



## Research Article

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# Flood-Irrigated Rice Response to Fertilizer-Phosphorus Sources in a Phosphorus-Deficient Silt-Loam Soil

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## Abstract

Phosphorus (P) is an essential plant macronutrient that is commonly applied as a fertilizer for optimal crop production. As the global supply of fertilizer-P sources, mainly derived from mined rock phosphate (RP), is decreasing, alternative nutrient sources need to be developed and tested, such as wastewater-recovered struvite-P materials. The objective of this greenhouse study was to evaluate below- and aboveground rice (*Oryza sativa*) response to various fertilizer-P sources [i.e., mono- and diammonium phosphate (MAP and DAP, respectively), triple superphosphate (TSP), RP, electrochemically and chemically precipitated struvite (ECST and CPST, respectively), and an unamended control (UC)] under flood-irrigation in a P-deficient, silt-loam soil. Of the 17 belowground properties evaluated, eight differed ( $P < 0.05$ ) among fertilizer-P sources, while three were at least numerically largest from CPST. Of the 17 aboveground properties evaluated, six differed ( $P < 0.05$ ) among fertilizer-P sources and all six were at least numerically largest from MAP or DAP. For all 22 rice properties that differed ( $P < 0.05$ ) among fertilizer-P sources, either ECST, CPST, or both had a similar response to TSP, DAP, and/or MAP, while belowground P and calcium (Ca) and grain potassium (K) concentrations from CPST were greater ( $P < 0.05$ ) than from TSP, DAP, or MAP. Results demonstrated that struvite-P sources (i.e., ECST and CPST) are a viable, alternative fertilizer-P source, as evidenced by the large frequency of similar rice responses to other commercially available fertilizer-P sources commonly used for flood-irrigated rice production on a silt-loam soil in Arkansas (i.e., TSP, DAP, or MAP).

## Keywords

Arkansas, Chemically precipitated struvite, Electrochemically precipitated struvite, Flood-irrigation, Phosphorus fertilizers

## Introduction

Phosphorus (P) is an essential plant macronutrient, thus P is commonly applied as a fertilizer to sustain agricultural production. However, P is mostly unavailable in soils, as P is fixed by iron (Fe) and/or aluminum (Al) in acidic soil or by calcium (Ca) in alkaline soil or bound to organic compounds [1]. Therefore, low P availability is a major limitation to plant growth and development in many soils.

The global supply of fertilizer-P sources is mainly derived from rock phosphate (RP), which is mined from only a few select locations and is generally considered non-renewable [2]. Rock phosphate reserves have been declining globally, where it is estimated that the amount of economically and feasibly mined RP will be exhausted within 100 to 250 years

[3]. Over 900 million kg of RP are consumed annually as fertilizer for crop production [4]. Furthermore, fertilizer-P use for agricultural production has been recognized as one of the largest inefficiencies in the P cycle because the majority of P derived from food wastes is lost to the environment via sewer

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systems, wastewater treatment, and landfills without being returned to the soil from which the P was extracted by plants [5]. Consequently, alternatives to RP-derived, fertilizer-P sources need to be identified and tested in a variety of agricultural crops and in a variety of crop-production settings (i.e., climates and soil textures).

As a nutrient-rich material, municipal and agricultural wastewaters offer an attractive option for nutrient recovery. Wastewaters are often composed of large concentrations of P, nitrogen (N), and organic matter, with an often a considerable quantity of magnesium (Mg), various macro- and micro-elements, and sometimes heavy metals [6-10]. Therefore, wastewaters are considered as one of the major polluting agents in the environment. However, wastewaters are increasingly being recognized as a valuable resource in terms of recoverable excess nutrients, water, and energy. Nutrient recovery from wastewaters would have two major benefits: i) ease future RP scarcity, and ii) decrease potential environmental water pollution. The discharge of excess nutrients, namely P and N, into surface receiving waters creates the environmental threat of potential eutrophication, which is a serious water quality issue in many surface water bodies world-wide and has major negative ecological consequences for the affected aquatic ecosystems. It has been estimated that only 20% of the globally produced wastewaters are treated to reduced nutrient concentrations before being discharged back into waterbodies across the world [11]. In addition, it has been estimated that 8 million Mg of P are lost from farms per year through soil erosion and leaching, in which much of the P ends up in nearby surface waters [2].

In recent decades, the P- and N-containing mineral struvite ( $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ ) has gained interest as a mechanism to recover both P and N from wastewaters [12]. Under the right aqueous conditions (i.e., pH, temperature, and P, N, Mg, and Ca concentrations), struvite will precipitate naturally in wastewater treatment plant (WWTP) pipes to create a major nuisance and economic problem for WWTPs [12,13]. Struvite precipitation requires equi-molar concentrations (1:1:1) of  $\text{Mg}^{2+}$ ,  $\text{NH}_4^+$  and  $\text{PO}_4^{3-}$  with an alkaline pH [14]. However, intentional struvite precipitation through biological [15], chemical [4,16,17], and electrochemical techniques [8,18-20] can yield a material that generally contains 11 to 26% total P [21] and has been described as an effective, alternative fertilizer-P source [22]. Struvite has also been characterized with only 4 to 6% water solubility in soil [23,24], while the remaining P is acid-soluble [25]. Reported chemical characteristics suggest struvite may be a slow-release P source, where the development and acidification of the plant rhizosphere stimulate struvite-P release to better match plant-P need throughout a growing season [26,27] compared to more water-soluble, fertilizer-P sources, such as monoammonium phosphate (MAP), diammonium phosphate (DAP), and triple superphosphate (TSP). Furthermore, struvite has been reported to contain 27 to 42%  $\text{P}_2\text{O}_5$  compared to 48, 42, 42, and 17%  $\text{P}_2\text{O}_5$  for MAP, DAP, TSP, and RP, respectively [28].

Monoammonium phosphate, DAP, and TSP are widely applied, commercially available, fertilizer-P sources used for flood-irrigated rice (*Oryza sativa*) production in the mid-southern United States (US), particularly Arkansas, which produces nearly 50% of the total US rice production annually [29]. Consequently, flood-irrigated rice production in Arkansas offers the ideal setting to investigate plant response to struvite-P materials relative to other commonly used fertilizer-P sources.

In a two-year, flood-irrigated, field study on a P-deficient, silt-loam soil in eastern Arkansas, Omidire, et al. [28] evaluated the response of a pure-line rice variety to six fertilizer-P sources, including MAP, DAP, and TSP, which are commonly used, commercially available materials for rice production, RP, and two struvite materials, electrochemically precipitated struvite (ECST) and chemically precipitated struvite (CPST), with an unamended control (UC). Results showed that many of the aboveground vegetative and grain tissue responses measured did not differ between the two struvite-P sources and most rice responses did not differ among one or both struvite-P sources and MAP, DAP, and/or TSP [28]. Omidire, et al. [28] concluded that struvite can be a viable, alternative fertilizer-P source for flood-irrigated rice. Furthermore, struvite was also concluded to be a viable, alternative fertilizer-P source for furrow-irrigated corn (*Zea mays*) [30] and furrow-irrigated soybean (*Glycine max*) [31] on silt-loam soils in eastern Arkansas.

Though Omidire, et al. [28] evaluated fertilizer-P source effects on rice response under flood-irrigation in the field, belowground rice responses (i.e., root dry matter and nutrient uptakes) were not comprehensively, or quantitatively assessed. Thus, the objective of this greenhouse study was to evaluate below- and aboveground rice response to various fertilizer-P sources (i.e., MAP, DAP, TSP, RP, ECST, CPST, and a UC) under flood-irrigation in a P-deficient, silt-loam soil in the greenhouse. It was hypothesized that flood-irrigated rice will have similar below- and aboveground and grain response among all P-fertilized treatments, but will be greater than the UC.

## Materials and Methods

### Soil collection, processing, and analyses

Soil was collected from the top 10 cm of a Calhoun silt loam (fine-silty, mixed, active, thermic Typic Glossaqualfs) [32] at the Pine Tree Research Station near Colt in St. Francis County, AR on 19 April, 2021 from an area that had been previously managed for several years in a rice-soybean rotation. Field-moist soil was sieved through a 6-mm mesh screen to remove coarse fragments and plant material and was air-dried in a greenhouse for ~7 days at ~24 °C.

Once air-dried, five sub-samples were collected, oven-dried in a forced-air dryer at 70 °C for at least 48 hours, mechanically crushed, and sieved again through a 2-mm mesh screen for initial soil physical and chemical property determinations. A modified 12-hr hydrometer method was used for sand, silt, and clay concentrations [33]. Weight-loss-on-ignition after 2 hours of combustion at 360°C was used

to determine soil organic matter (SOM) concentrations [34]. High-temperature combustion in a VarioMax carbon (C) and N analyzer (Elementar Americas Inc., Mt. Laurel, NJ) was used to determine total C (TC) and total N (TN) concentrations [35]. Inductively coupled, argon-plasma spectrophotometry was used to determine Mehlich-3 extractable soil nutrient (i.e., P, K, Ca, Mg, Fe, Mn, and Zn) concentrations after extraction in a 1:10 soil mass:extractant volume suspension [36]. Soil pH and electrical conductivity (EC) were determined potentiometrically in a 1:2 soil mass:water volume suspension. Table 1 summarizes initial soil property means.

**Table 1:** Summary of initial soil physical and chemical property means [n = 5; ± standard errors (SE)] for a phosphorus (P)-deficient, silt-loam soil used in the greenhouse study (modified from Della Lunga, et al. [46].).

Soil Property	Mean (± SE)
Sand (g g <sup>-1</sup> ) <sup>†</sup>	0.09 (< 0.01)
Silt (g g <sup>-1</sup> ) <sup>†</sup>	0.79 (< 0.01)
Clay (g g <sup>-1</sup> ) <sup>†</sup>	0.11 (< 0.01)
Soil organic matter (%)	2.6 (< 0.1)
Total C (%)	1.1 (< 0.1)
Total N (%)	0.1 (< 0.01)
Mehlich-3 extractable soil nutrients (mg kg <sup>-1</sup> )	
P	11.4 (0.1)
K	46.1 (0.9)
Ca	2006 (4.2)
Mg	276 (2.2)
Fe	304 (7.8)
Mn	244 (5.1)
Zn	2.5 (0.1)
pH	7.5 (< 0.1)
Electrical conductivity (dS m <sup>-1</sup> )	0.167 (< 0.1)

<sup>†</sup>Sand, silt, and clay fractions do not add to 1 due to rounding for reporting purpose

**Table 2:** Summary of the measured nitrogen (N), phosphorus (P), and magnesium (Mg) concentrations, resulting fertilizer grade, and pH for the six fertilizer-P sources used in this study. Means (± standard error) are reported (n = 5), reproduced from Omidire, et al. [28].

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

<sup>†</sup>Monoammonium phosphate (MAP), diammonium phosphate (DAP), triple superphosphate (TSP), rock phosphate (RP), chemically precipitated struvite (CPST), and electrochemically precipitated struvite (ECST); <sup>\*\*</sup>Fertilizer grade is reported as N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O based on measured concentrations of N, P, and K; <sup>‡</sup>Limited supply of ECST prohibited pH determination.

## Treatments and experimental design

This study was conducted in a greenhouse in Fayetteville, AR between May and September 2021. The six fertilizer-P sources evaluated in this study were ECST, CPST, MAP, DAP, TSP, RP, and a UC that received no fertilizer-P addition. Each of the seven fertilizer-P sources were replicated four times and arranged in soil-filled pots (described below) on a single greenhouse bench in a randomized complete block (RCB) design with four blocks.

Researchers in the Chemical Engineering Department at the University of Arkansas created the ECST material from a synthetic wastewater material prepared with known concentrations of P and N. Electrochemical precipitation was used with a sacrificial Mg electrode to precipitate the ECST material [20,29]. The CPST material was created via chemical precipitation from municipal wastewater in Atlanta, GA, where the Mg was provided by addition of Mg salts. The specific CPST material in the study was commercially available as the trade name Crystal Green (Ostara Nutrient Recovery Technologies, Inc., Vancouver, Canada). The MAP, DAP, TSP, and RP materials were purchased commercially. The fertilizer-P sources' original forms were pellets (i.e., for CPST, MAP, DAP, and TSP), powder (i.e., for RP), and crystalline flakes (i.e., ECST). Table 2 summarizes the N, P, and Mg concentrations, resulting fertilizer grades, and pH for the six fertilizer-P sources.

## Pot preparation and management

On 10 May, 2021, approximately 6315 cm<sup>3</sup> of air-dried, sieved soil were manually mixed in a large plastic bag (i.e., to simulate incorporation by tillage) with the appropriate mass of fertilizers to provide equivalent rates of 67.2 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> in the various fertilizer forms, 11.2 kg Zn ha<sup>-1</sup> as zinc sulfate, 134.4 kg K<sub>2</sub>O ha<sup>-1</sup> as muriate of potash, and 29.1 kg N ha<sup>-1</sup> as N-(n-butyl) thiophosphoric triamide (NBPT)-coated urea (46% N). Due to the limited amount of soil per pot to supply nutrients (i.e., ~6315 cm<sup>3</sup>), fertilizer-P, -Zn, -K, and -N additions were increased by 20% [37,38]. Due to the differential N concentrations among the fertilizer-P sources, additional N was added to the other five fertilizer-P sources to match

the N added in DAP, which had the largest N concentration among the fertilizer-P sources.

Once fertilizers were mixed with soil in bags, the mixture was added to plastic buckets, with an inside height of 23 cm and inside diameter of 23 cm (i.e., 415.5 cm<sup>2</sup> surface area), to a depth of approximately 15.2 cm inside the buckets. After soil-fertilizer mixtures were added to the buckets, 80% of the approximated volumetric field moisture capacity water content was added to each bucket to wet the air-dried soil. Field moisture capacity was estimated based on measured sand, clay, and SOM concentrations using multiple regression relationships [39], as part of the Soil Water Characteristics subroutine of the Soil-Plant-Atmosphere-Water (SPAW) model (version 6.02.75) [40]. The next day, on 11 May, 2021, three seeds of the pure-line rice variety 'Diamond', a short-season, high-yielding, long-grain rice variety developed by the University of Arkansas, Division of Agriculture at the Rice Research and Extension Center near Stuttgart, AR, were planted to a depth of 1.6 cm [41] in a triangular arrangement in the center of the bucket followed by the addition of 20% of the approximated volumetric field moisture capacity water content. Any emerged weeds were manually removed.

On 24 May, 2021, rice seedlings were thinned to one rice plant per bucket by keeping the healthiest plant. On 9 June, 2021, at the 3- to 4-leaf stage, the equivalent rate of 145.6 kg ha<sup>-1</sup> of NBPT-coated urea was surface-applied to each bucket as the pre-flood N application. The next day, on 10 June, 2021, a flood was applied to each bucket to an approximate depth of 10 cm and maintained until near harvest at the end of the growing season. Water was periodically added as needed to maintain the ~10-cm flood depth in each bucket. Filtered water from an adjacent greenhouse was used for all water additions. On 25 August, 2021, a fungicide (0.6 g L<sup>-1</sup>, Azoxystrobin, trade name Heritage, Syngenta Crop Protection AG, Basel, Switzerland) was sprayed on the foliage at a rate of 3 mL per pot to control an unidentified minor fungus outbreak. On 15 September, 2021, flood water was removed from each bucket to prepare for harvest. Weeds were manually removed as needed throughout the growing season. A daytime temperature of 31 °C and nighttime temperature of 22 °C were maintained in the greenhouse.

## Plant sampling and analyses

On 22 September, 2021, rice plants were harvested from each bucket by cutting the aboveground vegetation at the soil surface and bagged. Distilled water was added to each bucket to soften the dry soil to facilitate root collection. Roots were carefully, thoroughly rinsed with distilled water to remove the soil and bagged. Aboveground biomass and root materials were oven-dried at 55 °C for ~7 days and weighed for dry matter (DM) determinations. After drying and weighing, rice grains were manually stripped from the panicles and weighed to determine grain yield. For the purposes of this study, grain yields were reported on an oven-dried basis.

A sub-sample of root, aboveground vegetative, and grain tissues were mechanically ground and sieved through a 1-mm mesh screen for chemical analyses. Total N concentration

was determined by high-temperature combustion (Elementar VarioMax CN analyzer). After digestion in strong acid and heating [42], plant-tissue concentrations (i.e., P, K, Mg, Ca, Fe, Mn, and Zn) were measured by inductively coupled, argon-plasma, optical-emissions spectrometry with a Spectro Arcos ICP (SPECTRO Analytical Instruments, Inc., Mahwah, NJ) [43]. Nutrient uptakes for belowground, aboveground vegetative, and grain tissues were calculated from measured elemental tissue concentrations and tissue DMs. Total aboveground DM and nutrient uptakes were calculated as the sum of aboveground vegetative plus grain DMs and respective nutrient uptakes. In addition, total plant DM and nutrient uptakes were calculated as the sum of belowground plus aboveground vegetative plus grain DMs and respective nutrient uptakes.

## Statistical analyses

Based on the RCB design, a one-factor analysis of variance (ANOVA) was conducted using the PROC GLIMMIX procedure in SAS (version 9.4, SAS Institute, Inc., Cary, NC) to evaluate the effects of fertilizer-P source on rice responses (i.e., below- and aboveground and grain DM and nutrient concentrations and uptakes, total aboveground DM and nutrient uptakes, and total plant DM and nutrient uptakes). Due to the skewed, but > 0 magnitudes, a gamma distribution was used to analyze all measured rice responses and significance was judged at  $P < 0.05$ . Least-square means were reported and, when appropriate, were separated by least significant difference at the 0.05 level.

## Results and Discussion

### Initial soil properties

Initial Mehlich-3 extractable soil concentration confirmed the P-deficient soil condition that was specifically targeted for this greenhouse study. Initial soil-test-P concentration fell in the low category (i.e., 9 to 16 mg kg<sup>-1</sup>) for optimal flood-irrigated rice production in Arkansas (Table 1) [44], for which a rice response to fertilizer-P addition was expected. Initial soil-test-K concentration fell in the very low (i.e., < 60 mg kg<sup>-1</sup>) category and soil-test-Zn concentration fell in the low (i.e., 1.6 to 2.5 mg kg<sup>-1</sup>) category for optimal flood-irrigated rice production in Arkansas (Table 1) [44]. In addition, initial soil pH (7.5) was slightly outside the desired range for optimal flood-irrigated rice production in Arkansas (Table 1) [45], but was not corrected with any soil amendment.

### Belowground rice response

Once growing in fertilizer-amended soil, plant roots are the first to experience similarities or potential differences in fertilizer solubilities, interactions, and mobility in the soil. Contrary to expectations, numerous belowground rice properties differed ( $P < 0.05$ ) among P-fertilized treatments, including belowground DM, P, Mg, Ca, and Mn concentrations, and N, K, and Zn uptakes (Table 3). Belowground DM was numerically largest from MAP, which did not differ from TSP and DAP, and was numerically smallest from CPST, which did not differ from the UC, ECST, RP, or DAP (Table 3). Belowground DM was similar between the two struvite-P

**Table 3:** Summary of the effect of fertilizer-phosphorus (P) source on belowground tissue properties for rice grown in a P-deficient, silt-loam soil under flood-irrigated conditions in the greenhouse. Least square means are reported, with n = 4 observations for each fertilizer-P source treatment, except for ECST, for which n = 3 observations due to missing data from one dead plant.

Plant Property <sup>†</sup>	P-value	Fertilizer-P Source <sup>†</sup>							Overall mean
		ECST	CPST	MAP	DAP	TSP	RP	UC	
Belowground DM (kg m <sup>-2</sup> )	0.04	0.79 bc <sup>‡</sup>	0.62 c	1.4 a	0.89 abc	1.1 ab	0.82 bc	0.72 bc	-
Belowground DM concentration									
N (%)	0.32	0.98	1.27	0.95	1.32	1.02	0.98	0.86	1.05
P (%)	0.03	0.09 b	0.12 a	0.08 b	0.09 b	0.09 b	0.10 ab	0.09 b	-
K (%)	0.06	0.09	0.09	0.12	0.08	0.07	0.16	0.12	0.10
Mg (%)	< 0.01	0.09 cd	0.10 bc	0.08 cd	0.08 d	0.10 bc	0.13 a	0.11 ab	-
Ca (%)	0.01	0.29 bc	0.52 a	0.22 c	0.32 b	0.35 b	0.32 bc	0.33 b	-
Fe (g kg <sup>-1</sup> )	0.20	33.6	49.8	35.7	45.7	48.1	44.6	38.5	42.3
Mn (g kg <sup>-1</sup> )	0.01	2.1 bc	3.0 a	1.5 c	2.4 ab	2.7 ab	2.5 ab	2.3 ab	-
Zn (mg kg <sup>-1</sup> )	0.16	43.8	48.6	33.2	44.8	46.2	44.5	36.3	42.5
Belowground DM uptake									
N (g m <sup>-2</sup> )	0.03	7.1 bc	7.3 bc	14.1 a	9.1 ab	9.2 ab	7.9 bc	5.4 c	-
P (g m <sup>-2</sup> )	0.06	0.64	0.71	1.23	0.74	0.92	0.81	0.63	0.81
K (g m <sup>-2</sup> )	0.01	0.66 bc	0.57 c	2.0 a	0.68 bc	0.86 bc	1.3 ab	0.90 bc	-
Mg (g m <sup>-2</sup> )	0.12	0.73	0.61	1.2	0.71	1.1	1.0	0.81	0.89
Ca (g m <sup>-2</sup> )	0.45	2.2	2.7	3.1	2.4	3.5	2.6	2.0	2.6
Fe (g m <sup>-2</sup> )	0.16	26.6	32.5	50.0	37.5	50.1	35.6	25.7	36.9
Mn (g m <sup>-2</sup> )	0.28	1.7	1.8	2.1	1.9	2.9	2.1	1.5	2.0
Zn (mg m <sup>-2</sup> )	0.04	35.2 ab	28.1 b	45.5 a	36.4 ab	47.6 a	35.3 ab	25.5 b	-

<sup>†</sup>Dry matter (DM), electrochemically precipitated struvite (ECST), chemically precipitated struvite (CPST), monoammonium phosphate (MAP), diammonium phosphate (DAP), triple superphosphate (TSP), rock phosphate (RP), and unamended control (UC); <sup>‡</sup>Means in a row followed by different letters are different at  $P \leq 0.05$ .

sources, but both were lower than from MAP and similar to DAP and RP (Table 3).

In contrast to the results of this study, in a greenhouse tub study evaluating the effects of TSP, DAP, ECST, and CPST on flood-irrigated rice response in a silt-loam soil, Della Lunga, et al. [46] reported no effect of fertilizer-P source on belowground DM. However, similar to the results of this study, in a 79-day greenhouse potted-plant study using a silt-loam soil, Ylagan, et al. [47] reported that belowground corn DM differed among the same fertilizer-P sources as evaluated in the current study. In contrast, Ylagan, et al. [47] reported that belowground corn DM differed between the two struvite-P sources, with ECST greater than both CPST and MAP, which did not differ. Furthermore, in contrast to the results of this study, Ylagan, et al. [47] reported that belowground soybean DM was unaffected by the same fertilizer-P sources as evaluated in the current study.

In contrast to DM, belowground P concentration was numerically largest from CPST, which did not differ from RP, and was numerically smallest from MAP, likely due to a dilution effect, which did not differ from RP, ECST, DAP, TSP, or the UC (Table 3). Belowground P concentration was 1.3 times greater from CPST than from ECST and both were similar to

RP (Table 3). Unlike P, belowground Mg concentration was numerically largest from RP, which did not differ from the UC, and was numerically smallest from DAP, which did not differ from MAP or ECST (Table 3). Belowground Mg concentration was similar between the two struvite-P sources, but both were lower than from RP and similar to MAP and TSP (Table 3). Similar to P, belowground Ca concentration was largest from CPST and was numerically smallest from MAP, which did not differ from ECST or RP (Table 3). Belowground Ca concentration was 1.8 times greater from CPST than ECST, while ECST was similar to all other fertilizer-P sources (Table 3). Like P and Ca, belowground Mn concentration was numerically largest from CPST, which did not differ from TSP, RP, DAP, or the UC, and was numerically smallest from MAP, which did not differ from ECST (Table 3). Unlike DM and Mg, belowground Mn concentration was 1.4 times greater from CPST than from ECST, but both were similar to at least one other P-fertilized treatment (Table 3). Belowground N, K, Fe, and Zn concentrations did not differ ( $P > 0.05$ ) among fertilizer-P sources (Table 3).

In a 2-year, flood-irrigated, field study with the pure-line rice variety 'Diamond', similar to the results of the current study, though belowground rice DM was not measured, Omidire, et al. [28] reported no effect of the same fertilizer-P

sources as evaluated in the current study on belowground rice N concentration. However, in contrast to results of the current study, Omidire, et al. [28] reported belowground rice P and Mg concentrations did not differ among fertilizer-P sources.

Comparable to results of this study, Della Lunga, et al. [46] reported belowground Mg concentration differed among fertilizer-P sources and was similar between the two struvite-P sources and belowground N and K concentrations did not differ among fertilizer-P sources. However, no effect of fertilizer-P source occurred for belowground P concentration [46], which differed from the results of this study.

Similar to the results of this study, Ylagan, et al. [47] reported that belowground corn P and Ca and soybean P concentrations differed among the same fertilizer-P sources as evaluated in the current study, belowground corn P concentration was greater from CPST than ECST, and belowground soybean N and concentrations were unaffected by fertilizer-P source. However, unlike results of this study, Ylagan, et al. [47] reported that belowground corn N and K concentrations differed among fertilizer-P sources, both greater from CPST than ECST, and belowground soybean P concentration did not differ between the two struvite-P sources. Furthermore, Ylagan, et al. [47] reported that belowground corn and soybean Mg concentrations were unaffected by fertilizer-P source, which differed from the results of this study.

Combining both DM and concentration, belowground nutrient uptake responses varied from those individually for DM and concentration. In contrast to N concentration, belowground N uptake was numerically largest from MAP, which did not differ from DAP or TSP, and was numerically smallest from the UC, which did not differ from RP, ECST, or CPST (Table 3). Belowground N concentration was similar between the two struvite-P sources, while CPST was similar to DAP, TSP, and RP, but ECST was only similar to RP (Table 3). In contrast to K concentration, belowground K uptake was numerically largest from MAP, which did not differ from RP, and was numerically smallest from CPST, which did not differ from ECST, DAP, TSP, or the UC (Table 3). Belowground K uptake was similar between the two struvite-P sources and both were similar DAP, TSP, and the UC (Table 3). Unlike K, belowground Zn uptake was numerically largest from TSP, which did not differ from MAP, DAP, RP, or ECST, and was numerically smallest from the UC, which did not differ from CPST, ECST, MAP, DAP, and RP (Table 3). Belowground Zn uptake was similar between the two struvite-P sources and both were similar to at least one other P-fertilized treatment (Table 3). In contrast to concentrations, belowground P, Mg, Ca, and Mn uptakes did not differ ( $P > 0.05$ ) among fertilizer-P sources, while, similar to concentrations, belowground Fe uptake was also unaffected ( $P > 0.05$ ) by fertilizer-P source (Table 3).

In contrast to the results of this study, Della Lunga, et al. [46] reported no effect of fertilizer-P source on belowground N, P, K, or Zn uptake, while, similar to the results of this study, belowground Mg concentration was also unaffected

fertilizer-P source. Neither Omidire, et al. [28] nor Ylagan, et al. [47] measured or reported belowground plant nutrient uptakes.

Plant roots are the first to experience potentially differential behavior among fertilizers. Of the 17 belowground rice properties evaluated in the study, eight differed among fertilizer-P sources, while four of the eight were at least numerically largest from MAP or TSP, three were at least numerically largest from CPST, and one from RP (Table 3). Differential solubilities likely contributed to the measured differences in fertilizer-P source responses. The six fertilizer-P sources used in this study have reported water solubilities of ~87% for TSP, > 95% for DAP, ~92% for MAP [48], ~4 to 6% for CPST, ~5% for ECST, and < 2% for RP [48-50]. Thus, both MAP and TSP are documented to be moderately to highly water-soluble fertilizer-P sources, respectively.

In five of the eight belowground rice properties that differed among fertilizer-P sources, the two struvite-P sources did not differ, while CPST was greater than ECST in the other three instances. In combination with solubility, the form of application likely contributed to belowground rice responses between the two struvite-P sources, where ECST was applied in crystalline-flake form, with large surface area for reactions, while CPST was applied as pellets, with lower surface area [29-31,47,51]. The greater root DM under MAP and the lower DM under ECST and CPST were likely responsible for the significant differences in concentrations (Table 3) due to dilution [52,53]. When nutrient uptakes were calculated, the significant concentration differences were generally reversed, highlighting how nutrient concentrations alone can be misleading if dry matter production is not taken into account (Table 3).

The distance that P from different fertilizers travels in a period of time is an inverse measure of the water solubility [54]. Struvite-derived P likely travels through the soil profile less than MAP-derived P, causing roots, when a rich-P soil zone is scavenged, to reallocate resources from root growth to different metabolic processes, like exudation of organic compounds to solubilize nutrients [54].

### Aboveground vegetative rice response

Similar to belowground (Table 3), and contrary to expectation, numerous aboveground rice responses also differed ( $P < 0.05$ ) among fertilizer-P source, including DM, N concentration, and N, P, Fe, and Zn uptake (Table 4). Like belowground, aboveground DM was numerically largest from MAP, which did not differ from DAP, TSP, RP, ECST, or the UC, and was smallest from CPST (Table 4). Unlike belowground (Table 3), aboveground DM was 1.6 times greater from ECST than CPST and ECST was similar to, while CPST was lower than all other fertilizer-P sources (Table 4).

Omidire, et al. [28] and Della Lunga, et al. [46] reported that aboveground rice DM and Ylagan, et al. [47] reported aboveground soybean DM were unaffected fertilizer-P source, which differed from the results of this study. However, comparable to results of the current study, Ylagan, et al. [47] reported aboveground corn DM differed among fertilizer-P

**Table 4:** Summary of the effect of fertilizer-phosphorus (P) source on aboveground tissue properties for rice grown in a P-deficient, silt-loam soil under flood-irrigated conditions in the greenhouse. Least square means are reported, with n = 4 observations for each fertilizer-P source treatment, except for ECST, for which n = 3 observations due to missing data from one dead plant.

Plant Property <sup>†</sup>	P-value	Fertilizer-P Source <sup>†</sup>							Overall mean
		ECST	CPST	MAP	DAP	TSP	RP	UC	
Aboveground DM (kg m <sup>-2</sup> )	0.02	2.0 a <sup>‡</sup>	1.3 b	2.7 a	1.9 a	2.1 a	2.3 a	2.2 a	-
Aboveground DM concentration									
N (%)	0.03	2.1 ab	2.8 a	1.6 b	3.0 a	2.0 ab	1.6 b	1.4 b	-
P (%)	0.61	0.17	0.17	0.16	0.18	0.17	0.14	0.15	0.16
K (%)	0.24	0.33	0.74	0.32	0.53	0.45	0.43	0.42	0.46
Mg (%)	0.92	0.42	0.41	0.40	0.37	0.39	0.42	0.39	0.40
Ca (%)	0.92	0.50	0.53	0.56	0.56	0.56	0.60	0.50	0.54
Fe (g kg <sup>-1</sup> )	0.08	0.19	0.32	0.25	0.21	0.20	0.21	0.17	0.22
Mn (g kg <sup>-1</sup> )	0.88	1.9	2.1	2.1	1.8	2.0	2.2	1.8	2.0
Zn (mg kg <sup>-1</sup> )	0.11	52.4	44.4	51.7	40.3	54.8	40.6	45.4	47.1
Aboveground DM uptake									
N (g m <sup>-2</sup> )	0.01	41.7 abc	28.1 d	42.3 ab	52.8 a	38.9 bc	35.7 bcd	30.3 cd	-
P (g m <sup>-2</sup> )	0.02	3.3 a	2.0 b	4.3 a	3.6 a	3.5 a	3.2 a	3.4 a	-
K (g m <sup>-2</sup> )	0.68	6.5	7.2	8.8	8.9	9.0	10.1	9.5	8.6
Mg (g m <sup>-2</sup> )	0.30	8.4	5.7	10.6	7.6	8.3	9.5	8.5	8.4
Ca (g m <sup>-2</sup> )	0.35	10.1	7.7	14.6	11.8	12.2	13.8	11.0	11.6
Fe (g m <sup>-2</sup> )	0.05	0.38 b	0.34 b	0.63 a	0.42 b	0.43 b	0.45 ab	0.36 b	-
Mn (g m <sup>-2</sup> )	0.45	3.8	2.9	5.4	3.9	4.5	5.0	3.9	4.2
Zn (mg m <sup>-2</sup> )	0.03	106.8 ab	60.5 c	138.5 a	78.2 bc	118.2 ab	91.4 abc	96.2 ab	-

<sup>†</sup>Dry matter (DM), electrochemically precipitated struvite (ECST), chemically precipitated struvite (CPST), monoammonium phosphate (MAP), diammonium phosphate (DAP), triple superphosphate (TSP), rock phosphate (RP), and unamended control (UC); <sup>‡</sup>Means in a row followed by different letters are different at  $P \leq 0.05$ .

sources, but, unlike results of the current study, aboveground corn DM did not differ between the two struvite-P sources.

In contrast to belowground, aboveground N concentration was numerically largest from DAP, which did not differ from CPST, ECST, and TSP, and was numerically smallest from RP, which did not differ from MAP, ECST, TSP, and the UC (Table 4). Unlike DM, aboveground N concentration was similar between the two struvite-P sources and both were similar to more than one other fertilizer-P source (Table 4). Aboveground P, K, Mg, Ca, Fe, Mn, and Zn concentrations were all unaffected ( $P > 0.05$ ) by fertilizer-P source (Table 4).

Similar to the results of this study, Omidire, et al. [28] reported that aboveground rice P and Mg concentrations were unaffected by fertilizer-P source. However, unlike results of this study, Omidire, et al. [28] reported that aboveground rice N concentration was also unaffected by fertilizer-P source. In addition, Della Lunga, et al. [46] reported aboveground N was unaffected by fertilizer-P source, but that aboveground P concentration differed among fertilizer-P sources, which also differed from results of this study. Comparable to results of this study, Ylagan, et al. [47] reported that aboveground soybean stem-plus-leaves tissue K, Ca, and Fe concentrations were unaffected by fertilizer-P source, but, in contrast to

the results of the current study, soybean stem-plus-leaves tissue N concentration also did not differ among fertilizer-P sources. Furthermore, like results of this study, Ylagan, et al. [47] reported that aboveground corn stem-plus-leaves tissue N concentration differed among fertilizer-P sources and there was no difference between the two struvite-P sources. However, unlike results of this study, aboveground corn stem-plus-leaves tissue P, Mg, K, and Ca concentrations differed among fertilizer-P sources, with only aboveground corn stem-plus-leaves tissue P concentrations differing between the two struvite-P sources, where ECST was greater than CPST [47].

Similar to belowground uptake and aboveground concentration, aboveground N uptake was numerically largest from DAP, which did not differ from MAP, and was smallest from CPST, which did not differ from RP and the UC (Table 4). Like with DM, aboveground N uptake was 1.5 times greater from ECST than CPST, while ECST was similar to all other fertilizer-P sources (Table 4). In contrast to belowground uptake and aboveground concentration, aboveground P uptake was numerically largest from MAP, which did not differ from ECST, DAP, TSP, RP, and the UC, and was smallest from CPST (Table 4). Aboveground P uptake was 1.6 times greater from ECST than CPST, while ECST was similar to all other fertilizer-P sources (Table 4). In contrast to belowground

concentration and uptake and aboveground concentration, aboveground Fe uptake was numerically largest from MAP, which did not differ from RP, and was numerically smallest from CPST, which did not differ from ECST, DAP, TSP, RP, and the UC (Table 4). Aboveground Fe uptake was similar between the two struvite-P sources and both were similar to DAP, TSP, and RP (Table 4). In contrast to below- and aboveground concentration, but similar to belowground uptake, aboveground Zn uptake was numerically largest from MAP, which did not differ from ECST TSP, RP, and the UC, and was numerically smallest from CPST, which did not differ from DAP and RP (Table 4). Similar to N and P, aboveground Zn uptake was 1.8 times greater from ECST than CPST, while ECST was similar to all other fertilizer-P sources (Table 4). Comparable to their concentration, aboveground K, Mg, Ca, and Mn uptake were all unaffected ( $P > 0.05$ ) by fertilizer-P source (Table 4).

Omidire, et al. [28] and Della Lunga, et al. [46] also reported aboveground rice Mg uptake was unaffected by fertilizer-P sources, which were similar to the results of this study. However, unlike results of this study, aboveground rice N and P uptakes were also unaffected by fertilizer-P source [29,46].

Once in the root tissue, fertilizer nutrients must be

translocated to aboveground plant tissue. Thus, potential differential interactions among the specific nutrient forms inside the plant may contribute to differential fertilizer responses, especially for P which can exist in various phosphate forms with multiple valence states [47]. Of the 17 aboveground rice properties evaluated in the study, six differed among fertilizer-P sources, where all six were at least numerically largest from the highly water-soluble MAP or DAP (Table 4) [49,50]. In two of the six aboveground rice properties that differed among fertilizer-P sources, the two struvite-P sources did not differ, while ECST was greater than CPST in the other four instances, substantiating the differences in application form between the two struvite-P sources [29-31,47,51]. Furthermore, the differences in purity and elemental composition between the two struvite-P sources may have resulted in differential nutrient forms once inside the plant [47] to cause differential fertilizer response in the aboveground rice tissue.

### Rice grain response

Mostly similar to that hypothesized, with the exception of grain K concentration, grain DM, grain N, P, Mg, Ca, Fe, Mn, and Zn concentrations, and all nutrient uptakes were unaffected by fertilizer-P source (Table 5). In contrast to

**Table 5:** Summary of the effect of fertilizer-phosphorus (P) source on grain tissue properties for rice grown in a P-deficient, silt-loam soil under flood-irrigated conditions in the greenhouse. Least square means are reported, with  $n = 4$  observations for MAP and RP, but  $n = 3$  observations for DAP, ECST, TSP, and the UC and  $n = 2$  observations for CPST due to missing data from one dead plant and grain masses that were too low for any chemical analyses.

Plant Property <sup>†</sup>	P-value	Fertilizer-P Source <sup>†</sup>							Overall mean
		ECST	CPST	MAP	DAP	TSP	RP	UC	
Grain (kg m <sup>-2</sup> )	0.39	1.4	1.4	1.0	0.9	1.6	0.9	1.2	1.2
Grain concentration									
N (%)	0.19	1.5	1.3	1.4	1.8	1.3	1.3	1.3	1.4
P (%)	0.77	0.25	0.27	0.28	0.26	0.27	0.26	0.26	0.27
K (%)	0.02	0.69 ab <sup>‡</sup>	0.72 a	0.57 c	0.61 bc	0.61 bc	0.67 ab	0.67 ab	-
Mg (%)	0.61	0.13	0.13	0.13	0.12	0.13	0.13	0.13	0.13
Ca (%)	0.11	0.02	0.03	0.03	0.02	0.03	0.04	0.03	0.03
Fe (mg kg <sup>-1</sup> )	0.16	18.2	19.6	30.1	23.6	13.0	24.5	34.1	23.3
Mn (g kg <sup>-1</sup> )	0.17	0.23	0.27	0.26	0.22	0.27	0.29	0.24	0.25
Zn (mg kg <sup>-1</sup> )	0.69	34.4	36.0	35.7	38.9	32.7	39.4	37.5	36.4
Grain uptake									
N (g m <sup>-2</sup> )	0.24	19.7	21.2	13.5	14.0	21.9	12.2	15.3	16.8
P (g m <sup>-2</sup> )	0.26	3.5	3.7	2.7	2.3	4.4	2.4	3.1	3.2
K (g m <sup>-2</sup> )	0.40	9.5	10.0	5.7	5.5	10.2	6.3	8.2	7.9
Mg (g m <sup>-2</sup> )	0.32	1.8	1.8	1.2	1.1	2.1	1.2	1.6	1.5
Ca (g m <sup>-2</sup> )	0.23	0.32	0.43	0.26	0.20	0.49	0.38	0.35	0.35
Fe (mg m <sup>-2</sup> )	0.73	24.1	27.2	23.8	18.5	23.1	22.4	29.5	24.1
Mn (g m <sup>-2</sup> )	0.40	0.32	0.36	0.26	0.20	0.43	0.26	0.28	0.30
Zn (mg m <sup>-2</sup> )	0.20	47.2	51.9	33.6	32.2	53.7	36.7	41.3	42.4

<sup>†</sup>Electrochemically precipitated struvite (ECST), chemically precipitated struvite (CPST), monoammonium phosphate (MAP), diammonium phosphate (DAP), triple superphosphate (TSP), rock phosphate (RP), and unamended control (UC); <sup>‡</sup>Means in a row followed by different letters are different at  $P \leq 0.05$ .



below- and aboveground concentration and aboveground uptake, but similar to belowground uptake, grain K concentration was numerically largest from CSPT, which did not differ from ECST, RP, and the UC, and was numerically smallest from MAP, which did not differ from DAP and TSP (Table 5). Grain K concentration was similar between the two struvite-P sources and both were largest than MAP (Table 5).

In contrast to the results of this study, Omidire, et al. [28] reported rice grain yield differed among fertilizer-P sources in one year, but not in the other. However, in the year when rice yields differed among fertilizer-P sources, rice yields were low and similar between ECST and CPST [28]. Similarly, Della Lunga, et al. [46] also reported rice grain yield and grain N concentration differed among fertilizer-P sources; however, similar to the results of this study, grain P and Mg concentrations were also unaffected by fertilizer-P source. Similar to the result of this study, Omidire, et al. [28] reported rice grain P and Mg concentrations and P and Mg uptakes were unaffected by fertilizer-P source; however, in contrast to the results of this study, grain N uptake differed among fertilizer-P sources, but was similar between the two struvite-P sources. In contrast to the results of this study, Della Lunga, et al. [46] reported grain N, P, K, and Mg uptakes all differed among fertilizer-P source.

For fertilizer-response differences to manifest themselves in grain DM and tissue concentrations, plant metabolites and nutrients must be further translocated to the grain. However, of the 17 rice grain properties evaluated in the study, only one property differed among fertilizer-P sources, which was grain K concentration, not even one of the main constituents of any of the fertilizer-P sources (Table 5). This result suggests that the extra translocation step and the length of time nutrients, like P and N, spend in the aboveground plant tissue before being translocated to the grain near the end of the

growing season essentially normalize most fertilizer-P-source-response differences that occurred earlier in the plant's life span in the below- and aboveground tissue. Results suggest that the length of the vegetative stages of rice, during which nutrient uptake occurs at an almost constant increasing rate [55], is sufficient to solubilize the slow-release struvite-P materials, further substantiating the viability of struvite as a potential alternative fertilizer-P source for rice production and other crops.

### Total aboveground rice response

Summing aboveground vegetative and grain tissue, in contrast to that hypothesized, several total aboveground rice properties differed among fertilizer-P sources, including N, Fe, and Zn uptake (Table 6). Total aboveground N uptake was numerically largest from DAP, which did not differ from ECST, and was numerically smallest from the UC, which did not differ from CPST and RP (Table 6). Total aboveground N uptake was 1.3 times greater from ECST than CPST, while each were similar to at least two other fertilizer-P sources (Table 6). Like with N, total aboveground Fe uptake was numerically largest from MAP, which did not differ from DAP, TSP, and RP, and was numerically smallest from the UC, which did not differ from ECST, CPST, DAP, TSP, and RP (Table 6). In contrast to N, total aboveground Fe uptake was similar between the two struvite-P sources and both were similar to all other fertilizer-P sources, except for MAP (Table 6). Similar to N and Fe, total aboveground Zn uptake was numerically largest from TSP, which did not differ from MAP, ECST, and CPST, and was numerically smallest from DAP, which did not differ from ECST, CPST, RP, and the UC (Table 6). Total aboveground Zn uptake was similar between the two struvite-P sources and both were similar to all other fertilizer-P sources (Table 6). Total aboveground DM and P, K, Mg, Ca, and Mn uptake were all unaffected ( $P > 0.05$ ) by fertilizer-P source (Table 6).

**Table 6:** Summary of the effect of fertilizer-phosphorus (P) source on total aboveground tissue properties (aboveground vegetative plus grain) for rice grown in a P-deficient, silt-loam soil under flood-irrigated conditions in the greenhouse. Least square means are reported, with  $n = 4$  observations for MAP and RP, but  $n = 3$  observations for DAP, ECST, TSP, and the UC and  $n = 2$  observations for CPST due to missing data from one dead plant and grain masses that were too low for any chemical analyses.

Plant Property <sup>†</sup>	P-value	Fertilizer-P Source <sup>†</sup>							Overall mean
		ECST	CPST	MAP	DAP	TSP	RP	UC	
Total aboveground DM (kg m <sup>-2</sup> )	0.22	3.4	3.2	3.7	3.1	4.0	3.2	3.1	3.4
Total aboveground DM uptake									
N (g m <sup>-2</sup> )	< 0.01	61.0 ab <sup>‡</sup>	48.2 cde	55.8 bc	68.4 a	54.7 bcd	47.8 de	44.7 e	-
P (g m <sup>-2</sup> )	0.22	6.8	6.4	7.0	6.3	7.9	5.6	5.8	6.5
K (g m <sup>-2</sup> )	0.42	16.1	16.3	14.6	13.8	18.0	16.4	16.2	15.9
Mg (g m <sup>-2</sup> )	0.67	10.2	10.6	11.9	9.9	10.7	10.8	9.1	10.5
Ca (g m <sup>-2</sup> )	0.36	10.5	12.4	14.8	14.4	13.7	14.2	9.9	12.8
Fe (g m <sup>-2</sup> )	0.04	0.40 b	0.41 b	0.65 a	0.49 ab	0.51 ab	0.48 ab	0.37 b	-
Mn (g m <sup>-2</sup> )	0.37	4.2	4.8	5.6	4.9	5.7	5.3	3.5	4.9
Zn (g m <sup>-2</sup> )	0.03	0.15 ab	0.14 ab	0.17 a	0.12 b	0.19 a	0.13 b	0.13 b	-

<sup>†</sup>Dry matter (DM), electrochemically precipitated struvite (ECST), chemically precipitated struvite (CPST), monoammonium phosphate (MAP), diammonium phosphate (DAP), triple superphosphate (TSP), rock phosphate (RP), and unamended control (UC); <sup>‡</sup>Means in a row followed by different letters are different at  $P \leq 0.05$ .

Della Lunga, et al. [46] also reported no effect of fertilizer-P source on total aboveground DM and P, K, and Mg uptake, while N uptake also differed among fertilizer-P sources, which was similar to the results of this study. However, in contrast to the results of this study, total aboveground Zn uptake was unaffected by fertilizer-P source [46].

Of the nine total aboveground rice properties (i.e., aboveground vegetative plus grain) evaluated in the study, only three properties differed among fertilizer-P sources, where all three were at least numerically largest from TSP, DAP, or MAP (Table 6). This result further substantiates the likelihood of differential solubilities being the main contributor to differential rice responses [49,50]. In addition, ECST was greater than CPST for only one of the three total aboveground rice properties (Table 6), further substantiating the application-form difference between the two struvite-P sources.

### Total rice plant response

Summing belowground, aboveground vegetative, and grain tissue, in contrast to that hypothesized, several total rice plant properties differed among fertilizer-P sources, including DM, N, Fe, and Zn uptake (Table 7). In contrast to total aboveground, total rice DM was numerically largest from MAP and TSP, which did not differ from DAP and ECST, and was numerically smallest from the UC, which did not differ from ECST, CPST, DAP, and RP (Table 7). Total rice DM was similar between the two struvite-P sources and each was similar to at least two other fertilizer-P sources (Table 7).

Unlike results of this study, Della Lunga, et al. [46] reported total plant DM was unaffected by fertilizer-P source. However, similar to the results of this study, Ylagan, et al. [47] reported that total corn plant DM differed among fertilizer-P sources. Furthermore, ECST produced greater total corn plant DM than CPST [47], which differed from results of this study.

Like with DM, total rice N uptake was numerically largest from DAP, which did not differ from MAP and ECST, and was numerically smallest from the UC, which did not differ from RP and CPST (Table 7). Total rice N uptake was 1.2 times greater from ECST than CPST, while ECST was similar to MAP, DAP, and TSP (Table 7). Comparable to DM and N, total rice Fe uptake was numerically largest from TSP, which did not differ from MAP, DAP, CPST, and RP, and was numerically smallest from the UC, which did not differ from ECST (Table 7). In contrast to N, total rice Fe uptake was similar between the two struvite-P sources and both were similar to at least two other fertilizer-P sources (Table 7). Similar to DM, N, and Fe, total rice Zn uptake was numerically largest from TSP, which did not differ from ECST and MAP, and was numerically smallest from the UC, which did not differ from RP, DAP, CPST, and ECST (Table 7). Like with DM and Fe, total rice Zn uptake was similar between the two struvite-P sources and both were similar to at least two other fertilizer-P sources (Table 7). Total rice P, K, Mg, Ca, and Mn uptake were all unaffected ( $P > 0.05$ ) by fertilizer-P source (Table 7). Similar to the results of this study, Della Lunga, et al. [46] reported total plant N uptake differed and P, K, and Mg uptakes did not differ among fertilizer-P sources.

Similar to total aboveground rice properties, of the nine total rice plant properties (i.e., belowground plus aboveground vegetative plus grain) evaluated in the study, four properties differed among fertilizer-P sources, where all four were at least numerically largest from TSP, DAP, or MAP (Table 7). In addition, ECST was greater than CPST for one and CPST was greater than ECST for one of the four total rice plant properties (Table 7).

### Conclusions

This greenhouse study evaluated below- and aboveground

**Table 7:** Summary of the effect of fertilizer-phosphorus source on total plant tissue properties (belowground plus aboveground vegetative plus grain) for rice grown in a P-deficient, silt-loam soil under flood-irrigated conditions in the greenhouse. Least square means are reported, with  $n = 4$  observations for MAP and RP, but  $n = 3$  observations for DAP, ECST, TSP, and the UC and  $n = 2$  observations for CPST due to missing data from one dead plant and grain masses that were too low for any chemical analyses.

Plant Property <sup>†</sup>	P-value	Fertilizer-P Source <sup>†</sup>							Overall mean
		ECST	CPST	MAP	DAP	TSP	RP	UC	
Total plant DM (kg m <sup>-2</sup> )	0.03	4.2 ab <sup>‡</sup>	3.8 b	5.1 a	4.3 ab	5.1 a	4.0 b	3.7 b	-
Total plant DM uptake									
N (g m <sup>-2</sup> )	< 0.01	69.1 ab	55.6 cd	69.9 ab	80.2 a	64.5 bc	55.7 cd	49.6 d	-
P (g m <sup>-2</sup> )	0.09	7.5	7.0	8.2	7.3	8.7	6.4	6.4	7.4
K (g m <sup>-2</sup> )	0.56	16.8	17.1	16.6	14.6	19.1	17.8	16.8	17.0
Mg (g m <sup>-2</sup> )	0.48	11.0	11.2	13.1	10.9	11.9	11.8	9.8	11.4
Ca (g m <sup>-2</sup> )	0.23	12.9	14.7	17.9	17.3	17.7	16.8	11.7	15.6
Fe (g m <sup>-2</sup> )	0.01	27.6 bc	41.8 ab	50.6 a	47.8 a	58.3 a	36.1 ab	21.0 c	-
Mn (g m <sup>-2</sup> )	0.14	5.9	6.9	7.7	7.1	9.0	7.4	4.7	7.0
Zn (g m <sup>-2</sup> )	0.02	0.19 abc	0.16 bc	0.22 ab	0.17 bc	0.24 a	0.16 c	0.15 c	-

<sup>†</sup>Dry matter (DM), electrochemically precipitated struvite (ECST), chemically precipitated struvite (CPST), monoammonium phosphate (MAP), diammonium phosphate (DAP), triple superphosphate (TSP), rock phosphate (RP), and unamended control (UC); <sup>‡</sup>Means in a row followed by different letters are different at  $P \leq 0.05$ .

rice response to various fertilizer-P sources (i.e., ECST, CPST, MAP, DAP, TSP, RP, and a UC) under flood-irrigation. Contrary to that hypothesized, of the 69 total measured or calculated rice properties evaluated, 22 rice properties differed among fertilizer-P sources, including numerous below- and aboveground, total aboveground, and total rice properties. For all 22 rice properties with a significant fertilizer-P-source difference, either ECST, CPST, or both had a similar response to TSP, DAP, and/or MAP and, in three instances (i.e., belowground P and Ca and grain K concentration), CPST had a larger response than TSP, DAP, or MAP. Results clearly demonstrated that struvite-P sources (i.e., ECST and CPST) are a viable, alternative fertilizer-P source, as evidenced by the large frequency of similar rice responses to at least one of the other commercially available fertilizer-P sources commonly used for flood-irrigated rice production on a silt-loam soil in Arkansas (i.e., TSP, DAP, or MAP).

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