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Wastewater-recovered struvite evaluation as a fertilizer-phosphorus source for corn in eastern Arkansas

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Core Ideas

- Electrochemically precipitated struvite (ECST) was evaluated in corn grown under field conditions for two years
- Corn response from ECST was at least similar and sometimes greater than other conventional P fertilizers
- Technical and economically, struvite could be a viable substitute for other commercial P fertilizers for corn

Abbreviations:

ECST, electrochemically precipitated struvite; CPST, chemically precipitated struvite; RP, rock phosphate; MAP, monoammonium phosphate; TSP, triple superphosphate; DAP, diammonium phosphate; UC, unamended control; WWTP, wastewater treatment plant; DM, dry matter; EC, electrical conductivity; US, United States; ICP, inductively coupled, argon-plasma spectrometry; NBPT, N-(n-butyl) thiophosphoric triamide; ANOVA, analysis of variance; MLRA, major land resource area.

Wastewater-recovered struvite evaluation as a fertilizer-phosphorus source for corn in eastern Arkansas

Abstract

The perception of wastewater as a resource rather than a pollutant has not been well emphasized. Phosphorus (P) can be precipitated from wastewaters as the mineral struvite ($MgNH_4PO_4·6H_2O$), which can be a potential sustainable alternative to the limited, rock phosphate (RP)-dependent, traditional fertilizer-P sources for agricultural production. This field study evaluated the effects of electrochemically precipitated struvite (ECST) and chemically precipitated struvite (CPST) compared to other conventional fertilizer-P materials [monoammonium phosphate (MAP), diammonium phosphate (DAP), triple superphosphate (TSP), and RP] on corn (*Zea mays* L.) response in two consecutive growing seasons in a P-deficient, silt-loam soil (Aquic Fraglossudalfs) in eastern Arkansas. Averaged across years, corn yield was numerically largest from ECST (12.9 Mg ha^{-1}), which differed ($P < 0.05$) from all other treatments and was numerically smallest from DAP (10.1 Mg ha^{-1}), which was similar to MAP (10.7 Mg ha^{-1}), CPST (10.3 Mg ha^{-1}), and RP (10.3 Mg ha^{-1}). Corn yield and kernel P uptake from ECST were at least 1.2 times greater ($P < 0.05$) than from CPST, TSP, DAP, and RP. Yield from ECST was 1.2 times greater ($P < 0.05$) than from MAP. A partial budget analysis showed that, across both years, fertilizer-P treatment net revenues for ECST were greater than those associated with the other fertilizer-P sources. Results demonstrated that wastewater-recovered struvite materials have the potential to be a

sustainable source of P for corn production in P-deficient, silt-loam soil from both a technical and economic perspective.

1 | INTRODUCTION

The global reserves of rock phosphate (RP), from which most fertilizer-phosphorus (P) sources are created, are limited, non-renewable, and unevenly distributed, with the largest portion of mined RP located in Morocco (Stewart et al., 2005; Liu, Kumar, Kwag, & Ra, 2013). Additionally, existing world RP reserves will be halved by 2060, but the need for fertilizer-P is projected to increase as the global population is expected to be nearly 9 billion by 2050 (Vance, Uhde-Stone, & Allan, 2003; Cordell, Drangert, & White, 2009). As the finite global RP reserves are depleted, the cost of RP-derived, fertilizer-P sources is also anticipated to rise (Cordell & Neset, 2014).

A potential alternative to the fast-depleting RP reserves is the recovery of P as mineral struvite from wastewaters due to the relatively large P and nitrogen (N) concentrations in many wastewater effluent streams (Latifian, Liu, & Mattiasson, 2012; Uysal, & Kuru, 2015; Kataki, West, Clarke, & Baruah, 2016; Rahman et al., 2014; Ryu, & Lee, 2016; Li et al., 2019). Magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4{\cdot}6H_2O$), also known as struvite, is a white crystalline material that has been shown to be useful as fertilizer-P source (Le Corre et al., 2009). On average, struvite contains 5.7% N, 12.6% P, and 9.9% Mg (Latifian et al., 2012; Nongqwenga, Muchaonyerwa, Hughes, Odindo, & Bame, 2017), but the final concentrations vary based on the wastewater composition and recovery process used.

Struvite has been recovered from a variety of waste products through chemical, biological, and in recent years, electrochemical precipitation techniques (De-Bashan &

Bashan 2004; Latifian et al., 2012; Kékedy-Nagy, Teymouri, Herring, & Greenlee, 2020b). Unlike chemical precipitation of struvite from wastewater, where external chemical additions are needed, electrochemical precipitation is a newly adopted approach designed to also permit energy recovery and utilizes a reactor with an anode that supplies Mg ions through corrosion when an electrical current is present (Kékedy-Nagy et al., 2019,2020a).

Struvite is often regarded as a slow-release P source due to its reported lower solubility compared to common fertilizer-P sources used in large-scale production agriculture, such as monoammonium phosphate (MAP) and triple superphosphate (TSP; Chien, Prochnow, Tu, & Snyder, 2011), making struvite a potentially useful fertilizer-P material for a variety of plants in lowland, inadequately drained; and upland, humus-rich soils (Anderson, Brye, Greenlee, Roberts, & Gbur, 2021a; Anderson et al., 2021b,c).

Like most technological innovations, struvite has not entered the market as the lowest-cost option, with prices being roughly double that of other fertilizer-P sources in 2019 and 2020 (Siciliano et al., 2020; West Central Ag Services, 2020). Field trials conducted by Ostara Nutrient Technologies have shown greater yields for crops grown using a chemically precipitated struvite (CPST; i.e., Crystal Green) from a municipal wastewater, resulting in returns on investment reaching upwards of 4:1, but researchers note that fluctuations in prices for crops and alternative fertilizers can impact year-to-year profitability (Crystal Green, 2021; Lyseng, 2014). In rice, a partial budget analysis evaluating economic returns to fertilization showed that both CPST and an even newer material, electrochemically precipitated struvite (ECST) from synthetic wastewater, resulted in lower net revenues than those of four commercially available and most commonly used fertilizer-P sources [i.e., MAP, diammonium phosphate (DAP), TSP, and rock phosphate (RP); Omidire et al., 2020].

Corn (*Zea mays* L.) is a key crop grown throughout the world and is increasingly important in the southern Mississippi River Basin region, including Arkansas (USDA-NASS 2020). Considering P's immobility in soil, plant response mechanisms to enhance P acquisition from soil/fertilizer include changing root architecture and increasing root hair density, formation of mycorrhizal associations, up-regulating P transport systems, and secretion of rhizosphere acidification (Gahoonia & Nielsen, 1992; Lambers, Shane, Cramer, Pearse, & Veneklaas, 2006). For example, for a corn yield goal of 14.1 Mg ha^{-1} in Arkansas, recommended fertilizer-P rates range from 56 to 112 kg P_2O_5 ha^{-1} across soil textures (Espinoza and Ross, 2008), making corn a large-P-demanding crop for optimal production.

Several studies have examined crop response to wastewater-derived struvite as a fertilizer-P material relative to other widely used fertilizer-P sources (i.e., MAP and TSP). Many studies have reported positive results from struvite application, including similar crop response, such as plant nutrient uptake, between struvite and other common fertilizer-P materials (Li & Zhao, 2003; Kern et al., 2008; Thompson, 2013). However, other studies have reported reduced crop response from wastewater-derived struvite application compared to other conventional fertilizer-P materials (Ganrot, Dave, Nilsson, & Li, 2007; Ackerman, Zvomuya, Cicek, & Flaten, 2013; Everaert, Da Silva, Degryse, McLaughlin, & Smolders, 2017).

Recently, in a 2-year field study, ECST and CPST (i.e., Crystal Green) were evaluated in flood-irrigated rice (*Oryza sativa* L.) compared to MAP, RP, DAP, and TSP in a silt-loam soil

(Typic Glossaqualfs) in eastern Arkansas that was deficient in P, where results showed similarities in rice properties between struvite materials and among other commonly used fertilizer-P sources (Omidire et al., 2022b). Additionally, soybean (*Glycine max* L. [Merr.]) and corn response to struvite treatments (ECST and CPST) were evaluated in a 79-day, greenhouse pot study in a silt-loam soil (Typic Fragiudults), where results showed that the struvite materials were at least comparable to other conventional fertilizer-P sources (Ylagan, Brye, & Greenlee 2020). In a series of plant-less soil incubation studies, struvite materials were reported to have generally comparable response for plant-available and water-soluble P concentration changes over time to DAP, MAP, and TSP in several different soils under flooded- (Anderson et al., 2021a,c) and moist-soil (Anderson et al., 2021b) conditions.

Limited field studies have been performed to investigate the agronomic effectiveness of struvite materials (Collins, Kimura, Frear, & Kruger, 2016; Omidire & Brye, 2022a; Omidire et al., 2022b). However, many studies have evaluated struvite as a potential alternative fertilizer-P source in greater crop diversity in greenhouse pot studies (Uysal, Demir, Sayilgan, Eraslan, & Kucukyumuk, 2014; Katanda et al., 2016; Ylagan et al., 2020). In addition, no field studies have been conducted in the mid-southern United States to examine the effectiveness of ECST as a potential fertilizer-P material for corn production. Therefore, the objective of this field study was to investigate the effects of two struvite sources (i.e., CPST and ECST) compared to other commercially available, fertilizer-P materials (i.e., RP, MAP, TSP, and DAP) on corn response in two consecutive growing seasons in a P-deficient, silt-loam soil in eastern Arkansas.

Based on the greater initial Mg concentrations and reported low water solubility of struvite, it was hypothesized that both struvite sources (i.e., ECST and CPST) would have at least similar total aboveground dry matter (DM) and tissue P and N uptake, yield, and belowground P and N concentrations, but greater total aboveground tissue Mg uptake and belowground tissue Mg concentrations than other conventional fertilizer-P materials (i.e., RP, MAP, TSP, and DAP). In addition, it was hypothesized that corn grown in year two would have greater total aboveground DM, yield, total aboveground tissue Mg, P, and N uptake, and belowground tissue Mg, P, and N concentrations compared to that in year one due to a carry-over effect from fertilization in year one. Given the greater market prices for ECST and CPST relative to other fertilizer-P sources, it was also hypothesized that the struvite treatments would produce lower net returns than the other fertilizer-P treatments evaluated.

2 | MATERIALS AND METHODS

2.1 | Site description

A field study was conducted at the Lon Mann Cotton Branch Experiment Station (CBES) near Marianna, AR in 2019 and 2020 (34˚44'01" N; 90˚45'51" W). The research site was located in the Southern Mississippi Valley Loess, major land resource area (MLRA) 134 Brye, Mersiovsky, Hernandez, & Ward, 2013). The study area was 0.3 ha with Calloway silt loam (fine-silty, mixed, active, thermic Aquic Fraglossudalfs) mapped throughout (Soil Survey Staff, 2015). Generally, Calloway soils are developing in loess parent material and have a surface layer of brown to dark brown silt loam with a subsoil of light brownish-gray silt loam (NRCS, 2020). The soil was silt-loam textured in the top 10 cm, consisting of 7% sand, 80% silt, and 14% clay (Table 1).

The study area had been cultivated for the past 15 years with various crops including wheat (*Triticum aestivum* L.), soybean, and corn, and occasionally left fallow for no more than one growing season at a time. No consistent crop rotation had been followed.

The 30-year (i.e., 1981 to 2010) mean annual air temperature and precipitation within the study region are 16.6°C and 128.4 cm, respectively (NOAA, 2020). The study area has a 30-year average monthly minimum air temperature of 0.6°C in January and maximum of 32.3°C in July (NOAA, 2020). Thus, the regional climate is considered humid temperate, with periodic precipitation and warm weather year-round.

2.2 | Treatments and experimental layout

The study was conducted to investigate fertilizer-P treatment [i.e., CPST, ECST, RP, DAP, TSP, MAP, and an unamended control (UC)] effects on corn and soil response. Corn plots established in 2019 were the exact same plots used in 2020. Thus, two experimental factors, year (whole plot) and fertilizer-P source (split plot), were assessed in the field study. Each year, there were seven fertilizer-P-source treatments, which were randomized within each of four blocks within in the study area resulting in a randomized complete block, split-plot design.

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2.3 | Fertilizer-P materials and characterization

The ECST material represents the result of relatively new technology used to recover nutrients from a waste stream. The ECST used in this field study was a synthetic-wastewater-derived struvite that was generated by chemical engineers in the Department of Chemical Engineering at the University of Arkansas (Kékedy-Nagy et al., 2020b). After analyzing the resulting ECST material by scanning electron microscopy, results showed a morphology that suggests the formation of high-quality pure struvite, with a needle-shaped, elongated structure and smooth, sharp edges, indicating that there were no additional cations present other than the expected NH_4^+ and Mg^{2+} (Kékedy-Nagy et al., 2019). Two discrete batches of ECST were produced for this study. The first batch was used in the 2019 field season and the second batch was used in the 2020 field season. Unlike ECST, the CPST product, also known as Crystal Green, was derived from raw wastewater and sold by Ostara Nutrient Recovery Technologies, Inc. Though elemental compositions and morphology rom X-ray diffraction indicated that the CPST and ECST materials are comparable (Kékedy-Nagy et al., 2020b), the CPST derived from raw municipal wastewater had a more diverse composition, including trace amounts of arsenic, cadmium, chromium, lead, molybdenum, nickel, and zinc (Ostara, 2022) and organic compounds (Ylagan et al., 2020) relative to the synthetic-wastewater-derived ECST.

Five replicates of each of the two batches of ECST, and the RP, MAP, CPST, TSP, and DAP fertilizers were prepared for chemical analyses. The particle sizes of the fertilizer-P sources varied from powder (i.e., RP) to crystals (ECST) to small pellets (i.e., CPST, MAP, TSP, and DAP), with a mean diameter of 3.1 mm, where the CPST material had a mean pellet size of 2.9 (± 0.57) mm (Anderson, 2020). After crushing to improve uniformity among all seven fertilizer materials, chemical analyses were performed. For all but ECST, fertilizer pH was measured potentiometrically in a 1:2 fertilizer mass:water volume suspension (Sikora & Kissel, 2014). Fertilizer pH was not measured for the ECST material because there was a limited quantity of struvite available and all of it was needed for application in field studies. Total-recoverable Mg and P were determined by inductively coupled, argon-plasma spectrometry (ICP) after a nitric acid digestion (USEPA, 1996). High-temperature combustion was used to determine the total N (TN) concentration with a VarioMax CN analyzer (Elementar Americas, Inc., Mt. Laurel, NJ; Provin, 2014). All fertilizer analyses were conducted by the University of Arkansas, Division of Agriculture's Agricultural Diagnostic Lab in Fayetteville. Table 2 summarizes the measured chemical properties of the fertilizer-P materials (Omidire et al., 2022b.

2.4 | Field management

The soil was conventionally tilled to a 5- to 10-cm depth with three passes each with a tandem disc then a field cultivator to soften the seed bed and disperse soil clods followed by creation of raised beds that were leveled at the top with a roller. In May 2019, 28 field plots, 6.1-m long by 3.1-m wide, were established for all fertilizer treatments with the exception of ECST. The ECST plots were smaller sub-plots (1.5-m long by 1.5-m wide) of the larger plot area due to the limited supply of ECST for field plot application. Beds were approximately 7.6-cm tall and 50-cm wide at the top after leveling and the spacing between beds was 90 cm. The fertilizer-P rate applied to each plot was determined based on the initial soil-test-P concentration in the top 10 cm measured in Fall 2018 (24.8 mg P kg^{-1}), the recommended P-fertilization rate for corn (Espinoza & Ross, 2008), and the measured total-recoverable P concentrations of each fertilizer-P material (Table 2) such that an equivalent P-application rate of 29.4 kg P ha^{-1} was used for all six fertilizer-P treatments.

In order to unify the N concentrations among all fertilizer-P sources, including the unamended control, the amount of N needed to be added was determined based on the quantity of N added in DAP, which had the largest N concentration (Table 2). Due to researcher error, uncoated urea (460 g N kg^{-1}), rather than coated urea to minimize potential N volatilization losses, was added for the additional N needed in other fertilizer-P treatments.

On 18 May, 2019, plots were planted with the Pioneer 1870YHR corn variety at a rate of 81500 seed ha^{-1}, which resulted in four corn rows per plot. Dual II Magnum (1.4 L ha^{-1}; Syngenta, Greensboro, NC; 2-chloro-N-(2-ethyl-6-methylphenyl)-N-[(2S)-1-methoxypropan-2-yl] acetamide) herbicide was tractor-sprayer applied once after corn planting to control weeds. Two days after corn planting in 2019 (20 May), fertilizer-P materials and extra uncoated urea to balance the N were manually applied individually to each plot. All fertilizers were surface-applied in the original, solid form after planting because the beds, upon which corn was planted, had already been created, thus even light incorporation would have greatly disrupted the integrity of the beds. For a corn yield goal of

13.8 Mg ha^{-1} grown on a silt-loam soil, on 5 June, 2019, uncoated urea was manually broadcast-applied at 235.4 kg N ha^{-1} (Espinosa & Ross, 2008). Acuron (7.0 L ha^{-1}; Syngenta, Greensboro, NC; S-metolachlor), Atrazine (5.6 L ha^{-1}; Syngenta, Greensboro, NC; 2-chloro-4-ethylamino-6-isopropylamino-s-triazine), and PermitPlus (52.5 mL ha^{-1}; Gowan Company LLC, USA; Halosulfuron-methyl) were sprayed on 13 June, 2019. The corn crop was irrigated on 27 July, 13 August, and 21 August, 2019. Using a plot combine, corn grain was harvested from a 1.7-m width by 4.6-m length of the two middle rows in each plot on 1 October, 2019.

On 6 April, 2020, Glyphosate (2.8 L ha^{-1}; Bayer CropScience; 2-(phosphonomethylamino) acetate, propan-2-ylazanium) was sprayed once for weed control. In 2020, the exact same corn plots were used as were established in 2019. On 6 May, 2020, plots were planted with the Pioneer 1870YHR corn variety at a rate of 81500 seed ha^{-1}. On 13 May, 2020, fertilizer-P materials were hand-applied individually to each plot. Unlike in 2019 when uncoated urea was applied due to researcher error, in 2020, N-(n-butyl) thiophosphoric triamide (NBPT)-coated urea was applied to unify the N rate across all seven fertilizer sources, including the unamended control. The solid form of all fertilizers was surface-applied to the plots. On 1 June, 2020, NBPT-coated urea was manually broadcast-applied at 235.4 kg N ha^{-1} for a corn yield goal of 13.8 Mg ha^{-1} grown on a silt-loam soil (Espinosa & Ross, 2008). On 3 June, 2020, Halex GT (5.6 L ha^{-1}; Syngenta, Greensboro, NC; S-metolachlor) and Atrazine (2.8 L ha^{-1}) were sprayed to control weeds. The corn crop was irrigated on 18 June, 1 July, 20 July, 23 July, 29 July, and 7 August, 2020. Using a plot combine, corn grain was harvested from a 1.7-m width by 4.6-m length of the two middle rows in each plot on 21 August, 2020. Between corn harvest in 2019 and Spring 2020, no tillage operations occurred in the study area.

In both years, the harvested corn grain mass in each plot was recorded using a calibrated scale and the grain moisture content was measured using a calibrated sensor located on the combine. For yield reporting, corn grain masses were adjusted to 155 g kg^{-1} (15.5%) moisture content based on the grain moisture content.

2.5 | Soil sampling and characterization

On 20 May, 2019, soil samples were collected from 10 random locations in the second and third rows from the top 10 cm on the top of the beds in each plot and mixed together for one composite sample per block in the corn study. Though 0-15 cm is the suggested soil sampling depth for soil fertility recommendations in corn in Arkansas (Espinosa & Ross, 2008), the purpose of this soil sampling was not for soil fertility recommendations but was rather for systematically evaluating soil chemical properties over time following application of the various fertilizer-P materials, particularly since the fertilizer-P materials were surface applied without incorporation. Since the study location remained the same for the following year, on 13 May, 2020, soil samples were again randomly collected from 10 locations in the second and third rows from the top 10 cm on the top of the beds in each plot and mixed together for one composite sample per plot in the study area. On 5 October, 2020, at the end of the corn growing season in the second consecutive year, soil samples were again randomly collected from 10 locations in the second and third rows from the top 10 cm on the top of the beds in each plot and mixed together for one composite sample per plot in the study area.

All soil samples collected were oven-dried at 70°C for 48 h, ground, and sieved through a 2-mm mesh screen. In order to confirm the soil textural class, particle-size analyses were conducted on the initial soil samples collected from the corn study in 2019 using a modified 12-h hydrometer method (Gee & Or, 2002) to analyze sand, silt, and clay fractions. Soil electrical conductivity (EC) and pH were measured in a 1:2 soil mass:water volume suspension (Sikora & Kissel, 2014). Soil samples were chemically analyzed to measure extractable nutrient (i.e., K, P, Mg, Ca, S, Fe, Cu, Mn, Na, and Zn) concentrations by a Mehlich-3 extraction method (Zhang et al., 2014) with a 1:10 soil mass:extractant volume solution ratio followed by ICP analysis (Soltanpour, Johnson, Workman, Jones, & Miller, 1996). Weight-loss-ignition was used to determine soil organic matter (SOM) concentration in a muffle furnace at 360°C for 2 h (Zhang & Wang, 2014). Total carbon (TC) and TN concentrations were determined by high-temperature combustion (VarioMax CN analyzer; Provin, 2014). The soil C:N ratio was calculated from the measured TC and TN concentrations. All measured soil C was assumed to be organic C since the soil did not effervesce upon treatment with dilute hydrochloric acid. The Agricultural Diagnostic Laboratory of the University of Arkansas, Division of Agriculture in Fayetteville conducted all soil analyses. 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., October 2020 to May 2019).

2.6 | Plant sampling and characterization

On 2 September, 2019 and 20 August, 2020, when corn reached physiological maturity (Popp, Purcell, & Salmerón, 2016), aboveground biomass was cut at the soil surface in a 1-m row length from the second corn row in each plot and collected. Two corn root masses from the cut aboveground plant materials per plot were meticulously dug out of the soil with a shovel to a depth of approximately 20 cm. Plant samples were collected from within the smaller sub-plots for only the ECST treatment. Soil particles were removed from all sampled plant roots by shaking the roots and rinsing with tap water.

Both years, the total aboveground DM was separated into three parts: stalk + leaves, cob + husk, and kernels. Kernels were removed from cobs using a hand-operated corn sheller. After oven drying, the above- and belowground corn tissue samples were weighed. Additionally, dry matter per unit area was calculated for all aboveground plant tissue samples. Sub-samples of corn stalk + leaves, cob + husk, kernels, and belowground DM samples were mechanically crushed and passed through a 2-mm mesh screen for chemical analyses.

Using a VarioMax CN analyzer, the various parts of corn aboveground and belowground DM were analyzed separately for total N concentration by high-temperature combustion (Provin, 2014). After digestion in concentrated nitric acid with heating, extracts were analyzed by ICP (Soltanpour et al., 1996) to measure above- and belowground tissue P and Mg concentrations. Corn stalk + leaves, cob + husk, and kernel P, N, and Mg concentrations and their respective DMs were used to calculate corn stalk + leaves, cob + husk, and kernel P, N, and Mg uptake (kg ha^{-1}). Corn stalk + leaves, cob + husk, and kernel DM and nutrient uptake were summed to evaluate total aboveground DM and nutrient uptake. The Agricultural Diagnostic Laboratory of the University of Arkansas, Division of Agriculture in Fayetteville conducted all plant analyses.

Corn yields were determined based on the combine-collected kernel masses for all plots, which equated to a sample area of 7.8 m^2, except for the ECST treatment plots. On account of the limited supply of ECST that could be used in the field, only the sub-plots (1.5- by 1.5-m area) for the ECST treatment were combine-harvested, which equated to a smaller sample area of 2.25 m^2. Since a 1-m-row sample had already been collected from the combine-harvested area of each plot, including the ECST sub-plots, the kernel masses from the hand-collected, 1-m-row samples were added to the combine-collected kernel masses for the total corn grain yield each year reported at 15.5% moisture. The same sub-plot size was recently used for ECST in a similar fertilizer-P-source response study for rice (Omidire et al., 2022b.

2.7 | Statistical analyses

Soil data were analyzed based on a randomized complete block design, in which the effect of fertilizer-P source (CPST, ECST, MAP, RP, DAP, TSP, and UC) on the change in soil properties (i.e., extractable soil P, Mg, Ca, K, S, Mn, Cu, Fe, Na, and Zn, soil pH and EC, and SOM, TN, and TC concentrations, and C:N ratio) from their initial magnitudes before any fertilizer-P addition 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 were tested using a one-factor analysis of variance (ANOVA) in SAS version 9.4 (SAS, 2013) with the PROC GLIMMIX procedure. Since soil-property-change data could be positive or negative, a normal distribution was used for all soil properties after visually assessing the studentized residuals.

Plant data were analyzed according to a split-plot experimental design, in which a two-factor ANOVA was conducted using the PROC GLIMMIX procedure in SAS (SAS, 2013) to evaluate the effects of fertilizer-P source, year (2019 and 2020), and their interaction on stalk + leaves, cob + husk, kernel, and total aboveground DM; stalk + leaves, cob + husk, and kernel P, N, and Mg tissue concentrations; stalk + leaves, cob + husk, kernel, and total aboveground P, N, and Mg uptake; belowground P, N, and Mg tissue concentrations; and yield. Since the actual location of the plots did not change each year, the whole-plot factor was year, while the split-plot factor was fertilizer-P source. A gamma distribution was used for all DM, nutrient uptake, and yield data, as these properties are continuous, skewed variables with no upper boundary. However, due to non-convergence issues with the normal and gamma distributions being attempt first, the beta distribution was used for all nutrient concentration data, after dividing the raw percentage data by 100, to achieve model convergence. Significance was judged at $P < 0.05$ for all analyses and least square means were reported. Similar to recent studies (Ylagan et al., 2020; Anderson et al., 2021a,b,c; Omidire et al., 2022b), where similar fertilizer-P treatments were used, least significant difference at the 0.05 level was used to separate means, when appropriate for the current study.

2.8 | Economic analyses

A partial budget analysis was performed to evaluate the economic performance of struvite. Fertilization and yield data from the 2019 and 2020 field studies were coupled with relevant price data to estimate per hectare net revenues associated with each fertilizer-P and N treatment combination. Plot level yields, as well as N and P fertilization rates were scaled up to one hectare of production. Plot yields per treatment were averaged to create an average yield per treatment for both 2019 and 2020. Total revenue for each treatment was calculated by multiplying average annual yield per treatment by the relevant market price for corn in 2019 or 2020 (USDA NASS, 2022). Prices were gathered for urea and each fertilizer-P source (Chaney, 2020; MSU 2018, 2019; Quinn, 2020; Seven Springs Farm Supply, 2020; Watkins, 2021; West Central Ag Services, 2020) with the exception of ECST. Electrochemically precipitated struvite is not currently being produced or sold at the commercial scale. However, it is expected that the market price for ECST will be similar to that of CPST because 1) the equipment required to produce ECST at scale is similar to that for CPST and 2) although the processes will require some variation in inputs between the two struvite production methods (i.e., chemicals needed for CPST production vs. magnesium electrode needed for ECST production), overall input costs are expected to be similar between the two struvite materials. Consequently, the market price for CPST was also used for ECST. Urea and P source application amounts were multiplied by their relevant prices and then added together to create total fertilizer-P treatment costs. Per treatment net revenues were then calculated as total revenue minus total fertilizer-P costs. As TSP is a widely used fertilizer-P source for corn production throughout Arkansas (Watkins, 2021), TSP was used as a reference for comparing net revenues from the six other fertilizer-P treatments

3 | RESULTS AND DISCUSSION

3.1 | Initial soil properties

Corn studies were conducted in the same area of the same field each year and it was important to evaluate the initial soil properties, as a reference, to identify any change in soil properties after one and two growing seasons. Initial soil pH was slightly alkaline (pH = 7.16) and initial extractable soil Ca and Mg levels were above the optimum level (> 400 mg kg^{-1} for Ca and > 30 mg kg^{-1} for Mg) for many row crops grown in Arkansas (Espinosa, Slaton, & Mozaffari, 2021). Since 5.8 to 7.0 is the desirable soil pH range for corn (Espinosa & Ross, 2008), the slightly alkaline soil pH, coupled with the large extractable soil Ca concentration, could render some fraction of fertilizer-applied P unavailable to plant roots due to binding with soil Ca to form insoluble complexes (Espinosa & Ross, 2008). With respects to soil sampling in May 2019, after all plots were established, but before fertilizer application in the corn study, Mehlich-3 P concentration averaged 33.9 mg kg^{-1} [standard error (SE) = 4.7] in the top 10 cm, which was ~ 66% of the optimum for corn production in a silt-loam soil

(Espinosa & Ross, 2008); therefore, a plant response from the applied fertilizer-P treatments in 2019 and 2020 was expected. It was assumed that the soil-test P from the top 10 cm approximated the same soil-test P present in the top 15 cm since the field had a history of cultivated, row-crop production to mix and unify essential plant nutrients near the soil surface. Table 1 summarizes means for all initial soil properties in the corn-study site.

3.2 | Corn response

Corn response to the applied fertilizer-P treatments evaluated in a given year was variable. Seven of the 29 corn properties assessed were affected ($P < 0.05$) by fertilizer-P treatment, either as a main effect or interaction, while 10 corn properties were completely unaffected ($P > 0.05$) by fertilizer-P treatment or year (Table 3).

Corn stalk + leaves DM was unaffected ($P > 0.05$) by fertilizer-P treatment or year (Table 3). Stalk + leaves DM ranged from 7.0 Mg ha^{-1} from DAP in 2020 to 8.7 Mg ha^{-1} from the UC in 2019 and averaged 7.6 Mg ha^{-1} across both years and all seven treatments (Table 4). In contrast to the current results, Ylagan et al. (2020) reported differences in corn stalk + leaves DM among similar fertilizer-P

sources, where stalk + leaves DM was numerically largest from TSP, which did not differ from DAP, MAP, ECST, RP, or the no P/+N control and was numerically smallest from the no P/-N control. Stalk + leaves DM from the two struvite materials, CPST and ECST, did not differ and both were similar to that from MAP, RP, and no P/+N control (Ylagan et al., 2020).

Contrary to expectations, but similar to stalk + leaves DM, stalk + leaves P concentration was unaffected (*P* > 0.05) by fertilizer-P source or year (Table 3). Stalk + leaves P concentration ranged from 0.07 % from RP in 2019 to 0.18 % from CPST in 2020 and averaged 0.11 % across all seven sources and both years (Table 4). Results demonstrate that, despite the soil-test P concentration in the top 10 cm from Fall 2018 indicating a yield response was expected, the study site as a whole was generally unresponsive to fertilizer-P additions, as evidenced by the lack of stalk + leaves P concentration difference from any fertilizer-P source compared to the UC (Table 4). In contrast to the current results, Ylagan et al. (2020) documented corn stalk + leaves P concentration to be numerically greatest from ECST, which differed from other fertilizer-P treatments, and was numerically smallest from the no P/+N control. Stalk + leaves P concentration from CPST, which did not differ from TSP, MAP, DAP, or the no P/-N control, was 160% greater than from the no P/+N control (Ylagan et al., 2020).

Similar to stalk + leaves DM and P concentration, stalk + leaves Mg and N concentrations were unaffected ($P > 0.05$) by fertilizer-P treatment (Table 3). However, averaged across fertilizer-P treatments, stalk + leaves N and Mg concentrations were 3.3 and 1.7 times, respectively, greater ($P < 0.05$) in 2020 than in 2019 (Table 5). In contrast to the current results, Ylagan et al. (2020) documented differences in corn stalk + leaves N and Mg concentrations among fertilizer-P treatments. Stalk + leaves N concentration was numerically largest from CPST, which was similar to ECST, DAP, or RP, and was numerically smallest from the no P/-N control, which differed from all other treatments (Ylagan et al., 2020). Stalk + leaves N concentration from ECST, which was similar to MAP, DAP, or RP, was 1.2, 1.1, and 3.1 times greater than that from TSP, the no P/+N, and the no P/-N controls, respectively (Ylagan et al., 2020). Stalk + leaves Mg concentration was numerically largest from ECST and CPST, which was similar to RP, and numerically smallest from the no P/-N control, which differed from all other treatments (Ylagan et al., 2020).

Similar to stalk + leaves DM and nutrient concentrations, stalk + leaves P, N, and Mg uptake were also unaffected ($P > 0.05$) by fertilizer-P treatment (Table 3). However, averaged across fertilizer-P treatments, stalk + leaves P, N, and Mg uptake were 1.8, 2.8, and 1.6 times, respectfully, greater ($P < 0.05$) in 2020 than in 2019 (Table 5). In contrast to the current results, Cabeza, Steingrobe, Romer, & Claassen, (2011) in a 2-year pot experiment reported differences in corn shoot P uptake among fertilizer-P treatments. Cabeza et al. (2011) documented similar shoot P uptake between sewage-treatment-plant-derived struvite and TSP, which was 2.0 times greater than that from the UC. Additionally, in two soils in the first year, similar shoot P uptake from RP and the UC were reported to be comparable, but in year two, lower shoot P uptake was reported for the UC than that for RP (Cabeza et al., 2011).

Similar to stalk + leaves DM and nutrient concentrations and uptake, cob + husk DM was also unaffected ($P > 0.05$) by fertilizer-P treatment (Table 3). However, averaged across fertilizer-P treatments, cob + husk DM in 2019 was at least 1.1 times greater ($P = 0.02$) than in 2020 (Table 5). In contrast to the current results, Ylagan et al. (2020) documented differences in corn cob + husk DM among fertilizer-P sources. Cob + husk DM was numerically largest from CPST, which was similar to ECST, TSP, MAP, DAP, RP, and the no P/+N control, and was numerically smallest from the no P/-N control, which differed from all other treatments (Ylagan et al., 2020).

Similar to stalk + leaves DM and P concentration, cob + husk P concentration was also unaffected ($P > 0.05$) by fertilizer-P treatment or year (Table 3). Cob + husk P concentration ranged from 0.05 % from MAP in 2019 to 0.09 % from DAP in 2020 and averaged 0.07 % across all seven treatments and both years (Table 4). In contrast to the current results, Ylagan et al. (2020) documented differences in corn cob + husk P concentration among fertilizer-P sources. Cob + husk P concentration

was numerically largest from ECST, which was similar to MAP, DAP, and the no P/-N control, while cob + husk P concentration was numerically smallest from the no P/+N control, which was similar to CPST, TSP, and RP (Ylagan et al., 2020). Cob + husk P concentration was 1.2 times greater from ECST than from CPST and TSP, and at least 1.3 times greater than from RP and the no P/+N control (Ylagan et al., 2020). It is important to point out that the Ylagan et al. (2020) study was performed in space-

limited pots in the greenhouse, where roots had no access to deeper soil nutrients and had to completely rely on applied nutrients. However, in the field, such as in the current study, roots had ample access to deeper soil and more nutrients than those that were applied to potentially mask the effects of the various fertilizer-P sources evaluated.

Similar to stalk + leaves DM and nutrient concentrations and uptake and cob + husk DM and P concentration, cob + husk N and Mg concentrations were also unaffected ($P > 0.05$) by fertilizer-P treatment (Table 3). However, averaged across fertilizer-P treatments, cob + husk N and Mg concentrations were 2.0 and 1.7 times, respectfully, greater ($P < 0.05$) in 2020 than in 2019 (Table 5). In contrast to the current results, Ylagan et al. (2020) reported corn cob + husk N concentration was numerically largest from MAP, which was similar to ECST, CPST, TSP, RP, DAP, and the no P/+N control, and was numerically smallest from the no P/-N control, which differed from all other treatments. However, similar results to the current study were documented by Ylagan et al. (2020) where corn cob + husk Mg concentration were similar among fertilizer-P sources.

Similar to stalk + leaves DM, nutrient concentrations and uptake, cob + husk DM and nutrient concentrations, cob + husk P, N, and Mg uptake were also unaffected ($P > 0.05$) by fertilizer-P treatment (Table 3). However, averaged across fertilizer-P treatments, cob + husk

P, N, and Mg uptake in 2020 were 1.5, 1.8, and 1.4 times, respectfully, greater (*P* < 0.01) than in 2019 (Table 5).

In contrast to stalk + leaves DM, nutrient concentrations and uptake and cob + husk DM, nutrient concentrations, and uptake, kernel DM (i.e., from 1-m row samples) differed (*P* < 0.05; Table 3) among fertilizer-P treatments. Averaged across year, kernel DM was numerically largest from ECST (11.5 Mg ha^{-1}), which was similar to MAP and UC, and was numerically smallest from DAP (9.2 Mg ha^{-1}), which was similar to CPST, RP, TSP, and UC (Table 6). Kernel DM from ECST was at least 1.1 times greater than that from TSP, RP, CPST, or DAP, while kernel DM from MAP was at least 1.1 times greater than that from DAP (Table 6).

Similar to stalk + leaves DM and P concentration and cob + husk P concentration, kernel P, Mg, and N concentrations were also unaffected (*P* > 0.05) by fertilizer-P treatment or year (Table 3). Kernel P concentration ranged from 0.27 % from RP in 2020 to 0.33 % from ECST in 2020 and averaged 0.29 % across all seven treatments and both years (Table 4). Kernel N concentration ranged from 1.1 % from TSP in 2019 to 1.4 % from ECST in 2020 and averaged 1.2 % across both years and all seven treatments (Table 4). Kernel Mg concentration ranged from 0.09 % from MAP in 2019 to 0.12 % from ECST in 2020 and averaged 0.10 % across both years and all seven treatments (Table 4).

Similar to kernel DM, kernel P and Mg uptake differed (*P* < 0.05; Table 3) among fertilizer-P treatments. Averaged across year, kernel P uptake was numerically largest from ECST (35 kg ha^{-1}), which was similar to MAP, and was numerically smallest from DAP (26 kg ha^{-1}), which was similar to CPST, MAP, RP, TSP, and UC (Table 6). Kernel P uptake was at least 1.2 times greater from ECST than from CPST, TSP, RP, DAP, or UC (Table 6). Averaged across year, kernel Mg uptake was numerically largest from ECST (12.8 kg ha^{-1}), which was similar to MAP and UC, and was numerically smallest from DAP (9.5 kg ha^{-1}), which was similar to CPST, RP, MAP, TSP, and UC (Table 6). Kernel Mg uptake was at least 1.2 times greater from ECST than that from RP, DAP, TSP or CPST (Table 6).

Greater kernel Mg uptake from ECST was expected due to the composition and dissolution of the struvite, with an initial Mg concentration greater than that in other fertilizer-P treatments (Table 2). The slow dissolution of ECST likely maintained the Mg closer to the actively growing corn root zone for extended plant availability. However, kernel Mg uptake from CPST was expected to be greater than that from RP, TSP, MAP, DAP, and the UC because of greater initial Mg concentration in the CPST material (Table 2). The CPST dissolution rate to release available Mg likely did not match the timing of Mg requirement of the corn plants.

In contrast to stalk + leaves DM, nutrient concentrations and uptake, cob + husk DM, nutrient concentrations and uptake, kernel DM, nutrient concentrations and P and Mg uptake, only kernel N uptake differed across fertilizer-P treatments between years (P = 0.04; Table 3). In 2019, kernel N uptake was numerically largest from ECST (131 kg ha^{-1}), which was similar to DAP, MAP, TSP, and the UC, and was numerically smallest from RP (97 kg ha^{-1}), which was similar to CPST, DAP, MAP, and TSP (Table 7). In 2019, kernel N uptake was 1.3 and 1.4 times greater from ECST than from CPST and RP, respectively (Table 7). In 2020, kernel N uptake was numerically greatest from ECST (170 kg ha^{-1}), which was similar to MAP and RP, and numerically smallest from DAP (122 kg ha^{-1}), which was similar to CPST, TSP, and the UC (Table 7). In 2020, kernel N uptake from ECST was 1.2, 1.4, 1.2, and 1.3 times greater than that from CPST, DAP, TSP, and the UC, respectively (Table 7). Kernel N uptake from ECST, CPST, MAP, RP, and TSP in 2020 were greater those in 2019 (Table 7). However, kernel N uptake from DAP and the UC in 2020 did not differ from those in 2019 (Table 7). Though the same amount of total N was applied to all experimental units, the difference in kernel N uptake could have been in part due to a reduction in ammonia volatilization from the use of NBPT-coated urea in 2020.

Similar to stalk + leaves DM, but contrary to expectations and in contrast to kernel DM, total aboveground corn DM was also unaffected ($P > 0.05$) by fertilizer-P treatment or year (Table 3), though the initial soil-test-P category was below optimum, and a plant response was expected, at least from the fertilized treatments compared to the UC. Total aboveground corn DM ranged from 18.1 Mg ha^{-1} from DAP in 2020 to 21.5 Mg ha^{-1} from UC in 2019 and averaged 19.9 Mg ha^{-1} across both years and all fertilizer-P treatments (Table 4).

The lack of difference in stalk + leaves DM, nutrient concentrations and uptake, cob + husk

DM, P, N, and Mg concentrations and uptake, kernel tissue P, N, and Mg concentrations, and total aboveground DM across fertilizer-P treatments was likely due to the slightly alkaline initial soil in 2019 and large concentration of initial extractable soil Ca (Table 1) that facilitated P fixation as Ca-phosphate (Ca-P) minerals as the fertilizer materials dissolved. In neutral to alkaline soils, inorganic P can precipitate as a secondary mineral with Ca and Mg in soils with large Mg concentrations (Havlin, Tisdale, Nelson, & Beaton, 2014). Although soil pH after two growing seasons had generally decreased from the initial pH level across all fertilizer-P treatments (Figure 1; Table 8), soil pH in most treatments were still slightly alkaline (Figure 1). After fixation of P released from the added fertilizers, rendering at least some of the fertilizer-P unavailable for plant uptake, corn roots may have also explored soil below the top 10 cm, where the soil pH was likely lower than at the surface. Consequently, native soil P likely became the more reliable P source for root uptake (Perez, Steingrobe, Romer, & Claassen, 2009) resulting in no difference in aforementioned corn properties among fertilizer-P treatments. Furthermore, the fertilizer-P materials were surface-applied without incorporation, which likely rendered much of the fertilizer-P applied vertically stratified near the soil surface.

Similar results to the present study were documented in a 19-week field trial by Gell, De Ruijter, Kuntke, De Graaff, & Smit, (2011) who assessed the effects of TSP, blackwater-recovered and urine-recovered struvite on corn response in an acidic sandy loam Andisol. Gell et al. (2011) documented similar corn DM among TSP, struvite, and the UC.

In contrast, differences in aboveground DM among fertilizer-P treatments have been documented

by Thompson (2013), Rech et al. (2019), and Ylagan et al. (2020). Ylagan et al. (2020) showed that aboveground corn DM was numerically largest from TSP, which was similar to CPST, MAP, DAP, and RP, and was 1.1, 1.1, and 1.7 times greater than from ECST and the no P/+N and no P/-N controls, respectively, in a greenhouse study. Corn aboveground DM was numerically smallest from the no P/-N

control among all fertilizer-P treatments. Aboveground DM from ECST and CPST were similar to one other and aboveground DM from ECST was also similar to RP, DAP, MAP, and the no P/+N control.

Similar to stalk + leaves, cob + husk, and kernel tissue P concentrations and total aboveground DM, total aboveground tissue P uptake was also unaffected ($P > 0.05$) by fertilizer-P treatment or year

(Table 3). Total aboveground tissue P uptake ranged from 30.5 kg ha^{-1} from RP in 2019 to 50.9 kg ha^{-1} from ECST in 2020 and averaged 39.2 Mg ha^{-1} across both years and all seven treatments (Table 4). The lack of total aboveground tissue P uptake difference across fertilizer-P treatments was likely due to the adsorption of P to secondary mineral or clays and showed that the study site was generally non-responsive to fertilizer-P additions, despite soil-test P levels suggesting a yield response was expected. Though the soil texture across the study site was silt loam, there was, on average, 14% clay present in the top 10 cm (Table 1), which may have contributed to P adsorption. Large concentrations of Ca present in the top 10 cm (Table 1) of the alkaline soil in the study area likely precipitated some of the P released after fertilizer-P dissolution in the soil solution (Espinosa & Ross, 2008; Roberts et al., 2016; Table 1). The optimum soil pH for corn ranges from 5.8 to 7.0 (Espinosa & Ross, 2008). At soil pHs ≥7.0, P can bind with Ca forming insoluble Ca-P that are mostly unavailable to plant roots (Espinosa & Ross, 2008; Havlin et al., 2014). It is also plausible that corn roots may have extracted sufficient P from below the top 10 cm of the soil to nullify potential differences among fertilizer-P treatments.

Similar to results of the present study, Gell et al. (2011) documented similar corn P uptake among TSP, struvite, and UC. However, other studies have shown a difference in aboveground tissue P uptake across fertilizer-P sources in other crops (Rech et al., 2019). Rech et al. (2019) documented that wheat total P uptake was similar between TSP and two struvite sources but was at least 23% greater from TSP than from CPST and the UC.

In contrast to P uptake, total aboveground tissue N uptake was affected ($P < 0.05$) by fertilizer-P treatment or year (Table 3). Averaged across years, total aboveground tissue N uptake was numerically largest from ECST (228 kg ha^{-1}), which was similar to MAP, RP, and the UC, and was numerically smallest from DAP (179 kg ha^{-1}), which was similar to CPST, TSP and the UC (Table 6). Total aboveground tissue N uptake was at least 1.2 times greater from ECST than from CPST, DAP, and TSP, which were similar to one another (Table 6). Total aboveground tissue N uptake from MAP and RP, which averaged 205 kg ha^{-1}, was 1.1 times greater than from DAP (Table 6). Similar to stalk + leaves and cob + husk N and Mg concentrations and uptake, averaged across fertilizer-P treatments, total aboveground tissue N uptake in 2020 was 1.7 times greater ($P < 0.05$) than in 2019 (Table 5).

Similar to stalk + leaves, cob + husk, and kernel tissue P concentrations, total aboveground DM, and P uptake, total aboveground tissue Mg uptake was also unaffected ($P > 0.05$) by fertilizer-P treatment (Table 3), despite greater initial Mg concentrations in CPST and ECST, thus a plant response to Mg was expected, at least from the two struvite sources compared to the other fertilizer-P sources. Similar to total aboveground tissue N uptake, averaged across fertilizer-P treatments, total aboveground tissue Mg uptake in 2020 was 1.5 times greater ($P < 0.05$) than in 2019 (Table 5).

The differences in total aboveground tissue N uptake between CPST and ECST was at least partially due to the N in the ECST material originating from a synthetic rather than a real wastewater like the N in the CPST material were. It is possible that the presence of additional compounds, such as organic compounds and low concentrations of some heavy metals from the original wastewater (Ostara, 2022), in the CPST material rendered the N somewhat less mobile once in the plant than the chemically cleaner N in the ECST (Ylagan et al., 2020). Furthermore, struvite's dissolution can differ depending on the source material and purity of the struvite produced (Hertzberger, Cusick, & Margenot, 2020).

Greater stalk + leaves and cob + husk tissue P uptake in 2020 than in 2019 was likely due to reduction in initial soil pH in the second growing season (Table 8, Figure 1), thus releasing some P from precipitated/fixed Ca-P compounds. Greater total aboveground tissue N uptake in 2020 than in 2019 could in part be due to a reduction in ammonia volatilization from the use of NBPT-coated urea to unify the N rate among all fertilizer-P sources and as mid-season N fertilizer in 2020, whereas uncoated urea was mistakenly used in 2019 instead of coated urea. Additionally, it is plausible that total aboveground tissue N uptake in 2019 was lower than that in 2020 due to runoff of the surface-applied uncoated urea from the top of the beds into the furrows and/or leaching of N after 0.1 (later in the same day, but after mid-season N application), 1.0 (the following day after mid-season N application), and 9.2 cm (two days after mid-season N application) of rainfall fell on the study field in 2019. Greater total aboveground tissue Mg uptake in 2020 than in 2019 was likely a result of a carry-over effect from fertilization in 2019 since the same plots were used in both years.

Similar to stalk + leaves DM, P concentration, cob + husk P concentration, and kernel nutrient concentrations, belowground Mg, N, and P concentrations did not differ ($P > 0.05$) among fertilizer-P treatments or between years (Table 3). Belowground P concentration ranged from 0.05 % from the UC in 2020 to 0.12 % from TSP in 2019 and averaged 0.08 % across both years and among all fertilizer-P treatments (Table 4). Belowground N concentration ranged from 0.43 % from TSP in 2019 to 0.77 % from ECST in 2020 and averaged 0.57 % across both years and among all fertilizer-P treatments (Table 4). Belowground Mg concentration ranged from 0.12 % from MAP in 2019 to 0.21 % from ECST in 2020 and averaged 0.16 % across both years and among all fertilizer-P treatments (Table 4).

Application of a balanced amount of total N to all treatments, which was expected to be uniformly available for plant uptake, was likely why stalk + leaves, cob + husk, kernel, and belowground tissue N concentrations were unaffected by fertilizer-P treatments. The N in the urea likely became available at a similar time during corn growth for uniform uptake in all fertilizer-P treatments, creating no difference in stalk + leaves, cob + husk, kernel, and belowground tissue N concentrations. The product of significant kernel DM (Table 6), but only numeric kernel N concentration (Table 4) differences among fertilizer-P treatments was likely responsible for the kernel N uptake differences among fertilizer-P treatments. Despite no effect of fertilizer-P source on stalk + leaves, cob + husk, kernel, and belowground tissue Mg concentration in the current study, and even though the Mg concentration of fertilizer-P materials varied, Gell et al. (2011) reported 28% increase in Mg concentrations in corn aboveground tissue from struvite generated from blackwater than that from TSP and the UC. Thus, Gell et al. (2011) used a different struvite source material compared to the current study, where the solubility of struvite can differ depending on the source material and purity of the struvite produced (Hertzberger et al., 2020).

Similar to total aboveground tissue Mg and N uptake, corn combine yields differed ($P < 0.01$) among fertilizer-P treatments (Table 3). Averaged across years, yield was numerically largest from ECST (12.9 Mg ha^{-1}), which differed from all other treatments, and was numerically smallest from DAP (10.1 Mg ha^{-1}), which was similar to CPST, RP, MAP, and the UC (Table 6). Yield from ECST was at least 1.2 times greater than that from CPST, DAP, MAP, RP, and the UC, which were similar to one another (Table 6). Yield was 1.2 times greater from ECST than from TSP, which was similar to CPST, RP, MAP, and the UC (Table 6). Yield was 1.1 times greater from TSP than from DAP (Table 6).

Though stalk + leaves, cob + husk P concentration and uptake and kernel P concentration were similar across fertilizer-P treatments (Table 3), the differences in kernel P uptake, where ECST had the numerically largest kernel P uptake, which was also significantly greater than the UC (Table 6), likely contributed to ECST's yield differences. It is also possible that the corn yield differences dictated the differences in kernel P uptake. However, due to the necessarily small sub-plot size associated with the ECST treatment on account of the limited available supply of ECST, plot-level grain yields for the ECST treatment were based on a combined-harvested area of approximately 30% of that for plots of all other treatments. Consequently, the larger ECST yields recorded in this study could have been partially due to the differential sample size. Regardless, the limited available supply of ECST material to use in this field study necessitated use of a smaller sub-plot from which the smaller sample for yield was collected.

Similar to total aboveground tissue N and Mg uptake, but contrary to expectations and in contrast to total aboveground tissue P uptake, averaged across fertilizer-P sources, yield in 2019 was at least 1.1 times greater (P = 0.02) than in 2020 (Table 5). Since the actual monthly air temperature during the two corn growing seasons were similar, greater corn yields in 2019 may be attributed to greater rainfall in 2019 than in 2020 (Figure 2). Rainfall was 1.3, 1.4, and 2.5 times greater in May, June, and July 2019, respectfully, than similar months in 2020 (Figure 2). Despite being furrow-irrigated, corn growth and productivity would have benefitted from more uniform, well-watered soil moisture conditions in 2019 with lower magnitudes of soil moisture fluctuations than in 2020 with less timely rainfall events.

For a corn yield goal of 13.8 Mg ha^{-1} grown on a silt-loam soil (Espinosa & Ross, 2008), the application of fertilizer-P was expected to create a corn yield response because the initial soil-test P concentration was below optimum, indicating corn growth and productivity would likely be limited by P. Similar to kernel DM and P uptake, corn yield from ECST was numerically largest and differed from all other treatments likely because the reduction in soil pH from the initial soil pH by 0.35 units was numerically largest in the ECST (Figure 1), making the soil pH fall within the desirable soil pH range for corn (5.8 to 7.0;

Espinosa & Ross, 2008), thus greater dissolution and availability of P from precipitated/fixed Ca-P. The acidification effect of the ECST material in the soil may have also changed the available P species and ratio between HPO_4^{2-} and $H_2PO_4^-$ towards comparatively more $H_2PO_4^-$ in the soil solution, thus increasing dissolution and mobility of P from the ECST material and Ca-P (Gahoonia, Claassen, & Jungk, 1992). However, the timing of the pH change is unknown and temporal changes in

pH can occur from fluctuating soil moisture. The difference in kernel P uptake and combine yield from CPST and ECST that were used in the present study was at least partially due to the presence of

additional associated complexes, such as organic compounds in the actual wastewater-recovered CPST material, which likely rendered P less mobile in plant than the P taken up from the synthetic-wastewater-recovered ECST material that was purer in composition than CPST (Hertzberger et al., 2020; Ylagan et al., 2020).

Averaged across all fertilizer-P treatments, corn yields from the present study were lower in 2019 than the yield results from the Arkansas Corn Performance Trial in 2019 (13.5 Mg ha^{-1}) for the same Pioneer 1870YHR corn variety grown at CBES (Carlin, Bond, & Still, 2020). Corn yields from the present study ranged from 10.4 Mg ha^{-1} from RP to 13.2 Mg ha^{-1} from ECST in 2019 and averaged 11.4 Mg ha^{-1} among all fertilizer-P treatments. There was no report for the Pioneer 1870YHR from the Arkansas Corn Performance Trial yield results in 2020 at CBES, however the closest corn variety to that of the current study was Pioneer 1847VYHR (15.1 Mg ha^{-1}; Carlin, Bond, & Morgan, 2021). Similar to the current study, irrigated corn in the Arkansas Corn Performance Trial was grown on a Calloway silt loam in both years. Averaged across all fertilizer-P treatments, corn yields from the present study were also lower in 2020 than those from the Arkansas Corn Performance Trial yield results in 2020 at CBES. Corn yields from the present study ranged from 9.3 Mg ha^{-1} from CPST to 12.7 Mg ha^{-1} from ECST in 2020 and averaged 10.3 Mg ha^{-1} among all fertilizer-P treatments. Results for corn grown in 2019 and 2020 in the present study differed somewhat from the irrigated corn grown in the Arkansas Corn Performance Trial at CBES, which had earlier planting dates and 1.14 times more applied-N than what was used in the current study. A different corn variety used in the 2020 Arkansas Corn Performance Trial could also have been a contributing factor to greater yields than that from the current study.

3.3 | Change in soil properties

The effects of various fertilizer-P sources on the change in soil properties in the 0- to 10-cm depth from initial values after one year and after two growing seasons for the corn study were variable. The change in all 14 soil properties after one year were unaffected ($P > 0.05$; Table 8) by fertilizer-P treatment. Two of the 12 soil property changes from the initial evaluated after two growing seasons differed ($P < 0.05$) among fertilizer-P treatments, while 10 soil property changes from the initial were unaffected ($P > 0.05$) by fertilizer-P treatment (Table 8).

After two-growing seasons, soil pH generally decreased ($P < 0.05$; Table 8) from the initial values in all treatments (Figure 1). Soil pH decreased more for ECST (-0.35 pH units) than MAP, RP, and the UC (-0.19, -0.13, and -0.14 pH units, respectively), which were all a significant change from a change of zero. However, the change in soil pH from the initial pH did not differ from zero for CPST, DAP, and TSP (Figure 1). The acidifying effect that was present in ECST, MAP, RP, and the UC treatments after two corn growing seasons was likely due to differences in fertilizer compositions and forms of P present in the fertilizers (i.e., HPO_4^{2-} and $H_2PO_4^-$; FTRC, 2015). The dissolution of accumulated fertilizer-P and the influx of various cations (i.e., Mg^{2+}, Ca^{2+}, and NH_4^+), which displaced H^+ on soil exchange sites at potentially different concentrations (Nascimento, Pagliari, Faria, & Vitti, 2018; Anderson, Brye, Greenlee, & Gbur, 2020) likely reduced the soil pH among fertilizer-P sources after two growing seasons. Fertilizers containing P in the phosphate form ($H_2PO_4^-$), such as MAP and TSP, can cause an acidifying effect in alkaline soils due to the dissociation of H^+ (FTRC, 2015), which did not happen for TSP. The greater reduction in soil pH in the ECST treatment than in other fertilizer treatments was at least partly caused by greater initial Mg concentrations from both batches of ECST in 2019 and 2020 than all other fertilizer-P sources, which likely affected exchange-site equilibria with the soil solution as a greater concentration of Mg^{2+} from the dissolving ECST material could have replaced H^+ ions on soil exchange sites to increase the H^+ concentration in the soil solution.

After two growing seasons, the change in soil P concentration from the initial concentration differed among fertilizer-P sources ($P < 0.05$; Table 8). Though the change in soil P concentration did not differ from zero for all treatments, soil P concentration decreased the most in the UC (-17.4 mg kg^{-1}), which did not differ from ECST and RP (-13.2 and -15.4 mg kg^{-1}; Figure 1). Soil P concentration decreased least in the CPST treatment (-9.5

mg kg^{-1}), which did not differ from ECST, DAP, MAP, and TSP (Figure 1). The decrease in soil P concentration in CPST differed from RP and the UC (Figure 1). The soil-P concentration decrease in RP did not differ from ECST, DAP, MAP, and TSP (Figure 1). The soil-P concentration decrease in ECST was similar to all other treatments (Figure 1).

The larger reduction in soil pH from the initial for ECST likely enhanced nutrient dissolution and availability for corn uptake, which was demonstrated in greater kernel DM, tissue Mg and P uptake, total aboveground tissue Mg and N uptake, and yield in 2019 and 2020 than the most commonly used and more readily soluble fertilizer-P sources in Arkansas (i.e., TSP; Chien et al., 2011; Slaton et al., 2013). The large P uptake in the ECST treatment correlated with the reduction in soil-P concentration from the initial for ECST.

3.4 | Economic evaluation

Because the partial budget analysis included an evaluation of both revenues associated with yields and costs associated with fertilization, even statistically non-significant yield differences may lead to meaningful economic differences in net revenues for a producer. Relative returns to fertilizer-P source as compared to TSP for 2019 and 2020 are presented in Table 9. Although the price of wastewater-recovered struvite was roughly double that of other non-struvite fertilizer-P sources, economic returns to ECST out-performed all other fertilizer-P sources during both study years. Numerically greater yields achieved with ECST were large enough to offset the greater fertilizations. Across all seven treatments, returns to CPST ranked sixth and seventh for 2019 and 2020, respectively. In 2019, corn yields from

CPST were numerically greater than from MAP, DAP, and RP, which resulted in greater returns for

CPST than RP. However, greater numeric yields were not large enough to overcome the lower fertilization costs of MAP and DAP. In 2020, corn yields from CPST were lower than from all other treatments, resulting in substantially lower returns.

In addition to P, fertilizer-P sources contain varying amounts of other nutrients, such as N. Therefore, as N is an important input for corn production, the economic effect of varying N concentrations among the various fertilizer-P treatments (Table 2) was also evaluated. In 2019, fertilization costs associated with urea applications were 1.9 to 5.4% lower for the struvite fertilizers than for TSP. For 2020, costs of N fertilization were even lower for ECST because the ECST produced in 2020 contained a larger N concentration. This fertilizer-N cost difference suggests that ECST's N concentration can potentially impact profits and therefore, moving forward, should also be evaluated for the optimal N concentration to meet crop needs and maximize profits. Despite the total fertilizer-N

applied being equal across all treatments, to study the effects of fertilizer-P source, N had to be balanced among the fertilizer-P treatments, otherwise the experimental results would have been confounded between different fertilizer-P and -N amounts. The differences in ECST's N concentration between the two batches produced and used in this study would still have impacted the economics despite the equalized total N applied to all treatments because of the costs of N from ECST and urea differ.

3.5 | Implications

All corn responses evaluated showed that struvite (i.e., ECST and CPST) had no substantially adverse effects on crop growth and productivity. In some cases, ECST had a greater positive effect on corn properties than most other fertilizer-P treatments. Though several studies have reported the slow-release nature for struvite materials (Bhuiyan, Mavinic, & Beckie, 2007; Rahman et al., 2014; Nascimento et al., 2018; Anderson et al., 2020), the innovative ECST did not exhibit slow-release characteristics under field conditions in this study, as evidenced by the general lack of treatment differences among fertilizer-P treatments for P, N, and Mg tissue concentrations and uptake. It is important to highlight that the crystalline structure of the ECST had a considerably larger surface area to react with the soil and water than the pelletized CPST with a relatively larger diameter, and that the difference in surface area potentially allowed for more rapid dissolution of the ECST material. Whether slow-release or not, considering the many similar corn growth and yield responses from the two struvite materials (i.e., ECST and CPST) compared to other widely used, commercially available fertilizer-P sources, the struvite-P sources appear to be viable alternative fertilizer materials for furrow-irrigated corn production on a silt-loam soil in eastern Arkansas.

Though presently more expensive due to a young, developing industry and apart from the P supply from wastewater-recovered struvite, producers get N and Mg basically for free in struvite compared to TSP since struvite is generally marketed as a fertilizer-P source. With N prices reaching record highs in 2021 and the price of TSP having almost doubled in the last two years (Fernández, 2021; Outlaw et al., 2022), as a potential alternative fertilizer-P source, struvite could be a more sustainable and economical nutrient source to help offset some of the supply and demand issues of RP. Furthermore, the primary energy demand associated with fertilizer creation from RP is with the mining process of RP itself (Lee, Assi, Daher, Mengoub, & Mohtar, 2020; Jing, Hou, Wang, Yao, & Liu, 2021). Compared to the large energy inputs needed for mining RP, struvite could be considered a more energy-efficient, fertilizer alternative.

Struvite recovery is beneficial to the agricultural industry as a viable fertilizer-P product to maintain or improve crop yields and reduce global dependency on dwindling RP reserves for long-term sustainability of crop production, but also to the wastewater treatment industry to reduce P concentrations in effluents and improve treatment efficiencies, cost, and time (Parsons et al., 2001; Tansel, Lunn, & Monje, 2018; Hallas, Mackowiak, Wilkie, & Harris, 2019).

4 | CONCLUSIONS

Agronomic benefits of wastewater-recovered struvite had been documented in previous studies particularly in the greenhouse pot experiments. However, to date, no studies have documented ECST effects on corn growth and productivity relative to other commercially available fertilizer-P materials under field conditions.

The hypothesis that corn total aboveground DM and yield, total aboveground tissue P and N uptake, and belowground P and N concentrations from wastewater-recovered struvite materials (i.e., CPST and ECST) would not differ from other conventional, commercially available fertilizer-P materials (i.e., RP, DAP, TSP, and MAP) was only partially supported because total aboveground tissue N uptake and yield differed among all seven fertilizer-P treatments evaluated. Similarly, results did not support the hypothesis that corn belowground tissue Mg concentrations and total aboveground tissue Mg uptake would be greater for CPST and ECST due to their greater initial Mg concentrations. However, the hypothesis that corn grown in year two would have greater total aboveground, DM, yield, total aboveground tissue P, N, and Mg uptake, and belowground tissue P, N, and Mg concentrations compared to that in year one due to a carry-over effect from year-one fertilization was partially supported. Corn yields from year one (2019) were greater than from year two (2020) and total aboveground DM and tissue P uptake and belowground tissue P, N, and Mg concentrations did not differ between years.

Though this study had some logistical constraints, results clearly demonstrated that wastewater-removed struvite, derived by electrochemical or chemical precipitation methods, can potentially be a viable, alternative fertilizer-P material for corn, as evidenced by the abundance of similar corn responses to other fertilizer-P sources. All corn properties affected by fertilizer-P treatment (i.e., kernel DM, tissue P and Mg uptake, total aboveground tissue N and Mg uptake, and yield in 2019 and 2020) had at least similar (from CPST) and at times greater (from ECST) response than other widely used fertilizer-P materials (i.e., TSP, DAP, and RP). Furthermore, while costs for wastewater-recovered struvite were greater than other fertilizer-P sources, larger measured yields for ECST, and, in some cases CPST, indicated a potential for economic viability as well. Additionally, wastewater treatment industry could benefit from struvite recovery through the reduction of P concentrations in effluents and improvement in treatment efficiencies, cost, and time

(Parsons et al., 2001; Tansel, Lunn, & Monje, 2018; Hallas, Mackowiak, Wilkie, & Harris, 2019).

Overall, results provided useful information regarding the potential response of corn to crystalline ECST and pelletized CPST relative to other conventionally used fertilizer-P sources on a P-deficient silt-loam soil. Though a synthetic-wastewater-recovered ECST was evaluated in this study, additional research is needed to assess the effectiveness of ECST derived from a municipal or animal agriculture wastewater in various soil physiochemical conditions and other upland, row-crop production settings under field conditions. If struvite continues to perform at least on par with other fertilizer-P sources, expected reductions in struvite production costs, and/or continued volatility in conventional N and P fertilizer markets, could further improve the economic viability of struvite use in corn production.

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Figure Captions

FIGURE 1 Summary of the change in soil-test pH for the corn study (A) and the change in extractable soil phosphorus (P) concentration for the corn study (B) in the top 10 cm among fertilizer-P sources after two growing seasons on a P-deficient, silt-loam soil in eastern Arkansas. An asterisk (*) indicates mean value is different than zero ($P < 0.05$).

FIGURE 2 Summary of the 30-year (1981 to 2010) mean monthly rainfall and air temperature and actual monthly rainfall and air temperature during corn growing seasons in 2019 and 2020 at the Cotton Branch Experiment Station near Marianna, AR.

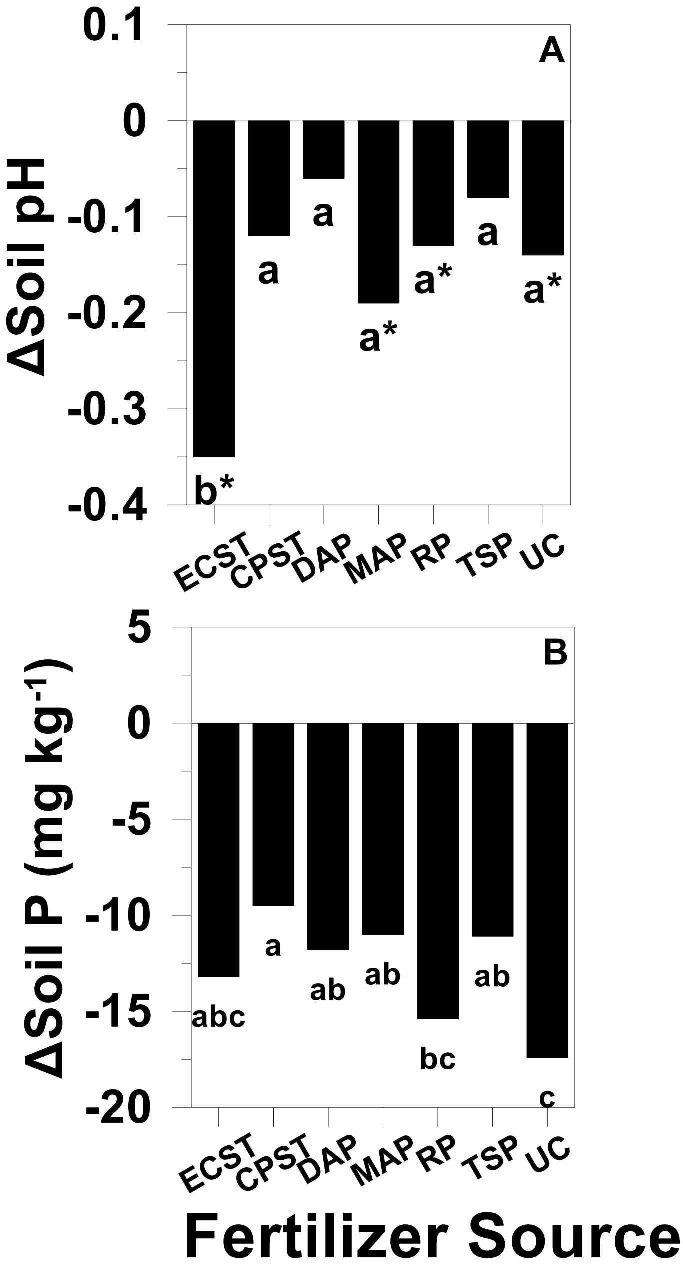
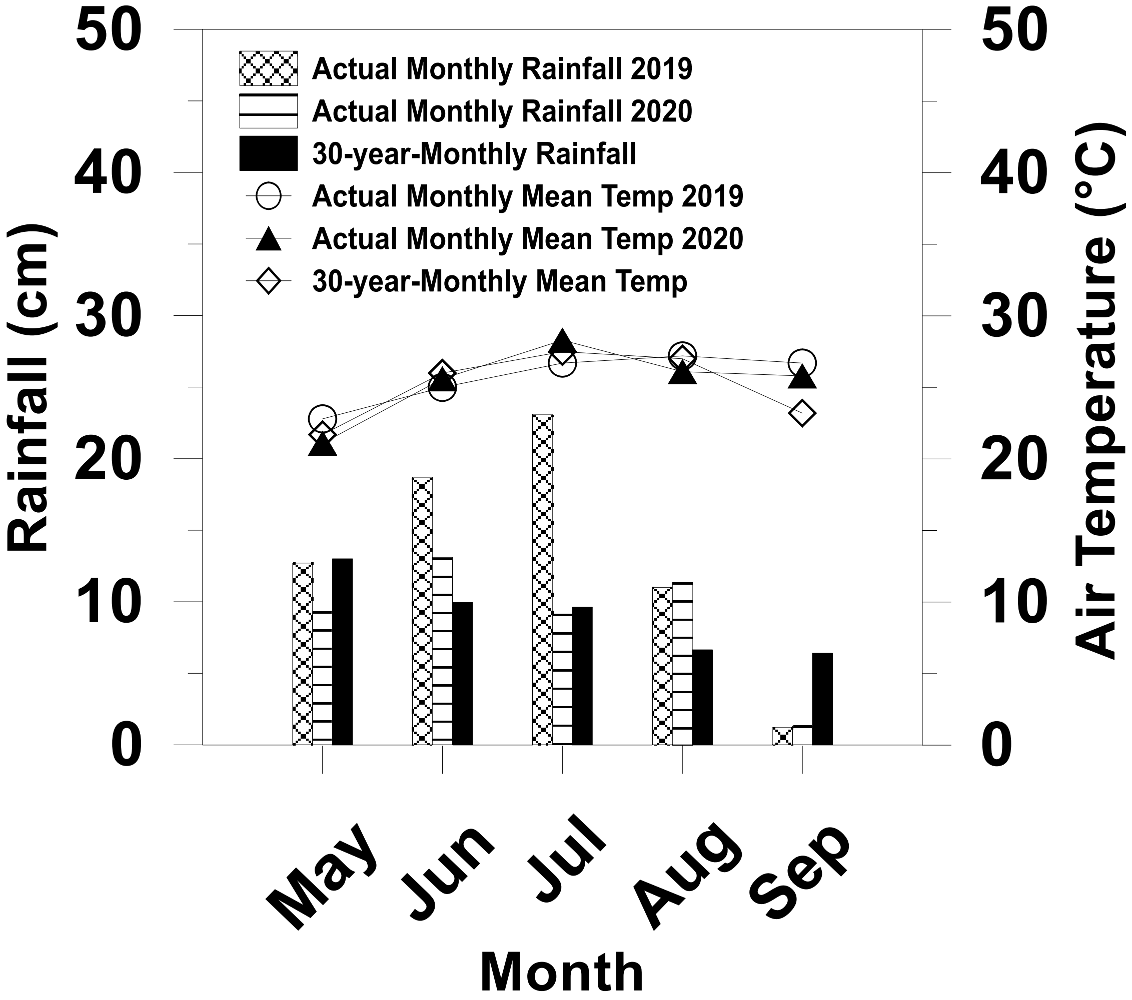

A
ΔSoil pH
0.1
0
-0.1
-0.2
-0.3
-0.4
b*
a
a
a*
a*
a
a*
ECST
CPST
DAP
MAP
RP
TSP
UC
B
ΔSoil P (mg kg-1)
5
0
-5
-10
-15
-20
abc
a
ab
ab
bc
ab
c
ECST
CPST
DAP
MAP
RP
TSP
UC
Fertilizer Source

FIGURE 1



50
40
30
20
10
0
Actual Monthly Rainfall 2019
Actual Monthly Rainfall 2020
30-year-Monthly Rainfall
Actual Monthly Mean Temp 2019
Actual Monthly Mean Temp 2020
30-year-Monthly Mean Temp
Rainfall (cm)
Air Temperature (°C)
May
Jun
Jul
Aug
Sep
Month

FIGURE 2

TABLE 1 Summary of initial soil properties in the top 10 cm for the corn study area in 2019 in a phosphorus (P)-deficient, silt-loam soil in eastern Arkansas. Means (± standard error) are reported (n = 4).

Soil Properties	**Mean (± standard error)**
Sand (kg kg^{-1})	0.07 (0.02)
Silt (kg kg^{-1})	0.80 (0.02)
Clay (kg kg^{-1})	0.14 (< 0.01)
pH	7.16 (0.05)
Electrical conductivity (dS m^{-1})	0.127 (0.01)
Phosphorus (mg kg^{-1})[†]	33.9 (4.7)
Potassium (mg kg^{-1})	110.5 (6.1)
Calcium (mg kg^{-1})	1081 (27.6)
Magnesium (mg kg^{-1})	284 (18)
Sulfur (mg kg^{-1})	8.4 (0.8)
Sodium (mg kg^{-1})	13.9 (0.9)
Iron (mg kg^{-1})	202.7 (16.2)
Manganese (mg kg^{-1})	162 (12)
Zinc (mg kg^{-1})	1.9 (0.3)
Copper (mg kg^{-1})	1.4 (0.04)
Total nitrogen (g kg^{-1})	1.0 (0.03)
Total carbon (g kg^{-1})	6.0 (0.3)

Carbon:nitrogen ratio	9.5 (0.2)
Soil organic matter (g kg^{-1})	17.0 (0.3)

† Orthophosphate P was measured.

TABLE 2 Summary of fertilizer chemical properties and measured fertilizer grade for the two separate batches of electrochemically precipitated struvite (ECST) used in 2019 and 2020 and the chemically precipitated struvite (CPST), rock phosphate (RP) monoammonium phosphate

(MAP), triple superphosphate (TSP), and diammonium phosphate (DAP)fertilizer-P materials

used for the corn study in a silt-loam soil in Marianna, Arkansas (n = 5; Omidire et al., 2022b).

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

† Measured fertilizer grade is reported as $N\text{-}P_2O_5\text{-}K_2O$

†† Limited quantity of ECST restricted pH determinations in 2019 and 2020

TABLE 3 Corn plant properties as affected by fertilizer-phosphorus (P) source, year, and their interaction for the 2019 and 2020 data in a P-deficient, silt-loam soil in eastern Arkansas.

	Source of Variation		
Plant Property	**Source**	**Year**	**Source x Year**
	P		
Stalk + leaves			
Dry matter	0.59	0.60	0.53
P concentration	0.27	0.20	0.39
N concentration	0.29	**0.04**	0.17
Mg concentration	0.06	**< 0.01**	0.76
P uptake	0.78	**0.04**	0.16
N uptake	0.25	**< 0.01**	0.06
Mg uptake	0.34	**< 0.01**	0.72
Cob + husk			
Dry matter	0.09	**0.02**	0.28
P concentration	0.88	0.06	0.93
N concentration	0.82	**0.03**	0.69
Mg concentration	0.06	**< 0.01**	0.57
P uptake	0.75	**< 0.01**	0.40
N uptake	0.06	**< 0.01**	0.46
Mg uptake	0.13	**< 0.01**	0.79
Kernel			

Dry matter	**0.04**	0.22	0.21
P concentration	0.31	0.85	0.31
N concentration	0.11	0.13	0.23
Mg concentration	0.67	0.26	0.59
P uptake	**0.04**	0.24	0.52
N uptake	< 0.01	0.02	**0.04**
Mg uptake	**0.03**	0.13	0.38
Total aboveground			
Dry matter	0.13	0.69	0.46
P uptake	0.14	0.06	0.25
N uptake	**0.01**	**< 0.01**	0.06
Mg uptake	0.14	**< 0.01**	0.72
Belowground			
P concentration	0.30	0.39	0.36
N concentration	0.06	0.17	0.80
Mg concentration	0.16	0.07	0.09
Yield	**< 0.01**	**0.02**	0.40

† Bolded values were considered significant at $P < 0.05$

†† Nitrogen (N) and magnesium (Mg)

TABLE 4 Corn plant properties that were unaffected ($P > 0.05$) by fertilizer-phosphorus (P) source or year in a P-deficient, silt-loam soil in eastern Arkansas.

Plant Property	**Minimum**	**Maximum**	**Mean**
Stalk + leaves dry matter (Mg ha^{-1})	7.0	8.7	7.6
Stalk + leaves tissue P concentration (%)	0.07	0.18	0.11
Cob + husk tissue P concentration (%)	0.05	0.09	0.07
Kernel tissue P concentration (%)	0.27	0.33	0.29
Kernel tissue N[†] concentration (%)	1.1	1.4	1.2
Kernel tissue Mg[†] concentration (%)	0.09	0.12	0.10
Total aboveground dry matter (Mg ha^{-1})	18.1	21.5	19.9
Total aboveground tissue P uptake (kg ha^{-1})	30.5	50.9	39.2
Belowground tissue P concentration (%)	0.05	0.12	0.08
Belowground tissue N concentration (%)	0.43	0.77	0.57
Belowground tissue Mg concentration (%)	0.12	0.21	0.16

[†] Nitrogen (N) and magnesium (Mg)

TABLE 5 Summary of corn properties that differed between years (2019 and 2020), averaged across fertilizer-phosphorus (P) treatments, in a P-deficient, silt-loam soil in eastern Arkansas.

	Year	
Plant Properties	**2019**	**2020**
Stalk + leaves tissue N[††] concentration (%)	0.4 b[†]	1.3 a
Stalk + leaves tissue Mg[††] concentration (%)	0.3 b	0.5 a
Stalk + leaves tissue P uptake (kg ha^{-1})	6 b	11 a
Stalk + leaves tissue N uptake (kg ha^{-1})	34 b	96 a
Stalk + leaves tissue Mg uptake (kg ha^{-1})	25 b	40 a
Cob + husk dry matter (kg ha^{-1})	2213 a	1953 b
Cob + husk tissue N concentration (%)	0.4 b	0.8 a
Cob + husk tissue Mg concentration (%)	0.06 b	0.10 a
Cob + husk tissue P uptake (kg ha^{-1})	1.1 b	1.6 a
Cob + husk tissue N uptake (kg ha^{-1})	9 b	16 a
Cob + husk tissue Mg uptake (kg ha^{-1})	1.4 b	1.9 a
Total aboveground tissue N uptake (kg ha^{-1})	153 b	257 a
Total aboveground tissue Mg uptake (kg ha^{-1})	36 b	54 a
Yield (kg ha^{-1})	11372 a	10265 b

[†] Means in a row with different letters are different at $P < 0.05$

[††] Nitrogen (N) and magnesium (Mg)

TABLE 6 Summary of corn total aboveground N (TANU) uptake, kernel dry matter (KDM), kernel tissue P (KPU) and Mg (KMgU) uptake, and grain yield among fertilizer-P sources, averaged across years, in a P-deficient, silt-loam soil in eastern Arkansas.

Fertilizer-P Source†	TANU	KDM	KPU	KMgU	Yield
	kg ha^{-1}				
ECST	228 a††	11530 a	35 a	12.8 a	12940 a
CPST	187 bc	9657 bc	28 b	9.9 b	10344 bc
DAP	179 c	9246 c	26 b	9.5 b	10165 c
MAP	205 ab	10556 ab	30 ab	10.9 ab	10782 bc
RP	205 ab	10054 bc	27 b	10.0 b	10251 bc
TSP	187 bc	10096 bc	29 b	10.3 b	11128 b
UC	201 abc	10313 abc	29 b	10.9 ab	10270 bc

† Electrochemically precipitated struvite (ECST), chemically precipitated struvite (CPST), rock phosphate (RP), diammonium phosphate (DAP), triple superphosphate (TSP), monoammonium phosphate (MAP), and unamended control (UC)

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

TABLE 7 Corn kernel tissue nitrogen (N) uptake among fertilizer-phosphorus (P)-source-year combinations in a P-deficient, silt-loam soil in eastern Arkansas.

	Kernel N Uptake (kg ha^{-1})	
Fertilizer-P Source	**2019**	**2020**
Electrochemically precipitated struvite	131 bcde[†]	170 a
Chemically precipitated struvite	102 f	139 bcd
Diammonium phosphate	103 ef	122 def
Monoammonium phosphate	110 def	155 abc
Rock phosphate	97 f	166 ab
Triple superphosphate	103 ef	139 bcd
Unamended control	124 cde	132 bcde

[†] Means across both columns with different letters are different at $P < 0.05$

TABLE 8 Change in soil properties as affected by fertilizer-phosphorus (P) source in the top 10 cm for the corn study after one year and after two growing seasons in a phosphorus (P)-deficient, silt-loam soil in eastern Arkansas.

Soil Properties	**Change After One Year**	**Change After Two Growing Seasons**
	P	
pH	0.42	**0.01**[†]
Electrical conductivity	0.82	0.14
Phosphorus	0.40	**0.02**
Potassium	0.88	0.82
Calcium	0.60	0.91
Magnesium	0.45	0.85
Sulfur	0.06	0.06
Sodium	0.65	0.30
Iron	0.66	0.46
Manganese	0.84	0.63
Zinc	0.86	0.26
Copper	0.66	0.81
Total nitrogen	0.76	-
Total carbon	0.95	-

[†] Bolded values were considered significant at $P < 0.05$

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

	2019		2020	
Fertilizer-P Source	**$ ha^{-1}**	**% Change**	**$ ha^{-1}**	**% Change**
Triple superphosphate	--	--	--	--
Electrochemically precipitated struvite	$175.99	11.83	$293.53	18.57
Chemically precipitated struvite	-$172.74	-11.61	-$346.85	-21.95
Diammonium phosphate	-$130.22	-8.75	-$137.34	-8.69
Monoammonium phosphate	-$57.10	-3.84	-$10.80	-0.68
Rock phosphate	-$272.42	-18.31	-$157.56	-9.97
Unamended control	-$6.64	-0.45	-$118.33	-7.49