still necessary to evaluate the application and performance of wastewater-recovered struvite under field conditions with a wider variation of management practices and crops in agricultural soils.

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AUTHOR CONTRIBUTIONS

Niyi S. Omidire: Data curation; Formal analysis; Investigation; Methodology; Writing – original draft. Kristofor R. Brye: Conceptualization; Funding acquisition; Project administration; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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