



Early Season Wheat Response to Electrochemically Precipitated Struvite in Various Soils in the Greenhouse

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Abstract

Fertilizer-phosphorus (P) materials can be recovered from wastewater and used to supplement mined phosphate rock, where one such material is struvite [$\text{MgNH}_4\text{PO}_4 \cdot 6(\text{H}_2\text{O})$]. This study aimed to compare electrochemically precipitated struvite (ECST) reclaimed from synthetic wastewater to other commercial fertilizer-P sources in cultivated soils from Arkansas [silty clay loam (AR-SiCL) and silt loam (AR-SiL)], Missouri [(silt loam; MO-SiL 1 and 2)], and Nebraska [silt loam (NE-SiL) and sandy loam (NE-SL)]. A greenhouse pot study was conducted for 60 days with unvernallized wheat (*Triticum aestivum*) using five fertilizer-P sources [ECST, chemically precipitated struvite (CPST), monoammonium phosphate (MAP), triple superphosphate (TSP), and an unamended control (UC)] to evaluate treatment effects on below (BG)- and aboveground (ABG) and total dry matter (DM) and tissue-N, -P, -K, -Ca, -Mg, and -Fe uptakes. The ECST treatment produced 44 g m^{-2} larger ABG-DM than CPST in the AR-SiCL, but 181 g m^{-2} larger than the UC in the MO-SiL 1. The ECST had similar or larger nutrient uptakes than CPST, MAP, TSP, and UC. Belowground-P, -N, and -Mg uptakes for ECST were generally similar for all soil-fertilizer-P source combinations, where ECST was 0.3 to 2.6 g m^{-2} larger than all other fertilizer-P sources. Plant property response from ECST was generally similar to or greater than CPST, MAP, TSP, and the UC across all soils. Results suggest that ECST is a prime candidate to be used as an effective, alternative fertilizer-P source, suitable for use in wheat production across multiple soil textures.

Keywords Recycled nutrients · Plant phosphorus response · Sustainable fertilizer · Soil texture · Struvite

1 Introduction

Phosphorus (P) is a primary plant macronutrient essential for various physiological processes in plant growth, including respiration, where P is important for energy transfer and storage (Ahmed et al. 2018; Mullins 2018). Phosphorus is also a vital element that plants need for cell division and elongation, formation of phospholipids, nucleic acids, and adenosine triphosphate (ATP; Peadar et al. 2011).

Wheat (*Triticum aestivum*) is among the top grain and cereal crops commercially produced in the United States (US). Up to 2019, the US produced 14.2% of the world's wheat supply (Zulauf and Swanson 2020); hence,

adequate crop nutrition must be maintained for maximum productivity.

The need for increased crop production for food and feed has fueled a growing fertilizer demand across the globe, particularly in developed countries, China, and other emerging economies (IFIA 2009). Fertilizer demand is set to increase at a 1.2 and 1.0% annual rate for P and nitrogen (N), respectively (IFA 2019). However, there is only a finite, non-renewable amount of P-containing minerals in the natural-P reserves, which are continuously being mined. Hence, to prevent nutrient-deficiency-induced yield or developmental losses, new and sustainable sources of producing fertilizer P need to be explored to supplement and reduce the dependence on mined phosphate rocks.

Both humans and intensive farming operations produce large quantities of nutrient-rich wastewaters daily, many of which contain elevated levels of N (0.12 to 2.2 mg L^{-1} total N), total P (0.001 to 0.075 mg L^{-1} ; Erel et al. 2019; USEPA 2020), and magnesium (Mg). Phosphorus, ammonium

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(NH_4^+), and Mg are all essential nutrients for plant life; therefore, these elements must be supplied as fertilizers.

Beyond being good stewards for conserving natural-P reserves, it is imperative to sustainably manage the amount of P being cycled through the environment. Strategies, such as P recovery from wastewaters, can create useful fertilizer materials, with the added benefit of improved water quality. Municipal, industrial, and agricultural wastewaters are potential substantial sources of P, N, and Mg (Fatah 2012; Brye et al. 2022), which, when combined, can be problematic for wastewater treatment plant operations, and require special attention to prevent the creation and build-up of the mineral struvite (Parsons et al. 2001; Stratful et al. 2004; Jabr et al. 2019; Brye et al. 2022). Under the right conditions, struvite, magnesium ammonium phosphate hexa-hydrate [$\text{MgNH}_4\text{PO}_4 \cdot 6(\text{H}_2\text{O})$] can naturally precipitate from wastewaters (Bouropoulos & Koutsoukos 2000; Malanda et al. 2016). Alternatively, struvite can be intentionally precipitated via chemical and/or electrochemical precipitation methods (Kékedy-Nagy et al. 2020). Electrochemical precipitation uses pure, sacrificial Mg electrodes, removing the need for addition of Mg salts (Wu et al. 2019; Kékedy-Nagy et al. 2020) as is necessary for chemical struvite precipitation.

Because struvite is a phosphate (PO_4^{3-})-based mineral from the orthophosphate group, struvite contains P that is suitable for biological uptake. Hence, struvite could be a suitable candidate fertilizer-P source for large-scale crop production (Brye et al. 2022). Phosphorus from commercially available P fertilizers, such as monoammonium phosphate (MAP) and triple superphosphate (TSP), tends to quickly bind to aluminum (Al), iron (Fe), and manganese (Mn) at acidic soil pH and calcium (Ca) and Mg at alkaline soil pH levels. However, in struvite, the P is bound to Mg before entering the soil and is only removed if the plants require the phosphate, signaled by the release of root-derived organic acids (Dietz 2020), making struvite a potentially slow-release fertilizer. Hence, struvite may be effective in releasing just enough of the P the plant needs, in response to the exudation of the organic acids from the plant roots close to the fertilizer molecule.

Struvite has been gaining attention as a potential slow-release P fertilizer in recent years. Anderson et al. (2020, 2021) studied the dissolution dynamics of struvite, both chemically precipitated struvite (CPST) and electrochemically precipitated struvite (ECST), in a 6- to 9-month, plant-less, moist- and flooded-soil laboratory incubation. Furthermore, plant-less, moist-soil incubation studies using the struvites, CPST and ECST, in various soil textures have shown soil chemical property changes including pH, P, NH_4 , Ca, Fe, and Mg starting as early as 2 weeks depending on the pellet sizes and soil textures (Anderson et al. 2020; Simms et al. 2023). Simms et al. (2023, 2024a, b) investigated the

leaching potential and vertical distribution of P from ECST in loam, silt-loam, and sandy-loam soils in a laboratory environment compared to that of CPST, MAP and TSP over a 15-week incubation period with intermittent leachings. Several studies have also been conducted at greenhouse and field scales and reported positive results to support struvite's fertilizer potential (Thompson et al. 2013; Hilt et al. 2016; Talboys et al. 2016; Nongqwenga et al. 2017; Samreen & Kausar 2019; Dietz 2020; Ylagan et al. 2020; Omidire et al. 2021, 2022, 2023; Omidire & Brye 2022), ECST's economic feasibility (Brye et al. 2022; Omidire et al. 2022), and struvite's potential environmental impacts (Rahman et al. 2014; Simms et al. 2023, 2024a). However, due to recent developments with varying struvite-creation processes and initial materials from which struvite has been created, there are inconsistent reports as to the early reported slow-release characteristics of struvite in general, which warrants further research and comparisons among various struvite materials.

Conclusions drawn from the fertilizer-crop-response studies indicated that struvite has the ability to provide plant nutrients comparable to that of other common fertilizer-P sources in a variety of crops and cropping systems, and struvite's soil behavior is at least similar to that of other common fertilizer-P sources. However, these studies were conducted using a single soil texture, predominantly silt loam, from only one geographic location, mainly Arkansas, and the soils were also not considered low in soil-test-P level to really test the effectiveness of struvite as a fertilizer-P source. Consequently, there is a need to evaluate ECST's effects on crop response across multiple soil textures, originating from varying agronomic locations.

The objective of this study was to investigate early season wheat response (i.e., below- and aboveground and total wheat dry matter and nutrient uptakes) to ECST compared to CPST and other commonly used fertilizer-P sources in a greenhouse potted-plant study with agriculturally relevant soils from Arkansas (AR), Missouri (MO), and Nebraska (NE). Since Thompson et al. (2013) and others reported comparable crop response of struvite to superphosphate, and Ylagan et al. (2020), Brye et al. (2022), and Omidire et al. (2021, 2022, 2023), reported that ECST had plant-P uptake and crop biomass similar to or better than that of CPST, TSP, and MAP, it was hypothesized that total plant biomass (i.e., above- plus belowground) from ECST will be comparable to or greater than that of CPST, MAP, and TSP under greenhouse conditions. It was also hypothesized that wheat grown in soil treated with ECST and CPST would have similar above- and belowground P uptakes in their biomass than those grown in soils treated with MAP and TSP or from an unamended control.

A greenhouse-response study necessarily preceded a field study due to having only a small, finite quantity of available ECST, as ECST is still an experimental material. The

controlled conditions provided by the greenhouse also facilitated minimization of the many uncontrollable features of field studies and facilitated the ability to uniformly manage wheat growth among numerous different soils. Furthermore, results of greenhouse studies can also serve as a guide for designing future, larger-scale field studies.

2 Materials and Methods

2.1 Fertilizer-P Sources and Characterization

Five fertilizer-P treatments were used in the greenhouse pot study, including i) ECST (approximate fertilizer grade: 5–37-0), precipitated from synthetic wastewater by means of electrolysis utilizing a sacrificial Mg anode, ii) MAP (fertilizer grade: 11–48-0), formed by the 1:1 molar blend of ammonia (NH₃) to phosphoric acid (H₃PO₄) and subsequent granulation, iii) TSP (fertilizer grade: 0–39-0), formulated from a reaction between rock phosphate (RP) and H₃PO₄ (IPNI, 2019), iv) a CPST material (i.e., Crystal Green; approximate fertilizer grade: 6–52-0, with 10% elemental Mg), commercially produced by chemical precipitation from a real wastewater, and v) an unamended control (UC) that received no P additions. Fertilizer pH, total N (TN) concentrations, Mehlich-3-extractable nutrient concentrations (i.e., P, Ca, Mg, and Fe) concentrations were determined as outlined in Simms (2023). Chemical properties of the fertilizer materials used in this study are summarized in Table 1.

2.2 Soil Collection

Soils from agriculturally relevant regions of eastern Nebraska (NE), southwest Missouri (MO), and western and eastern Arkansas (AR) were collected for use in the greenhouse pot study. At each location, soils were collected in

18.9-L (5 gallons) buckets. Ten to 12 buckets of soil were manually collected from the top 15 to 20 cm (i.e., above the local plow layer and above any prominent argillic horizon) at each location. All collected soils were transported to the Milo J. Shult Arkansas Agricultural Research and Extension Center in Fayetteville, AR for further processing. The Arkansas soils included Dardanelle silty clay loam (AR-SiCL; fine silty, mixed, superactive, thermic Typic Argiudolls; NRCS, 2003), and Calloway silt loam (AR-SiL; fine silty, mixed, active, thermic, Aquic Fraglossudalfs; NRCS, 2018). The Dardanelle series soil was collected from an irrigated field previously cultivated in soybeans, also located near Kibler, AR in a floodplain with 0% slope at the Vegetable Research Station. The Calloway series soil was collected on 14 December, 2017 from a field at the Cotton Branch Experiment Station in Marianna, AR that was plowed and under a 16-year, wheat-soybean, double-crop production system on a loess-covered stream terrace with < 0.5% slope. The Arkansas soils differed in origin, where the Calloway soil was derived from loess deposited over alluvium on stream terraces and has a fragipan at depth (NRCS 2018), while the Dardanelle soil originated from loamy alluvial deposits from the Arkansas River (NRCS 2003).

In Missouri, the Creldon silt loam (fine, mixed, active, mesic Oxyaquic Fragiudalfs) and Dapue silt loam (fine-silty, mixed, active, mesic Fluventic Hapludolls) soil series were collected on 19 March, 2019 from managed pasturelands located at the University of Missouri's Southwest Research Center, near Mount Vernon, MO, established in tall fescue (*Festuca arundinacea*). The Creldon soil (MO-SiL 1) was collected from a backslope position with approximately 1% slope and consisted of a thin layer of loess covering a subsoil that is largely clay-rich and developed from a weathered limestone residuum (NRCS 2006). The Dapue soil (MO-SiL 2) was collected from a < 1% slope on a floodplain developed from silty alluvium (NRCS 1997).

Table 1 Summary of fertilizer pH, total nitrogen (N), and Mehlich-3-extractable elements for electrochemically precipitated struvite (ECST), chemically precipitated struvite (CPST), monoammonium phosphate (MAP), and triple superphosphate (TSP) fertilizer materi-

als used in the greenhouse pot study. Means ($n=5$) are reported with standard errors in parentheses for all properties, except pH for ECST where $n=3$

Fertilizer property	Fertilizer-P source			
	CPST	ECST	MAP	TSP
pH	8.8 (0.13)	6.6 (0.01)	4.4 (0.02)	2.4 (0.02)
Total N (%)	5.7 (0.21)	5.1 (0.19)	10.7 (0.06)	0.02 (<0.01)
Mehlich-3-extractable elements				
P (g kg ⁻¹)	22.9 (0.26)	16.3 (0.20)	18.2 (1.3)	17.1 (3.8)
Ca (g kg ⁻¹)	0.1 (<0.01)	<0.01 (<0.01)	1.9 (0.04)	106 (2.3)
Mg (g kg ⁻¹)	21.4 (0.25)	23.8 (0.09)	6.8 (0.1)	4.7 (0.1)
Measured fertilizer grade [†]	6–52–0	5–37–0	11–48–0	0–39–0

[†]Fertilizer grade reported as percent N-P₂O₅-K₂O

In Nebraska, soils were collected from sections of the University of Nebraska's Eastern Nebraska Research and Extension Center near Mead. Olmitz sandy loam (fine-loamy, mixed, superactive, mesic Cumulic Hapludolls; NRCS 2016) and Yutan silt loam (fine-silty, mixed, superactive, mesic, Mollic Hapludalfs; NRCS 2007) soils were collected on 11 May, 2019. The Olmitz sandy loam (NE-SL) was collected from a cultivated field cropped with rye grass (*Lolium perenne*) in a foot-slope position with ~2% slope. The Olmitz soil had a dark brown to black, moist surface color that was friable, abundant with earthworms, and originated from loamy alluvium of mixed mineralogy deposition in drainage ways. The Yutan silt loam (NE-SiL) was collected from an annual corn-soybean rotation system on a backslope position with ~3% slope with corn present at the time of soil collection. The Yutan soil had a very dark, grayish brown, moist surface color, with a thick layer of crop residue and abundant earthworms. The soils collected from each of the three states represented examples of typical soils under agricultural management in the respective regions. Bulk soil with low soil test-P was intentionally accumulated from various locations over the course of several years, sieved, air-dried, and stored for later use. The storage of dry soil for a period of time was not expected to have any effect on the study results, rather it was more important to be able to use soils with low soil-test P in this study. Additional details about the six soils used in this study were reported in Simms et al. (2023, 2024a).

2.3 Soil Processing and Analyses

All field-collected soil was moist-sieved through a 6-mm mesh screen. Debris, coarse fragments, pieces of crop residues, and root clumps were manually removed. The soil was then air-dried for a week at approximately 35°C. Subsamples of each soil were collected, oven-dried at 70 °C for 48 hours, and ground to pass through a 2-mm mesh screen for physical and chemical property evaluations.

Soil pH was potentiometrically determined using a one-part soil mass to two-part water volume ratio measured with an electrode. Plant-available soil nutrient (i.e., P, Ca, Mg, and Fe) concentrations were determined from Mehlich-3 extraction with a 1:10 soil-mass-to-extractant-volume ratio solution and then analyzed by ICAPS (Zhang et al. 2014). The concentration of soil organic matter (SOM) was obtained gravimetrically via the weight loss-on-ignition method at 360 °C for 2 h in a muffle furnace (Zhang & Wang 2014). Total N concentrations were determined by high-temperature combustion using an Elementar VarioMax CN analyzer. Soil NH₄⁻ and NO₃⁻-N concentrations were determined colorimetrically on a Skalar autoanalyzer after potassium chloride (KCl) extraction and filtration using the Nesslerization and cadmium-reduction methods, respectively (Miller & Sonon 2014). Sand, silt, and clay percentages were determined using a modified 12-h hydrometer method (Gee & Or 2002) and the textural class of each soil confirmed. The initial soil physical and chemical properties among the six soils used in this study are summarized in Table 2. Detailed soil property characteristics can be found in Simms (2023).

Table 2 Summary of the initial soil physical and chemical properties among the soils used in the greenhouse pot study. Means (n=5) are reported with standard errors in parentheses

Soil property	AR-SiCL	AR-SiL	MO SiL 1	MO SiL 2	NE-SiL	NE-SL
Sand (g g ⁻¹)	0.07 (<0.01) e	0.12 (<0.01) d	0.24 (<0.01) b	0.20 (<0.01) c	0.24 (<0.01) b	0.64 (<0.01) a
Silt (g g ⁻¹)	0.56 (0.1) d	0.75 (<0.01) a	0.67 (<0.01) b	0.74 (<0.01) a	0.60 (<0.01) c	0.30 (<0.01) e
Clay (g g ⁻¹)	0.37 (0.01) a	0.14 (0.01) c	0.09 (<0.01) d	0.07 (<0.01) e	0.16 (<0.01) b	0.06 (<0.01) f
Total N (g kg ⁻¹)	1.1 (<0.1) bc	1.1 (<0.1) bc	1.1 (<0.1) bc	1.7 (<0.1) b	3.2 (0.1) a	0.9 (<0.1) c
SOM [§] (g kg ⁻¹)	25.3 (0.3) d	23.5 (0.3) e	28.7 (0.3) c	33.7 (0.3) b	58.0 (0.6) a	21.3 (0.2) f
pH	6.5 (<0.1) a	6.5 (<0.1) a	6.0 (<0.1) c	5.9 (<0.1) c	6.2 (<0.1) b	5.9 (<0.1) c
NO ₃ -N [§] (mg kg ⁻¹)	6.3 (0.8) d	15.8 (1.9) b	10.8 (1.0) c	21.0 (1.9) ab	27.1 (2.5) a	0.6 (0.1) e
NH ₄ -N [§] (mg kg ⁻¹)	6.3 (0.7) e	8.2 (0.8) de	8.6 (0.7) cd	10.7 (0.9) bc	21.9 (1.7) a	12.4 (1.0) b
Mehlich-3 extractable elements (mg kg ⁻¹)						
P	143 (5.3) a	33.7 (1.3) d	13.8 (0.4) f	27.6 (0.8) e	62.2 (1.8) b	44.2 (1.3) c
Ca	4328 (124) a	1842 (53) c	1027 (23) e	1484 (33) d	3287 (73) b	1058 (23) e
Mg	774 (21) a	444 (12) c	288 (6) d	217 (5) e	494 (10) b	156 (3) f
Fe	175 (3) b	186 (4) a	102 (2) f	158 (2) c	122 (2) e	137 (2) d

[§]AR-SiCL, Arkansas silty-clay loam (Dardanelle series); AR-SiL, Arkansas silt loam (Calloway series); MO-SiL1, Missouri silt loam (Crelton series); MO-SiL 2, Missouri silt loam (Dapue series); NE-SL, Nebraska sandy loam (Olmitz series); NE-SiL., Nebraska silt loam (Yutan Series); SOM, soil organic matter; NO₃-N, nitrate-N; NH₄-N, ammonium-N

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

2.4 Pot Preparation

Wheat was grown with all five fertilizer treatments using each of the six soils: AR-SiL, AR-SiCL, MO-SiL 1, MO-SiL 2, NE-SL, and NE-SiL. While there were 15 pots prepared with each soil, wheat plants were grown in triplicate for all soil-fertilizer treatment combinations for approximately 60 days, for a total of 90 pots that were prepared. Environmental conditions (i.e., air temperature and relative humidity) were monitored and recorded throughout the duration of plant growth.

A uniform P rate was applied for each fertilizer material, excluding the UC, based on the mean initial Mehlich-3 P concentration for each soil and average crop-P requirement as recommended from each state. With the exception of ECST, which was applied as a crystalline flake, CPST, MAP, and TSP were applied in their original forms as commercial-grade, pelletized fertilizers and mixed into the soil to represent cultivated land recently tilled in preparation for crop production.

The wheat grown was an unvernallized, soft red winter wheat (var. 'Jamestown', Reg. No. CV-1041, plant introduction 653,731). Wheat plants were grown in 15-cm-diameter (6 in) plastic nursery pots. Quantitative glass-fiber filter paper discs (#454) were trimmed and used to cover the holes at the base of each pot to prevent soil loss. A mass of 1800 g (± 0.5 g) of each of the six air-dried soils was added to 3.8-L (1 gal) plastic bags, after which the target-P application rate (260.2, 359.3, 200.5, and 230.2 mg for ECST, CPST, MAP, and TSP, respectively) was weighed out and added to the respective soil bags.

The target fertilizer-P rate was calculated by averaging the recommended P rate for all three states: wheat [79 kg ha⁻¹ (70 lb ac⁻¹) P₂O₅ for AR (Kelley et al. 2019), 50 kg ha⁻¹ (45 lb ac⁻¹) P₂O₅ for MO (Brown et al. 2004), and 28 kg ha⁻¹ (25 lb ac⁻¹) P₂O₅ based on soil test P, yield goal, pH and fertilizer cost for NE (Hergert & Shaver 2009)]. Based on the mean total-recoverable P concentration of each fertilizer material, the mean soil-test-P concentration of each soil, and the mean crop-P recommendations for wheat across the three states, a single, agronomically appropriate, field-scale fertilizer-P rate was determined for application to wheat, which was 23 kg ha⁻¹ (20.5 lb ac⁻¹). The field-scale fertilizer-P rate was scaled back to the surface area of the pots used (182.3 cm²) so that the fertilizer-P amount applied to each pot would result in an equivalent fertilizer-P rate of 23 kg P ha⁻¹. Due to the differential P concentrations of the fertilizer-P sources used, there were varying amounts of each fertilizer-P source that needed to be added to the pots in a given treatment to result in a uniform P rate across all fertilizer treatments. For ECST, CPST, MAP, and TSP, the amounts of actual raw fertilizer material applied to a pot was 260.2, 359.3, 200.5, and 230.2 mg. The soil and

fertilizer in the bags were shaken to mix the fertilizer into the soil mimicking fertilizer incorporation by tillage as a common field practice. The fertilizer-incorporated soil was transferred to respective pots. The pots were oriented in a randomized complete block design within an 8.8-m² area on a greenhouse bench.

Based on regression equations among soil properties (Saxton et al. 1986) used in the Soil, Plant, Atmosphere, Water (SPAW) Model (Saxton et al. 1986; Ayele et al. 2020), the Soil Water Characteristics subroutine was used to estimate each soil's gravimetric field moisture capacity (FMC) and permanent wilting point (PWP) water contents and in-situ bulk density to facilitate determining the amount of water to add to each soil prior to planting. The target water contents were set at 2% (v/v) less than the estimated volumetric FMC water contents [i.e., 30% (AR-SiL), 38% (AR-SiCL), 26% (MO-SiL 1), 26% (MO-SiL 2), 14% (NE-SL), and 28% (NE-SiL)]. However, actual pot watering occurred on a gravimetric basis that was determined using the estimated in-situ soil bulk densities for each soil. To ensure adequate moistening of the different soils, while preventing moisture loss, 50 mL less than the total estimated amount of water to add for each soil were added the day the soil-fertilizer mixtures were added to the pots to moisten the air-dry soil prior to seed sowing. Based on the SPAW model estimates, the soils required 524, 363, 261, 312, 146, and 306 mL of water to achieve the initial target gravimetric water contents for the AR-SiCL, AR-SiL, MO-SiL 1, MO-SiL 2, NE-SL, and NE-SiL soils, respectively.

2.5 Plant Establishment, Management, and Measurements

Wheat was planted on 17 April, 2020. Twenty-four hours following initial soil moistening to near FMC, three seeds were planted close to the center of each pot in a triangular arrangement at a depth of 1.3 cm (0.5 in) and ensuring good seed to soil contact. An additional 50 mL of water was then added to each pot to achieve the final desired target water content to ensure that there was sufficient moisture close to the planted seeds to optimize germination.

A soil moisture meter and moisture sensor (HH150/SM150, Dynamax, Inc., Houston, TX) was used to monitor the moisture content in multiple pots of each soil multiple times per week. Six pots from each soil were randomly selected and the soil moisture contents were measured prior to re-watering. One pot from each soil was randomly selected each watering event and slowly watered with small additions of water, with a moisture measurement every 10 to 15 min after each water aliquot addition until the desired water content was reached. The total volume of water required to obtain the desired volumetric water content (VWC) for each soil was then added to all pots containing

that soil. Watering events were carried out on alternate days or on an as-needed basis based on visual observation of dry soil conditions. The current greenhouse air temperature and relative humidity and the day's minimum and maximum air temperatures were recorded at each watering.

About 7 days after germination and emergence, plants were thinned to one plant per pot. The visually healthiest seedling was retained based on seedling height, number of leaves, leaf color, vigor, and/or position in the pot if all seedling characteristics were similar. Seedlings were thinned by gently manually pulling them out of the soil or pinching the unwanted seedlings at the soil surface and leaving the roots in the pot. Pots were rotated, changing their location on the bench, at 20-day intervals so that the same plants were not always occupying the same location.

Plants were observed frequently for potential pest problems. Once identified, a pest control regimen was implemented based on the pest detected, level of infestation, and suitability and availability of pesticides. At day 32 into wheat growth, aphids (Bird cherry-oat aphid, *Rhopalosiphum padi*) were observed on several plants. The plants were spray-treated the following day with Ultra-fine oil (98.8% Paraffinic Oil; EPA Registration No. 862–23–499) at a rate of 10.5 mL per liter of distilled water. A week later, aphids were again observed on several plants and were spray-treated with the insect growth regulator Azatin O (Azadirachtin; EPA Registration No. 70051–9–59,807) at a rate of 1.3 mL per liter of distilled water to kill the young aphids. A follow-up treatment of Ultra-fine oil at a rate of 10.5 mL per liter of distilled water was applied 3 days later to control the remaining adult aphids. Wheat plants were grown for 60 days, after which time plants were harvested and processed for above- and belowground dry matter and nutrient concentrations. The 60-days study duration facilitated focus on early season wheat response to help address struvite's viability as a potential alternative fertilizer-P source during wheat root establishment.

2.6 Pot Deconstruction, Plant Biomass, and Soil Processing

To begin deconstructing pots, light pressure was manually applied to the sides of each pot to loosen the soil from the sides and bottom and empty the soil into a plastic tub. Any remaining filter paper at the base of the pot was manually removed and discarded. The soil was manually massaged to separate the soil from the mass of plant roots. The wheat biomass was gently washed in an 18.9-L (5 gal) bucket of tap water to remove any remaining soil from the rhizosphere and the rhizosphere was gently squeezed to remove excess water. After washing soil from the roots, the aboveground portion of the plant biomass was cut at the soil surface to

separate the belowground portion. Above- and belowground plant materials were collected separately.

The soil from each pot was moist-sieved by passing through a 2-mm mesh screen into plastic tubs to remove the remaining small roots. Once collected, micro-roots were gently washed in an 18.9-L bucket of tap water to remove the attached soil, gently squeezed to remove excess moisture, and added to the rest of the belowground biomass. Above- and belowground plant materials were oven-dried at 67 °C for approximately five days and weighed for dry matter determinations.

Sub-samples of above- and belowground dry matter were ground and sieved separately to pass initially through a 6-mm mesh screen and further ground to pass through a 2-mm mesh screen for tissue chemical analyses. Plant-tissue concentrations (i.e., P, Ca, Mg, and Fe) were measured by ICAPS (Spectro Arcos ICP; Zhang et al. 2014) after digestion in strong acid and heating. Total N concentration was determined by high-temperature combustion (Elementar VarioMax CN analyzer). Plant nutrient uptake for each element (i.e., P, Ca, Mg, and Fe) in both the above- and belowground dry matter was calculated by multiplying the plant's dry matter mass by the associated elemental concentration on a replicate-by-replicate basis. Total plant dry matter and total plant nutrient uptake were calculated on a replicate-by-replicate basis by summing the below- and aboveground dry matter and nutrient uptakes.

2.7 Statistical Analyses

A one-factor analysis of variance (ANOVA) was conducted, based on a completely random design, using the PROC GLIMMIX procedure in SAS 9.4 (SAS Institute, Inc., Cary, NC) to evaluate soil property [i.e., pH, TN, SOM, sand, silt, and clay, Mehlich-3, elemental concentrations (i.e., P, Ca, Mg, and Fe), and NO₃ and NH₄ concentrations] differences among the six soils. A gamma distribution was used to analyze the data for pH, NH₄-N, NO₃-N, Mehlich-3 extractable soil P, Ca, Mg, and Fe concentrations. A beta distribution was used to analyze the data for soil properties that were reported as percentages (i.e., SOM, TN, sand, silt, and clay concentrations).

Based on a randomized complete block design, a two-factor ANOVA was conducted using the PROC GLIMMIX procedure in SAS 9.4 to evaluate the effects of soil (i.e., AR-SiL, AR-SiCL, MO-SiL 1, MO-SiL 2, NE-SL, and NE-SiL), fertilizer treatment (i.e., ECST, CPST, MAP, TSP, and UC), and their interactions on wheat properties (i.e., above- and belowground and total plant dry matter and N, P, Ca, Mg, and Fe uptakes). A gamma distribution was used to analyze all plant properties. When appropriate, least significant difference (LSD) was used to separate means at the 0.05 level.

3 Results

3.1 Fertilizer Properties

Among the four fertilizer-P sources used, there were expected variations in numerous fertilizer properties [i.e., pH, TN, and Mehlich-3 (M3) nutrients; Table 1]. Fertilizer pH ranged from 2.4 for TSP to 8.8 for CPST (Table 1). The TN concentration was largest for MAP (10.7%) followed by CPST (5.7%) and ECST (5.1%) and was smallest for TSP (0.02%; Table 1).

Monoammonium phosphate contained the largest M3-P concentrations (182 g kg⁻¹), among the four fertilizer-P sources followed by TSP (171 g kg⁻¹; Table 1). Of the struvite-P sources, CPST had the smallest M3-P concentration (24.5 g kg⁻¹), while ECST contained 26.9 g kg⁻¹. As was expected, the struvite's both had considerably lower numeric M3-P concentrations than for MAP and TSP due to struvite being only partially soluble in water (Table 1).

Prior studies on struvite solubility have identified that struvite-P had only limited solubility in water, where only 1 to 5% of the P is water-soluble and the remaining 95 to 99% is more tightly bound, but can become more soluble in the presence of acids, such as those produced by plants roots in the rhizosphere. While the struvites contained less M3-P than the readily soluble fertilizers (Table 1), this could be an environmentally beneficial effect by reducing soil-P binding or excess runoff-P provided that the struvite-P is released in response to the organic acids from growing roots and root exudates is enough to support plant growth and development. Hence, struvite could be a viable fertilizer-P source (Bhuiyan et al. 2007; Katakai et al. 2016; Shih & Yan 2016; Talboys et al. 2016).

While struvite can be considered a multi-nutrient-providing fertilizer, struvite is not a complete fertilizer source, as K is not a part of the struvite molecule, hence, neither CPST nor ECST, or the other predominantly used fertilizer-P sources were expected to contain considerable amounts of K. Struvite is also not a Ca-bearing mineral, nor is MAP, which explains the small M3-Ca concentrations. However, TSP (calcium dihydrogen phosphate) contains appreciable Ca as a carrier cation (106 g kg⁻¹ for M3-Ca; Table 1), which can potentially affect soil properties, such as pH, and soil and plant tissue-P concentrations, particularly due to TSP's water solubility.

However, expectedly, the struvite-P sources, which had Mg as part of their molecule, had larger M3-Mg (21.4 and 23.8 g kg⁻¹ for CPST and ECST, respectively) than for MAP and TSP (i.e., 6.8 and 4.7 g kg⁻¹ for M3-Mg respectively; Table 1). The larger M3-Mg concentrations present in the CPST and ECST supports the reports of struvite's

low water solubility and potential slow-release capabilities for liberating plants nutrients (i.e., N, P, and Mg) in response to organic acids in the rhizosphere (Bhuiyan et al. 2007; Katakai et al. 2016; Shih & Yan 2016; Talboys et al. 2016).

3.2 Initial Soil Properties

Many initial soil properties differed ($P < 0.05$) among the six agricultural soils used (Table 2). Sand, silt, and clay differed among the six soils, ranging from 0.07 g g⁻¹ sand in the AR-SiCL to 0.64 g g⁻¹ sand in the NE-SL, 0.06 g g⁻¹ clay in the NE-SL to 0.37 g g⁻¹ clay in the AR-SiCL, and 0.30 g g⁻¹ silt in the NE-SL to 0.75 g g⁻¹ silt in the AR-SiL (Table 2).

Total N concentration among the soils ranged from 0.9 g kg⁻¹ in the NE-SL to 3.2 g kg⁻¹ in the NE-SiL, however, there were no TN differences among the AR-SiCL, AR-SiL, and MO-SiL 1 and 2 soils, nor between the AR-SiCL, AR-SiL, MO-SiL 1, and NE-SL soils (Table 2). Soil pH ranged from 5.9 in the MO-SiL 2 and NE-SL to 6.5 in the AR-SiCL and AR-SiL (Table 2), which likely affected fertilizer-P behavior.

The SOM concentration varied among all six soils, ranging from 21.3 g kg⁻¹ in the NE-SL to 58.0 g kg⁻¹ in the NE-SiL (Table 2). Nitrate (NO₃)- and NH₄-N concentrations varied among the soils, ranging from 0.6 mg kg⁻¹ NO₃-N for NE-SL to 27.1 mg kg⁻¹ for NE-SiL, which was similar to that for MO-SiL 2, while NH₄-N ranged from 6.3 mg kg⁻¹ in the AR-SiCL to 21.9 mg kg⁻¹ for NE-SiL (Table 2).

Initial M3 concentrations varied ($P < 0.05$) among the soils (Table 2). Mehlich3-P concentrations varied greatly, ranging from 13.8 mg kg⁻¹ in the MO-SiL 1 to 143 mg kg⁻¹ in the AR-SiCL (Table 2). There were also wide variations in M3-Ca across the six soils, ranging from 1027 mg kg⁻¹ in the MO-SiL to 4328 mg kg⁻¹ in the AR-SiCL (Table 2). Similarly, the M3-Mg concentrations varied among soils, ranging from 156 mg kg⁻¹ in the NE-SL to 774 mg kg⁻¹ in the AR-SiCL (Table 2). Like M3-Mg, there were differences in M3-Fe concentrations among soils, ranging from 102 mg kg⁻¹ in the MO-SiL 1 to 186 mg kg⁻¹ in the AR-SiL (Table 2).

3.3 Belowground Dry Matter

After 60 days of growth, below- and aboveground and total wheat dry matter differed ($P < 0.05$) among soils and fertilizer-P sources (Table 3). Belowground wheat dry matter ranged from 63.6 g m⁻² for the AR-SiL fertilized with ECST to 213.6 g m⁻² in the MO-SiL 2 fertilized with CPST (Fig. 1).

In the AR-SiCL soil, belowground dry matter was smallest for wheat grown in the UC (74.3 g m⁻²) and largest for

Table 3 Analysis of variance summary of the effects of soil, fertilizer-phosphorus source, and their interactions on the differences in unvernallized wheat tissue parameters relative to the mean unamended control treatment in the 60-day greenhouse crop response study

Plant properties	Soil	Fertilizer	Soil x fertilizer
Belowground dry matter	<0.01	0.01	0.05
Belowground nutrient uptake			
N	<0.01	0.03	0.03
P	<0.01	<0.01	<0.01
Ca	<0.01	<0.01	0.04
Mg	0.01	0.08	0.16
Fe	0.10	0.09	0.01
Aboveground dry matter	<0.01	<0.01	<0.01
Aboveground nutrient uptake			
N	<0.01	<0.01	<0.01
P	<0.01	<0.01	<0.01
Ca	<0.01	<0.01	<0.01
Mg	<0.01	<0.01	<0.01
Fe	<0.01	<0.01	<0.01
Total dry matter	<0.01	<0.01	<0.01
Total uptake			
N	<0.01	<0.01	<0.01
P	<0.01	<0.01	<0.01
Ca	<0.01	<0.01	<0.01
Mg	<0.01	<0.01	<0.01
Fe	<0.01	0.02	<0.01

[†]Bolded values indicate significant effects at $P < 0.05$

wheat fertilized with MAP (144.4 g m⁻²; Fig. 1). However, belowground dry matter did not differ between wheat grown in the UC and wheat fertilized with CPST and ECST, both of which were similar to that of TSP (Fig. 1). Similarly, belowground wheat dry matter did not differ among CPST, TSP, and MAP (Fig. 1).

In the AR-SiL soil, the belowground dry matter was smallest for wheat fertilized with ECST (63.6 g m⁻²), which did not differ from wheat fertilized with CPST (82.1 g m⁻²), TSP (83.1 g m⁻²) or the UC (89.3 g m⁻²), and was largest for wheat fertilized with MAP (124.1 g m⁻²; Fig. 1). However, dry matter for wheat fertilized with ECST differed only from that for MAP (Fig. 1).

In the MO-SiL 1 soil, belowground dry matter was smallest for the wheat grown in the UC (64.6 g m⁻²) and largest for wheat grown in TSP (176.1 g m⁻²; Fig. 1). Belowground dry matter did not differ between wheat fertilized with CPST, ECST, or MAP (90.7, 110.9, and 123.9 g m⁻², respectively; Fig. 1). However, belowground dry matter for wheat fertilized with ECST was also similar to that for TSP but was greater than for the UC (Fig. 1).

In the MO-SiL 2, belowground dry matter was smallest for the wheat fertilized with ECST (122.7 g m⁻²) and largest for wheat fertilized with CPST (213.6 g m⁻²;

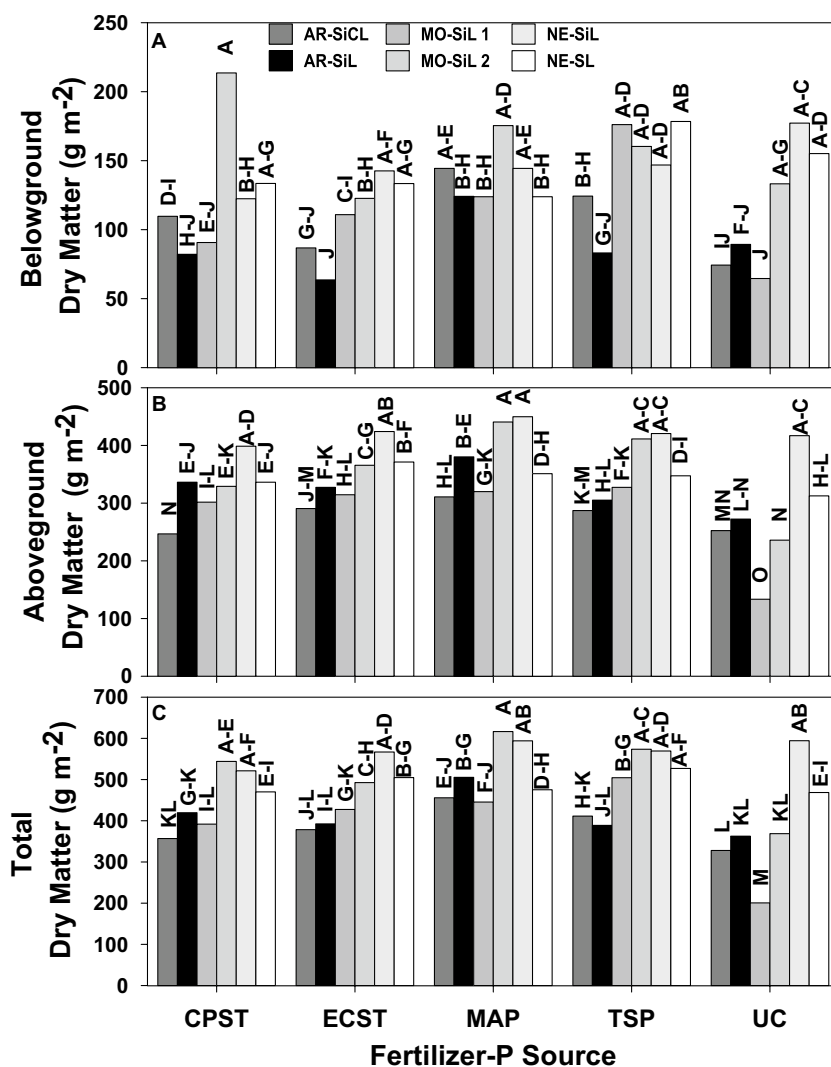
Fig. 1). Belowground dry matter did not differ in wheat fertilized with ECST, UC, TSP, or MAP (133.2, 160.3, and 175.4 g m⁻² for UC, TSP, and MAP, respectively), but belowground dry matter was 90.9 g m⁻² less for wheat fertilized with ECST than for CPST (Fig. 1). In the NE-SiL and NE-SL, belowground dry matter did not differ among wheat fertilized with any of the four fertilizer-P sources or the UC (Fig. 1).

Overall, there were no differences in belowground dry matter for wheat fertilized with the two struvite-P sources (CPST and ECST) in any of the six soils, except for MO-SiL 2, where belowground dry matter was 90.9 g m⁻² greater for wheat fertilized with CPST than for ECST. Likewise, there were no differences among wheat fertilized with the soluble fertilizers (MAP and TSP), which also had similar belowground dry matter to wheat fertilized with CPST, except in the MO-SiL 1, where belowground dry matter was less for wheat fertilized with CPST than for MAP and TSP (Fig. 1).

3.4 Aboveground Dry Matter

Aboveground wheat dry matter ranged from 133.5 g m⁻² in the unfertilized MO-SiL-1-UC to 449.8 g m⁻² in the NE-SiL soil fertilized with MAP, but there were no aboveground wheat dry matter differences among any fertilizer-P source in the NE-SiL soil (Fig. 1). Aboveground wheat dry matter in the MO-SiL-2-MAP (440.7 g m⁻²) and -TSP (411.4 g m⁻²) combinations were similar to one another and to all fertilizer-P sources in the NE-SiL soil, but were greater than for the CPST (329.1 g m⁻²) and ECST (365.7 g m⁻²; Fig. 1). Between the struvite-P sources, aboveground wheat dry matter did not differ in any of the soils, except in the AR-SiCL, where ECST (290.7 g m⁻²) had a larger aboveground dry matter than for CPST (246.8 g m⁻²; Fig. 1). Aboveground wheat dry matter was numerically largest from MAP in four of the six soils (i.e., AR-SiCL, AR-SiL, MO-SiL 2, and NE-SiL; 310.8, 380.3, 440.7, and 449.8 g m⁻², respectively), but was largest for TSP (327.3 g m⁻²) in the MO-SiL 1 and for ECST (371.2 g m⁻²) in the NE-SL soil (Fig. 1). Fertilizer-P from ECST produced similar aboveground wheat dry matter to that from TSP in all six soils and was similar to that for MAP in four of the six soils (i.e., AR-SiCL, MO-SiL 1, NE-SiL, and NE-SL; Fig. 1). In the AR-SiL and MO-SiL 2 soils, ECST's aboveground wheat dry matter was 53 and 75 g m⁻² less, respectively than for MAP (Fig. 1). However, aboveground wheat dry matter for ECST was always larger than for the UC, except in the AR-SiCL and NE-SiL soils where the ECST and UC did not differ (Fig. 1). Between the struvite-P sources, aboveground wheat dry matter did not differ in any of the soils, except for the AR-SiCL soil, where wheat fertilized with ECST (290.7 g m⁻²) had 43.9 g m⁻² more biomass than wheat fertilized with CPST (246.8 g m⁻²; Fig. 1).

Fig. 1 Belowground (A), aboveground (B), and total (C) wheat dry matter response to selected fertilizer-phosphorus (P) sources [i.e., chemically precipitated struvite (CPST), electrochemically precipitated struvite (ECST), monoammonium phosphate (MAP), triple superphosphate (TSP), and an unamended control (UC)] among soils from Arkansas [AR-silty-clay loam (SiCL) and AR-silt loam (SiL)], Missouri [MO-SiL 1 and 2], and Nebraska [NE-sandy loam (SL) and NE-SiL] from a 60-day greenhouse potted-plant study. Different letters atop bars within a plant property are significantly different at $P < 0.05$. Letters separated by a hyphen (-) represent a range of letters that include each letter between the beginning and ending letter. Standard errors of the mean range from 11 to 36, 7 to 23, and 13 to 40 for belowground, aboveground, and total dry matter



3.5 Total Plant Dry Matter

Total wheat dry matter ranged from 200.6 g m⁻² in the MO-SiL-1-UC combination to 616.5 g m⁻² in the MO-SiL 2 soil fertilized with MAP (Fig. 1). However, there were no total wheat dry matter differences among any fertilizer-P sources in the NE-SiL and NE-SL soils (Fig. 1). Total wheat dry matter between the struvite-P sources did not differ in any of the soils (Fig. 1). Total wheat dry matter was numerically largest from MAP in three of the six soils (i.e., AR-SiCL, AR-SiL, and MO-SiL 2; 455.8, 505.4, and 616.5 g m⁻², respectively), but was largest for TSP in the MO-SiL 1 and NE-SL soils (504.5 and 526.9 g m⁻², respectively); however, total wheat dry matter was largest (594.2 g m⁻²) for the NE-SiL soil among the other UC treatments (Fig. 1). Fertilizer-P from ECST produced similar total wheat dry matter to that from TSP in all six soils and was similar to that for MAP in four of the six soils (i.e., AR-SiCL, MO-SiL 1, NE-SiL, and NE-SL; Fig. 1). In the AR-SiL and MO-SiL 2 soils, ECST's

total wheat dry matter was 112.8 and 123.9 g m⁻² less than for MAP (Fig. 1). However, total wheat dry matter for ECST was similar to that of the UC in four of the six soils (i.e., AR-SiCL, AR-SiL, NE-SiL, and NE-SL; Fig. 1). Additionally, ECST's total wheat dry matter was 227.0 g m⁻² larger than for the UC in the MO-SiL 1 and 124.0 g m⁻² larger for the MO-SiL 2 soils (Fig. 1).

3.6 Belowground Nutrient Uptake

3.6.1 P Uptake

Belowground wheat dry matter P uptake ranged from 0.1 g m⁻² in the MO-SiL-1-UC to 0.6 g m⁻² in the MO-SiL-2-CPST combination (Table 4). There were no belowground wheat dry matter P uptake differences among fertilizer-P sources in the NE-SiL and NE-SL soils (Table 4). However, for the AR-SiCL soil, belowground wheat dry matter P uptake was smallest in the UC (0.1 g m⁻²), which

Table 4 Elemental uptake in belowground dry matter for fertilizer-phosphorus (P) materials [electrochemically precipitated struvite (ECST), chemically precipitated struvite (CPST), monoammonium phosphate (MAP), and triple superphosphate (TSP) and unamendedcontrol (UC)] from unvernallized wheat grown for 60-days in six soils in the greenhouse. Means ($n=3$) are reported with standard errors in parentheses

Plant property	Fertilizer-P source	Soil					
		AR-SiCL [§]	AR-SiL	MO-SiL 1	MO-SiL 2	NE-SiL	NE-SL
g m ⁻²							
N	CPST	1.6 (0.3) i-l [†]	1.9 (0.3) f-k	2.2 (0.4) d-j	5.0 (0.8) a	2.4 (0.4) c-i	2.6 (0.4) b-h
	ECST	1.3 (0.2) kl	1.4 (0.2) j-l	2.7 (0.4) b-h	2.9 (0.5) b-g	3.3 (0.5) a-d	2.8 (0.5) b-g
	MAP	2.3 (0.4) d-j	2.6 (0.4) b-h	2.9 (0.5) b-g	3.7 (0.6) a-c	3.2 (0.5) a-e	2.9 (0.5) b-g
	TSP	1.9 (0.3) g-k	1.8 (0.3) g-k	4.1 (0.7) ab	3.7 (0.6) a-c	3.0 (0.5) b-f	3.9 (0.6) ab
	UC	1.1 (0.2) l	2.0 (0.3) e-k	1.7 (0.3) h-k	3.4 (0.6) a-d	3.9 (0.6) ab	3.8 (0.6) a-c
P	CPST	0.3 (<0.1) b-g	0.2 (<0.1) e-h	0.1 (<0.1) hi	0.6 (0.1) a	0.2 (<0.1) d-h	0.3 (<0.1) b-g
	ECST	0.2 (<0.1) gh	0.1 (<0.1) hi	0.2 (<0.1) d-h	0.2 (<0.1) b-g	0.3 (<0.1) b-g	0.3 (<0.1) b-g
	MAP	0.3 (0.1) bc	0.2 (<0.1) b-g	0.2 (<0.1) d-h	0.3 (<0.1) b-g	0.3 (<0.1) b-e	0.3 (<0.1) b-g
	TSP	0.3 (<0.1) b-e	0.2 (<0.1) f-h	0.3 (<0.1) b-f	0.4 (0.1) ab	0.3 (0.1) b-d	0.4 (0.1) b
	UC	0.1 (<0.1) hi	0.2 (<0.1) d-h	0.1 (<0.1) i	0.2 (<0.1) c-h	0.3 (0.1) b-e	0.3 (0.1) b
Ca	CPST	0.4 (0.1) d-i	0.3 (0.1) f-i	0.2 (0.1) h-j	1.0 (0.2) a	0.4 (0.1) b-g	0.4 (0.1) c-i
	ECST	0.3 (0.1) f-i	0.2 (0.1) ij	0.3 (0.1) f-i	0.4 (0.1) b-g	0.5 (0.1) b-f	0.5 (0.1) b-f
	MAP	0.5 (0.1) b-g	0.7 (0.1) ab	0.3 (0.1) f-i	0.6 (0.1) a-c	0.5 (0.1) b-f	0.4 (0.1) b-i
	TSP	0.4 (0.1) c-i	0.4 (0.1) b-g	0.4 (0.1) b-g	0.7 (0.1) ab	0.6 (0.1) a-d	0.5 (0.1) b-e
	UC	0.3 (0.1) g-j	0.3 (0.1) e-i	0.2 (0.1) j	0.4 (0.1) c-i	0.6 (0.1) a-c	0.4 (0.1) b-h
Fe	CPST	0.4 (0.1) b-g	0.2 (0.1) f-h	0.2 (0.1) gh	0.5 (0.1) a-c	0.3 (0.1) b-g	0.4 (0.1) a-g
	ECST	0.3 (0.1) b-g	0.2 (0.1) f-h	0.5 (0.1) a-e	0.3 (0.1) d-g	0.4 (0.1) a-f	0.4 (0.1) a-g
	MAP	0.5 (0.1) a-d	0.6 (0.1) ab	0.3 (0.1) c-g	0.4 (0.1) a-g	0.4 (0.1) a-g	0.3 (0.1) b-g
	TSP	0.5 (0.1) a-d	0.4 (0.1) a-f	0.5 (0.1) a-e	0.3 (0.1) b-g	0.4 (0.1) a-f	0.5 (0.1) a-d
	UC	0.5 (0.1) a-d	0.2 (0.1) f-h	0.1 (<0.1) h	0.2 (0.1) e-h	0.7 (0.1) a	0.4 (0.2) a-e

[§]AR-SiCL, Arkansas silty-clay loam; AR-SiL, Arkansas loam; MO-SiL1, Missouri silt loam; MO-SiL 2, Missouri silt loam; NE-SL, Nebraska sandy loam; NE-SiL, Nebraska silt loam

[†] Means for an element among soils and fertilizer-P sources with different letters are different at $P < 0.05$. Letters separated by a hyphen (-) represent a range of letters that include each letter between the beginning and ending letter

did not differ from that for ECST, and were both smaller than for MAP and TSP, which did not differ from that for CPST (Table 4). Belowground wheat dry matter P uptake in the AR-SiL were numerically larger from CPST, MAP, TSP, and the UC, which did not differ, and was numerically smallest from ECST, which did not differ from that for MAP (Table 4). Belowground wheat dry matter P uptake in the MO-SiL 1 soil did not differ among CPST, ECST, and MAP, but was largest for TSP (0.3 g m⁻²), which did not differ from that for ECST and MAP, while the UC had the smallest belowground wheat dry matter P uptake (0.1 g m⁻²) and was similar to that for CPST (Table 4). For the MO-SiL 2 soil, belowground wheat dry matter P uptake did not differ among ECST, MAP, and the UC, but was largest in the CPST (0.6 g m⁻²), which was similar to that for TSP (0.4 g m⁻²; Table 4). Belowground wheat dry matter P uptake did not differ between the struvite-P sources in any of the soils, except for the MO-SiL 2, where CPST was 0.4 g m⁻² larger than for ECST (Table 4).

3.6.2 Ca Uptake

Belowground wheat dry matter Ca uptake differed ($P=0.04$) among soil-fertilizer-P-source combinations (Table 3). Belowground wheat dry matter Ca uptake ranged from 0.2 g m⁻² in the MO-SiL-1-UC to 1.0 g m⁻² in the MO-SiL-2-CPST combination (Table 4). There were no belowground wheat dry matter Ca uptake differences among fertilizer-P sources in three of the six soils (i.e., AR-SiCL, NE-SiL, and NE-SL; Table 4). For the AR-SiL soil, belowground wheat dry matter Ca uptake was lowest for ECST (0.2 g m⁻²), which did not differ from that for CPST and the UC, and was largest for MAP, which was similar to that for TSP (0.4 g m⁻²) and the UC (Table 4). Belowground wheat Ca uptake in the MO-SiL 1 soil did not differ among CPST, ECST, and MAP, but was smallest in the UC (0.2 g m⁻²) and largest for TSP (0.4 g m⁻²; Table 4). There were no belowground wheat Ca uptake differences between the UC and CPST in the MO-SiL 1 soil (Table 4). Belowground

wheat dry matter Ca uptake in the MO-SiL 2 soil was smallest for ECST and the UC (0.4 g m^{-2}) and largest for CPST (1.0 g m^{-2}), which was similar to that for MAP and TSP (Table 4). Belowground wheat dry matter Ca uptake did not differ between the struvite-P sources in five of the six soils (i.e., AR-SiCL, AR-SiL, MO-SiL 1, NE-SiL, and NE-SL; Table 4). Belowground wheat dry matter Ca uptake in the MO-SiL 2 soil was 0.6 g m^{-2} larger for CPST than for ECST (Table 4).

3.6.3 Mg Uptake

Belowground wheat dry matter Mg uptake differed ($P=0.01$) among soils, but was unaffected ($P>0.05$) by fertilizer-P source (Table 3). Averaged across fertilizer-P sources, belowground wheat dry matter Mg uptake ranged from 0.1 g m^{-2} in the MO-SiL 1, which was similar to that in the AR-SiL and NE-SL soils, to 0.3 g m^{-2} in the MO-SiL 2, which did not differ from that in the AR-SiCL and NE-SiL soils (Fig. 2).

3.6.4 Fe Uptake

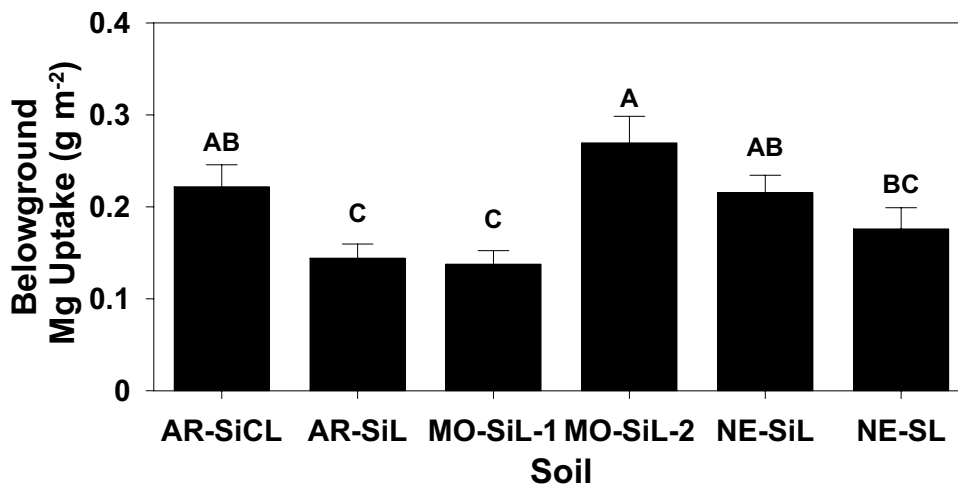
Belowground wheat dry matter Fe uptake differed ($P=0.01$) among soil-fertilizer-P source combinations (Table 3). Belowground wheat dry matter Fe uptake ranged from 0.1 g m^{-2} in the MO-SiL-1-UC to 0.7 g m^{-2} in the NE-SiL-UC combination (Table 4). There were no belowground wheat dry matter Fe uptake differences among any of the fertilizer-P sources in the AR-SiCL and NE-SL soils (Table 4). For the AR-SiL soil, belowground wheat Fe uptake for MAP (0.6 g m^{-2}) was only similar to that for TSP (0.5 g m^{-2}) and was larger than all other fertilizer-P sources (0.2 g m^{-2} ; Table 4). In the MO-SiL 1 soil, belowground wheat Fe uptake was lowest for MAP and the UC (0.1 g m^{-2}), which did not differ, and largest from ECST and TSP (0.5 g m^{-2}), which did not differ

from CPST (0.2 g m^{-2}) and MAP (0.3 g m^{-2}) (Table 4). For the MO-SiL 2 soil, CPST had the numerically largest belowground wheat dry matter Fe uptake (0.5 g m^{-2}), which was similar to that for MAP (0.4 g m^{-2}) and TSP (0.3 g m^{-2}); however, there were no belowground wheat dry matter Fe uptake differences between ECST (0.3 g m^{-2}), MAP, TSP, and the UC (0.2 g m^{-2} ; Table 4). There were no belowground wheat dry matter Fe uptake differences among CPST (0.3 g m^{-2}), ECST (0.4 g m^{-2}), MAP (0.4 g m^{-2}), and TSP (0.4 g m^{-2}) in the NE-SiL soil; however, belowground wheat dry matter Fe uptake was largest in the UC (0.7 g m^{-2} ; Table 4). Belowground wheat dry matter Fe uptake did not differ between the struvite-P sources in any of the soils, except for the MO-SiL 1, where ECST was 0.3 g m^{-2} larger than for CPST, and for the MO-SiL 2, where CPST was 0.2 g m^{-2} larger than for ECST (Table 4). Belowground wheat Fe uptake for ECST did not differ among fertilizer -P sources in the AR-SiL and MO-SiL 2 soils except for MAP in the AR-SiL which was 0.4 g m^{-2} larger, and for CPST in the MO-SiL soil which was 0.2 g m^{-2} larger (Table 4). For the MO-SiL 1 soil, belowground wheat Fe uptake of ECST was similar to that of MAP and TSP, but 0.3 and 0.4 g m^{-2} larger than for CPST and the UC (Table 4). However, belowground wheat Fe uptake for CPST differed from that for MAP and TSP only in the MO-SiL 1 soil, where belowground wheat dry matter Fe uptake for TSP was 0.3 g m^{-2} larger than for CPST (Table 4).

3.7 Aboveground Nutrient Uptake

After 60 days of growth, aboveground dry matter nutrient uptake differences among soils by fertilizer-P sources were complex. Aboveground wheat dry matter N, P, Ca, Mg, and Fe uptake differed ($P<0.01$) among soils within fertilizer-P sources (Table 3).

Fig. 2 Belowground Mg uptake in wheat among soils from Arkansas [AR-silty clay loam (SiCL) and AR-silt loam (SiL)], Missouri (MO-SiL 1 and MO-SiL 2), and Nebraska [NE-sandy loam (SL) and NE-SiL], in a 60-day greenhouse potted-plant study, averaged across fertilizer-P sources. Different letters atop bars are significantly different at $P<0.05$. Error bars represent the standard error of the mean



3.7.1 N Uptake

Aboveground wheat dry matter N uptake ranged from 5.4 g m⁻² in the MO-SiL-1-UC to 17.4 g m⁻² in the NE-SiL-MAP combination (Table 5). For the AR-SiCL soil, aboveground wheat dry matter N uptake was smallest for CPST (7.4 g m⁻²) and numerically largest for ECST (9.8 g m⁻²); however, there were no differences among MAP (9.2 g m⁻²), TSP (8.6 g m⁻²), and the UC (8.6 g m⁻²; Table 5). For the AR-SiL soil, aboveground wheat dry matter N uptake was least in the UC (10.2 g m⁻²), which was similar to that for TSP (11.0 g m⁻²), and numerically greatest for MAP (13.3 g m⁻²), which did not differ among CPST (12.7 g m⁻²), ECST (12.0 g m⁻²; Table 5). Aboveground wheat dry matter N uptake in the MO-SiL 1 soil was least in

the UC (5.4 g m⁻²) and was numerically greatest from ECST (11.7 g m⁻²; Table 5). Unlike the AR-SiCL and AR-SiL soils, aboveground wheat dry matter N uptake for the MO-SiL 1 soil did not differ among fertilizer-P sources, and were all greater than for the UC (Table 5). Aboveground wheat dry matter N uptake in the MO-SiL 2 was smallest in the UC (9.5 g m⁻²) and numerically largest from MAP (14.7 g m⁻²), which did not differ among ECST, CPST, and TSP (Table 5).

Between the struvite-P sources, aboveground wheat dry matter N uptake did not differ in four of the six soils (i.e., AR-SiL, MO-SiL 1 and 2, and NE-SiL), but ECST had larger aboveground wheat dry matter N uptake than for CPST in the AR-SiCL and NE-SL soils (9.8 and 13.6 g m⁻², respectively, for ECST and 7.4 and 11.6 g m⁻², respectively, for CPST; Table 5). Aboveground wheat dry matter N.

Table 5 Elemental uptake in aboveground dry matter for fertilizer-phosphorus (P) materials [electrochemically precipitated struvite (ECST), chemically precipitated struvite (CPST), monoammonium phosphate (MAP), and triple superphosphate (TSP) and unamended

control (UC)] from unvernallized wheat grown for 60-days in six soils in the greenhouse. Means (n=3) are reported with standard errors in parentheses

Plant property	Fertilizer-P source	Soil					
		AR-SiCL [§]	AR-SiL	MO-SiL-1	MO-SiL-2	NE-SiL	NE-SL
g m ⁻²							
N	CPST	7.4 (0.4) q [†]	12.7 (0.7) e-i	10.6 (0.5) k-n	12.6 (0.6) e-j	15.2 (0.8) a-d	11.6 (0.6) h-l
	ECST	9.8 (0.5) m-p	12.0 (0.6) f-k	11.7 (0.6) g-l	13.5 (0.7) d-g	17.2 (0.9) a	13.6 (0.7) d-f
	MAP	9.2 (0.5) op	13.3 (0.7) d-h	11.3 (0.6) i-l	14.7 (0.8) b-d	17.4 (0.9) a	12.0 (0.6) f-k
	TSP	8.6 (0.4) p	11.0 (0.6) j-m	11.0 (0.6) j-n	14.3 (0.7) e-d	16.8 (0.9) ab	12.3 (0.6) f-k
	UC	8.6 (0.4) p	10.2 (0.5) l-o	5.4 (0.3) r	9.5 (0.5) n-p	15.8 (0.8) a-c	11.0 (0.6) j-m
P	CPST	0.9 (0.1) c-f	1.0 (0.1) c-e	0.6 (<0.1) i	0.6 (0.1) hi	0.9 (0.1) c-e	0.8 (0.1) e-g
	ECST	1.0 (0.1) c-e	1.0 (0.1) c-e	0.7 (0.1) gh	1.0 (0.1) c-e	1.3 (0.1) ab	1.1 (0.1) a-c
	MAP	1.1 (0.1) a-c	1.0 (0.1) c-e	0.5 (<0.1) i	0.7 (0.1) f-h	1.4 (0.1) a	1.0 (0.1) c-e
	TSP	1.0 (0.1) c-e	0.9 (0.1) d-g	0.6 (<0.1) hi	0.7 (0.1) gh	1.4 (0.1) a	1.1 (0.1) b-d
	UC	0.9 (0.1) d-g	0.7 (0.1) f-h	0.2 (<0.1) k	0.3 (<0.1) j	1.0 (0.1) c-e	0.9 (0.1) c-e
Ca	CPST	1.3 (0.1) g-i	2.8 (0.2) a-c	1.3 (0.1) g-i	2.8 (0.2) a-c	2.7 (0.2) b-d	1.2 (0.1) hi
	ECST	1.6 (0.1) f	2.4 (0.2) c-e	1.5 (0.1) f-h	3.1 (0.2) ab	3.0 (0.2) ab	1.5 (0.1) fg
	MAP	1.6 (0.1) f	3.0 (0.2) ab	1.4 (0.1) f-h	3.2 (0.2) a	3.1 (0.2) ab	1.5 (0.1) fg
	TSP	1.4 (0.1) f-h	2.3 (0.1) de	1.5 (0.1) fg	3.2 (0.2) a	2.9 (0.2) ab	1.5 (0.1) fg
	UC	1.4 (0.1) f-h	2.1 (0.1) e	0.6 (<0.1) j	2.1 (0.1) e	2.6 (0.2) b-d	1.1 (0.1) i
Mg	CPST	0.5 (<0.1) n	1.5 (0.1) ab	0.9 (0.1) f-h	1.3 (0.1) cd	0.8 (<0.1) hi	0.6 (<0.1) k-n
	ECST	0.6 (<0.1) j-l	1.3 (0.1) bc	1.0 (0.1) ef	1.4 (0.1) a-c	0.9 (0.1) f-h	0.7 (<0.1) ij
	MAP	0.6 (<0.1) j-m	1.6 (0.1) a	1.0 (0.1) e-g	1.5 (0.1) ab	0.9 (0.1) f-h	0.6 (<0.1) j-l
	TSP	0.5 (<0.1) l-n	1.2 (0.1) cd	1.0 (0.1) ef	1.5 (0.1) ab	0.9 (0.1) gh	0.7 (<0.1) jk
	UC	0.5 (<0.1) mn	1.1 (0.1) de	0.4 (<0.1) o	0.8 (<0.1) hi	0.8 (0.1) hi	0.6 (<0.1) k-n
Fe	CPST	0.04 (<0.1) j	0.09 (<0.1) b-g	0.04 (<0.1) h-j	0.07 (<0.1) d-i	0.12 (<0.1) a-e	0.07 (<0.1) d-j
	ECST	0.12 (<0.1) a-e	0.16 (<0.1) ab	0.07 (<0.1) e-j	0.15 (<0.1) a-c	0.11 (<0.1) a-f	0.09 (<0.1) b-g
	MAP	0.05 (<0.1) g-j	0.17 (<0.1) ab	0.09 (<0.1) b-g	0.1 (<0.1) b-g	0.2 (<0.1) a	0.06 (<0.1) f-j
	TSP	0.04 (<0.1) h-j	0.11 (<0.1) a-e	0.06 (<0.1) f-j	0.09 (<0.1) b-g	0.14 (<0.1) a-d	0.06 (<0.1) f-j
	UC	0.07 (<0.1) d-i	0.08 (<0.1) c-h	0.02 (<0.1) k	0.04 (<0.1) ij	0.2 (<0.1) a	0.07 (<0.1) d-j

[§]AR-SiCL, Arkansas silty-clay loam; AR-SiL, Arkansas loam; MO-SiL1, Missouri silt loam; MO-SiL 2, Missouri silt loam; NE-SL, Nebraska sandy loam; NE-SiL, Nebraska silt loam

[†]Means for an element among soil-fertilizer-P sources with different letters are different at $P < 0.05$. Letters separated by a hyphen (-) represent a range of letters that include each letter between the beginning and ending letter

uptake for CPST was numerically smaller than for MAP and TSP in five of the six soils, but smallest in the AR-SiCL soil (Table 5). Aboveground wheat N uptake for ECST did not differ among MAP and TSP in any of the six soils (Table 5).

3.7.2 P Uptake

Aboveground wheat dry matter P uptake ranged from 0.2 g m^{-2} in the MO-SiL-1-UC to 1.4 g m^{-2} in the NE-SiL-MAP and -TSP combinations (Table 5). For the AR-SiCL soil, aboveground wheat dry matter P uptake was smallest in the UC and CPST (0.9 g m^{-2}), but there were no differences in aboveground P uptake among ECST, MAP, and TSP, and only MAP had larger aboveground wheat dry matter P uptake than the UC (Table 5). Aboveground wheat dry matter P uptake in the AR-SiL soil was smallest in the UC (0.7 g m^{-2}) and largest among CPST, ECST, and MAP (1.0 g m^{-2}) (Table 5). However, TSP (0.9 g m^{-2}) did not differ from any of the other fertilizer-P sources (Table 5). For the MO-SiL 1 soil, aboveground wheat dry matter P uptake was smallest in the UC (0.2 g m^{-2}) and numerically largest for ECST (0.7 g m^{-2} ; Table 5). Aboveground wheat dry matter P uptake for the MO-SiL 1 soil was larger for ECST and TSP, which did not differ, than for CPST and MAP (Table 5). There were no aboveground wheat dry matter P uptake differences among CPST, MAP, and TSP, but aboveground wheat P uptake was greater for all four fertilizer-P sources than for the UC in the MO-SiL 1 soil (Table 5). Similar to the MO-SiL 1 soil, aboveground wheat P uptake in the MO-SiL 2 soil was smallest in the UC (0.3 g m^{-2}) and largest for ECST (1.0 g m^{-2}), which was larger than all other fertilizer-P sources (Table 5).

Aboveground wheat dry matter P uptake differed between the struvite-P sources in four of the six soils (i.e., MO-SiL 1 and 2, NE-SiL, and NE-SL), where aboveground wheat P uptake for ECST was 0.1 , 0.4 , 0.4 , and 0.3 g m^{-2} , respectively, larger than for CPST (Table 5). Aboveground wheat dry matter P uptake for CPST did not differ from that for MAP and TSP among the AR-SiCL, AR-SiL, and MO-SiL 1 and 2 soils; however, for the NE-SiL soil, both MAP and TSP had 0.5 g m^{-2} larger aboveground wheat P uptake than for CPST, while, for the NE-SL soil, aboveground wheat P uptake for CPST did not differ from that for MAP, but was 0.3 g m^{-2} less than for TSP (Table 5). Aboveground wheat P uptake for ECST did not differ from that for MAP and TSP in four of the six soils (i.e., AR-SiCL, AR-SiL, NE-SiL, and NE-SL), but was 0.1 and 0.2 g m^{-2} larger than for MAP and TSP, respectively, in the MO-SiL 1 and 0.3 g m^{-2} larger than for both MAP and TSP in the MO-SiL 2 soil (Table 5).

3.7.3 Ca Uptake

Aboveground wheat dry matter Ca uptake ranged from 0.6 g m^{-2} in the MO-SiL-1-UC to 3.2 g m^{-2} in the MO-SiL-2-MAP and -TSP combinations (Table 5). For the AR-SiCL soil, aboveground wheat Ca uptake was smallest for CPST (1.3 g m^{-2}), while that for ECST and MAP were largest (1.6 g m^{-2}) and did not differ (Table 5). Aboveground wheat dry matter Ca uptake for the AR-SiL soil was numerically smallest in the UC (2.1 g m^{-2}), but was only different from that for CPST and MAP (2.8 and 3.0 g m^{-2} ; Table 5). There were no aboveground wheat dry matter Ca uptake differences among ECST and the other fertilizer-P sources, except for MAP, which was 0.6 g m^{-2} larger than for ECST (Table 5). Unlike for the AR-SiCL and AR-SiL soils, aboveground wheat dry matter Ca uptake for both the MO-SiL 1 and 2 soils did not differ among fertilizer-P sources, except for the UC, which was numerically least (0.6 and 2.1 g m^{-2} for the MO-SiL 1 and 2 soils, respectively; Table 5). For the NE-SL soil, aboveground wheat Ca uptake did not differ among ECST, MAP, and TSP (all 1.5 g m^{-2}), and were all more than 0.3 g m^{-2} greater than for the CPST (1.2 g m^{-2}) and the UC (1.1 g m^{-2} ; Table 5).

Aboveground wheat dry matter Ca uptake did not differ between the struvite-P sources in four of the six soils (i.e., AR-SiL, MO-SiL 1 and 2, and NE-SiL; Table 5). Aboveground wheat dry matter Ca uptake in the AR-SiCL and NE-SL soils were 0.3 g m^{-2} larger for ECST than for CPST (Table 5). Aboveground wheat dry matter Ca uptake for ECST did not differ from that for MAP and TSP in any of the soils, except for MAP in the AR-SiL, where MAP was 0.6 g m^{-2} larger than for ECST (Table 5). For CPST, aboveground wheat Ca uptake did not differ among the MO-SiL 1 and 2 and NE-SiL soils, but that for CPST was 0.3 g m^{-2} smaller than for both MAP and TSP in the NE-SL soil, was similar to that for TSP in the AR-SiCL soil, and was 0.3 g m^{-2} less than for MAP (Table 5). Aboveground Ca uptake for the AR-SiL soil was similar for CPST and MAP, but CPST was 0.5 g m^{-2} larger than TSP (Table 5).

3.7.4 Mg Uptake

Aboveground wheat dry matter Mg uptake ranged from 0.4 g m^{-2} in the MO-SiL-1-UC to 1.6 g m^{-2} in the AR-SiL-MAP combination (Table 5). For the AR-SiCL soil, there were no aboveground wheat Mg uptake differences among ECST, MAP, and TSP (0.6 , 0.6 , and 0.5 g m^{-2} , respectively; Table 5). Aboveground wheat dry matter Mg uptake also did not differ among CPST (0.5 g m^{-2}), TSP, and the UC (0.5 g m^{-2} ; Table 5) in the AR-SiCL soil. For the AR-SiL soil, aboveground wheat Mg uptake was lowest from the UC and TSP to and was largest from MAP and CPST (1.5 g m^{-2}) (Table 5). Unlike for the AR-SiL soil, aboveground wheat

Mg uptake did not differ among fertilizer-P sources in the MO-SiL 1, except for the UC, which was the smallest (0.4 g m^{-2} ; Table 5). For the MO-SiL 2 soil, there were no aboveground wheat dry matter Mg uptake differences among ECST (1.4 g m^{-2}), MAP (1.5 g m^{-2}), and TSP (1.5 g m^{-2}), while aboveground wheat dry matter Mg uptake for CPST (1.3 g m^{-2}) was similar to that for ECST, and that for the UC (0.8 g m^{-2}) was smallest (Table 5). Aboveground wheat dry matter Mg uptake in the NE-SL soil did not differ among ECST (0.7 g m^{-2}), MAP (0.6 g m^{-2}), and TSP (0.7 g m^{-2}); however, aboveground wheat dry matter Mg uptake was numerically largest from ECST and did not differ among any of the other fertilizer-P sources (Table 5).

Aboveground wheat dry matter Mg uptake did not differ between struvite-P sources in four of the six soils (i.e., AR-SiL, MO-SiL 1 and 2, and NE-SiL), but, for both the AR-SiCL and NE-SL soils, aboveground wheat Mg uptake for ECST was 0.1 g m^{-2} larger than for CPST (Table 5). Aboveground wheat dry matter Mg uptake did not differ among ECST, MAP, and TSP in any of the other soils, except for in the AR-SiL soil where MAP was 0.3 g m^{-2} larger than for ECST (Table 5). Aboveground wheat dry matter P uptake for CPST was similar to that for MAP and TSP in the MO-SiL 1, NE-SiL, and NE-SL soils, but aboveground wheat Mg uptake for CPST was smaller than for both MAP and TSP in the MO-SiL 2 soil (Table 5). For the AR-SiCL soil, aboveground wheat Mg uptake was similar for CPST and TSP, but that for MAP was 0.1 g m^{-2} larger than for CPST, while, in the AR-SiL soil, aboveground wheat Mg uptake for CPST was similar to that for MAP, but 0.3 g m^{-2} larger than for TSP (Table 5).

3.7.5 Fe Uptake

Aboveground wheat dry matter Fe uptake ranged from 0.02 g m^{-2} in the MO-SiL-1-UC to 0.20 g m^{-2} in the NE-SiL-MAP and -UC combinations (Table 5). For the AR-SiCL soil, aboveground wheat Fe uptake was smallest for CPST and TSP (0.04 g m^{-2}) but was similar to that for MAP (0.05 g m^{-2}), and was largest for ECST (0.12 g m^{-2}), which did not differ from that for the UC (Table 5). Aboveground wheat dry matter Fe uptake in the AR-SiL soil for all fertilizer-P sources was larger than for the UC (0.08 g m^{-2}), except for CPST (0.09 g m^{-2}), which was similar to that for the UC (Table 5). In the MO-SiL 1 soil, aboveground wheat Fe uptake was smallest in the UC (0.02 g m^{-2}) and largest from MAP (0.09 g m^{-2} ; Table 5). There were no aboveground wheat dry matter Fe uptake differences in the MO-SiL 1 soil among ECST (0.07 g m^{-2}), CPST, MAP, and TSP (0.06 g m^{-2}) (Table 5). Similar to that for the MO-SiL 1 soil, in the MO-SiL 2 soil, aboveground wheat Fe uptake was also smallest for the UC (0.04 g m^{-2}), which did not

differ from that for CPST (0.7 g m^{-2}) and was numerically largest for ECST (0.15 g m^{-2} ; Table 5).

Aboveground wheat dry matter Fe uptake did not differ between the struvite-P sources in four of the six soils (i.e., AR-SiL, MO-SiL 1, NE-SiL, and NE-SL); however, aboveground wheat Fe uptake for ECST was 0.08 g m^{-2} larger than for CPST in the MO-SiL 2 and AR-SiCL soils (Table 5). Aboveground wheat Fe uptake for ECST in the MO-SiL 2 soil did not differ between ECST, MAP, and TSP in any of the other soils, except for AR-SiCL, where ECST had a 0.07 and 0.08 g m^{-2} larger aboveground wheat Fe uptake than for MAP and TSP, respectively (Table 5). In contrast, aboveground wheat dry matter Fe uptake for CPST did not differ from that for MAP and TSP, except in the AR-SiL, where MAP and TSP were 0.08 and 0.02 g m^{-2} larger than for CPST, and in the MO-SiL 1 soil, where MAP did not differ from CPST, but TSP was 0.2 g m^{-2} larger than for CPST (Table 5).

3.8 Total Plant Uptake

Total wheat dry matter nutrient uptake differences among soils by fertilizer-P sources after 60 days of growth were complex. Total wheat dry matter N, P, Ca, Mg, and Fe uptake differed ($P < 0.01$) among soils within fertilizer-P sources (Table 3).

3.8.1 Total N Uptake

Total wheat dry matter N uptake ranged from 7.2 g m^{-2} in the MO-SiL-1-UC to 20.5 g m^{-2} in the NE-SiL-ECST, which was similar to that for NE-SiL-MAP and -TSP combinations (Table 6). For the AR-SiCL soil, total wheat dry matter N uptake was smallest from CPST (9.0 g m^{-2}) and numerically largest from MAP (11.5 g m^{-2} ; Table 6). Total wheat dry matter N uptake for the AR-SiL soil was numerically lower in the UC (12.3 g m^{-2}), but differed only from that for CPST (14.7 g m^{-2}) and MAP (15.9 g m^{-2} ; Table 6). Total wheat dry matter N uptake in the MO-SiL 1 and 2 soils did not differ among CPST, ECST, MAP, and TSP, which all were greater than for the UC (7.2 and 12.9 g m^{-2} , respectively for MO-SiL 1 and 2; Table 6).

Between the struvite-P sources, total wheat dry matter N uptake did not differ in five of the six soils, (i.e., AR-SiL, MO-SiL 1 and 2, NE-SiL, and NE-SL), but ECST had a 2.1 g m^{-2} larger total wheat dry matter N uptake than for CPST in the AR-SiCL soil (Table 6). Total wheat dry matter N uptake did not differ among ECST, MAP, and TSP in five of the six soils; however, in the AR-SiL soil, total dry matter N uptake for MAP was larger than for both ECST and TSP, while total wheat dry matter N uptake for CPST differed from that for MAP only in the AR-SiCL soil and did not differ from that for TSP in any of the six soils.

Table 6 Total elemental uptake of dry matter for fertilizer-phosphorus (P) materials [electrochemically precipitated struvite (ECST), chemically precipitated struvite (CPST), monoammonium phosphate (MAP), and triple superphosphate (TSP) and unamended control

(UC)] from unvernalized wheat grown for 60-days in six soils in the greenhouse. Means (n=3) are reported with standard errors in parentheses

Plant property	Fertilizer-P source	Soil					
		AR-SiCL [§]	AR-SiL	MO-SiL-1	MO-SiL-2	NE-SiL	NE-SL
g m ⁻²							
N	CPST	9.0 (0.5) I [†]	14.7 (0.8) ef	12.8 (0.7) f-i	17.6 (1.0) a-d	17.7 (1.0) a-c	14.2 (0.8) e-g
	ECST	11.1 (0.6) i-k	13.4 (0.8) f-h	14.4 (0.8) e-g	16.4 (1.0) b-e	20.5 (1.2) a	16.4 (0.9) b-e
	MAP	11.5 (0.7) h-j	15.9 (0.9) b-e	14.2 (0.8) e-g	18.4 (1.0) ab	20.5 (1.2) a	14.9 (0.9) d-f
	TSP	10.5 (0.6) j-l	12.9 (0.7) f-i	15.1 (0.9) c-f	18.0 (1.0) ab	19.9 (1.1) a	16.2 (0.9) b-e
	UC	9.7 (0.6) kl	12.3 (0.7) g-j	7.2 (0.4) m	12.9 (0.7) f-i	19.6 (1.1) a	14.8 (0.8) ef
P	CPST	1.2 (0.1) c-g	1.2 (0.1) c-g	0.7 (0.1) k	1.2 (0.1) c-g	1.1 (0.1) d-h	1.1 (0.1) e-h
	ECST	1.2 (0.1) c-g	1.1 (0.1) d-h	0.9 (0.1) ij	1.3 (0.1) b-f	1.6 (0.1) ab	1.4 (0.1) a-d
	MAP	1.4 (0.1) a-c	1.3 (0.1) c-f	0.7 (0.1) jk	1.0 (0.1) g-i	1.6 (0.1) a	1.3 (0.1) b-e
	TSP	1.3 (0.1) a-e	1.0 (0.1) f-i	0.9 (0.1) ij	1.1 (0.1) e-h	1.6 (0.1) a	1.4 (0.1) a-c
	UC	1.0 (0.1) g-i	0.9 (0.1) hi	0.3 (<0.1) m	0.5 (<0.1) l	1.3 (0.1) b-e	1.2 (0.1) c-f
Ca	CPST	1.7 (0.1) j-m	3.1 (0.2) b-d	1.6 (0.1) m	3.8 (0.3) a	3.1 (0.2) b-d	1.6 (0.1) k-m
	ECST	1.9 (0.1) h-k	2.7 (0.2) de	1.8 (0.1) h-m	3.6 (0.2) ab	3.5 (0.2) ab	2.0 (0.1) g-i
	MAP	2.0 (0.1) g-j	3.7 (0.2) ab	1.7 (0.1) i-m	3.8 (0.3) a	3.6 (0.2) ab	1.9 (0.1) h-l
	TSP	1.8 (0.1) h-m	2.7 (0.2) c-e	2.0 (0.1) h-j	3.9 (0.3) a	3.5 (0.2) ab	2.1 (0.1) f-h
	UC	1.7 (0.1) i-m	2.4 (0.2) e-g	0.8 (0.1) n	2.5 (0.2) ef	3.3 (0.2) a-c	0.5 (0.1) lm
Mg	CPST	0.8 (0.1) i	1.6 (0.1) ab	1.0 (0.1) f-h	1.8 (0.1) a	1.0 (0.1) f-h	0.8 (0.1) i
	ECST	0.8 (0.1) i	1.4 (0.1) bc	1.2 (0.1) d-f	1.6 (0.1) ab	1.1 (0.1) ef	0.9 (0.1) g-i
	MAP	0.9 (0.1) g-i	1.8 (0.1) a	1.1 (0.1) ef	1.7 (0.1) a	1.1 (0.1) ef	0.8 (0.1) i
	TSP	0.8 (0.1) i	1.4 (0.1) b-d	1.3 (0.1) c-e	1.8 (0.1) a	1.1 (0.1) ef	0.9 (0.1) hi
	UC	0.8 (0.1) i	1.2 (0.1) c-e	0.5 (<0.1) j	1.0 (0.1) e-g	1.1 (0.1) ef	0.8 (0.1) i
Fe	CPST	0.4 (0.1) c-f	0.3 (0.1) d-f	0.3 (<0.1) fg	0.6 (0.1) a-c	0.4 (0.1) c-e	0.5 (0.1) c-e
	ECST	0.5 (0.1) b-e	0.4 (0.1) c-f	0.4 (0.1) c-f	0.4 (0.1) c-e	0.5 (0.1) b-d	0.5 (0.1) b-e
	MAP	0.5 (0.1) a-c	0.8 (0.1) ab	0.4 (0.1) c-f	0.5 (0.1) b-e	0.6 (0.1) a-c	0.4 (0.1) c-f
	TSP	0.5 (0.1) a-c	0.5 (0.1) a-c	0.5 (0.1) a-c	0.4 (0.1) c-e	0.5 (0.1) a-c	0.5 (0.1) a-c
	UC	0.6 (0.1) a-c	0.3 (0.1) d-f	0.2 (<0.1) g	0.3 (0.1) ef	0.9 (0.2) a	0.5 (0.1) bc

[§]AR-SiCL, Arkansas silty-clay loam; AR-SiL, Arkansas loam; MO-SiL1, Missouri silt loam; MO-SiL 2, Missouri silt loam; NE-SL, Nebraska sandy loam; NE-SiL, Nebraska silt loam

[†]Means for an element among soil-fertilizer-P sources with different letters are different at $P < 0.05$. Letters separated by a hyphen (-) represent a range of letters that include each letter between the beginning and ending letter

3.8.2 Total P Uptake

Total wheat dry matter P uptake ranged from 0.3 g m⁻² in the MO-SiL-1-UC to 1.6 g m⁻² in the NE-SiL-ECST, -MAP, and -TSP combinations (Table 6). For the AR-SiCL soil, total wheat dry matter P uptake was numerically smallest in the UC (1.0 g m⁻²) and numerically largest from MAP (1.4 g m⁻²), but there were no differences between total P uptake for CPST (1.2 g m⁻²), ECST (1.2 g m⁻²), MAP, and TSP (1.3 g m⁻²), where all fertilizer-P sources had larger total wheat dry matter P uptake than for the UC (Table 6). Total wheat dry matter P uptake in the AR-SiL soil was numerically smallest in the UC (0.9 g m⁻²), and numerically largest for MAP (1.3 g m⁻²), and did not differ among CPST, ECST, and TSP; however, total wheat dry matter

N uptake for ECST did not differ from that for the UC (Table 6). For the MO-SiL 1 soil, total wheat dry matter P uptake was smallest in the UC (0.3 g m⁻²) and numerically largest for ECST and TSP (0.9 g m⁻²; Table 6). Total wheat dry matter P uptake for the MO-SiL 1 soil also did not differ among ECST, MAP, and TSP, but was larger for ECST than for MAP and CPST (0.7 g m⁻²; Table 6). Similar to the MO-SiL 1 soil, total wheat P uptake for the MO-SiL 2 was smallest in the UC (0.5 g m⁻²) and numerically largest in the ECST (1.3 g m⁻²), which was similar to that for CPST (1.2 g m⁻²) and TSP (1.1 g m⁻²), but larger than for MAP (1.0 g m⁻²; Table 6). Unlike for the MO-SiL 2 soil, total wheat P uptake for the NE-SiL soil was numerically smallest from CPST (1.1 g m⁻²) and numerically largest (1.6 g m⁻²) from ECST, MAP, and TSP, but did not differ

between the UC (1.3 g m^{-2}) and ECST or between the UC and CPST (Table 6). For the NE-SL soil, total wheat P uptake was numerically smallest for CPST (1.1 g m^{-2}) and numerically largest for ECST and TSP (1.4 g m^{-2}), but did not differ among ECST, MAP (1.3 g m^{-2}), TSP, and the UC (1.2 g m^{-2}), while all were larger than CPST (Table 6).

Total wheat dry matter P uptake differed between the struvite-P sources in three of the six soils (i.e., MO-SiL 1, NE-SiL, and NE-SL), where total wheat P uptake for ECST was larger than for CPST by 0.2, 0.5, and 0.3 g m^{-2} , respectively (Table 6). Total wheat dry matter P uptake between the struvite-P sources did not differ among the AR-SiCL, AR-SiL, and MO-SiL 2 soils (Table 6). Total wheat P uptake for ECST did not differ from that for MAP and TSP in any of the soils, except for the MO-SiL 1 soil, where wheat total P uptake for ECST was 0.3 and 0.2 g m^{-2} larger than for MAP and TSP, respectively (Table 6). Total wheat P uptake for CPST differed from that for MAP and TSP in the MO-SiL 1, NE-SiL, and NE-SL soils, where total wheat P uptake for CPST was similar to that for MAP and 0.2 g m^{-2} less than for TSP (Table 6). For the NE-SiL soil, total wheat P uptake for CPST was 0.5 g m^{-2} less than for MAP and TSP, while total wheat P uptake for CPST in the NE-SL soil was 0.2 and 0.3 g m^{-2} less than for MAP and TSP, respectively (Table 6).

3.8.3 Total Ca Uptake

Total wheat dry matter Ca uptake ranged from 0.8 g m^{-2} in the MO-SiL-1-UC to 3.9 g m^{-2} in the MO-SiL-2-TSP combination (Table 6). Total wheat dry matter Ca uptake for the AR-SiL soil was numerically smallest in the UC (2.4 g m^{-2}) and was numerically largest from MAP (3.7 g m^{-2}), but total wheat Ca uptake for MAP was only similar to that for CPST (3.1 g m^{-2} ; Table 6). There were no total wheat dry matter Ca uptake differences among ECST and any fertilizer-P source, except for MAP, which was 1.0 g m^{-2} larger (Table 6). Similar to that for the AR-SiL soil, total wheat dry matter Ca uptake for MO-SiL 1 was smallest for the UC (0.8 g m^{-2}) and largest for TSP (2.0 g m^{-2}), which did not differ among ECST (1.8 g m^{-2}) and MAP (1.7 g m^{-2} ; Table 6). Total wheat Ca uptake for the MO-SiL 2 soil was smallest in the UC (2.5 g m^{-2}) and numerically largest from TSP (3.9 g m^{-2}); however, total wheat Ca uptake did not differ among any fertilizer-P source, except for the UC, which was the least (Table 6). Unlike in the MO-SiL 2 soil, total wheat Ca uptake in the NE-SL soil was numerically smallest in the UC (0.5 g m^{-2}) and numerically largest for TSP (2.1 g m^{-2}), which did not differ from that for ECST or MAP (2.0 and 1.9 g m^{-2} , respectively; Table 6).

Total wheat dry matter Ca uptake did not differ between the struvite-P sources in five of the six soils (i.e., AR-SiCL, AR-SiL, MO-SiL 1 and 2, and NE-SiL; Table 6). Total wheat dry matter Ca uptake in the NE-SL soil was 0.4 g m^{-2}

larger for ECST than for CPST (Table 6). Total wheat dry matter Ca uptake for ECST did not differ from that for MAP and TSP in any of the soils, except for MAP in the AR-SiL, where MAP was 1.0 g m^{-2} larger than for ECST (Table 6). Total wheat Ca uptake for CPST differed from that for MAP and TSP in the MO-SiL 1 and NE-SL soils, where total wheat Ca uptake for CPST was 0.4 g m^{-2} smaller than that for TSP, but did not differ from that for MAP in the MO-SiL 1 soil and was 0.5 g m^{-2} less than for TSP in the NE-SL, but did not differ from that for MAP (Table 6).

3.8.4 Total Mg Uptake

Total wheat dry matter Mg uptake ranged from 0.5 g m^{-2} in the MO-SiL-1-UC to 1.8 g m^{-2} in the AR-SiL-MAP and in the MO-SiL-2-CPST and -TSP combinations (Table 6). For the AR-SiL soil, total wheat Mg uptake was again most variable among fertilizer-P sources, ranging from 1.2 g m^{-2} in the UC to 1.8 g m^{-2} from MAP; however, total wheat dry matter Mg uptake in the AR-SiL soil did not differ among ECST (1.4 g m^{-2}), TSP (1.4 g m^{-2}), and the UC (Table 6). Similarly, total wheat Mg uptake for CPST (1.6 g m^{-2}) did not differ from that for MAP in the AR-SiL soil (Table 6). For the MO-SiL 1 soil, total wheat Mg uptake was smallest for the UC (0.5 g m^{-2}) and numerically largest for TSP (1.3 g m^{-2}), but did not differ among that for CPST (1.0 g m^{-2}), ECST (1.2 g m^{-2}), and MAP (1.1 g m^{-2}), and did not differ between ECST and TSP (1.3 g m^{-2} ; Table 6). Like for the MO-SiL 1 soil, total wheat Mg uptake in the MO-SiL 2 was smallest for the UC (1.0 g m^{-2}), but was largest for both CPST and TSP (1.8 g m^{-2}), which did not differ among the other fertilizer-P sources (Table 6).

Total wheat dry matter Mg uptake did not differ between the struvite-P sources in any of the six soils (Table 6). Total wheat dry matter Mg concentrations did not differ between the ECST and MAP or TSP in any of the soils, except in the AR-SiL soil where MAP was 1.0 g m^{-2} larger than for ECST, but total wheat Mg uptake for ECST did not differ from that for TSP (Table 6). Total wheat Mg uptake for CPST differed from that for MAP and TSP in the MO-SiL 1 soil, where total wheat Mg uptake for CPST was similar to that for MAP, but was 0.3 g m^{-2} smaller than that for TSP (Table 6).

3.8.5 Total Fe Uptake

Total wheat dry matter Fe uptake ranged from 0.2 g m^{-2} in the MO-SiL-1-UC to 0.9 g m^{-2} in the NE-SiL-UC combination (Table 6). Total wheat dry matter Fe uptake in the AR-SiL soil was smallest (0.3 g m^{-2}) for CPST and UC, which did not differ from that for ECST (0.4 g m^{-2}) and was largest for MAP (0.8 g m^{-2}), which was similar to that for TSP (0.5 g m^{-2} ; Table 6). In addition, in the AR-SiL

soil, total wheat Fe uptake for TSP did not differ from that for ECST (Table 6). In the MO-SiL 1 soil, total wheat Fe uptake was smallest in the UC (0.2 g m^{-2}) and numerically largest for TSP (0.5 g m^{-2} ; Table 6). There were no total wheat dry matter Fe uptake differences in the MO-SiL 1 soil among ECST (0.4 g m^{-2}), MAP (0.4 g m^{-2}), and TSP, while total wheat Fe uptake for CPST (0.3 g m^{-2}) did not differ from that for ECST or MAP (Table 6). Similar to that for the MO-SiL 1 soil, in the MO-SiL 2 soil, total wheat Fe uptake was also numerically smallest for the UC (0.3 g m^{-2}), which did not differ from that for ECST (0.4 g m^{-2}), MAP (0.5 g m^{-2}), and TSP (0.4 g m^{-2}) and numerically largest for CPST (0.6 g m^{-2} ; Table 6). Unlike for the MO-SiL 2 soil, total wheat Fe uptake for the NE-SiL soil was numerically smallest from CPST (0.4 g m^{-2}), which did not differ from that for ECST (0.5 g m^{-2}), MAP (0.6 g m^{-2}), and TSP (0.4 g m^{-2}), and was numerically largest in the UC (0.9 g m^{-2}), which also did not differ from that for MAP and TSP (Table 6).

Total wheat dry matter Fe uptake did not differ between the struvite-P sources in any of the six soils (Table 6). Total wheat Fe uptake for ECST in the MO-SiL 2 soil did not differ between ECST and MAP or TSP in any of the soils, except in the AR-SiL soil, where total wheat Fe uptake for ECST was 0.4 g m^{-2} smaller than for MAP and did not differ from that for TSP (Table 6). Total wheat dry matter Fe uptake for CPST did not differ from that for MAP and TSP in four of the six soils (i.e., AR-SiCL, MO-SiL 2, NE-SiL, and NE-SL), but was 0.5 and 0.2 g m^{-2} less than for MAP and TSP, respectively, in the AR-SiL and was 0.2 g m^{-2} less than for TSP in the MO-SiL 1 soil, but did not differ from that for MAP (Table 6).

4 Discussion

Plant biomass accumulation (i.e., below- and aboveground and total dry matter) are important indicators of plant growth and development, as well as how efficiently the plant utilizes nutrients in combination with the other plant growth factors. Below- and aboveground and total dry matter were influenced by different soil-fertilizer-P-source combinations. There was a general trend for aboveground and total dry matter to be largest among all fertilizer-P sources in the NE-SiL soil and generally numerically largest among ECST, MAP, and TSP across soils. While both ECST and CPST are struvite, ECST treatments in several cases had numerically larger dry matter than CPST. For wheat, belowground dry matter was larger for ECST in the AR-SiCL and smaller for CPST in the AR-SiL soil.

Though fertilizer P and N were added in equal total amounts, all soils had initial differences in physical and chemical properties, including general fertility-related

properties, thus plant responses were expected to differ. The soils with the largest initial $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, SOM, and P and lower Fe concentrations, loamy texture, and more-neutral pH (i.e., NE-SiL, NE-SL, MO-SiL 1 and 2, AR-SiCL, and AR-SiL) generally resulted in plants with the largest dry matter. A similar greenhouse study conducted by Ylagan et al. (2020) in an Arkansas Alfisol reported a similar corn and soybean dry matter response to the results of the current study, where, due to their larger initial surface areas from the crystalline-flake/powder application forms, ECST and RP were more easily solubilized, leading to more available P for plants to use, hence, larger dry matter production. Overall, soil P and N concentrations and the more-neutral soil pH for optimum P availability contributed to increased plant biomass by facilitating increased activity in the apical meristem, photosynthesis, cell division, cell enlargement, and elongation, as well as the ability of the plant to transport nutrients and assimilates between the roots and shoots (Rodríguez et al. 1999; Sharma et al. 2012; Purbajanti et al. 2019; Bauer and Wirén, 2020; Mancho et al. 2023).

For nutrient uptakes, the effects of soil and fertilizer-P sources were evaluated on a total of 21 early season wheat response variables. Belowground nutrient uptakes varied greatly among fertilizer-P sources for the six soils. Wheat dry matter uptake variations between the struvites were likely because CPST was applied in pelletized form, while ECST was applied in a crystalline-flake form, allowing for greater soil-fertilizer-water surface area contact, leading to greater solubility from ECST than from CPST. Among all belowground nutrient uptake properties, belowground uptakes for ECST in at least one soil were similar or larger than for CPST in one or more of five wheat properties (i.e., belowground N, P, Ca, and Fe uptake), while CPST was larger than for ECST in at least one soil in four wheat properties (i.e., belowground N, P, and Ca uptakes). Hence, the agronomic potential of ECST as an alternative fertilizer-P source for implementation in row-crop production was demonstrated. Previous studies, including a meta-analysis, have pointed out the dynamic nature of struvite dissolution in the soil. Due to the simultaneous release of struvite's component nutrients, it is difficult to identify individual effects of soil properties since many factors drive struvite dissolution (Hertzberger et al. 2020).

The MO-SiL 1 and 2 and the NE-SL soils had the lowest initial soil pH and small initial soil-P concentrations, while the AR-SiCL soil had a more alkaline pH and larger clay concentration, but small soil-P concentration, which were all factors that could have led to a greater solubility of P from the crystalline ECST due to larger surface area. Hence, combined with greater precipitation of P with available Fe, these factors may have reduced the concentration of ECST-P available for plant uptake in the soils where ECST was less. In contrary, the pelletized CPST-P was solubilized more

slowly due to the smaller surface area available for reaction, allowing P to be more available for plants to use for a longer time, instead of being tied-up with Fe. However, soil pH and general initial fertility differences among the different soils could also have assisted in solubilizing ECST to release P and N, allowing for greater tissue nutrient concentrations and uptake in other soils, particularly the NE-SiL soil, which was most fertile and generally had the largest tissue nutrient concentrations and uptakes.

Similar to the current study, Ylagan et al. (2020) also showed greater corn and soybean belowground nutrient responses from ECST than from CPST, likely due to the differences in form in which both products were applied. While both struvites are characteristically only partially water-soluble, and more soluble in the presence of weak acids (Cabeza et al. 2011; Talboys et al. 2016; Anderson et al. 2020; Wu et al. 2022), CPST was applied as a pellet and, hence, only the portion of the pellet's surface that is in contact with water or a slightly acidic soil solution would dissolve first. However, for ECST that was applied as a crystalline flake, the larger surface area in contact with water and/or soil solution would immediately experience a much more rapid dissolution and, hence, more available nutrients for plant uptake, particularly in soils with optimum pH and small Fe concentrations, where Fe–P binding potential was reduced. Similarly, a soil column-leaching study by Simms et al. (2024a), using the same soils and fertilizer-P sources as used in the current study, showed greater initial (i.e., first 1 to 3 weeks) water-soluble P from ECST than from CPST. A plant-less, moist-soil incubation study conducted by Anderson et al. (2020) also reported greater initial P availability from powdered CPST than from the pelletized CPST and, similar to results of the current study, reported that soil pH and texture also influenced the behavior of the two struvite-P sources.

Similar to belowground, across all aboveground nutrient uptakes (i.e., N, P, Ca, Mg, and Fe), ECST frequently produced similar or larger aboveground plant nutrient uptakes than for CPST and the UC. Aboveground nutrient uptakes for the ECST material for wheat were predominantly similar or larger than for CPST in the five wheat properties across all six soils. Like for both the below- and aboveground, across all total nutrient uptakes (i.e., N, P, Ca, Mg, and Fe), ECST frequently produced larger aboveground plant nutrient uptakes than for CPST and the UC, but largely similar responses to that for MAP and TSP. Total nutrient uptakes for ECST were also larger than for CPST in three of five wheat properties (i.e., total N, P, and Ca uptake), while CPST was similar to that for ECST for total Mg and Fe uptakes.

Overall, the struvite-P sources, particularly ECST, generally had similar or greater belowground nutrient uptakes compared to MAP, TSP, and the UC. In only 10 instances

out of 108 possibilities, ECST produced the numerically smallest dry matter or nutrient uptakes among the measured crop properties. The smallest wheat response from ECST occurred mainly in two soils (i.e., AR-SiL and MO-SiL 2) for belowground N, P, and Ca uptake. Furthermore, ECST was either statistically and/or numerically largest, but similar to other fertilizer-P sources, for eight of 21 plant properties in at least one soil. The instances where ECST produced the smallest nutrient response may have been due to factors such as soil pH, texture, and initial soil-P and -Fe concentrations limiting nutrient uptake (Kratz et al. 2019).

The explanation for the variations among belowground uptakes remains valid for aboveground uptakes and for total nutrient uptakes, where differences among initial soil pH, -N, -P, and -Fe concentrations along with varied soil textures were likely responsible for measured differences among soils and fertilizer-P sources. Soils with larger clay and Fe concentrations contributed to the variations among aboveground nutrient uptakes by facilitating greater clay-P adsorption, as well as soils with the more acidic initial pH likely allowed for the formation of more Fe–P insoluble compounds, making P from ECST more unavailable as it semi-rapidly dissolved. In contrast, in soils that would favor a slower ECST dissolution due to their greater initial pH, greater initial soil-P, -N, and SOM concentration, and smaller initial soil-Fe and -Ca concentrations would allow for nutrients to be more readily available for plant uptake, leading to larger dry plant matter and nutrient uptakes.

Results of the current study were similar to those of Ylagan et al. (2020), where corn and soybean responses to ECST were also generally similar to those from MAP and TSP, and were also similar to results of 2-year field studies with corn (Omidire et al. 2022), soybean (Omidire et al. 2023), and wheat (Omidire & Brye 2022) using the same fertilizer-P sources, except ECST was not used in wheat. While ECST was not included, Omidire & Brye (2022) studied CPST, TSP, and a UC over two growing seasons on a silt-loam soil in eastern Arkansas, where wheat properties largely did not differ between CPST and TSP. The present study also recorded similar response where CPST and TSP largely had similar wheat response. The studies of Omidire et al. (2022, 2023) were conducted in a low-P Arkansas Alfisol and reported that the struvite materials also generally had similar growth effects as the commonly used inorganic-P fertilizers. Rech et al. (2018) compared the solubilities along with wheat and soybean plant tissue concentrations and uptakes in a Eutric Cambisol fertilized with three different struvites compared to that for TSP over a 38-day period and reported that plant tissue concentrations and uptakes were generally similar among the fertilizers and was even greatest from one of the struvites recovered from poultry manure. However, results of the current study support previous recommendations

of ECST's fertilizer-P effectiveness, where the plant responses from wheat across all soils and fertilizer-P source combinations were comparable to that for CPST and across soils, despite their varied initial physical and chemical properties.

5 Conclusions

While several studies have been conducted on the agronomic potential of chemically precipitated struvite, only a few studies have recently been conducted using electrochemically produced struvite. Moreover, no studies, in the greenhouse or the field, have been conducted on wheat using electrochemically precipitated struvite (ECST) as the fertilizer-phosphorus (P) source. The objective of this study was to investigate the fertilizer potential of ECST, particularly noting plant tissue property variations among plants fertilized with ECST compared to those fertilized with conventional P fertilizers across varying soil properties and textures. Specifically, this study aimed to investigate wheat response to ECST compared to chemically precipitated struvite (CPST) and other commonly used fertilizer-P sources [i.e., monoammonium phosphate (MAP) and triple superphosphate (TSP)] with multiple agriculturally relevant soils.

Based on prior reports, it was hypothesized that total plant biomass (i.e., above- plus belowground) from ECST would be comparable to or greater than that of CPST, MAP, and TSP under greenhouse conditions. The agronomic effectiveness of ECST as a potential fertilizer-P source for implementation in wheat production was demonstrated, as ECST had either similar, or even frequently larger, magnitudes for many plant properties (i.e., above- and belowground and total dry matter) in soils of varied textures and initial properties. However, as with all other fertilizer-P sources, soil texture, pH, and initial soil properties differed to affect the effectiveness of the fertilizer-P sources.

It was also hypothesized that wheat grown in ECST- and CPST-treated soil would have greater tissue-P uptakes than those grown in soils treated with MAP and TSP or from an unamended control. Wheat responses [i.e., above- and belowground and total nitrogen (N), P, potassium (K), calcium (Ca), magnesium (Mg), and iron (Fe)] from plants fertilized with ECST were generally similar to or greater than that for CPST, MAP, and TSP for wheat grown in six agricultural mid-western to mid-southern soils and with varying initial physical and chemical properties and textures. It can be concluded that ECST is just as agronomically effective as CPST, MAP, and TSP, thus is suitable for use in wheat production in various soils.

Declarations

Competing Interest The authors declare no competing interests.

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