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Soybean growth and production as affected by struvite as a phosphorus source in eastern Arkansas

Niyi S. Omidire[1] | **Kristofor R. Brye**[1] | **Leah English**[2] | **Laszlo Kekedy-Nagy**[3] | **Lauren Greenlee**[4] | **Jennie Popp**[5] | **Trenton L. Roberts**[1]

[1]Dep. of Crop, Soil, and Environmental Sciences, Univ. of Arkansas, Fayetteville, AR 72701, USA

[2]Dep. of Agricultural Economics & Agribusiness, Univ. of Arkansas, Fayetteville, AR 72701, USA

[3]Dep. of Chemical Engineering, Univ. of Arkansas, Fayetteville, AR 72701, USA

[4]Dep. of Chemical Engineering, Penn State Univ., State College, PA 16801, USA

[5]Dep. of Agricultural Economics & Agribusiness, Univ. of Arkansas, Fayetteville, AR 72701, USA

Correspondence
Kristofor R. Brye, Dep. of Crop, Soil, and Environmental Sciences, Univ. of Arkansas, Fayetteville, AR 72701, USA.
Email: kbrye@uark.edu

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Abstract

Struvite ($MgNH_4PO_4{\cdot}6H_2O$) has been precipitated from liquid waste streams to recover valuable nutrients, such as phosphorus (P) and nitrogen (N), that can be used as an alternative fertilizer-P source. Because prior research has focused on greenhouse studies, it is necessary to expand struvite evaluations to the field-scale to include row-crop responses. The objective of this field study was to evaluate the effects of two struvite materials (electrochemically precipitated struvite, ECST; and chemically precipitated struvite, CPST) relative to other common fertilizer-P sources (diammonium phosphate, DAP; triple superphosphate, TSP; rock phosphate, RP; and monoammonium phosphate, MAP) on soybean [*Glycine max* (L.) Merr.] response and economics in two consecutive growing seasons in a P-deficient, silt-loam soil (Aquic Fraglossudalfs) in eastern Arkansas. Averaged across years, soybean aboveground tissue P uptake was largest ($P < .05$) from ECST (28.4 kg ha^{-1}), which was similar to CPST (26.7 kg ha^{-1}) and TSP (25.9 kg ha^{-1}) and was smallest from RP (21.4 kg ha^{-1}). In 2019, seed yield was largest ($P < .05$) from ECST (4.1 Mg ha^{-1}), which was similar to DAP, CPST, RP, TSP, and MAP, and was smallest from the unamended control (3.6 Mg ha^{-1}). In 2020, seed yield was numerically greatest from CPST (2.8 Mg ha^{-1}) and was numerically smallest from ECST (2.2 Mg ha^{-1}). Results showed that wastewater-recovered struvite materials have the potential to be a viable, alternative fertilizer-P source for soybean production in a P-deficient, silt-loam soil, but further work is needed to confirm struvite's cost effectiveness.

1 | INTRODUCTION

As the world's human population increases, agricultural sustainability will become a top priority to provide enough food for a growing population, which will likely require additional fertilizer-nutrient applications. As most of the current, rock-phosphate (RP)-derived fertilizer-phosphorus (P) sources are nonrenewable and unsustainable; sustainable sources of P will be needed in the future. One possible source is to recover fertilizer nutrients from liquid waste streams.

Struvite, magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4{\cdot}6H_2O$), is a sparingly soluble, white, crystalline material that has been gaining popularity as a way to recover P from various wastewater sources, such as municipal and agricultural wastewaters. Traditionally, struvite has been precipitated by chemical methods (i.e., chemically precipitated

Abbreviations: CPST, chemically precipitated struvite; DAP, diammonium phosphate; DM, dry matter; EC, electrical conductivity; ECST, electrochemically precipitated struvite; ICAPS, inductively coupled, argon-plasma spectrometry; MAP, monoammonium phosphate; RP, rock phosphate; TSP, triple superphosphate; UC, unamended control.

struvite, CPST), which requires the addition of external chemicals, namely magnesium (Mg) salts. However, a newly developed method for struvite precipitation, electrochemical precipitation (i.e., electrochemically precipitated struvite, ECST), from P- and nitrogen (N)-containing solutions eliminates the need for external chemical inputs, where the Mg is supplied as a Mg electrode corrodes (Kékedy-Nagy et al., 2019).

Struvite recovery from wastewaters can help to create a closed-loop, waste-to-resource system where the struvite material generated could be an alternative P-source for crop production, eliminating pipe blockages that cause increased labor and infrastructure costs in wastewater treatment plants. Clean water is a crucial resource for drinking and irrigation and is necessary for supporting many biologically diverse and threatened aquatic species. Recovery of struvite could reduce the potential risk of surface water eutrophication and groundwater contamination, thereby possibly becoming an integral part of humanity, providing food, energy, and ensuring clean water resources for human consumption. This innovative technology could create a source of income for wastewater treatment plants by commercializing the recovered struvite.

Regardless of the original source, fertilizer nutrients are used for all major commodity crops. As one of the most important economic grain crops for a large human population, soybean [*Glycine max* (L.) Merr.] is grown in many areas around the globe. In contrast to cereal grains, such as corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), and rice (*Oryza sativa* L.), soybean is rich in proteins and lipids. In 2019, soybean supplied close to 90% of the total national oilseed produced in the United States (USDA-ERS, 2021).

Soybean can be grown on a wide range of soils. The optimum soil pH to grow soybean ranges from 6 to 6.5. In low-fertility soils, where nutrient supply does not meet crop demand, fertilization becomes essential to maximize yields. Phosphorus and N are primary nutrients required by soybean plants to complete their life cycle. The relationships between soybean seed yield and N uptake have been well documented (Yang et al., 2017); however, relationships between P uptake and seed yield have received less attention. In Arkansas, research has shown that increased soybean yields may occur in soils with low soil-test-P when fertilizer-P is added, but not expected from fertilizer-P additions in soils with medium soil-test-P levels, except to replenish soil P removed by harvested grains (Slaton et al., 2013). In the entire life cycle of soybean plants, P is needed most during pod and seed development (Usherwood, 1998). In soils with low soil-test P, soybean responded to soil-P additions by increasing root absorption surface area and organic acid exudation (Lyu et al., 2016). As a source of protein, soybean is nutrient intensive, with approximately 2.5 kg P ha^{-1} removed from the soil for each 67 kg of soybean seed harvested per ha (Slaton et al., 2013), thus periodic fertilizer-P additions are needed for optimal soybean production to replenish soil P.

Core Ideas

- Field evaluations were conducted with struvite as a P source for soybean grown in a P-deficient soil.
- Soybean responses were similar for electrochemically precipitated struvite and other fertilizer-P sources.
- Electrochemically precipitated struvite may be a viable, alternative fertilizer-P source for soybean production.

Nitrogen fertilizer is not commonly applied in soybean production because biological N fixation provides 50 to 80% of the N uptake in soybean plant (Salvagiotti et al., 2008). If soybean plants are N deficient early in the growing season, application of a small amount of early season fertilizer N may be warranted to stimulate plant growth. However, in Arkansas and other soybean-producing states, soybean response to small fertilizer-N application has not been consistent when proper root nodulation occurs (Slaton et al., 2013). Soils with large levels of nitrate-N typically result in decreased biological N fixation in legumes (Harper, 1987).

Though struvite contains some N, struvite's main benefit is as a fertilizer-P source. The majority of struvite-evaluating studies have been conducted in the greenhouse with various crops, including corn (Kern et al., 2008; Thompson, 2013;), ryegrass (*Lolium perenne*; Antonini et al., 2012), buckwheat (*Fagopyrum esculentum*; Talboys et al., 2015), and spring wheat (Talboys et al., 2015; Everaert et al., 2017). Variable crop responses to struvite have been reported, which may be due to excessive P application rates or small soil masses in space-limited pots in the greenhouse where plant roots do not have access to deeper soil nutrients and have to completely rely on applied nutrients. Consequently, greenhouse potted-plant studies may have over-estimated struvite suitability for field-scale row crops. In a recent study, Omidire and Brye (2022) evaluated the effects of CPST in a wheat–soybean, double-cropped production system in eastern Arkansas. Although ECST has been previously evaluated in other crops in the field, such as rice (Omidire et al., 2022a) and corn (Omidire et al., 2022b), in the greenhouse with corn and soybean (Ylagan et al., 2020), or in plant-less soil incubation studies (Anderson et al., 2021a,b,c), field evaluations of ECST have not been previously conducted for soybean. Therefore, the objective of this field study to was evaluate soybean response to ECST, CPST, and other common fertilizer-P sources (i.e., triple superphosphate, TSP; RP; diammonium phosphate, DAP; and monoammonium phosphate, MAP) in two consecutive growing seasons in a P-deficient, silt-loam soil in eastern Arkansas.

It was hypothesized that the two struvite sources (i.e., ECST and CPST) would have similar aboveground dry matter (DM) and yield, above- and belowground tissue, seed P and N concentrations, and aboveground and seed P and N uptake than other common fertilizer-P sources. It was hypothesized that the two struvite sources would have greater aboveground tissue and seed Mg concentration and uptake and belowground tissue Mg concentrations than other common fertilizer-P sources. In addition, it was expected that soybean grown in Year 2 would have greater aboveground DM; yield; above- and belowground tissue and seed P, N, and Mg concentrations; and aboveground tissue and seed P, N, and Mg uptake compared with the same properties in Year 1.

2 | MATERIALS AND METHODS

2.1 | Site description

Field research investigating the effects of fertilizer-P source on soybean and soil response were conducted at the Lon Mann Cotton Branch Experiment Station (CBES) near Marianna, AR (34˚44’01“N; 90˚45’51”W) during the 2019 and 2020 growing seasons. The 2-yr soybean study was conducted on a Calloway silt loam (fine-silty, mixed, active, thermic Aquic Fraglossudalfs; Soil Survey Staff, 2015), where the previous crops were corn, wheat, and soybean. The study area was also occasionally left fallow for one growing season at a time. The study area had a silt-loam texture in the top 10 cm that was comprised of 10% sand, 75% silt, and 15% clay (Table 1). The 30-year (i.e., 1981 to 2010) mean annual air temperature and precipitation around CBES were 16.6 ˚C and 1284 mm, respectively (NOAA, 2020). Figure 1 depicts the monthly rainfall and air temperatures for the study area for both years during the five-month growing season (i.e., May–Sept.).

2.2 | Fertilizer-P sources and analyses

Two struvite sources were used in this study, ECST and CPST. The CPST was a municipal-wastewater-derived struvite material from near Atlanta, GA sold under the trade name Crystal Green by Ostara Nutrient Recovery Technologies, Inc. The innovative ECST material was derived from synthetic wastewater in a process described by Kékedy-Nagy et al. (2020) in the Department of Chemical Engineering at the University of Arkansas. Two separate batches of ECST were produced for this study. The first batch was created and applied in 2019 and the second batch was created and applied in 2020. Kékedy-Nagy et al. (2020) showed the ECST and CPST materials had similar elemental compositions and morphology from X-ray diffraction, though the municipal-wastewater-derived CPST had a more diverse composition than the synthetic-wastewater-derived ECST material. The ECST material was expected to behave similar to CPST because of similar elemental compositions (Anderson et al., 2020; Ylagan et al., 2020; Omidire, 2021) and general

TABLE 1 Initial soil properties in the 2019 soybean study area in a phosphorus (P)-deficient, silt-loam soil in eastern Arkansas. Means (± standard error) are presented ($n = 4$)

Soil properties	Mean (± standard error)
pH	7.02 (0.04)
Electrical conductivity, dS m^{-1}	0.147 (0.01)
Phosphorus, mg kg^{-1}	28.3 (3.1)
Magnesium, mg kg^{-1}	337 (33.4)
Potassium, mg kg^{-1}	119.9 (9.1)
Sulfur, mg kg^{-1}	7.8 (0.1)
Calcium, mg kg^{-1}	1171 (43.5)
Iron, mg kg^{-1}	195.7 (5.6)
Sodium, mg kg^{-1}	17.1 (1.0)
Zinc, mg kg^{-1}	1.8 (0.2)
Manganese, mg kg^{-1}	159 (2.2)
Copper, mg kg^{-1}	1.7 (0.2)
Total carbon, g kg^{-1}	6.0 (0.1)
Total nitrogen, g kg^{-1}	1.0 (0.01)
Carbon/nitrogen ratio	8.9 (0.4)
Soil organic matter, g kg^{-1}	18.0 (0.6)
Sand, kg kg^{-1}	0.10 (0.04)
Silt, kg kg^{-1}	0.75 (0.03)
Clay, kg kg^{-1}	0.15 (0.02)

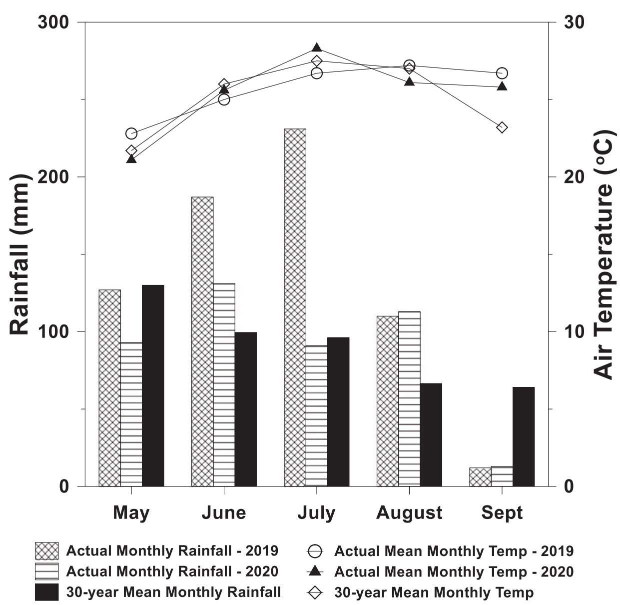

FIGURE 1 Thirty-year (1981 to 2010) mean monthly rainfall and air temperature (Temp) and actual monthly rainfall and air temperature during the 5-mo soybean growing seasons in 2019 and 2020

TABLE 2 Fertilizer pH, total nitrogen (N), phosphorus (P), and magnesium (Mg) concentrations and resulting measured fertilizer grade for the two batches of electrochemically precipitated struvite (ECST) used each year and the chemically precipitated struvite (CPST), diammonium phosphate (DAP), triple superphosphate (TSP), monoammonium phosphate (MAP), and rock phosphate (RP) fertilizer-P materials used in a P-deficient, silt-loam soil in eastern Arkansas. Means (± standard error) are presented (n = 5)

Fertilizer-P source	Nutrient concentration				
	N[a]	P[a]	Mg[a]	pH[a]	Measured fertilizer grade[a,b]
	%				
RP	< 0.1 (<0.1)	7.6 (0.1)	0.3 (<0.1)	6.67 (0.04)	0–17–0
TSP	< 0.1 (<0.1)	18.2 (0.4)	0.6 (<0.1)	2.42 (0.02)	0–42–0
DAP	18.1 (0.1)	18.3 (0.1)	0.7 (<0.1)	7.32 (0.03)	18–42–0
MAP	10.7 (0.1)	20.9 (0.2)	1.5 (<0.1)	4.37 (0.02)	11–48–0
CPST	5.7 (0.2)	11.7 (0.2)	8.3 (0.2)	8.77 (0.13)	6–27–0
ECST 2019	3.3 (0.2)	18.5 (0.1)	13.3 (0.1)	-[c]	3–42–0
ECST 2020	5.1 (0.2)	16.1 (0.3)	12.7 (0.3)	–	5–37–0

[a]Data are reproduced from Omidire et al. (2022a).
[b]Measured fertilizer grade is reported as $N–P_2O_5–K_2O$.
[c]pH in 2019 and 2020 was not determined due to limited quantity of ECST.

characteristics of struvite as a slow-release fertilizer-P source. However, ECST was reported to show faster dissolution than CPST in a corn trial due to the crystalline structure of the applied ECST, which had a larger surface area to react with the soil and water than the pelletized CPST (Omidire et al., 2022b).

Using five replicates of each batch of ECST and the TSP, RP, CPST, DAP, and MAP fertilizers, chemical analyses were conducted. There were differences among the fertilizer-P sources in terms of particle sizes ranging from powder (i.e., RP) to crystals (ECST) to small pellets (i.e., TSP, DAP, MAP, and CPST), with a mean diameter of 3.1 mm (Anderson, 2020). Chemical analyses were conducted following mechanical grinding for uniformity among all fertilizer-P sources. Fertilizer pH was determined potentiometrically using a 1:2 fertilizer mass/water volume ratio, except for ECST, for which pH was not measured due to limited quantity available for field application. Total N concentration was determined via high-temperature combustion on a VarioMax CN analyzer (Elementar Americas; Provin, 2014). Total-recoverable P and Mg were measured after nitric acid extraction by inductively coupled, argon-plasma spectrometry (ICAPS; USEPA, 1996). All fertilizer analyses were conducted by the University of Arkansas, Division of Agriculture's Agricultural Diagnostic Laboratory in Fayetteville. Chemical analyses for all fertilizer-P materials are summarized in Table 2.

2.3 | Experimental layout and plot management

Because the exact same plots were used each year to evaluate potential carry-over effects, this field study had a split-plot experimental design, where the whole-plot factor was year (2019 and 2020) and the split-plot factor was fertilizer-P source (ECST, TSP, CPST, RP, MAP, DAP, and unnamed control, UC). There were four blocks, and the seven fertilizer-P-source treatments were randomly assigned to each block and were the same in both years. Though soybean is commonly grown in rotation with other crops in Arkansas (Slaton et al., 2013), growing soybean on the same plots in consecutive years, which was also recently done with a study evaluating struvite effects on corn growth (Omidire et al., 2022b), facilitated achievement of the study objective.

The soil was conventionally tilled, consisting of three passes with a tandem disc to a 5-to-10-cm depth, three passes of a field cultivator to disperse soil clods, and creation of raised beds, leveled at the top using a roller. After levelling, beds were approximately 50-cm wide at the top and 7.6-cm tall and the spacing between beds was 90 cm. The study consisted of a total of 28 field plots, where each plot was 3.1-m wide by 6.1-m long consisting of four soybean rows for all fertilizer treatments, with a minor exception for ECST. Due to the limited quantity of ECST material available for field application, the ECST plots consisted of smaller sub-plots (1.5-m wide by 1.5-m long) of the larger plot area. Thus, within the four soybean rows in ECST plots, the two middle rows were designated for ECST application and harvest, which was similar to recent procedures for ECST evaluation in corn (Omidire et al, 2022b).

The fertilizer-P rate applied per plot from each fertilizer-P source was 29.4 kg P ha^{-1}, which was based on the initial Mehlich-3 (M-3) soil-test-P concentration in the top 10 cm measured in Fall 2018 (24.8 mg P kg^{-1}), the recommended fertilizer-P rate for soybean in Arkansas (Slaton et al., 2013), and the measured total-recoverable P concentration of each fertilizer-P material (Table 2). The M-3-P concentration of 24.8 mg P kg^{-1} is in the low soil-test-P category for soybean production in Arkansas, for which a yield response to fertilizer-P addition is expected and P fertilization is recommended for optimal soybean production (Slaton et al., 2013). The UC treatment did not receive any fertilizer-P application. Based on the quantity of N added in DAP, which had the largest N concentration (Table 2), the amount of N needed to be applied to balance N across all fertilizer-P treatments was determined and applied in the form of uncoated urea (460 g N kg^{-1}).

On 17 May 2019, Pioneer 46A70L SU26, a Liberty Link, maturity group 4.6, soybean variety, was planted at a seeding rate of 321,230 seed ha^{-1}, which resulted in each plot containing four soybean rows, with the exception of the ECST plots, which had a two-row application area in the middle of the four-row plot. Three days after soybean planting in 2019 (20 May), fertilizer-P materials and extra uncoated urea to balance the N were manually applied separately to each plot. The original, solid form of all fertilizers were surface-applied due to the prior creation of the raised beds and to avoid bed disruption from even light incorporation. Despite fertilizer incorporation before planting being the most common practice, surface-application of fertilizers after planting is sometimes necessary when raised beds are already in place in a field to maintain the integrity of the beds.

On 13 July 2019, the Liberty (2.8 L ha^{-1}; Bayer CropScience; azanium, 2-amino-4-[hydroxy (methyl)phosphoryl] butanoate) herbicide was tractor-sprayer applied. On 19 July 2019, Dual II Magnum (2.8 L ha^{-1}) and Liberty (2.8 L ha^{-1}) herbicides were sprayed once to control weeds (i.e., Palmer amaranth [*Amaranthus palmeri* S.] and perennial ryegrass). The soybean crop was irrigated on 27 July, 13 Aug., and 21 Aug. 2019. Intrepid Edge (0.35 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 Inc.; *O*,*S*-dimethyl acetyl phosphoramidothioate) were tractor-sprayer applied on 29 Aug. 2019 to control insects. On 23 Oct. 2019, soybean grain was harvested with a plot combine from an area of 7.82 m^2 comprising the central two rows in each four-row plot.

On 6 Apr. 2020, glyphosate (2.8 L ha^{-1}) was sprayed for weed control. In 2020, the exact same soybean plots were used as were established in 2019. The USG 7469 GTL, a Liberty Link, maturity group 4.6, soybean variety was planted at a seeding rate of 321,230 seed ha^{-1} on 12 May 2020. A different soybean cultivar was planted in 2020 due to not being able to obtain the same cultivar as was planted in 2019. However, in both years, a Liberty Link, maturity group 4.6 soybean cultivar was planted, thus it was assumed differential cultivars had minimal effect on the results of this study. Fertilizer-P materials and extra *N*- (*n*-butyl) thiophosphoric triamide (NBPT)-coated urea to balance the N were manually applied on 13 May 2020. All fertilizers were surface-applied in the original solid form without incorporation. On 4 and 15 June 2020, glyphosate (2.8 L ha^{-1}) and Liberty (2.8 L ha^{-1}) herbicides were tractor-sprayer applied to control weeds. Liberty (2.8 L ha^{-1}) and Dual II Magnum (1.4 L ha^{-1}) herbicides were sprayed for weed control on 18 July 2020. The soybean crop was irrigated on 18 June, 1 July, 20 July, 23 July, 29 July, and 7 Aug. 2020. Soybean grain was harvested from the central two rows in each four-row plot with a plot combine on 1 Oct. 2020.

Each year, the mass of soybean grain harvested and the grain moisture content per plot were recorded on the combine. The moisture measured in the seed at weighing from the combine was used to adjust each plot's seed yield to the standard moisture content of 0.13 g H_2O g^{-1} seed biomass in both years.

2.4 | Soil sampling and analyses

On 20 May 2019, initial soil fertility status was determined by collecting samples from 10 random spots in the top 10 cm of the beds in the central two rows in each plot to form one composite sample per block. Because the location for both studies did not change the following year, on 13 May 2020, soil samples were again collected from 10 random locations in the central two rows from the top 10 cm on the top of the beds in each plot, combined, and mixed for one composite sample per plot. On 5 Oct. 2020, at the end of the second consecutive soybean growing season, soil samples were again collected from 10 random locations in the central two rows from the top 10 cm on the top of the beds in each plot, combined, and mixed for one composite sample per plot in the study area.

Soil samples were oven-dried at 70 ˚C for 48 h and ground to pass through a 2-mm sieve. Particle-size analyses were conducted on the initial soil samples collected in 2019 using a modified 12-h hydrometer method (Gee & Or, 2002). Sample pH and electrical conductivity (EC) were determined potentiometrically using a 1:2 soil mass/water volume (Sikora & Kissel, 2014). Total carbon (TC) and total nitrogen (TN) concentrations were measured via high-temperature combustion on a VarioMax CN analyzer (Provin, 2014). The measured TC and TN concentrations were used to calculate soil C/N ratio. Based on the absence of effervesce when soil was treated with dilute hydrochloric acid, all measured soil C was assumed to be organic C. Soil organic matter (SOM) concentration was determined via weight-loss-ignition in a muffle furnace at 360 ˚C for 2 h (Zhang & Wang, 2014). Extractable nutrient (i.e., calcium, potassium, Mg, sulfur, copper, P, iron, manganese, sodium, and zinc) concentrations were determined via M-3 extraction in a 1:10 soil mass/extractant solution and analyzed by ICAPS (Soltanpour et al., 1996; Zhang et al., 2014).

The change in soil properties over time was determined by subtracting the single initial soil property value per study block from the respective soil property on a plot-by-plot basis after one complete year (i.e., May 2020–May 2019) and then again after the second consecutive growing season (i.e., Oct.2020–May 2019). All soil analyses were conducted at the University of Arkansas, Division of Agriculture's Agricultural Diagnostic Laboratory.

2.5 | Plant tissue sampling and analyses

A 1-m row section of aboveground plant material was cut from the second soybean row at the soil surface in each plot on 29 Sept. 2019 and 20 Aug. 2020 when the soybeans reached reproductive stage 6.5 (i.e., ∼ R6; Fehr et al., 1971), which is the growth stage when dry weight and nutrient accumulation is maximized in soybean (Popp et al., 2016). Five soybean root masses from the cut aboveground plants in each plot were collected using a shovel to a depth of approximately 15 cm. The same plant samples were collected from within the smaller sub-plots for the ECST treatment.

Soybean aboveground plant samples were not partitioned into any individual plant parts. The above- and belowground tissue samples were oven-dried at 55 ˚C for 7 d and weighed. Dry matter per unit area was determined for all aboveground plant tissue samples. Chemical analyses were conducted on subsamples of soybean above- and belowground DM samples following mechanical grinding to pass through a 2-mm sieve. Total N concentration was determined via a high-temperature combustion on a VarioMax CN analyzer (Provin, 2014). Above- and belowground tissue P and Mg concentrations were measured following nitric acid extraction and ICAPS analysis (USEPA, 1996). Soybean aboveground P, Mg, and N uptake (kg ha^{-1}) were determined from measured aboveground P, Mg, and N concentrations and measured DM. All plant analyses were conducted at the University of Arkansas, Division of Agriculture's Agricultural Diagnostic Laboratory.

Each year, due to the finite amount of available of ECST material to apply in the field, the ECST treatment was combine-harvested from only the subplot area (2.25 m^2). The seed masses from the hand-collected, 1-m-row sample that had already been collected from the combine-harvested area of each plot, including the ECST subplots, were added to the combine-collected seed masses for the total soybean seed yield each year corrected to and reported at 13% moisture for all treatments. Omidire et al. (2022a, 2022b) recently used the same sub-plot size and harvest procedures for the ECST treatment for similar fertilizer-P-source response studies in rice and corn, respectively.

Soybean seed samples from the combine harvest were air-dried at 25 ˚C for 14 d. A subsample of air-dried soybean seeds from each plot was oven-dried at 70 ˚C for 48 h and was ground for Mg, N, and P concentration measurement as previously described. Magnesium, P, and N concentrations and oven-dried seed yield were used to calculate Mg, P, and N uptake (kg ha^{-1}) in the soybean seeds. The 2-yr cumulative aboveground DM, aboveground nutrient uptake, and yield were also calculated by summing the plant parameters on a plot-by-plot basis from the 2 yr.

2.6 | Statistical analyses

Based on a randomized complete block design, the PROC GLIMMIX procedure in SAS (SAS, 2013) was used to evaluate the effect of fertilizer-P treatment on the change in soil properties (i.e., soil pH and EC, extractable soil potassium, calcium, P, Mg, sulfur, sodium, copper, zinc, manganese, and iron, and SOM, TN and TC concentrations, and C:N ratio) from their initial values before the addition of any fertilizer-P to the beginning of the second year before fertilizer-P addition and from their initial magnitudes to the end of the second growing season after harvest. After normality was confirmed for most of the soil property changes, a normal distribution was used for the analysis of all soil properties.

A two-factor analysis of variance (ANOVA) was conducted, based on a split-plot design, using the PROC GLIMMIX procedure in SAS (SAS, 2013) to assess the effects of fertilizer-P treatment, year, and their interaction on total aboveground soybean DM; above- and belowground and seed P, N, and Mg tissue concentrations; aboveground and seed P, N, and Mg tissue uptake; and soybean yield.

In addition, the PROC GLIMMIX procedure in SAS (SAS, 2013) was used to evaluate the effects of fertilizer-P treatment on 2-yr cumulative total aboveground soybean DM, total aboveground and seed P, N, and Mg uptake, and yield. A beta distribution was used for all nutrient concentration data, whereas a gamma distribution was used for all DM, nutrient uptake, and yield data. Significance was judged at $P < .05$ for all analyses and least square means were reported. When appropriate, means were separated by least significant difference at the .05 level.

2.7 | Economic analyses

General production practices (i.e., tillage, herbicide applications, and irrigation) were the same across treatments, therefore only differences in fertilization costs and yield-based revenues were considered for each treatment scenario. To determine fertilization cost, the total amount of fertilizer (in kg) required to treat 1 ha was estimated based on amounts of P and N fertilizers applied to each plot during the 2019 and 2020 field studies. Price data were collected for each type of fertilizer (Chaney, 2020; MSU, 2018, 2019; Quinn, 2020; Seven Springs Farm Supply, 2020; Watkins, 2021; West Central Ag Services, 2020). Although there is no current market price available for ECST, materials and equipment required to produce ECST at a commercial scale were assumed similar to the production of CPST, for which a market currently exists. Therefore, pricing for ECST was also assumed to be the same as for CPST for this study.

Plot-level yield data from the field studies were used to estimate an average yield for each treatment in 2019 and 2020. Treatment yield averages were multiplied by the market price reported for soybean (USDA-NASS, 2022) in each respective year to provide an estimate for total revenue per treatment per year. Net returns from fertilization were calculated by subtracting the total fertilization cost from total revenue. Because it is the most commonly used fertilizer-P source for soybean production in Arkansas (Watkins, 2021), TSP was used at a point of reference to compare net returns across study treatments in the partial budget analysis.

3 | RESULT AND DISCUSSION

3.1 | Initial soil properties

Initial soil properties were assessed and used as a reference to determine change in soil properties after 1 yr and two soybean growing seasons. In the top 10 cm, initial soil pH was slightly alkaline (pH = 7.02; Table 1) and initial soil Mg and calcium (Ca) levels (Table 1) were above the optimum level (>30 mg kg^{-1} for Mg and >400 mg kg^{-1} for Ca) for common row crops in Arkansas (Espinoza et al., 2021). Soybeans generally grow well in a soil pH range of 6.0 to 7.0, though the optimal range is between 6.3 and 6.5 (Staton, 2012). However, some fraction of fertilizer-applied P could be unavailable to plant roots due to the slightly alkaline soil pH and the large soil Ca concentration, enabling P binding with soil Ca to form insoluble complexes (Espinoza & Ross, 2008). In both years, plant response from the addition of fertilizer-P was expected because the initial M-3-extractable soil P averaged 28.3 mg kg^{-1} (standard error [SE] = 3.1; Table 1), which was below optimum for soybean production on a silt-loam soil in Arkansas (Slaton et al., 2013).

3.2 | Soybean response

Soybean response to fertilizer-P treatments was variable. Thirteen of the 17 soybean properties evaluated were affected ($P < .05$) by fertilizer-P source, either as a main effect or as an interaction with year, whereas four soybean properties were unaffected ($P > .05$) by fertilizer-P source or year (Table 3).

Although a plant response was expected due to the initial soil-test-P level being below optimum, soybean aboveground DM was unaffected ($P > .05$) by fertilizer-P source or year (Table 3). Aboveground DM ranged from 7.5 Mg ha^{-1} from the UC in 2019 to 8.7 Mg ha^{-1} from TSP in 2020 and averaged 8.2 Mg ha^{-1} across the seven fertilizer-P sources and both years (Table 4). Omidire and Brye (2022) reported similar results, where there was no difference in soybean aboveground DM among CPST, TSP, and UC treatments in a field study on the same soil and at the same location as the current study. Ylagan et al. (2020) also reported similar soybean response to the same fertilizer-P sources used in a greenhouse study.

TABLE 3 Analysis of variance summary of the effects of fertilizer-phosphorus source, year, and their interaction on soybean properties

Plant property	Source of variation: Source	Year	Source × year
	P		
Aboveground			
Dry matter	.15	.87	.89
P concentration	<.01*	.06	.70
N concentration	.30	.06	.36
Mg concentration	.89	.01*	.46
P uptake	<.01*	<.01*	.81
N uptake	.02*	<.01*	.39
Mg uptake	.15	.02*	.53
Seed			
P concentration	.37	<.01*	.63
N concentration	.62	<.01*	.20
Mg concentration	.98	.96	.33
P uptake	.13	<.01	.03*
N uptake	.46	<.01	.03*
Mg uptake	.38	<.01	.03*
Belowground			
P concentration	.30	<.01*	.73
N concentration	.67	.06	.81
Mg concentration	.91	.02*	.70
Yield	.39	<.01	.03*

*Significant at the .05 probability level.

TABLE 4 Summary statistics for soybean properties that were unaffected ($P > .05$) by fertilizer-phosphorus (P) source or year

Plant property	Minimum	Maximum	Mean
Aboveground dry matter, Mg ha^{-1}	7.5	8.7	8.2
Aboveground tissue N concentration, %	2.6	3.8	3.2
Seed Mg concentration, %	0.32	0.34	0.33
Belowground tissue N concentration, %	0.7	1.4	1.0

TABLE 5 Soybean aboveground tissue phosphorus (P) concentration (APC) and aboveground tissue phosphorus uptake (APU) and aboveground tissue nitrogen uptake (ANU) uptake as affected by fertilizer-P source, averaged across years

Fertilizer-P source	APC	APU	ANU
	—%—	kg ha^{-1}	
Electrochemically precipitated struvite	0.33 a	28.4 a	277 a
Chemically precipitated struvite	0.32 ab	26.7 ab	276 a
Diammonium phosphate	0.30 bcd	24.3 bc	270 ab
Monoammonium phosphate	0.29 cd	23.6 cd	244 bc
Rock phosphate	0.28 d	21.4 e	239 c
Triple superphosphate	0.31 abc	25.9 abc	268 abc
Unamended control	0.29 cd	22.0 de	240 c

Note. Within a column, means with different letters are significantly different at $P < .05$.

TABLE 6 Soybean properties that differed between years (2019 and 2020), averaged across fertilizer-phosphorus (P) sources. N, nitrogen; Mg, magnesium

Plant properties	Year 2019	Year 2020
Aboveground tissue Mg concentration, %	0.45 b	0.52 a
Aboveground tissue P uptake, kg ha^{-1}	28.2 a	21.3 b
Aboveground tissue N uptake, kg ha^{-1}	294 a	228 b
Aboveground tissue Mg uptake, kg ha^{-1}	37 b	42 a
Seed P concentration, %	0.64 a	0.59 b
Seed N concentration, %	6.4 b	6.6 a
Belowground tissue P concentration, %	0.06 b	0.20 a
Belowground tissue Mg concentration, %	0.14 b	0.40 a

Note. Within a row, means with different letters are significantly different at $P < .05$.

In contrast to aboveground DM, aboveground tissue P concentration differed ($P < .01$) among fertilizer-P sources (Table 3). Averaged across years, aboveground tissue P concentration was numerically largest from ECST (0.33%), which was similar to CPST and TSP, and was numerically smallest from RP (0.28%), which was similar to DAP, MAP, and the UC (Table 5). Aboveground tissue P concentration from ECST was at least 1.1-times greater than that from DAP, MAP, RP, and the UC (Table 5). Aboveground tissue P concentration from CPST was at least 1.1-times greater than that from MAP, RP, and the UC (Table 5). Aboveground tissue P concentration from TSP, which did not differ from DAP, MAP, and the UC, was 1.1-times greater than that from RP (Table 5). Similar results were reported by Ylagan et al. (2020), where stem + leaves tissue P concentration was similar between TSP, DAP, ECST, CPST, and MAP, but were greater than from RP and a no P/+N and no P/−N control treatments. In contrast to the current result, Omidire and Brye (2022) documented no effect of fertilizer-P source on soybean aboveground tissue P concentration.

Similar to aboveground DM, aboveground tissue N concentration was unaffected ($P > .05$) by fertilizer-P source or year (Table 3). Aboveground N concentration ranged from 2.6% from the UC in 2020 to 3.8% from ECST in 2019 and averaged 3.2% across the seven fertilizer-P treatments and both years (Table 4). Omidire and Brye (2022) in a field study documented similar aboveground soybean tissue N concentration results to the current study.

Similar to aboveground DM and tissue N concentration, aboveground tissue Mg concentration did not differ ($P > .05$) among fertilizer-P treatments (Table 3). However, averaged across fertilizer-P treatments, aboveground tissue Mg concentration was 1.2-times greater ($P = .01$) in 2020 than in 2019 (Table 6). In contrast to the results of the current study, Omidire and Brye (2022) documented that aboveground soybean tissue Mg concentration was 1.1-times greater from CPST than from TSP or the UC, which did not differ.

In contrast to aboveground DM and tissue N concentration, aboveground tissue P and N uptake differed ($P < .05$) among fertilizer-P sources or years (Table 3). Averaged across years, aboveground tissue P uptake was numerically largest from ECST (28.4 kg ha^{-1}), which was similar to CPST or TSP, and was numerically smallest from RP (21.4 kg ha^{-1}), which was comparable to the UC (Table 5). Aboveground tissue P uptake from ECST was at least 1.2-times greater than that from DAP or MAP (Table 5). Aboveground tissue P uptake from ECST was at least 1.3-times greater than that from RP or the UC (Table 5). Aboveground tissue P uptake from CPST, which was comparable to DAP or TSP, was at least 1.1-times greater than that from MAP and at least 1.2-times greater than that from RP or the UC (Table 5). In contrast to the current study, Omidire and Brye (2022) reported no difference in soybean aboveground tissue P uptake among CPST, TSP, and the UC treatment.

The differences in aboveground P concentration and uptake may have related to varying effects on the rhizosphere pH by the fertilizer-P sources. Greater aboveground P concentration and uptake from ECST could be due to rapid dissolution of the ECST material, which was more water-soluble than DAP, MAP, and RP (Anderson et al., 2021c). Similar aboveground P concentration and uptake between the two struvite materials (ECST and CPST) and the highly water-soluble TSP contradicts the slow-release characteristic of struvite previously reported (Rahman et al., 2014; Talboys et al., 2015). The struvite materials used in this study demonstrated a more rapid-release characteristic, which has also been reported in plantless soil incubation experiments under moist- and flooded-soil conditions (Anderson et al., 2021a, 2021c). In addition, soybean root exudation of carboxylate compounds could have also contributed to greater aboveground P concentration and uptake from the struvite materials, ECST and CPST, as struvite dissolution likely increased in the presence of organic acids exuded by plant roots (Tang et al., 2007; Cabeza et al., 2011; Antonini et al., 2012).

Averaged across years, aboveground N uptake was numerically largest from ECST (277 kg ha^{-1}), which was comparable to CPST, DAP, or TSP, and was numerically smallest from RP (239 kg ha^{-1}), which was similar to MAP, TSP, or the UC (Table 5). Aboveground N uptake from ECST or CPST was at least 1.1-times greater than that from MAP, RP, and the UC (Table 5). Though the N rate was balanced across all fertilizer-P sources using urea, greater aboveground tissue N uptake from CPST and ECST than RP, MAP, and the UC could have been due to more rapid dissolution of the struvite materials, which met the N demand of the soybean plants. In contrast to the current study, Omidire and Brye (2022) reported no difference in soybean aboveground tissue N uptake among CPST, TSP, and the UC treatment. In addition to greater N uptake from the soil, it is plausible that soybean's N-fixation ability was affected by fertilizer-P sources, to either induce greater fixation or reduce N fixation. However, this possible explanation cannot be confirmed from the data collected in this study.

Averaged across fertilizer-P sources, aboveground tissue P and N uptake were at least 1.3-times greater ($P < .01$) in 2019 than in 2020 (Table 6). Similar to the results of the current study, Rech et al. (2019) reported that soybean total P uptake from TSP, which did not differ from three struvite materials, was 1.7-times greater than that from the UC.

Contrary to expectations, but similar to aboveground tissue Mg concentration, aboveground tissue Mg uptake was unaffected ($P > .05$) by fertilizer-P treatment (Table 3). However, averaged across fertilizer-P sources, aboveground tissue Mg uptake was at least 1.1-times greater ($P = .02$) in 2020 than in 2019 (Table 6). Similar to the current results, Omidire and Brye (2022) reported no difference in soybean aboveground tissue Mg uptake among TSP, CPST, and the UC treatment.

Similar to aboveground tissue Mg concentration and uptake, seed P and N concentrations were unaffected ($P > .05$) by fertilizer-P source (Table 3). However, averaged across fertilizer-P treatments, seed P concentration was 1.1-times greater ($P < .01$) in 2019 than in 2020 (Table 6), whereas seed N concentration was also greater ($P < .01$) in 2020 than in 2019 (Table 6).

Similar to aboveground DM and tissue N concentration, seed Mg concentration was unaffected ($P > .05$) by fertilizer-P source or year (Table 3). Seed Mg concentration ranged from 0.32% from DAP in 2020 to 0.34% from MAP in 2020 and averaged 0.33% across all fertilizer-P sources and both years (Table 4). Similar to the current study, Omidire and Brye (2022) reported no difference in soybean seed P and N concentrations among TSP, CPST, and the UC treatment.

In contrast to aboveground DM, tissue nutrient concentrations and uptake and seed nutrient concentrations and seed P, N, and Mg uptake differed among fertilizer-P sources between years ($P = .03$; Table 3). In 2019, seed P uptake was numerically largest from ECST (25.2 kg ha^{-1}), which was comparable to TSP, RP, CPST, DAP, and MAP, and was numerically smallest from the UC (21.0 kg ha^{-1}), which was comparable to TSP, RP, CPST, DAP, and MAP (Table 7). In 2019, seed P uptake from ECST was 1.2-times greater than that from the UC (Table 7). In 2020, seed P uptake was numerically greatest from CPST (15.5 kg ha^{-1}), which was comparable to RP, DAP, MAP, and TSP, and was numerically smallest from ECST (11.9 kg ha^{-1}), which was similar to the UC (Table 7). In 2020, seed P uptake from CPST was at least 1.3-times greater than that from ECST and the UC (Table 7). In 2020, seed P uptake from RP, MAP, and TSP, which did not differ, was at least 1.2-times greater than that from ECST and the UC (Table 7). In 2020, seed P uptake from DAP, which did not differ from the UC, was at least 1.2-times greater than that from ECST (Table 7). Seed P uptake from all fertilizer-P sources in 2019 were greater than those in 2020 (Table 7).

In 2019, seed N uptake was numerically largest from ECST (254 kg ha^{-1}), which was comparable to RP, CPST, MAP, DAP, and TSP, and was numerically smallest from the UC (215 kg ha^{-1}; Table 7). In 2020, seed N uptake was numerically greatest from RP (168 kg ha^{-1}), which was comparable to TSP, CPST, DAP, MAP, and the UC, and was numerically smallest from ECST (129 kg ha^{-1}), which was similar to the UC (Table 7). Seed N uptake from all fertilizer-P treatments in 2019 was greater than their corresponding treatment in 2020 (Table 7).

In 2019, seed Mg uptake was numerically largest from ECST (13.2 kg ha^{-1}), which was comparable to all other treatments (Table 7). In 2020, seed Mg uptake was numerically greatest from RP (8.7 kg ha^{-1}), which was similar to DAP, CPST, MAP, and TSP, and was numerically smallest from ECST (6.6 kg ha^{-1}), which was similar to the UC (Table 7). Seed Mg uptake from all fertilizer-P treatments in 2019 were greater than those in 2020 (Table 7). In contrast to the current study, Omidire and Brye (2022) reported no difference in soybean seed P, N, and Mg uptake among TSP, CPST, and the UC.

Similar to aboveground tissue Mg concentration and uptake and seed P and N concentrations, belowground tissue P and Mg concentrations were unaffected ($P > .05$) by fertilizer-P source (Table 3). However, averaged across fertilizer-P sources, belowground P and Mg concentrations were 3.3 and 2.9 times, respectively, greater ($P < .05$) in 2020 than in 2019 (Table 6), which was likely due to a carry-over effect from the 2019 fertilization.

TABLE 7 Soybean yield, seed phosphorus (P), nitrogen (N), and magnesium (Mg) uptake as affected by fertilizer-P–source–year combination

Fertilizer-P source	Year	Yield	Seed P uptake	Seed N uptake	Seed Mg uptake
		kg ha^{-1}			
ECST	2019	4,148 a	25.2 a	254 a	13.2 a
CPST	2019	3,761 ab	23.0 ab	225 ab	12.0 a
DAP	2019	3,721 ab	22.1 ab	224 ab	12.0 a
MAP	2019	3,807 ab	22.8 ab	229 ab	11.9 a
RP	2019	3,735 ab	21.8 ab	224 ab	11.9 a
TSP	2019	3,776 ab	23.0 ab	229 ab	12.3 a
UC	2019	3,559 b	21.0 b	215 bc	11.6 a
ECST	2020	2,168 d	11.9 e	129 e	6.6 d
CPST	2020	2,756 c	15.5 c	167 cd	8.7 b
DAP	2020	2,650 c	14.3 cd	158 d	8.0 bc
MAP	2020	2,642 c	14.9 c	161 d	8.5 bc
RP	2020	2,722 c	14.8 c	168 cd	8.7 b
TSP	2020	2,690 c	14.9 c	163 d	8.3 bc
UC	2020	2,386 cd	12.4 de	143 de	7.3 cd

Note. Within a column, means with different letters are significantly different at $P < .05$. CPST, chemically precipitated struvite; DAP, diammonium phosphate; ECST, electrochemically precipitated struvite; MAP, monoammonium phosphate; RP, rock phosphate; TSP, triple superphosphate; UC, unamended control.

The lack of fertilizer-P-source differences in aboveground DM, seed P concentration and uptake, and belowground P concentration may have occurred from relatively uniform precipitation or fixation of dissolved P from the fertilizer materials by the large concentration of initial soil Ca coupled with the slight alkaline soil. It is also plausible that N-fixing legumes, such as soybean, may have taken up more cations than anions, thus releasing protons from their roots to balance their charge (Hinsinger, 2001; Tang et al., 2007). Consequently, the rhizosphere acidification, which occurred as a result of net export of protons to the rhizosphere, could have, at least in part, increased P availability through the dissolution of precipitated or fixed Ca–P in the alkaline soil (Hinsinger, 2001; Tang et al., 2007; Richardson et al., 2009; Gao et al., 2019), creating relatively uniform P availability from all fertilizer-P treatments for the soybean plants to experience. Though a low concentration of carboxylate compounds is produced from soybean roots relative to other legumes (Tang et al., 2007), the effect of carboxylate root exudation could have, at least in part, reduced the rhizosphere pH, thus releasing some Ca-bound P. The lack of difference could have also been due to soil organic P mineralization related to increased phosphatase activity in the soybean rhizosphere (Nuruzzaman et al., 2006; Wang et al., 2009; Kong et al., 2018). Plants are known to synthesize various enzymes that exist in soils, which may remain active for some time after synthesis. Soybean roots can exude acidic phosphatase (Wang et al., 2009, Li et al., 2012, Kong et al., 2018), which mineralizes organic P by catalyzing hydrolytic cleavage of inorganic P from organic-P compounds.

Similar to the current study, Omidire and Brye (2022) reported no difference in soybean belowground tissue P concentration among TSP, CPST, and the UC treatment. However, Ylagan et al. (2020) reported that belowground P concentration was numerically largest from MAP, which did not differ from TSP, and was numerically smallest from the no P/-N control treatment, which did not differ from the no P/+N control treatment.

The lack of difference in aboveground and seed Mg concentrations and uptake and belowground Mg concentration among fertilizer-P sources was likely due to the inherent large concentrations of initial extractable soil Mg (>300 mg kg^{-1}) in the top 10 cm of the soil (Table 1) and more available soil Mg below the top 10 cm, despite the two struvite sources containing greater initial Mg concentrations than the other fertilizer-P sources (Table 2). In addition, soybean plants may have uniformly accumulated Mg from P fertilization, which increased the concentration and uptake of Mg. Tang et al. (1998) reported that specific acid production in legumes was correlated with concentrations of excess cations, such as Mg. Results of this study were similar to that of Ylagan et al. (2020), however, Omidire and Brye (2022) reported that soybean belowground tissue Mg concentration was 1.2-times greater from the UC than TSP, whereas that from CPST was similar to both TSP and the UC.

Similar to aboveground DM and tissue N concentration and seed Mg concentration, belowground N concentration was unaffected ($P > .05$) by fertilizer-P treatments or year (Table 3). Belowground N concentration ranged from 0.7% from ECST in 2019 to 1.4% from RP in 2020 and averaged

1.0% across all fertilizer-P sources and both years (Table 4). Similar to other legumes, soybean has the ability to increase N availability by biological N_2 fixation (Tamagno et al., 2017; Santachiara, Salvagiotti, & Rotundo, 2019; Wang et al., 2019). The mechanism could have provided additional plant-available N that masked potential and expected differences in aboveground N concentration, seed N concentration and uptake, and belowground N concentration among fertilizer-P sources. Similar to the current study, Omidire and Brye (2022) reported no differences in soybean belowground N concentration among similar fertilizer-P sources as used in the current study.

As expected and similar to seed P, N, and Mg uptake, seed yield, as measured with the plot combine, differed among fertilizer-P sources between years ($P = .03$; Table 3). In 2019, seed yield was numerically largest from ECST (4.1 Mg ha^{-1}), which was comparable to DAP, CPST, RP, TSP, and MAP, and was numerically smallest from the UC (3.6 Mg ha^{-1}), which was comparable to RP, DAP, TSP, MAP, and CPST (Table 7). In 2019, seed yield from ECST was 1.2-times greater than that from the UC (Table 7) likely due to quick dissolution of the ECST material releasing P for root uptake, which is contrary to the reported slow-release characteristics of struvite (Nascimento et al., 2018; Anderson et al., 2020; Omidire, 2022a, Omidire and Brye, 2022). In 2020, seed yield was numerically greatest from CPST (2.8 Mg ha^{-1}), which was similar to TSP, DAP, RP, MAP, and the UC, and was numerically smallest from ECST (2.2 Mg ha^{-1}), which was comparable to the UC (Table 7). In 2020, seed yield from DAP, CPST, RP, TSP, and MAP was at least 1.2-times greater than that from ECST (Table 7). Because two batches of the ECST materials were generated, it appears that the second batch of the ECST was slower to dissolve than the first batch, resulting in lower yield and seed P, N, and Mg uptake than that from DAP, CPST, RP, TSP, and MAP in 2020.

Seed yield from all fertilizer-P sources in 2019 were greater than those in 2020 (Table 7), which was likely at least partially due to greater monthly rainfall during the growing season in 2019 than in 2020 (Figure 1). Though all plots were furrow-irrigated in both years, soybean growth and productivity would have benefitted from more uniform, properly watered soil moisture conditions in 2019, with lower magnitudes of soil moisture fluctuations than in 2020, which had less timely rainfall events. It is also plausible that well-watered soil conditions in 2019 promoted P diffusion from the fertilizer-P source, which resulted in greater yield, aboveground tissue P uptake, and seed P concentration and uptake in 2019 than in 2020. However, it remains unclear why there was a lower belowground tissue P concentration in 2019 than in 2020. Additionally, although the effect of differential cultivars grown in the 2 yr was assumed negligible, differences in soybean yields between years were confounded with two different cultivars that were grown. Despite numerous similarities between the two cultivars, the assumption of negligible effect of differential cultivars may not have been valid, as soybean yields are closely related to genetic potential (Scaboo et al., 2010). In nearby field study, Omidire and Brye (2022) reported no difference in soybean yield among CPST, TSP, and UC.

TABLE 8 Analysis of variance summary of the effects of fertilizer-phosphorus (P) source on the change in soil properties in the top 10 cm after 1 yr and after two growing seasons in a P-deficient, silt-loam soil in eastern Arkansas

Soil properties	Change after 1 yr	Change after two growing seasons
	P	
pH	.47	.03*
Electrical conductivity	.38	.98
Phosphorus	.67	< .01*
Potassium	.66	.78
Calcium	.91	.85
Magnesium	.95	.58
Sulfur	.51	.69
Sodium	.67	.81
Iron	.39	.79
Manganese	.53	.80
Zinc	.57	.71
Copper	.27	.61
Total nitrogen	.54	–
Total carbon	.67	–

*Significant at the .05 probability level.

3.3 | Change in soil response

Soil property changes over time among fertilizer-P sources were variable. After one year, all 14 soil property changes from the initial were unaffected ($P > .05$; Table 8) by fertilizer-P treatment. However, after two growing seasons, two of the 12 soil property changes from the initial differed ($P < .05$) among fertilizer-P source, whereas 10 soil property changes from the initial were unaffected ($P > .05$) by fertilizer-P source (Table 8).

After two growing cycles, the change in soil pH from the initial pH differed among fertilizer-P sources ($P < .05$; Table 8), where soil pH decreased from the initial pH in MAP (−0.20 pH units) and DAP (−0.06 pH units) treatments, but increased in the ECST (0.01 pH units), CPST (0.12 pH units), RP (0.03 pH units), and TSP (0.02 pH units) treatments. The soil pH minimally changed from the initial value in the UC (<−0.01 pH units; Figure 2). However, the change in soil pH

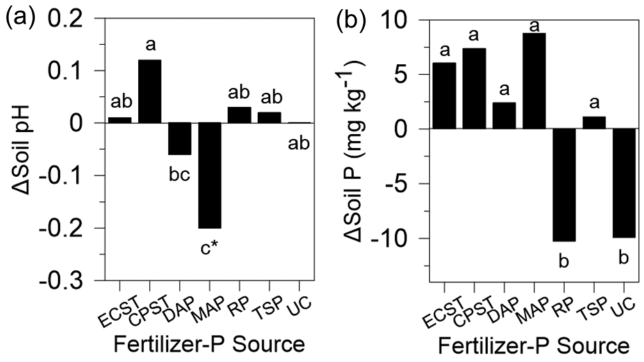

FIGURE 2 Change in soil-test pH (a) and extractable soil phosphorus (P) concentration (b) in the top 10 cm among fertilizer-P sources (ECST, electrochemically precipitated struvite; CPST, chemically precipitated struvite; DAP, diammonium phosphate; MAP, monoammonium phosphate; RP, rock phosphate; TSP, triple superphosphate; and UC, unamended control) after two growing seasons in a P-deficient, silt-loam soil. An asterisk (*) indicates mean value is different than zero ($P < .05$). Bars within a panel with different letters are significantly different at $P < .05$

differed from zero only in MAP and did not differ from zero in all other treatments (Figure 2). The change in soil pH for MAP (−0.20 pH units), which was similar to DAP (−0.06 pH units), differed from TSP, ECST, RP, CPST, and the UC. The change in soil pH for CPST, which was similar to ECST, RP, TSP, and the UC, differed from DAP (Figure 2).

After two growing seasons, the change in soil P concentration from the initial soil concentration differed among fertilizer-P sources ($P < .05$; Table 8). Though soil P concentration did not differ from zero in all treatments, soil P concentration decreased the most in the RP treatment (−10.25 mg kg^{-1}), which did not differ from the UC (−9.91 mg kg^{-1}; Figure 2). The change in soil P concentration from the initial value increased in the ECST, CPST, MAP, DAP, and TSP treatments, which did not differ (Figure 2). Similar trends were observed in the change in soil pH and soil P concentration among ECST, CPST, and TSP, which suggests that the struvite materials used in this study behaved similar to the highly water-soluble TSP, which was also evident in the aboveground tissue P concentration and uptake and N uptake.

3.4 | Economic evaluation

Net revenues were affected by three primary variables in this study: yield, fertilizer price, and the nutrient composition of each fertilizer. Although fertilizer-P and -N were applied at the same total rate across treatments, except for the UC, differing nutrient compositions for each fertilizer (Table 2) resulted in variations in the actual amounts of each fertilizer material applied in a treatment. As fertilizers are priced by total weight and not nutrient concentration, these differences affected total fertilizer costs across treatments. For instance, at \$0.39 kg^{-1}, RP was the cheapest fertilizer-P source used in the study. However, RP's lower P and N concentration required larger masses of RP to be applied, resulting in RP having the second largest overall treatment cost per plot in 2019 and 2020.

Although the price of ECST was more than 67% greater than TSP in 2019, ECST's measured P and N concentrations were slightly greater, resulting in a lower amount of ECST material being required to meet target fertilization rates compared with TSP. The differential nutrient compositions, coupled with significantly greater yields for ECST in 2019 (Table 7) resulted in ECST net returns that were 6.9% greater than for TSP and was the greatest value for 2019 (Table 9). In the case of CPST, the greater price, coupled with lower P concentration and soybean yield resulted in CPST with the lowest relative net return for 2019 (Table 9).

Differences in nutrient concentrations for the ECST application used in 2020 compared with 2019 resulted in more ECST material being applied in 2020 than in 2019 to provide the same total fertilizer-P rate in both years, which led to greater fertilization costs for the ECST treatment in 2020 relative to 2019. The lower nutrient concentrations, hence greater

TABLE 9 Estimated differences in net revenues and percent change per hectare per year from various fertilizer-phosphorus (P) sources compared with triple superphosphate

Fertilizer-P source	2019		2020	
	\$ ha^{-1}	% change	\$ ha^{-1}	% change
Triple superphosphate	–	–	–	–
Electrochemically precipitated struvite	77.38	6.89	−282.91	−27.76
Chemically precipitated struvite	−130.76	−11.64	−107.98	−10.59
Diammonium phosphate	14.02	1.25	−12.52	−1.23
Monoammonium phosphate	42.78	3.81	−16.08	−1.58
Rock phosphate	−80.60	−7.17	−69.09	−6.78
Unamended control	12.31	1.10	−63.06	−6.19

cost, coupled with lower yields in general for all fertilizer-P treatments in 2020 than in 2019, particularly ECST (Table 7), resulted in net returns being 27.8% lower for ECST than TSP in 2020, with ECST replacing CPST as the least-profitable fertilizer-P treatment for 2020 (Table 9).

4 | CONCLUSIONS

This study assessed soybean growth and productivity as affected by two struvite-P sources relative to other conventional fertilizer-P sources. Many previous studies that evaluated the effectiveness of struvite on plant growth were conducted at the greenhouse-scale. However, a strength of the current soybean study is that this study was conducted at the field-scale, which is much needed for evaluating struvite's agronomic effectiveness.

The hypothesis that soybean aboveground DM and yield, above- and belowground tissue and seed P and N concentrations, and aboveground and seed P and N uptake from ECST and CPST would be similar to TSP, RP, DAP, and MAP was only partially supported because aboveground tissue P concentration and P and N uptake differed among fertilizer-P treatments. Additionally, results partially supported the hypothesis that soybean aboveground tissue and seed Mg concentration and uptake and belowground tissue Mg concentrations would be greater for the struvite materials (CPST and ECST) because above- and belowground tissue and seed Mg concentrations and aboveground Mg uptake did not differ among ECST, CPST, TSP, MAP, DAP, and RP treatments. Similarly, results partially supported the hypothesis that soybean grown in Year 2 would also have greater aboveground DM; yield; above- and belowground tissue and seed P, N, and Mg concentrations; and aboveground tissue and seed P, N, and Mg uptake compared with that in Year 1, where soybean aboveground tissue P and N uptake and seed P concentration from Year 1 (2019) was greater than that from Year 2 (2020), but aboveground DM and tissue N concentration, belowground tissue N concentration, and seed Mg concentration did not differ between years. However, the struvite materials used in this study seemed to quickly dissolve, which is contrary to the generally reported slow-release characteristics of various struvite materials.

Whether the struvite was chemically or electrochemically precipitated, results revealed that the wastewater-derived struvite sources used in this study have potential to be a viable, alternative fertilizer-P source for soybean from a functional standpoint. All soybean properties affected by fertilizer-P source (i.e., aboveground tissue P concentration and uptake and N uptake in 2019 and 2020) had similar response among ECST, CPST, and TSP, and in some cases, greater response from both struvite treatments than from RP, DAP, or MAP. In addition to being potentially more sustainable, the ECST material was more profitable in 2019 than other fertilizer-P sources. Based on the results of this field study, it is clear that struvite is a viable, alternative fertilizer-P source for field-scale soybean production on a silt-loam soil.

Economic analyses showed variability in the cost-effectiveness of struvite use. As the current price of wastewater-recovered struvite is greater than that of fertilizers sourced from mined phosphate rock, this cost difference must be offset by greater yields and/or greater nutrient compositions relative to other fertilizer-P sources. However, in striving for global agricultural sustainability with decreasing quantities of minable RP, struvite recovery could become economically competitive and contribute immensely to future food security as a recovered fertilizer-P source. Future research should focus on field evaluation of a pelletized form of ECST and a real-wastewater-derived ECST in various row crops.

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AUTHOR CONTRIBUTIONS

Niyi S. Omidire: Data curation; Formal analysis; Investigation; Methodology; Writing – original draft. Kristofor R. Brye: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Supervision; Writing – review & editing. Leah English: Formal analysis; Investigation; Methodology; Writing – original draft. Laszlo Kekedy-Nagy: Methodology; Writing – review & editing. Lauren Greenlee: Funding acquisition; Project administration; Writing – review & editing. Jennie Popp: Funding acquisition; Project administration; Supervision; Writing – review & editing. Trenton L. Roberts: Methodology; Writing – review & editing.

CONFLICT OF INTEREST

The authors report no conflict of interest.

ORCID

Kristofor R. Brye https://orcid.org/0000-0001-9353-4009
Trenton L. Roberts https://orcid.org/0000-0001-5558-7257

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