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Struvite Effects on Rice Growth and Productivity under Flood-Irrigation in the Greenhouse

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Abstract

In recent years, electrochemical precipitation has gained interest as an alternative method for the synthesis of various minerals, including struvite, from waste streams that can serve as an alternative fertilizer. Studies in lowland cultivations, specifically rice (*Oryza sativa*) under flood-irrigated conditions, evaluating struvite as a possible alternative phosphorus (P) fertilizer source have been limited. The objective of this study was to evaluate rice response to electrochemically precipitated struvite (ECST) compared to triple superphosphate (TSP), diammonium phosphate (DAP), a chemically precipitated struvite (CPST), and an unamended control (UC), grown under flooded-soil conditions in the greenhouse. Aboveground vegetative dry matter (DM) P concentration was greatest from the UC (0.18%) and was lowest from DAP (0.08%). Root DM Mg concentration was greatest from ECST (0.13%) and was lowest from TSP (0.10%). Grain yield was greatest from DAP (11.2 $Mg \cdot ha^{-1}$) and was lowest from the UC (4.0 $Mg \cdot ha^{-1}$). Grain N, P, K, and Mg uptake were consistently greatest from DAP and consistently lowest from the UC. Grain N concentration was 1.1 times greater from CPST than from ECST, while all other measured rice properties did not differ between the struvite-P sources. The many similar rice responses between struvite materials (ECST and CPST) and TSP and DAP demonstrate that struvite, particularly ECST, is a valid alternative fertilizer-P source for rice-production systems. Further studies should evaluate potential environmental implications (*i.e.*, runoff water quality and greenhouse gas emissions) from struvite use that could affect agricultural sustainability.

Keywords

Greenhouse, Nitrogen, Phosphorus, Rice Production, Struvite

1. Introduction

The improvement of phosphorus (P) availability and the enhancement of plant-P uptake is necessary to meet the global rising demand for rice (*Oryza sativa*) production [1]. Under flood irrigation, the primary water management scheme for rice production, soil-P availability tends to be less constrained than in upland rice production systems [2] [3] because reducing conditions typically develop within weeks to release iron-bound P that commonly provides additional plant-available P after several weeks of flood-water presence. However, a decrease in soil-solution P due to resorption and precipitation of iron-compounds has been often reported in rice paddies [4].

The need for P fertilizer to support global rice demand combined with limited world-wide rock phosphate deposits has inspired serious consideration of reuse and recycling scenarios to address the P scarcity crisis [5]. Several technologies exist that allow recovery of P from waste materials, such as wastewaters and sludges associated with wastewater treatments plants (WWTPs) and/or from animal waste materials [6]. One such wastewater-recovered fertilizer material that has shown some promise as an alternative fertilizer-P material is the mineral struvite. Struvite is described as a soft mineral with low specific gravity (*i.e.*, 1.7) and a chemical composition that contains on average 13%, 6%, and 10%, by weight, of P, nitrogen (N), and magnesium (Mg), respectively [7]. The solubility of struvite increases as the pH decreases, which also occurs in the rhizosphere of growing plants [3] [8].

In recent years, electrochemical precipitation has gained interest in the scientific community as an alternative method for the synthesis of various minerals from waste streams, including struvite [8]. Electrochemical precipitation involves the hydrolysis of a solution that contains the adequate ratio of ammonium (NH_4^+), phosphate (PO_4^{3-}), and Mg [8]. Electrochemically precipitated P compounds can be obtained in one single step due to the high pH environment created around the cathode [8]. At the cathode surface, water is reduced into H_2 and OH^- raising the pH; subsequently, cations move toward the cathode due to electric migration, causing the saturation index of P minerals to increase, leading to the precipitation of the mineral at the cathode surface [8]. In contrast, struvite has also been generated by chemical precipitation methods [*i.e.*, chemically precipitated struvite (CPST)], where salts are added to supply the Mg. The low water solubility, yet large citrate (*i.e.*, citric acid) solubility of struvite in general, including electrochemically precipitated struvite (ECST) and CPST, renders struvite a potential candidate as an agricultural fertilizer-P source, reducing possible nutrient losses via timelier plant-P uptake from rhizosphere acidification from root exudates production [9]. Struvite has been reported to provide a longer-term source of P, closely matching the plant-P demand during late growth stages, thus increasing struvite's fertilizer-use efficiency [10]. However, despite both being struvite materials, the differential methods to create ECST and CPST suggest that ECST and CPST may have differential soil and/or plant responses.

Results of various recent studies in Arkansas, with numerous row crops, under greenhouse and field conditions, indicate the potential use of struvite as an alternative fertilizer-P source [11] [12] [13] [14]. However, studies in lowland cultivations, specifically rice under flood-irrigated conditions, evaluating struvite as a possible alternative fertilizer-P source in low soil-test-P soil have been limited. A recent study by Omidire *et al.* [12] evaluated rice response to numerous alternative fertilizer-P sources, including ECST, a chemically precipitated struvite (CPST), superphosphate (TSP), monoammonium phosphate (MAP), diammonium phosphate (DAP), and rock phosphate, in a 2-yr field study in a P-deficient, silt-loam soil under flood-irrigation in eastern Arkansas. Based on many similar aboveground rice responses among ECST, CPST, and the other commercially available, commonly used fertilizer-P sources, Omidire *et al.* [12] concluded that both ECST and CPST, as wastewater-recovered nutrient sources, appear to be viable, alternative fertilizer-P sources for flood-irrigated rice production. However, as a field study, belowground rice response was limited to only a qualitative assessment of root nutrient concentrations. Consequently, a more complete, quantitative assessment of belowground rice root response (*i.e.*, root biomass and nutrient concentrations and uptakes) is warranted to comprehensively evaluate struvite effects on rice production.

The objective of this study was to evaluate rice response to ECST compared to TSP, DAP, CPST, and an unamended control (UC) grown under flooded-soil conditions in the greenhouse. It was hypothesized that 1) due to solubility differences among the fertilizer-P sources, ECST would have the largest and DAP would have the smallest root dry matter, but ECST would have the lowest and DAP would have the largest root dry matter P concentration, while there would be no difference in root nutrient uptakes among P-fertilized treatments, 2) due to solubility differences, ECST would have the smallest and DAP would have the largest aboveground vegetative dry matter, but ECST would have the largest and DAP would have the smallest aboveground vegetative P concentration, while there would be no difference in aboveground vegetative nutrient uptakes among P-fertilized treatments, and 3) there would be no difference in grain properties among P-fertilized treatments.

2. Materials and Methods

2.1. Initial Soil Collection, Processing, and Analyses

On 19 April, 2021, soil was collected from the top 10 cm of a Calhoun silt loam (fine-silty, mixed, active, thermic Typic Glossaqualfs) [15] at the Pine Tree Research Station near Colt in St. Francis County, AR. The field from which soil was collected was managed in a rice-soybean (*Glycine max*) rotation for at least the previous seven years. Moist soil was sieved through a 6-mm mesh screen and air-dried at ~ 24˚C in a greenhouse for ~ 7 days. Five sub-samples were then collected randomly for soil chemical and physical analyses.

Sub-samples of air-dried soil were oven-dried in a forced-air dryer for at least 48 hours at 70˚C, then mechanically ground, and sieved through a 2-mm mesh screen. Soil pH, electrical conductivity (EC) extractable soil nutrients (*i.e.*, P, K, Ca, Mg, S, Na, Fe, Mn, and Zn), soil organic matter (SOM) concentrations, total C (TC) and total N (TN) concentrations were measured according to procedures detailed in previous studies [16] [17] [18] [19]. A modified 12-hr hydrometer method [20] was used for soil particle-size analyses.

2.2. Treatments and Experimental Design

This study was conducted between May and September 2021 in a greenhouse at the Milo J. Shult Agricultural Research and Extension Center (SAREC) in Fayetteville, AR. Four fertilizer-P treatments were evaluated in this study: TSP, DAP, CPST, ECST, and a UC that received no fertilizer-P addition at any time. On 8 May, 2021, 15, 51-L plastic tubs (51-cm wide by 67-cm long by 15-cm deep) were placed on a greenhouse bench under controlled ambient conditions in a randomized complete block (RCB) design with three replications (*i.e.*, blocks) of the five treatments.

Fertilizer grades varied among DAP (18-46-0), TSP (0-46-0), ECST (5-37-0) [21], and CPST (6-27-0.1) [21]. The CPST material, commercially available under the trade name Crystal Green, was produced by Ostara Nutrient Recover Technologies, Inc. (Vancouver, Canada) through chemical precipitation of wastewater in a WWTP in Atlanta, GA. The ECST material was produced by the Chemical Engineering Department at the University of Arkansas from a synthetic wastewater material with known concentrations of P and N by electrochemical precipitation, where the Mg was supplied by a sacrificial Mg electrode [12] [22]. The four fertilizer-P sources were also characterized by different solubilities, with reports indicating ~ 97% water-soluble phosphate for TSP, ~ 90% for DAP, between ~ 4 and 6% for CPST, and ~ 5% for ECST [9] [23].

2.3. Tub Preparation and Management

Each tub was filled with 26.4 kg of sieved, air-dried soil. Soil bulk density (BD) was estimated by dividing the oven-dry soil mass in the tub by the average estimated soil volume. The estimated average soil BD of 1.16 $g \cdot cm^{-3}$ and 10-cm soil depth were used to convert measured soil nutrient, SOM, TC, and TN concentrations to contents ($kg \cdot ha^{-1}$) for reporting.

On 15 May, 2021, each tub was seeded on moist soil with the pure-line rice variety "Diamond" (RiceTec, Inc., Alvin, TX) at a rate of 290 $seeds \cdot m^{-2}$, which was equivalent to a field seeding rate of 79.6 kg·ha^{-1}, to a depth of 1.6 cm according to University of Arkansas recommendations [24]. In each tub, three rows of seeds parallel to the long side of the tub were planted to achieve a final stand of 10 plants per row. Row spacing was 15 cm and intra-seed spacing within a row was 5 cm.

On 25 May, 2021 (*i.e.*, 10 days after planting), zinc (Zn) was applied as zinc sulfate at a rate of 11.2 kg Zn ha^{-1} according to initial soil-test results. On 31 May, 2021 (*i.e.*, 16 days after planting), fertilizer-P was added at the equivalent rate 29.4 kg P ha^{-1} using the four different fertilizer-P sources, while potassium (K) was added as muriate of potash to all tubs at a rate of 111.2 kg K ha^{-1} according to initial soil-test results and University of Arkansas recommendations [24]. Due to the greater N concentration in DAP compared to the other fertilizer-P sources, N-(n-butyl) thiophosphoric triamide (NBPT)-coated urea was applied to the TSP, CPST, ECST, and UC tubs at the same time of P application to balance the amount of applied N among all treatments. On 11 June, 2021 (*i.e.*, 27 days after planting), at the 3 - 4 leaf stage, N was applied as coated urea at a rate of 145.7 kg N ha^{-1} (2021) according to the University of Arkansas recommendations [24]. Though not commonly done under field conditions, fertilizer nutrients were surface applied after planting to facilitate weed control, where weeds may have differentially competed with rice plants for fertilizer nutrients.

Soil was maintained visually moist until a flood was established on 12 June, 2021 (*i.e.*, 28 days after planting). The flood layer in the tubs was replenished every two days to maintain a depth of at least 4 cm. At 46 days after planting, a second application of N as coated urea at a rate of 22.4 kg N ha^{-1} was applied to all tubs directly into the flood water. Consequently, the total fertilizer-N application made was 168 kg N ha^{-1}. Weeds were manually removed as needed on a daily basis throughout the duration of the study. A primary and secondary heating system kept the daytime temperature in the greenhouse at 31˚C and the nocturnal temperature at 27˚C.

2.4. Plant and Soil Sampling and Analyses

At the end of each growing season, below- (*i.e.*, roots) and aboveground (*i.e.*, vegetative and grains) biomass were collected and oven-dried at 55˚C for at least five days and weighed to determine above- and belowground dry matter. Rice grains were manually stripped from the panicles and weighed on a chamber-by-chamber basis to determine yield. Rice grain yields were corrected to 12% moisture for reporting purposes. A sub-sample of root, aboveground vegetative, and grain dry matter was mechanically pulverized, sieved, and analyzed for total N and for total P, K, Mg, and Zn concentrations as described in previous studies [25] [26] [27]. Elemental tissue concentrations and tissue dry masses were used to determine nutrient uptake for belowground, aboveground vegetative, and grain dry matters. Aboveground dry matter (ABGDM) and uptake (ABGUP) were calculated as the sum of aboveground vegetative plus grain dry matters and uptakes, while total plant dry matter and total plant uptake were calculated as the sum of belowground plus aboveground vegetative plus grain dry matters and uptakes. Nutrients uptakes and dry matters were converted to kg·ha^{-1} and Mg·ha^{-1}, respectively, for reporting purposes.

2.5. Statistical Analyses

The PROC GLIMMIX procedure in SAS (version 9.4, SAS Institute, Inc., Cary, NC) was used to conduct a one-factor analysis of variance (ANOVA), based on the RCB design, to evaluate the effects of fertilizer-P source on below- and aboveground dry matter and nutrient concentrations and uptakes, total plant dry matter and nutrient uptakes, grain yield, nutrient concentrations, and uptakes. All plant properties were analyzed using a gamma distribution. Significance was judged at $P < 0.05$, thus, when appropriate, treatment means were separated by least significant difference at the 0.05 level.

3. Results and Discussion

3.1. Initial Soil Properties

The soil textural class was confirmed as silt loam, with an average pH of 7.5, which is outside the optimal pH range for rice grown under flooded-soil conditions (**Table 1**) [28]. Initial soil-test-P concentrations were within the low category (*i.e.*, 9 - 16 mg·kg^{-1}), while soil-test-K concentrations were within the low (*i.e.*, 61 - 90 mg·kg^{-1}) and very low (*i.e.*, <60 mg·kg^{-1}), categories, respectively (**Table 1**) [29]. Soil-test-Zn concentrations were in the low (*i.e.*, 1.6 - 2.5 mg·kg^{-1}) category (**Table 1**) [29]. Soil nutrient concentrations represented a soil fertility condition in where a positive plant growth response to P fertilization was expected [29].

Initial SOM concentration was within the range commonly measured in cultivated fields in Arkansas (**Table 1**) [30]. Total C was slightly numerically greater than TC concentrations reported for similar soil series under row-crop agriculture in Arkansas in the top 15 cm (**Table 1**) [30]. In contrast, the TN concentration was numerically lower than TN concentrations reported from cultivated soils in Arkansas (**Table 1**) [30]. The C:N ratio depicted a soil condition where rapid mineralization of inorganic N was expected (**Table 1**) [31]. The relatively large soil C:P ratio suggested that microbial P immobilization and biological P sorption was expected (**Table 1**) [32].

3.2. Above- and Belowground Plant Response

During the 2021 growing season in the greenhouse, plants experienced healthy growth, reaching maturity and producing grain, creating the opportunity to evaluate treatment effects on grain yield and other grain-related properties. Among all plant-response properties, only VDM P concentration, root DM Mg concentration, grain yield, grain N concentration, and grain N, P, K, and Mg uptake differed ($P < 0.05$) among fertilizer-P treatments (**Table 2**).

Table 1. Summary of initial soil physical and chemical property means [n = 5; ±standard errors (SE)] for the Calhoun silt-loam soil from the Pine Tree Research Station near Colt, AR used in the 2021 greenhouse study.

Soil property	Mean (± SE)
Sand ($g \cdot g^{-1}$)	0.09 (<0.01)
Silt ($g \cdot g^{-1}$)	0.79 (<0.01)
Clay ($g \cdot g^{-1}$)	0.11 (<0.01)
Bulk density ($g \cdot cm^{-3}$)	1.16 (0.01)
pH	7.5 (<0.1)
Electrical conductivity ($dS \cdot m^{-1}$)	0.167 (<0.1)
Mehlich-3 extractable nutrients ($mg \cdot kg^{-1}$)	
Phosphorus	11.4 (0.1)
Potassium	46.1 (0.9)
Calcium	2006 (4.2)
Magnesium	276 (2.2)
Sulfur	11.9 (0.4)
Sodium	29.8 (0.6)
Iron	304 (7.8)
Manganese	244 (5.1)
Zinc	2.5 (0.1)
Soil organic matter (%)	2.6 (< 0.1)
Total carbon (%)	1.1 (< 0.1)
Total nitrogen (%)	0.1 (< 0.01)
Carbon:nitrogen ratio (mass/mass)	10.0 (< 0.1)
Carbon:phosphorus ratio (mass/mass)	997 (15)

Table 2. Analysis of variance summary of the effect of fertilizer-phosphorus treatment [*i.e.*, triple superphosphate (TSP), electrochemically precipitated struvite (ECST), chemically precipitated struvite (CPST), diammonium phosphate (DAP), and unamended control (UC)] on aboveground vegetative dry matter (VDM), root dry matter, grain yield, and aboveground vegetative and root dry matter and grain elemental concentrations and uptake for rice grown in the greenhouse under flooded conditions during the 2021 growing season.

Plant property	*P*-value	TSP	ECST	CPST	DAP	UC	Overall mean
VDM ($Mg \cdot ha^{-1}$)	0.66	22.3	21.2	20.9	26.9	22.0	22.7
			VDM concentration				
N (%)	0.43	0.79	0.69	0.92	0.73	0.79	0.78
P (%)	**0.03**‡	0.11† BC	0.13 A-C	0.15 AB	0.08 C	0.18 A	-
K (%)	0.54	1.28	1.58	1.63	1.24	1.51	1.45

Continued

Mg (%)	0.27	0.39	0.38	0.40	0.43	0.35	0.39
Zn (mg·kg^{-1})	0.18	84.3	65.5	68.4	76.2	74.3	73.7
VDM uptake							
N (kg·ha^{-1})	0.08	172	143	185	195	172	173
P (kg·ha^{-1})	0.15	22.5	26.9	30.6	21.8	39.9	28.3
K (kg·ha^{-1})	0.31	279	322	320	334	327	316
Mg (kg·ha^{-1})	0.46	87.4	80.6	82.3	115.6	77.0	88.6
Zn (kg·ha^{-1})	0.35	1.9	1.4	1.5	2.0	1.6	1.7
Root DM (mg·ha^{-1})	0.88	4.8	5.3	6.3	7.2	5.3	5.8
Root concentration							
N (%)	0.80	0.80	0.76	0.85	0.71	0.79	0.78
P (%)	0.81	0.11	0.11	0.11	0.10	0.11	0.11
K (%)	0.10	0.15	0.25	0.19	0.11	0.25	0.19
Mg (%)	**0.01**	0.10 B	0.13 A	0.13 A	0.11 B	0.13 A	-
Zn (mg·kg^{-1})	0.91	65.0	61.4	60.4	66.2	68.8	64.4
Root uptake							
N (kg·ha^{-1})	0.81	37.9	38.9	50.6	50.8	41.9	44.0
P (kg·ha^{-1})	0.95	5.5	6.1	6.8	7.4	5.8	6.3
K (kg·ha^{-1})	0.48	6.7	12.3	10.6	8.5	13.0	10.2
Mg (kg·ha^{-1})	0.77	4.8	7.1	8.3	7.7	7.0	7.0
Zn (kg·ha^{-1})	0.92	0.3	0.3	0.4	0.5	0.4	0.4
Grain yield (mg·ha^{-1})	**0.03**	8.0 AB	6.8 A-C	6.0 BC	11.2 A	4.0 C	-
Grain concentration							
N (%)	**< 0.01**	1.5 B	1.4 C	1.6 A	1.5 B	1.6 AB	-
P (%)	0.15	0.49	0.52	0.53	0.49	0.52	0.51
K (%)	0.68	0.58	0.60	0.58	0.57	0.59	0.58
Mg (%)	0.24	0.21	0.22	0.23	0.21	0.22	0.22
Zn (mg·kg^{-1})	0.09	48.2	50.4	55.8	49.3	61.8	53.1
Grain uptake							
N (kg·ha^{-1})	**0.03**	120.5 AB	98.0 BC	96.5 BC	170.9 A	62.7 C	-
P (kg·ha^{-1})	**0.04**	39.2 A	35.8 AB	31.3 AB	54.2 A	20.8 B	-
K (kg·ha^{-1})	**0.04**	46.0 AB	40.9 A-C	35.0 BC	63.4 A	23.7 C	-
Mg (kg·ha^{-1})	**0.04**	16.9 A	15.1 AB	13.4 AB	23.1 A	8.9 B	-
Zn (kg·ha^{-1})	0.14	0.4	0.3	0.3	0.5	0.2	0.3

†Means followed by a letter with the same case within a row do not differ (P > 0.05). ‡Bolded P-values indicate significance at the 0.05 level.

The VDM P concentration was greatest from the UC, which did not differ from ECST and CPST, and was lowest from DAP, which did not differ from ECST and TSP (**Table 2**). The large VDM P concentration from the UC could be related to the numerically lower VDM that masked the actual nutrient status in the vegetative tissue [33]. Root DM Mg concentration was greatest ($P = 0.01$) from ECST, which did not differ from CPST and the UC, and was lowest from TSP, which did not differ from DAP (**Table 2**). The presence of Mg in the ECST and CPST fertilizers likely explains the greater Mg concentration in the root tissue in tubs treated with the struvite materials, although the explanation for the relatively large Mg concentration in the UC compared to DAP and TSP was unclear (**Table 2**) [7].

Results of the current greenhouse study were similar to those reported by Omidire *et al.* [12], where aboveground dry matter, aboveground N and Mg tissue concentrations, and aboveground P and N tissue uptakes did not differ among fertilizer-P sources in both studies. In addition, results of the current greenhouse study were similar to those reported by Omidire *et al.* [12], where belowground Mg tissue concentration differed among fertilizer-P sources in both studies. In contrast, results of the current greenhouse study were dissimilar to those reported by Omidire *et al.* [12], as in the current study aboveground P tissue concentration differed among fertilizer-P sources and aboveground Mg tissue uptake was unaffected by fertilizer-P sources (**Table 2**). Furthermore, results of the current study were also similar to those of Omidire *et al.* [12], where few differences in rice above- and belowground properties between ECST and CPST were measured.

In contrast to aboveground vegetative and root properties, numerous rice grain properties differed among fertilizer-P treatments (**Table 2**). Grain yield was greatest ($P = 0.03$) from DAP, which did not differ from TSP and ECST, and was lowest from the UC, which did not differ from ECST and CPST (**Table 2**). Except for the UC, grain yields from the various P-fertilized treatments were generally in the same range or exceeded the average yield (*i.e.*, 8.3 $Mg \cdot ha^{-1}$) reported in field trials in eastern Arkansas [34]. Similar to grain yield, among fertilizer-P treatments, CPST had the greatest ($P < 0.01$) grain N concentration, which did not differ from the UC, while ECST had the lowest (**Table 2**).

The differences in grain yield could have affected the grain N concentration during the nutrient transfer process. Elemental grain uptakes had more consistent results among all plant properties evaluated in the current study (**Table 2**). Grain N, P, K, and Mg uptake were consistently greatest ($P < 0.05$) from DAP and were consistently lowest from the UC (**Table 2**). Grain N uptake from DAP did not differ from TSP, while grain P, K and Mg uptake from DAP did not differ from TSP and ECST (**Table 2**). Additionally, grain P and Mg uptake from DAP did not differ from CPST (**Table 2**). With the exception of grain N concentration, none of the other measured aboveground vegetative, belowground, or grain properties differed between the two struvite materials (*i.e.*, ECST and

CPST; **Table 3**). However, grain N concentration was 1.1 times greater from CPST than from ECST (**Table 2**).

Results of the current greenhouse study were similar to those reported by Omidire *et al.* [12], where grain P and Mg tissue concentration did not differ among fertilizer-P sources in both studies, while grain yield and grain N uptake differed among fertilizer-P sources in both studies. In contrast, results of the current greenhouse study were dissimilar to those reported by Omidire *et al.* [12], as in the current study grain N concentration and grain P and Mg uptake differed among fertilizer-P sources (**Table 2**). Furthermore, results of the current study were also similar to those of Omidire *et al.* [12], where few differences in rice grain properties between ECST and CPST were measured.

The feasibility of struvite as alternative P-source is, however, tied to the economical aspect of the recovery process [35]. Although full-scale production of ECST is not yet ready, modeling analyses and economic assessments have indicated that recovered struvite material could be available at ~$480 ton^{-1}, rendering the recovered P (*i.e.*, chemically and electrochemically precipitated) competitive in the market place [35].

Table 3. Analysis of variance summary of the effect of fertilizer-phosphorus treatment [*i.e.*, triple superphosphate (TSP), electrochemically precipitated struvite (ECST), chemically precipitated struvite (CPST), diammonium phosphate (DAP), and unamended control (UC)] on aboveground dry matter (ABGDM, vegetative + grain), total plant dry matter (TDM, vegetative + grain + roots), aboveground elemental uptake (vegetative + grain), and total plant elemental uptake (vegetative + grain + roots) for rice grown in the greenhouse under flooded conditions during the 2021 growing seasons.

Plant property	*P*-value	TSP	ECST	CPST	DAP	UC	Overall mean
ABGDM (Mg·ha^{-1})	0.37	30.3	28.0	27.0	38.0	26.0	30.0
TDM (Mg·ha^{-1})	0.55	35.2	33.5	33.5	45.5	31.4	35.8
Aboveground uptake (kg·ha^{-1})							
N	**0.04**[‡]	293 AB	241 B	283 AB	366 A	235 B	-
P	0.68	62.2	62.9	62.2	76.0	7.3	54.1
K	0.27	326	363	356	397	20.2	292
Mg	0.35	104	95.7	95.7	139	85.9	104
Zn	0.32	2.3	1.7	1.8	2.6	1.9	2.1
Total plant uptake (kg·ha^{-1})							
N	**0.02**	271 B	231 B	273 AB	345 A	228 B	-
P	0.29	48.9	49.7	49.2	61.1	48.3	51.4
K	0.27	332	376	366	406	364	369
Mg	0.07	70.4	66.3	66.9	96.3	60.4	72.1
Zn	0.31	1.8	1.5	1.5	2.2	1.6	1.7

[†]Means followed by a letter with the same case within a row do not differ ($P > 0.05$). [‡]Bolded *P*-values indicate significance at the 0.05 level.

3.3. Total Plant Response

Aboveground (*i.e.*, vegetative plus grain) and total plant DM did not differ among fertilizer-P treatments (Table 3). Similarly, no difference in aboveground and total plant P, K, Mg, and Zn uptake occurred among fertilizer-P treatments (Table 3). However, aboveground and total plant N uptake differed ($P < 0.04$) among fertilizer-P treatments, where both were greatest from DAP and were lowest from the UC (Table 3). Similar to aboveground vegetative and belowground rice properties, aboveground (*i.e.*, vegetative plus grain) and total plant DM properties did not differ between the two struvite materials (*i.e.*, ECST and CPST; Table 3).

4. Conclusions

Among the more pressing concerns related to essential plant nutrients and the need to increase fertilization to feed a growing human population, P represents the most compelling challenge due to the scarce mineral reserves worldwide and to the relation of P to cultural eutrophication. The recent development of electrochemical processes has created opportunities to recover nutrients, including P and N, from WWTPs in the form of struvite that can be subsequently used as fertilizer materials in agricultural production.

Considering the lack of knowledge related to the behavior of struvite in rice production systems, the current study aimed to evaluate the agronomic impacts of ECST compared to other common fertilizer-P sources (*i.e.*, TSP and DAP) and the commercially available CPST under flooded-soil conditions in the greenhouse. In contrast to the hypothesis that ECST would have the largest and DAP would have the smallest root dry matter, but ECST would have the lowest and DAP would have the largest root dry matter P concentration, root dry matter and root dry matter P concentration were unaffected by fertilizer-P sources. However, results supported the hypothesis there would be no difference in root nutrient uptakes among P-fertilized treatments. In contrast to the hypothesis that ECST would have the smallest and DAP would have the largest, aboveground vegetative dry matter was unaffected by fertilizer-P source and ECST did not have the largest and DAP did not have the smallest aboveground vegetative P concentration. However, results supported the hypothesis there would be no difference in aboveground vegetative nutrient uptakes among P-fertilized treatments. In contrast to the hypothesized that there would be no difference in grain properties among P-fertilized treatments, grain yield and grain N, P, K, and Mg uptake differed among fertilizer-P sources. With the exception of grain N concentration, all other measured rice properties did not differ between the struvite-P sources (*i.e.*, ECST and CPST).

Results of this greenhouse study clearly indicate that struvite-P sources, particularly ECST, are viable, alternatives to commercially available, commonly used fertilizer-P sources (*i.e.*, TSP and DAP). Additional research should evaluate potential environmental implications (*i.e.*, runoff water quality and greenhouse gas emissions) from struvite use that could affect agricultural sustainability.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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