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Rice Biomass Response to Various Phosphorus Fertilizers in a Phosphorus-deficient Soil Under Simulated Furrow-irrigation

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Abstract

Wastewater-recovered phosphorus (P), in the form of the mineral struvite ($MgNH_4PO_4 \cdot 6H_2O$), may provide a sustainable alternative to rapidly decreasing rock phosphate reserves. Struvite can be generated via chemical and/or electrochemical precipitation methods, potentially reducing the amount of P runoff to aquatic ecosystems. The objective of this greenhouse tub study was to evaluate the effects of chemically- and electrochemically precipitated struvite (CPST and ECST, respectively) on above- and belowground plant response in a hybrid rice cultivar (Gemini 214, RiceTec) grown using furrow-irrigation compared to other common fertilizer-P sources [i.e., triple super phosphate (TSP) and diammonium phosphate (DAP)] in a P-deficient silt loam (Aquic Fraglossudalfs). Below- and aboveground rice dry matter (DM), belowground P concentration and uptake, aboveground DM P uptake, total aboveground and total plant DM, grain yield, and grain P uptake from CPST and ECST did not differ ($P > 0.05$) from DAP or TSP. However, aboveground DM P concentration was numerically largest from TSP (0.05 %), which did not differ from DAP, and was at least 2.5 times larger than that from ECST, CPST, and the unamended control (UC). Similarly, total aboveground DM (i.e., vegetative plus grain) P uptake was numerically largest from TSP (4.8 g m^{-2}), which did not differ from DAP or CPST, and was at least 1.1 times greater than from ECST and the UC. The many similar rice responses among struvite and other common fertilizer-P sources suggest that struvite, especially ECST, is a possible alternative fertilizer-P source that warrant further research into their role in food production and water quality restoration and preservation.

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Literature Review

Since the beginning of modern agriculture, the use of fertilizers has been a necessity for producing maximum-yielding crops to provide food for the increasing global human population. All cultivated crops require nitrogen (N), phosphorus (P), and potassium (K) as plant macro-nutrients, and, when the soil is deficient, micro-nutrients (i.e., zinc, iron, magnesium) are also required for optimal productivity (Pimentel & Pimentel, 1990). With the exception of legume crops, such as peanuts (*Arachis hypogaea*) and soybeans (*Glycine max*), which can satisfy their own N requirement by fixing atmospheric N_2, all other cultivated crops need relatively large quantities of N, whereas, despite being plant macro-nutrients, P and K requirements are substantially lower for most crops compared to the N requirement (Weil & Brady, 2016). Thus, fertilizer applications tend to be the largest for N and smaller for both P and K across a wide range of crops. However, due to the large difference in crop N and P need, when N- and P-containing fertilizers are used (i.e., blended fertilizers/multi-nutrients fertilizers), fertilizer additions have often historically been made based on the crop-N requirement, with little to no attention paid to the crop-P requirement (Weil & Brady, 2016). Consequently, long-term fertilization of the same field based on plant-N, and not plant-P, requirements, can greatly increase soil-P concentrations, which, in turn, can lead to potentially major, negative environmental consequences, such as surface water eutrophication from P-containing runoff from agricultural fields and/or soil nutrient imbalances (FAO, 2006). Therefore, it is critical to study the impacts of P fertilization on crop growth and productivity to minimize potential off-site P transport to cause environmental issues, such as eutrophication.

Role of P in Plants

In plants, P plays an important role in deoxyribonucleic acid (DNA), ribonucleic acid (RNA), and in the primary energy storage and transfer molecule, adenosine triphosphate (ATP) (Weil & Brady, 2016). In an agronomic setting, optimal P improves systematic functions of photosynthesis, leading to healthier and more productive plants, which ultimately often correlates to greater crop yields. Despite the importance P plays in plant functions, P is not readily available to plants in large quantities because of how P behaves in the soil (Weil & Brady, 2016).

P Behavior in Soil

In contrast to N and K, in moist, upland soils, P is generally highly insoluble in the soil, which leads to limited plant-available P in the soil solution (Weil & Brady, 2016). Upon soil application of fertilizer-P material, the P is generally quickly fixed and immobilized by reaction with cations, such as iron (Fe^{2+}) and aluminum (Al^{3+}) under acidic conditions and calcium (Ca^{2+}) under alkaline soil pH conditions (Weil & Brady, 2016). Generally, a pH between 5 and 7 is optimal for P availability (Weil & Brady, 2016) Consequently, because P is not readily available to plants and is quickly immobilized upon application, P is often over-applied to ensure sufficient P is available for crops (Weil & Brady, 2016). In contrast to upland cultivation, in lowland soils that are saturated and/or flooded, such as for rice (*Oryza sativa*) production, soil water content quickly reaches saturation. Soil saturation leads to decreased oxygen concentrations, hence shifting the soil redox potential to reducing conditions (Brye et al., 2013). Once flooded soils reach reducing conditions, oxidized iron (Fe^{3+}), which is responsible for abundant P binding and is ubiquitous in soil, is reduced to Fe^{2+}. Reduced Fe^{2+} is highly soluble, causing once chemically bound P to be released into the soil, thereby temporarily increasing P availability until Fe^{+2} starts to precipitate again and increasing ambient soil-P concentrations in saturated/flooded soils typically used for rice production (Anderson et al., 2021a; Ponnapempura, 1972).

Fertilizer-P Sources

Approximately 90% of the current global P supply is mined as phosphorite or rock phosphate (RP), which is then processed to create several fertilizer-P materials, namely RP (0-3-0) itself, triple superphosphate (TSP; 0-46-0), monoammonium phosphate (MAP; 11-52-0), and diammonium phosphate (DAP; 18-46-0) (Cordell et al., 2009). However, RP production is expected to reach a peak in the next 50 years, when Earth's finite supply of RP will be nearly depleted (Cordell et al., 2009). Consequently, an alternative source of P will be critically necessary to be used as a fertilizer-P source for crop production that feeds Earth's continually growing population. One possible solution to the limited supply of mined RP is the mineral struvite ($MgNH_4PO_4 \cdot 6H_2O$) (Omidire et al., 2020).

Struvite Production

Under the right physio-chemical conditions, struvite precipitates inside wastewater treatment plant (WWTP) pipes, which is a major problem for WWTP operation on account of clogged pipes. However, when struvite-producing conditions are controlled in specialized reactors through manipulated sludge digesting processes, WWTPs can intentionally produce an abundance of struvite and prevent struvite buildup in WWTP pipes (Talboys et al., 2015).

Struvite is a white, crystalline, P-containing mineral that is intentionally produced by controlled chemical precipitation from wastewaters (Doyle & Parsons 2002). Struvite has been produced not only from sewage sludge in WWTPs (Münch & Barr, 2001), but also from semiconductor wastewater and dairy wastewater (Ahmed et al., 2018).

In addition to chemical precipitation, other P-extracting technologies from wastewater are available. For example, more recently, electrochemical precipitation of struvite from synthetic wastewater has been developed and studied. Electrochemical precipitation can synthesize struvite using an electrical current applied to a solution of known N and P concentration, while magnesium (Mg) is supplied to the solution through a Mg anode that partially decays in the process to release Mg ions (Kékedy-Nagy et al., 2020). Since struvite is a P-containing mineral and there is an abundance of wastewater, struvite could be an alternative fertilizer-P source for agricultural use (Omidire et al., 2020).

Struvite Studies

Struvite has been shown to create similar soil and plant responses compared to commonly used RP-derived fertilizers in multiple soil- and crop-focused studies (Anderson et al., 2020, 2021a,b,c; Omidire et al., 2020, 2022a; Ylagan et al., 2020). In a plant-less, moist-soil incubation study, Anderson et al. (2020) evaluated soil-P concentrations over time as affected by powderized and pelletized chemically precipitated struvite (CPST) in a loam (Typic Udifluvents), a silty-clay-loam (Typic Argiudolls), and two silt-loam soils (Aquic Fraglossudalfs and Typic Fragiaqualfs). Anderson et al. (2020) reported that WS-P concentration was initially largest from powderized CPST, but decreased over the 6-month study period. In contrast to powderized CPST, pelletized CPST did not exhibit a prevalent decrease in WS-P because the pelletized CPST dissolved more gradually, which appeared to reduce P fixation. In a plant-less incubation study with flooded soil, struvite recovered from wastewater has been shown to have similar total water-soluble (WS) and Mehlich-3-extractable soil-P concentrations in two silt-loams (Aquic Fraglossudalfs and Typic Fragiaqualfs) and a silty-clay-loam (Typic Argiudolls) soil from Arkansas with a history of agricultural production compared to MAP and TSP

(Anderson et al., 2021b). In another plant-less, flooded-soil incubation experiment comparing electrochemically precipitated struvite (ECST), CPST, RP, and DAP, ECST and CPST both demonstrated similar WS-P concentrations throughout the four months of the study among DAP, ECST, and CPST (Anderson et al., 2021a). An additional plant-less, moist-soil incubation study evaluated total extractable soil P from soils amended with ECST and CPST relative to TSP, MAP, DAP, and RP using a loam (Typic Udifluvents), two silt loams (Aquic Fraglossudalfs and Typic Fragiaqualfs), and a silty clay loam (Typic Argiudolls) and showed that WS-P concentration from the struvite treatments did not differ from MAP, DAP, RP, and TSP, which corroborates previous reports supporting struvite as a potential sustainable, alternative fertilizer-P material (Anderson et al., 2021c; Omidire et al., 2020). Fertilization with struvite has been shown to produce similar below- and aboveground tissue P concentration in corn (*Zea mays*) and soybean (*Glycine max*) compared to TSP, MAP, DAP, and RP in a potted-plant, greenhouse study using a silt-loam (Typic Fragiudults) soil from northwest Arkansas (Ylagan et al., 2020). Furthermore, a two-year field study conducted in east-central Arkansas that sought to evaluate the effects of CPST and ECST relative to DAP, TSP, and MAP in a P-deficient, flood-irrigated rice field showed that above- and belowground rice tissue and grain P and N concentrations, rice aboveground dry matter, and grain and aboveground tissue P uptake were similar to the other common, commercially available, fertilizer-P material (Omidire et al., 2022a). However, an important difference among struvite sources and commonly used fertilizer-P sources is the variation in water solubilities. Generally, commonly used fertilizer-P sources are highly soluble in water and readily provide plant-available P, whereas struvite, which has been reported as having slow-release characteristics, is also soluble in water, but not to the same degree (2 to 3.8% soluble among different struvite sources; Rech et al., 2019) as fertilizer sources like TSP (84 to 95% soluble; Chien et al., 2011; Johnston & Richards, 2003), MAP (85 to 90% soluble;

Chien et al., 2011), or DAP (85 to 90% soluble; Chien et al., 2011). Despite multiple studies testing struvite's effects on plant and soil properties, few studies have tested struvite's effects on plant response in the relatively new, furrow-irrigated rice production system.

Rice Production and Water Management

Rice is an essential food for a large portion of the human population. In 2020, 753.5 million Mg of rice were produced globally (USDA-ERS, 2021). In 2020, total rice production in the United States (US) was 10.3 million Mg (USDA-ERS, 2021), contributing approximately 1.4% to the total global rice production. In 2020, the average rice yield in the US was 8.53 Mg ha^{-1} from a harvested area of 1.21 million hectares (USDA-ERS, 2021). The main rice-producing region in the US is the Lower Mississippi River Valley (LMRV), which encompasses southeastern Missouri, eastern Arkansas, eastern Louisiana, and western Mississippi. In Arkansas, mostly eastern Arkansas, in 2020, an average rice yield of 8.4 Mg ha^{-1} was produced, which equated to 4.9 million Mg of total rice production in Arkansas, representing 47.5% of the total US rice production (USDA-ERS, 2021).

Traditionally, because rice is semi-aquatic, soils used for rice production are flooded during the growing season to minimize or prevent weed pressure, although the amount of water required to establish and maintain the flood is substantially greater than for other irrigation regimes (Hardke, 2021). It is estimated that a flood-irrigated rice production system in Arkansas requires an annual average of 763 mm of water, much of which comes from irrigation water (Henry et al., 2016). The large irrigation water requirement to flood-irrigate soils for rice production has led to excessive groundwater withdrawal in the LMRV (Reba & Massey, 2020; USGS, 2010). Therefore, alternative water management schemes to traditional flooding have been developed and used, such as mid-season drain (MSD), alternate wet and dry (AWD), intermittent flooding, and furrow-irrigation (i.e., row rice), on account of trying to conserve and reduce water use.

Mid-season drain is the act of completely draining a rice field approximately 20 days after the establishment of a flood and reestablishing the flood after the soil has dried and cracks begin to form in the soil surface (Humphreys, 2018). Historically, mid-season drain has been used to control straighthead, which is a disorder known to reduce yields, cause sterility in spikelets, and is caused by excess plant-available arsenic (IPCC, 2014). Studies have shown that practicing mid-season drain can decrease methane (CH_4) emissions by as much as 65%, but the benefit of CH_4 emissions reduction is off-set by an increase in nitrous oxide (N_2O) emissions from the soil drying caused by the mid-season drain (Smartt et al., 2016; Lu et al., 2000; Bronson et al., 1997).

Alternate-wet-and-dry irrigation uses a repeating cycle of approximately 10 days of flooding followed by approximately 10 days without flood-irrigation or drying, where the flood water dissipates via evapotranspiration and/or infiltration into the soil (Chapagain et al., 2011). Reports have shown that AWD uses about 29% less water than conventional flood-irrigation, while resulting in only slightly lower yields (Chapagain et al., 2011).

Similar to AWD, intermittent flooding is another alternative rice irrigation method that prioritizes water conservation. Intermittent flooding is practiced by flooding a rice field, allowing the flood to naturally subside via evapotranspiration and/or infiltration until high-elevation areas of the field are revealed and then reestablishing the flood once a threshold of water loss had been reached. Intermittent flooding has shown to use up to 50% less irrigation compared to traditional continuous flooding, which can be accredited to decreased percolation, field-edge seepage, and runoff of the continuous flood (Massey et al., 2014). If intermittent flooding is coupled with multiple inlet rice irrigation (MIRI), which consists of installing plastic tubing (i.e., polypipe) perpendicular to levees and simultaneously distributing water to all paddy areas from holes punched in the polypipe at the location of the furrows or at regular intervals if furrows are not present, rice yield quantity and quality can be maintained compared to conventional flood-irrigated rice (Massey et al., 2014).

Furrow-irrigated Rice

Furrow-irrigation is conducted by the establishment of raised beds separated by furrows that extend the length of the field between the raised beds. Water flows from the high to low elevation end of the field, often delivered to the rice field via the MIRI approach, supplying water to rice by infiltrating into the side of the beds and lapping up and over the raised beds (Dieter et al., 2018). In the past decade, furrow-irrigated rice production in Arkansas has risen in area from ~ 0.3% to greater than 15% of the practiced irrigation schemes used in rice production and continues to increase annually (Hardke, 2021).

Furrow-irrigation has been shown to use 41 to 48% less water than conventional irrigation methods (i.e., flooding) (He, 2010). Despite the benefits, furrow-irrigation has several drawbacks. For example, furrow-irrigation has been documented to create spatially variable soil reduction-oxidation potential, soil moisture content, and soil temperature conditions among site positions in a production-scale, furrow-irrigated field on a silt-loam soil (Typic Albaqualf) in east-central Arkansas (Della Lunga et al., 2020b). Spatially variable soil properties within a furrow-irrigated rice field could affect nutrient and/or fertilizer behavior (i.e., transformations, translocations, and losses), nutrient uptake, and yield. Thus, further research into the potential effects of furrow-irrigation on soil and plant responses are warranted (Della Lunga et al., 2020b). Recently, furrow-irrigation has been studied in Arkansas to determine minimum soil moisture thresholds before irrigating again, while maximizing grain and milling yield, but little new agronomic research on furrow-irrigated rice in Arkansas soils has been conducted (Chlapecka et al., 2020).

Justification

Due in part to the relative newness of both struvite as a potential alternative fertilizer-P source and furrow-irrigation as an alternative management practice for rice production and in part to the decreasing global supply of phosphate rock, no studies have investigated rice response to struvite as a fertilizer-P source under furrow-irrigated conditions. Furthermore, recovering struvite from WWTP effluent could improve WWTP effectiveness in reducing P loads to receiving waters, all the while improving time, energy, cost, and treatment efficiency (Kataki et al., 2016; Rahman et al., 2014; Tansel et al., 2018), which facilitates reducing P pollution from wastewater effluent in surface waters. Consequently, struvite may have more far-reaching benefits that just as an alternative fertilizer-P source than can be used for agricultural purposes.

Objective and Hypotheses

The objective of this study was to evaluate the effects of struvite (i.e., ECST and CPST) compared to several other commercially available, fertilizer-P sources (i.e., DAP and TSP) on above- and belowground plant response to rice grown under furrow-irrigation in a P-deficient, silt-loam soil. It was hypothesized that both struvite-P sources (ECST and CPST) will have similar above- and belowground dry matter and above- and belowground tissue-P concentrations, but that above- and belowground dry matter and tissue-P concentrations will differ between the two struvite-P sources themselves (ECST and CPST) due to differences in source materials, where ECST was prepared from a synthetic solution containing N and P and CPST was generated from municipal wastewater. It was also hypothesized that both ECST and CPST will have similar above- and belowground dry matter and similar above- and belowground tissue concentrations compared to TSP and DAP.

Materials and Methods

This study was conducted in conjunction with a broader study evaluating trace gas emissions from rice amended with various fertilizer-P sources. Rice was grown from May to September 2021 in a greenhouse at the University of Arkansas, Division of Agriculture Milo J. Shult Agricultural Research & Extension Center in Fayetteville, AR for both the current study and the broader study.

Soil Collection, Processing, and Characterization

The soil used in this study was a Calloway silt loam (fine-silty, mixed, active, thermic Aquic Fraglossudalfs) collected on 19 April, 2021 with a shovel from the upper 10 to 15 cm from a tilled field at the Pine Tree Research Station near Colt in St. Francis County, AR. After collection, the soil was sieved through a 6-mm screen to ensure roughly uniform sized peds and air-dried in a greenhouse at approximately 31ºC for at least seven days until the soil was no longer visibly moist. Once air-dry, five subsamples were collected from the sieved, air-dried soil for initial soil property determinations.

Sub-samples of air-dried soil were oven-dried at 70°C for 48 hours, crushed, and sieved through a 2-mm mesh screen. Soil particle-size analysis was conducted using a modified 12-hour hydrometer test (Gee & Or, 2002). Electrical conductivity (EC), soil pH, total C and N, soil organic matter (SOM), and extractable nutrient (i.e., K, P, Ca, Mg, Fe, Na, Mn, Cu, S, and Zn) concentrations were measured. Soil pH and EC were measured potentiometrically in a 1:2 soil mass:water volume suspension. Using a Mehlich-3 extraction solution in a 1:10 soil mass:water volume ratio, soil was extracted, and then analyzed for plant available nutrients using inductively coupled, argon-plasma spectrophotometry (Tucker, 1992). Soil organic matter was determined by weight-loss-on-ignition by 2 hours of combustion at 360°C. Total carbon (TC) and total nitrogen (TN) were measured by high-temperature combustions on a VarioMax carbon nitrogen analyzer (Elementar Americas Inc., Mt. Laurel, NJ; Nelson and Sommers, 1996). All measured C was assumed to be organic, as the soil did not effervesce upon treatment with dilute hydrochloric acid. The C:N ratio was calculated from the measured TC and TN concentrations. Table 1 summarizes initial soil property means and their variability.

The soil used in this study had 9% sand, 79% silt, and 12% clay, which classified as a silt-loam texture (Table 1). Initial SOM averaged 25.7 g kg^{-1}, while TC averaged 11.4 g kg^{-1} (Table 1). The soil's initial Mehlich-3 extractable K concentration averaged 11.4 mg kg^{-1} (Table 1), which placed the soil-test K into the very low category (< 60 mg kg^{-1}, Hardke, 2021) for rice production on a silt-loam soil. Therefore, a plant response to fertilizer-K additions was expected and K was uniformly applied to all treatments. Initial soil pH averaged 7.5, where soil pH of 7.5 is generally considered above the optimum pH for rice production and may have influenced soil-P availability due to P fixation with soil Ca and/or Mg (Table 1; Hardke, 2021). However, soil pH was not adjusted to a more optimum level in order to replicate field growing conditions in eastern Arkansas where slightly alkaline conditions are typically not modified in rice production systems due to localized groundwater generally being alkaline. (Norman et al., 2013). The soil's initial Mehlich-3 extractable P concentration averaged 11.4 mg kg^{-1} (Table 1), and, similar to K, placed the initial soil-test P into the low category (9 to 16 mg kg^{-1}; Hardke, 2021). Therefore, a plant response to fertilizer-P treatment was also expected and P was applied at a uniform total P rate among the various fertilizer-P sources. The soil's initial Mehlich-3 extractable Zn concentration averaged 2.5 mg kg^{-1} (Table 1), and, similar to K and P, placed the initial soil-test

Zn into the low category (1.6 to 2.5 mg kg^{-1}; Hardke, 2021), consequently, a plant response to fertilizer-Zn addition was also expected and Zn was applied uniformly to all treatments. Overall, all agronomically important elemental deficiencies were addressed for optimum rice production on a silt-loam soil.

Treatments and Experimental Design

This study was designed to evaluate rice response to five fertilizer-P treatments with varying fertilizer grades, including ECST, CPST, TSP, DAP, and an unamended control (UC). Treatments were arranged in a randomized complete block (RCB) design on a single greenhouse bench and replicated three times for a total of 15 tubs.

Tub Preparation and Management

Approximately 26.4 kg of sieved and air-dried soil was placed into 15 plastic tubs (51 cm wide by 67 cm long by 15 cm deep) (Figure 1) on the same greenhouse bench and separated into three blocks, with each block containing five tubs. The soil was moistened daily to allow the soil to settle and to allow weeds to sprout to be manually removed. In the event of crust formation due to soil drying, the crust was manually broken up prior to seeding. Additionally, wooden planks were placed underneath all 15 tubs on top of the greenhouse bench to ensure uniform soil settling and relatively uniform water distribution in each tub. Each tub in a block was randomly assigned one of five fertilizer-P treatments.

Tubs were seeded manually with a hybrid cultivar (Gemini 214, RiceTec) on 15 May, 2021 (Figure 2). Following University of Arkansas recommendations (Hardke, 2021), 30 seeds were planted per tub, 10 seeds per row in three rows parallel to the long side of each tub, which is equivalent to a seeding rate of 877,963 seeds ha^{-1}. The outer-most rice rows were 4 cm from the long side of the tub and 6 cm from the short side with 15 cm between rows. Within rows, seeds were planted to a depth of about 1.6 cm with 5 cm between each seed. The same soil used to initially fill each tub was used to fill in the small holes remaining where seeds were placed.

The first of four fertilizer applications occurred approximately 10 days after seeding (DAS), where 1 g of zinc sulfate was surface applied to the soil surface of each tub and was watered into the soil by lightly irrigating with tap water to prevent zinc deficiency to create a more ideal rice growing condition. At 16 DAS, approximately the 2-3 leaf stage, fertilizer-P treatments were applied manually to the soil surface of each respective tub. Each tub received 0.76 g of total P, which was equivalent to the recommended fertilizer-P rate of 29.4 kg P ha^{-1} based on the initial soil-test P concentration (Table 1; Hardke, 2021), from each fertilizer-P source (i.e., DAP, TSP, ECST, and CPST). The fertilizer grades ($N-P_2O_5-K_2O$) were as follows: 18-46-0 for DAP, 0-46-0 for TSP, 5-37-0 for ECST, and 6-27-0 for CPST. Due to differing N concentrations of the fertilizer-P sources used, where DAP contained the largest initial N concentration, N was balanced among the TSP, ECST, and CPST treatments with N-(n-butyl) thiophosphoric triamide (NBPT)-coated urea (fertilizer grade: 46-0-0) based on the N added in the DAP treatment. In total, each tub received 2 g N initially, either from the fertilizer-P source, urea, or a combination of both. Potassium (2.89 g K per tub as muriate potash) was added at a rate equivalent to the recommended fertilizer-K rate of 111.2 kg K ha^{-1} based on the initial soil-test K concentration and was also manually surface-applied uniformly to all tubs (Hardke, 2021). Fertilizer-P and -K were watered into the soil by lightly irrigating with tap water.

At 27 DAS, a second N application of 3.78 g N per tub, which was equivalent to 145.7 kg N ha^{-1}, as coated urea was surface-applied to each tub and watered into the soil by lightly irrigating with tap water. At 46 DAS, a second and final split application of 0.58 g N per tub, which was equivalent to a rate of 22.4 kg N ha^{-1}, was manually surface-applied to each tub and watered into the soil by lightly irrigating with tap water.

From 11 June, 2021 to 17 September, 2021 all tubs were manually watered using distilled water approximately every other day. The frequency of watering was adjusted as necessary later in the growing season as plant transpiration increased. The volumetric soil water content was measured in the top 6 cm in each tub (SM150, Dynamax, Inc., Houston, TX). Water was added to each tub to raise the volumetric soil water content to approximately 0.56 cm^3 cm^{-3} both inside and outside base collars (30-cm-diameter, polyvinyl chloride collars), which were implemented as part of a larger study seeking to quantify greenhouse gas emissions of the rice. Although the tubs did not have furrows and the tubs were not inclined in the greenhouse, similar to the recent procedures of Slayden et al. (2022), this method of irrigation is referred to as simulated furrow-irrigation because the method mimics the alternating wet and dry cycles as would occur in a furrow irrigated field.

A daily air temperature of 31°C was maintained during daylight hours through a primary heating system in the greenhouse. A secondary heating system kept the nocturnal air temperature above 22°C throughout the growing season. Insects had to be managed throughout the growing season in the greenhouse. Commercially available general insect spray (Houseplant & Garden Insect Killer, Schultz, Bridgeton, MO) was manually applied three times and adhesive insect traps were inserted into each tub to help control and prevent plant damage from fungus gnats (*Sciaridae spp*.) and white flies (*Aleyrodidae spp*.).

Biomass and Final Soil Collection, Processing, and Analyses

Biomass collection took place on 25 September, 2021, when the rice plants were at harvest maturity. Because this study was part of a larger study seeking to quantify greenhouse gas emissions (GHG) from furrow-irrigated rice, biomass samples were collected from inside 30-cm-diameter, polyvinyl chloride (PVC) collars that were manually installed to a depth of approximately 10 cm in all tubs 20 days after seeding (Figure 3). The PVC collars served as a base for PVC-collar extenders and caps that measure GHG emissions. All rice plants outside the base collars were cut at the soil surface and discarded, then all rice plants inside the base collars were cut at the soil surface and bagged for further analyses. After removing rice from outside the base collars, five to seven, 2-cm diameter soil cores were manually collected at random to the bottom of the tub from outside the base collars and combined for one soil sample per tub. Soil samples were processed and analyzed for final soil pH similar to that described above for initial soil properties.

To facilitate root biomass collection, base collars were removed from the tubs with the soil and roots still intact. The soil-root mass was manually massaged under a light stream of water to wash away the soil. Above- and belowground biomass from inside each base collar was dried for approximately seven days at 55°C and weighed to determine dry matter. Rice seeds were manually stripped from the aboveground dry matter and collected to determine grain yield per tub.

Subsamples of rice grain and above- and belowground plant tissue were mechanically ground and sieved to < 1 mm for subsequent laboratory analyses for total N, P, K, Mg, and Zn. Similar to Della Lunga et al. (2021), total C and N in plant tissue was measured by high-temperature combustion (VarioMax CN analyzer, Elementar Americas Inc., Mt. Laurel, NJ). Total P, K, Mg, Mn, and Zn concentrations were measured by inductively coupled, argon-plasma spectrometry after strong-acid digestion. Plant nutrient uptake was determined by multiplying the vegetative dry mass and measured elemental concentrations on a plot-by-plot basis. For reporting purposes, rice yield was adjusted to 12% moisture.

Statistical Analyses

Similar to Della Lunga et al. (2020a), based on the RCB design with three replications, a one-factor analysis of variance (ANOVA) was conducted using PROC GLIMMIX in SAS (version 9.4, SAS Institute, Inc., Cary, NC) to evaluate the effect of fertilizer-P source (i.e., DAP, TSP, CPST, ECST, and UC) on above- and belowground plant properties in furrow-irrigated rice. Significance was judged at $P < 0.05$. When appropriate, means were separated by least significant difference at the 0.05 level.

Results and Discussion

Belowground Dry Matter and Nutrient Concentrations and Uptake

Considering the chronological order of plant parts that could be affected by fertilizer treatments, the rice roots are the first to potentially be affected by the fertilizer-P sources and any other soil amendments added to correct soil nutrient deficiencies. Most belowground rice properties were unaffected ($P > 0.05$) by fertilizer-P source, while only belowground Zn concentration differed ($P < 0.01$) among fertilizer-P sources (Table 2). Belowground rice dry matter was unaffected ($P = 0.26$) by fertilizer-P source, which ranged from 0.76 kg m^{-2} from ECST to 1.29 kg m^{-2} from TSP and averaged 1.11 kg m^{-2} overall among all fertilizer-P sources (Table 2). The four fertilizer treatments' belowground dry matter behaved similarly to each other because they were all fertilized with the same total P rate, but the four fertilizer treatments did not differ from the UC, which was unexpected because the UC received no P. Despite the low initial soil-test-P concentration (Table 1), by the end of the growing season, the average soil pH had decreased to 7.2 across all fertilizer-P sources. The decrease in soil pH increased soil-P availability by releasing a portion of previously immobilized P that was bound to Ca and Mg (Hardke, 2021).

Belowground rice dry matter Zn concentrations differed ($P < 0.01$) among fertilizer-P sources (Table 2). Belowground Zn concentration was numerically largest from DAP, which did not differ from TSP, and was at least 1.1 times greater than from the other three fertilizer-P sources (Table 2). In addition, belowground Zn concentration from the UC was similar to ECST, and belowground Zn concentration was lowest from CPST among all fertilizer-P sources (Table 2). Although differences were small, it is unclear why Zn concentrations differed among fertilizer-P sources considering Zn was uniformly applied to all fertilizer-P sources to rectify a slight Zn deficiency. It is possible that there was a differential interaction between the added Zn and the various fertilizer-P sources to cause differences in root-Zn concentrations among the fertilizer-P sources (Table 2).

Similar to belowground rice dry matter, belowground rice tissue N, P, K, and Mg concentrations were unaffected ($P > 0.27$) by fertilizer-P source (Table 2). Belowground rice dry matter N concentration ranged from 0.67% from the UC to 0.85% from the DAP and averaged 0.77%. Similar to N concentration, belowground rice dry matter P concentration ranged from 0.08% from the UC to 0.89% from DAP and averaged 0.26% overall among all fertilizer-P sources (Table 2). Similar to N and P concentrations, belowground rice dry matter K concentration ranged from 0.04% from the UC to 0.09% from DAP and averaged 0.06% overall among all fertilizer-P sources, while belowground Mg concentration ranged from 0.13% from ECST and DAP to 0.16% from TSP and averaged 0.14% overall among all fertilizer-P sources (Table 2). Uniform N and K applications and sufficient soil Mg concentration likely explain the similar N, K, and Mg concentrations among fertilizer-P sources. Despite different chemical compositions and solubilities among fertilizer-P sources, root-P assimilation was uniform among all four P-fertilized sources and in the UC. This result indicates that the rice plant's first exposure to the fertilizer-P sources did not result in differential root-P concentrations.

Although few studies have evaluated belowground rice tissue concentrations in response to struvite-P sources, some similarities and differences to results of the current study have been reported in other studies (Ylagan et al., 2020; Omidire et al., 2022a; Omidire & Brye, 2022; Slayden et al., 2022). A greenhouse tub study evaluating the effects of fertilizer-N application timing on N_2O emissions from a hybrid rice cultivar grown under simulated furrow-irrigation in a silt loam (Typic Albaqualfs) reported belowground DM ranging from 11.6 to 13.6 Mg ha^{-1} across three fertilizer-N treatments (Slayden et al., 2022), which was similar to the belowground DM measured in the current study, 7.6 to 12.9 Mg ha^{-1} across all fertilizer-P sources (Table 2). However, Slayden et al. (2022) applied a total of 310 kg N ha^{-1}, which was 1.3 times greater than the total fertilizer-N rate applied in the current study. Similar to the current study, a 2-year field study conducted in eastern Arkansas investigating the effects of ECST, CPST, TSP, MAP, DAP, and RP in a P-deficient, silt loam (Typic Glossaqualfs) under flood-irrigated, pure-line rice cultivation reported that belowground P, N, and Mg concentrations were unaffected by fertilizer-P source (Omidire et al., 2022a). Omidire and Brye (2022) evaluated CPST and TSP in a wheat-soybean, double-crop production system on a silt loam (Aquic Fraglossudalfs) in eastern Arkansas and reported that belowground soybean-P, -N, and -Mg and wheat-P concentrations did not differ between CPST and TSP, which were similar to results of the current study. However, in contrast to results of the current study, wheat-N concentration was significantly greater from TSP than CPST, while belowground wheat-Mg concentration was significantly greater from CPST than TSP (Omidire & Brye, 2022). An aobjectivedditional greenhouse pot study that evaluated corn and soybean response to ECST, CPST, TSP, DAP, MAP, and RP in a silt loam (Typic Fragiudults) reported that belowground dry matter, and belowground N, Mg, and K concentrations did not differ among fertilizer treatments in soybeans, which also occurred in the current study (Ylagan et al., 2020). However, in contrast to the current study, belowground P in the soybeans differed among fertilizer treatments where, of the fertilizer-P sources used in both studies, TSP was numerically largest and did not differ from DAP or ECST, and the fertilized treatments were at least 1.1 times greater than either of the UC's and CPST was similar to ECST (Ylagan et al., 2020). In the corn, similar to the current study, belowground Mg concentration did not differ among fertilizer treatments, but, in contrast to the current study, Ylagan et al., (2020) reported significant belowground N, P, and K concentration differences among the same fertilizer-P sources that were used in the current study.

Similar to their elemental concentrations, belowground N, P, K, and Mg root uptakes were unaffected by fertilizer-P source ($P > 0.10$), but, contrary to expectations, Zn root uptake was also unaffected by fertilizer-P source ($P = 0.10$) despite belowground Zn concentration differing among fertilizer-P sources (Table 2). Belowground N uptake ranged from 5.80 g m^{-2} from ECST to 9.9 g m^{-2} from DAP and averaged 8.5 g m^{-2}, while P uptake ranged from 0.8 g m^{-2} from ECST to 1.4 g m^{-2} from TSP and averaged 1.1 g m^{-2} overall among all fertilizer-P sources (Table 2). Similar to belowground N uptake, belowground K uptake ranged from 0.4 g m^{-2} from ECST to 1.2 g m^{-2} from DAP and averaged 0.7 g m^{-2} overall among all fertilizer-P sources (Table 2). Similar to belowground P uptake, belowground Mg uptake ranged from 1.0 g m^{-2} from ECST to 2.0 g m^{-2} from TSP and averaged 1.6 g m^{-2} overall among all fertilizer-P sources (Table 2). Similar to belowground N and K uptake, belowground Zn uptake ranged from 64.7 mg m^{-2} from ECST to 104.3 mg m^{-2} from DAP and averaged 88.7 mg m^{-2} overall among all fertilizer-P sources (Table 2). The combination of large variability among replicates, numeric belowground dry matter differences, and differential root-Zn concentrations, but similar root-N, -P, -K, and -

Mg concentrations resulted in similar root-Zn, -N, -P, -K, and -Mg uptakes among fertilizer-P sources.

Aboveground Dry Matter and Nutrient Concentrations and Uptake

In contrast to belowground rice tissue properties and despite the initial low soil-test P (Table 1), for which an aboveground plant tissue response to fertilizer-P additions was expected, numerous aboveground rice tissue properties were affected ($P < 0.05$) by fertilizer-P source, while others were unaffected ($P > 0.05$) by fertilizer-P source (Table 3). Contrary to expectation, but similar to belowground dry matter, aboveground rice dry matter was unaffected ($P = 0.24$) by fertilizer-P source (Table 3). Aboveground rice dry matter ranged from 1.31 kg m^{-2} from ECST to 2.16 kg m^{-2} from TSP and averaged 1.70 kg m^{-2} overall among all fertilizer-P sources (Table 3). Similar to belowground dry matter, the four fertilizer treatments behaved similarly as expected, but the fertilized treatments did not differ from the UC, which, similar to belowground dry matter, was likely because of the decrease in soil pH that caused previously immobilized P to release into the soil solution and become plant available to overcome initial soil-P deficiency (Hardke, 2021). Additionally, the plants in the UC treatments likely allocated more metabolites to root development than to the aboveground tissue (Table 2 and 3). Although not significant, root and aboveground DM in the UC treatments were numerically greater and lower, respectively, than in the ECST, CPST, and DAP treatments (Table 2 and 3). The growth and branching of rice roots are driven by the soil's local nutrient concentration status, which, when the soil is nutrient deficient, activates a systematic mechanism that induces the plants to scavenge for more nutrients through additional root growth (Desnos, 2008). Furthermore, all treatments received uniform amounts of total N as recommended for optimal rice production and uniform K to overcome the initial soil-K deficiency.

In a 2-year field study in eastern Arkansas evaluating aboveground rice productivity and nutrient uptake between different tillage regimes and among different site positions in a production-scale, furrow-irrigated, hybrid rice agroecosystem on a silt loam, Della Lunga et al. (2021) reported aboveground rice dry matter ranged from 10.3 to 13.4 Mg ha^{-1} across two years from conventional tillage, which is on the low end of that measured in the current study (13.1 to 21.6 Mg ha^{-1}), but the current study received 1.5 times more fertilizer-N on a per area basis than the field study. Similar to the current study, Omidire et al. (2022a) reported that aboveground rice dry matter ranged from 11.8 to 16.1 Mg ha^{-1} across two years of rice growth in the field in a silt-loam soil in eastern Arkansas. Aboveground rice (Omidire et al., 2022a) and wheat and soybean (Omidire & Brye, 2022) dry matter were unaffected by fertilizer-P source, including TSP and CPST, which was similar to the result of the current study. Ylagan et al. (2020) also reported that aboveground soybean dry matter did not differ among fertilizer-P sources, but that aboveground corn dry matter differed among fertilizer-P sources, where corn dry matter from TSP, CPST, MAP, DAP, and RP were similar to one another and all greater than from the no-P/no-N UC.

In contrast to aboveground dry matter, aboveground rice dry matter P, K, and Zn concentrations differed ($P < 0.05$) among fertilizer-P sources (Table 3). In contrast to belowground P, aboveground P concentration was numerically largest from TSP, which did not differ from DAP, and was at least 2.5 times greater than from the other three fertilizer-P sources, which did not differ among themselves (Table 3). In addition, aboveground P concentration from the UC was similar to DAP (Table 3). It appears that, once in the plant, P translocation from below- to the aboveground tissue was affected by the chemical formulations of the various fertilizer-P sources. It is possible that, despite similar total root-P concentrations (Table 2), the plant available P species taken up by the plant and/or the resulting P species once absorbed by the root may have differed among fertilizer-P sources (Ylagan et al., 2020). It is also possible that solubility differences among fertilizer-P sources could have resulted in more plant-available P being released from fertilizer-P sources with larger solubilities (i.e., TSP or DAP), thus causing the aboveground dry matter P concentration to be greater from TSP and DAP than from struvite.

In contrast to aboveground P and belowground K, aboveground K concentration was numerically largest from the UC, which did not differ from CPST, and was at least 1.5 times greater than the other three fertilizer-P sources, which did not differ among themselves (Table 3). In addition, aboveground K concentration from ECST and DAP, which did not differ, was similar to CPST (Table 3). Similar to belowground Zn concentration, it is unclear why K concentrations differed among fertilizer-P sources considering K was uniformly added to all fertilizer-P sources. However, it is again possible that there was a differential interaction between the added K and the fertilizer-P source once in the plant to result in aboveground tissue K concentration differences among the fertilizer-P sources. It is also plausible that the rice plants in the P-deficient soil of the UC treatment may have taken up more soil K to offset the low P fertility (Table 3). Additionally, the numerically lower dry matter in the UC treatments likely masked the dilution effect on nutrient concentration, specifically for K, since the majority of the K in rice plants remains in the shoots and is not transferred to the grain, which is opposite of what happens for P and N (Roy et al., 2018).

Similar to aboveground K and belowground Zn, aboveground Zn concentration was numerically largest from the UC, which did not differ from DAP, and was at least 1.4 times greater from ECST, CPST, and TSP, which did not differ among themselves (Table 3). In addition, aboveground Zn concentration from CPST and TSP, which did not differ, were similar to DAP (Table 3). Similar to K, Zn was also uniformly added to all treatments. However, considering that root-Zn concentrations differed among fertilizer-P sources (Table 2), it stands to reason that aboveground Zn concentrations also differed among fertilizer-P sources, where, for both above- and belowground, one of the two struvite sources had at least the numerically lowest Zn concentration (Table 3). Furthermore, the rice plants in the P-deficient soil of the UC treatment may have taken up more soil Zn to help offset the low P fertility (Table 3).

Similar to aboveground rice dry matter and belowground N and Mg, aboveground N and Mg concentrations were unaffected ($P > 0.15$) by fertilizer-P source (Table 3). Aboveground rice dry matter N concentration ranged from 0.53% from CPST to 0.65% from TSP and averaged 0.57%, while aboveground rice dry matter Mg concentration ranged from 0.55% from the UC to 0.72% from ECST and averaged 0.65% overall among all fertilizer-P sources (Table 3).Since N was applied uniformly to all treatments, it stands to reason that aboveground N concentration would be unaffected by fertilizer-P source, but, in contrast to N, Mg was not initially applied to any treatments and with CPST and ECST both containing Mg, where TSP and DAP did not contain Mg, a plant response to Mg may have been expected. However, it is likely that there was ample Mg in the soil to be taken up by plants in the non-struvite treatments (Table 1). Additionally, in contrast to P, K, and Zn, it appears that, once in the plant, N and Mg translocation from the roots to the aboveground tissue are unaffected by fertilizer-P sources.

Compared to results from a production-scale, furrow-irrigated field study with a hybrid cultivar (Della Lunga et al., 2021), aboveground dry matter P and N concentrations were more than 50% less for the current study conducted in space-restrictive tubs in the greenhouse. In contrast to the current study, in a field study with alkaline soil pH, Omidire et al. (2022a) reported that aboveground rice tissue P concentration did not differ among fertilizer-P sources. The lack of a fertilizer-P-source effect on aboveground rice tissue P concentration in Omidire et al. (2022a) could potentially be explained by rice roots penetrating deeper than 10 cm to assimilate adequate P to mask differences between fertilizer-P sources. In addition, similar to the current study, Omidire et al. (2022a) also reported aboveground rice tissue N and Mg concentrations did not differ among fertilizer-P sources. In contrast to results of the current study, Omidire & Brye (2022) reported that aboveground soybean dry matter P concentration was unaffected by fertilizer-P source. Additionally, in contrast to the current study, Omidire & Brye (2022) reported that aboveground soybean dry matter Mg concentration differed among fertilizer-P source.

In contrast to above- and belowground dry matter and belowground Zn uptake, aboveground dry matter Zn uptake differed ($P = 0.03$) among fertilizer-P sources, but, similar to above- and belowground dry matter and their above- and belowground elemental concentration, aboveground dry matter N and Mg uptakes were unaffected ($P > 0.10$) by fertilizer-P source (Table 3). Aboveground Zn uptake was numerically largest from TSP, which did not differ from CPST, DAP, and the UC, and was at least 1.6 times greater from ECST, which was smallest among all fertilizer-P sources (Table 3). The combination of numeric dry matter differences and differential Zn concentrations in the aboveground dry matter caused Zn uptake to differ among fertilizer-P sources. Aboveground rice dry matter N uptake ranged from 7.1 g m^{-2} from ECST to 14.1 g m^{-2} from TSP and averaged 9.9 g m^{-2}, while aboveground rice dry matter Mg uptake ranged from 8.5 g m^{-2} from the UC to 13.8 g m^{-2} from TSP and averaged 10.8 g m^{-2} overall among all fertilizer-P sources (Table 3). Uniform N application and sufficient soil Mg concentration likely explain the similar N and Mg uptakes among fertilizer-P sources. However, contrary to expectations and in contrast to their aboveground concentrations that differed among treatments, but similar to their belowground concentrations and uptakes, aboveground dry matter P and K uptakes were unaffected ($P > 0.10$) by fertilizer-P source (Table 3). Aboveground rice dry matter P uptake ranged from 0.24 g m^{-2} from ECST to 0.90 g m^{-2} from TSP and averaged 0.47 g m^{-2}, while aboveground rice dry matter K uptake ranged from 18.6 g m^{-2} from ECST to

31.3 g m^{-2} from the UC and averaged 25.3 g m^{-2} overall among all fertilizer-P sources (Table 3). The combination of numeric dry matter differences and differential P and K concentrations in the aboveground rice tissue caused P and K uptake to differ among fertilizer-P sources.

Similar to belowground rice dry matter, few studies have evaluated aboveground rice dry matter nutrient uptake in response to struvite-P sources. However, some similarities to and differences from results of the current study have been reported in other recent field studies (Omidire et al., 2022a; Della Lunga et al., 2021). Della Lunga et al. (2021) reported that aboveground rice N uptake from conventional tillage was 77.6 kg ha^{-1} in 2018 and 74.4 kg ha^{-1} in 2019, rice P uptake was 7.9 kg ha^{-1} in 2018 and 9.7 kg ha^{-1} in 2019, and rice K uptake was 150 kg ha^{-1} in 2018 and 301 kg ha^{-1} in 2019, which were similar to the N, P, and K uptakes measured in the current study (Table 3). Additionally, similar to the current study, Omidire et al. (2022a) reported that aboveground rice N, P, and Mg uptake were also unaffected by fertilizer-P source.

Grain Yield and Nutrient Concentrations and Uptake

Similar to aboveground rice tissue properties, most rice grain properties were unaffected ($P > 0.05$) by fertilizer-P source, while only grain P and Mg concentrations differed ($P < 0.04$) among fertilizer-P sources (Table 4). A rice yield response to fertilizer-P additions was expected due to the initial low soil-test P (Table 1), however, grain yield was unaffected ($P = 0.44$) by fertilizer-P source, which ranged from 1.11 kg m^{-2} from DAP to 1.47 kg m^{-2} from TSP and averaged 0.44 kg m^{-2} overall among all fertilizer-P sources (Table 4). Similar to below- and aboveground dry matter, the four fertilizer treatments behaved similarly as expected, but grain yield from the fertilized treatments was not greater than from the UC, which, similar to below- and aboveground dry matter, was likely because of the decreased soil pH that released additional P over the course of the growing season.

In contrast to the current study, Della Lunga et al. (2021) reported mean furrow-irrigated rice grain yields from conventional tillage, averaged across up-, mid-, and down-slope field positions, in a production-scale field was 4.2 Mg ha^{-1} in 2018 and 5.8 Mg ha^{-1} in 2019, which was, on average, 2.5 times smaller than measured rice grain yields from the current study that was conducted in space-restrictive tubs and with greater fertilizer-N additions compared to the field study. Similar to the current study, Omidire et al. (2022a) reported that, in 2019, flood-irrigated rice yields from a pureline cultivar did not differ among fertilizer-P sources (i.e., TSP, DAP, ECST, CPST, and UC). However, in contrast to the current study, Omidire et al. (2022a) reported that, in 2020, yield was numerically largest from TSP, which did not differ from DAP and the UC, and was numerically smallest from ECST, which did not differ from CPST and was lower than from DAP, TSP, and the UC.

In contrast to grain yield, grain P and Mg concentrations were numerically largest from TSP and DAP, which did not differ from ECST or CPST, and were at least 1.2 times greater than the UC, which were smallest among all fertilizer-P sources (Table 4). It is unclear why Mg concentration differed between the fertilized treatments and the UC considering there was likely adequate initial soil Mg among all treatments, but it is possible that there was a differential interaction between the soil Mg and the fertilizer-P sources during plant Mg uptake.

Similar to grain yield, grain N, K, and Zn concentrations were unaffected ($P > 0.11$) by fertilizer-P source (Table 4). Grain N concentration ranged from 1.6% from the UC to 1.8% from CPST and averaged 1.7%, while grain K concentration ranged from 0.30% from CPST, DAP, and the UC to 0.33% from TSP and averaged 0.31% overall among fertilizer-P sources (Table 4). Grain Zn concentration ranged from 32.4 mg kg^{-1} from ECST to 40.5 mg kg^{-1} from TSP and averaged 35.6 mg kg^{-1} among fertilizer-P sources. Among N, K, and Zn concentrations in the grain, belowground dry matter, and aboveground dry matter, N was the only elemental concentration of the three to be unaffected by fertilizer-P source in the grain and below- and aboveground dry matter, indicating there was no differential effect of fertilizer-P source on initial N uptake by the roots, nor N translocation to the aboveground tissue or grain once in the plant. However, both K and Zn differed among fertilizer-P sources in the aboveground dry matter and Zn differed among fertilizer-P source in the belowground dry matter. Despite K and Zn differing in either the above- or belowground dry matter, fertilizer-P source did not affect the translocation of K and Zn in the aboveground tissue to the grain (Table 4).

Compared to results from a production-scale, furrow-irrigated field study with a hybrid cultivar (Della Lunga et al., 2021), grain N concentration was similar, despite the current study being conducted in space-restrictive tubs and fertilized with more nutrient inputs on a per-area basis to compensate for the limited soil volume. Contrary to the current study, Omidire et al. (2022a) reported that grain P and Mg concentrations in a flood-irrigated, pureline cultivar were unaffected by fertilizer-P source (i.e., TSP, DAP, ECST, CPST, and UC), but, similar to the current study, grain N concentration was also unaffected by fertilizer-P source. In contrast to the current study, a 2-year field study evaluating ECST, CPST, MAP, DAP, TSP, and RP in corn on a silt loam (Aquic Fraglossudalfs) in eastern Arkansas reported that kernel P and Mg concentrations were unaffected, but, similar to the current study, kernel N concentration was also unaffected by fertilizer-P source (Omidire et al., 2022b).

Similar to belowground root uptakes (Table 3) and grain concentrations, grain N, K, and Zn uptakes were unaffected ($P > 0.11$) by fertilizer-P source (Table 4). Grain N uptake ranged from 18.9 g m^{-2} from the UC to 24.6 g m^{-2} from TSP and averaged 21.3 g m^{-2} among fertilizer-P sources, while grain K uptake ranged from 3.3 g m^{-2} from DAP to 4.7 g m^{-2} from TSP and averaged 3.9 g m^{-2} among fertilizer-P sources (Table 4). Grain Zn uptake ranged from 36.6 mg m^{-2} from ECST to 57.5 mg m^{-2} and averaged 44.9 mg m^{-2} among fertilizer-P sources (Table 4).

However, contrary to expectations and in contrast to their grain concentrations that differed among treatments, grain P and Mg uptake were unaffected (*P* > 0.09) by fertilizer-P source (Table 4). Similar to grain N uptake, grain P uptake ranged from 2.4 g m^{-2} from the UC to 3.9 g m^{-2} from TSP and averaged 3.2 g m^{-2} among fertilizer-P sources (Table 4). Similar to grain N and P uptake, grain Mg uptake ranged from 1.1 g m^{-2} from the UC to 1.7 g m^{-2} from TSP and averaged 1.4 g m^{-2} among fertilizer-P sources (Table 4). The combination of numeric grain yield differences and differential P and Mg concentrations in the grain caused P and Mg uptake to differ among fertilizer-P sources.

Compared to results from a production-scale, furrow-irrigated field study with a hybrid cultivar (Della Lunga et al., 2021), grain N uptake was approximately two times greater for the current study, which was conducted in space-restrictive tubs and was fertilized with more nutrient inputs on a per-area basis to compensate for the limited soil volume. Similar to the current study, Omidire et al. (2022a) reported that P and Mg uptakes in a flood-irrigated, pureline cultivar in the field were unaffected, but, in contrast to the current study, N uptake differed by fertilizer-P source (i.e., TSP, DAP, ECST, CPST, and UC). However, in contrast to the current study, Omidire et al. (2022b) reported that corn-kernel tissue P uptake was numerically largest from ECST and was numerically smallest from DAP, which did not differ from CPST, TSP, or the UC. However, in contrast to the current study, Omidire et al. (2022b) also reported that corn-kernel tissue Mg uptake was numerically largest from ECST, which did not differ from the UC, and was numerically smallest from DAP, which did not differ CPST, TSP, or the UC.

Total Aboveground Dry Matter and Nutrient Uptake

As the sum of the aboveground dry matter and grain yield, and similar to grain yield by itself, total aboveground dry matter and N, K, and Mg uptakes were unaffected (*P* > 0.05) by fertilizer-P source, while total aboveground dry matter P and Zn uptakes differed ($P < 0.04$) among fertilizer-P sources (Table 5). A total aboveground dry matter response to fertilizer-P additions was expected due to the initial low soil-test P (Table 1), but total aboveground dry matter did not differ ($P = 0.18$) among fertilizer-P source, which ranged from 2.44 kg m^{-2} from ECST to 3.63 kg m^{-2} from TSP and averaged 2.96 kg m^{-2} overall among all fertilizer-P sources (Table 5).

In contrast to total aboveground dry matter, total aboveground P uptake was numerically largest from TSP, which did not differ from DAP or CPST, and was at least 1.1 times greater than from ECST and the UC, which did not differ among themselves (Table 5). In addition, total aboveground P uptake from ECST was similar to from CPST and DAP (Table 5). Similar to total aboveground P uptake with a significant fertilizer-P effect, total aboveground Zn uptake was numerically largest from TSP, which did not differ from DAP, CPST, or the UC, all of which were at least 1.5 times greater than ECST, which was smallest among all fertilizer-P sources (Table 5).

Similar to total aboveground dry matter, total aboveground N, K, and Mg uptakes were unaffected ($P > 0.09$) by fertilizer-P source (Table 5). Total aboveground N uptake ranged from 27.4 g m^{-2} from ECST to 38.7 g m^{-2} from TSP and averaged 31.2 g m^{-2} (Table 5). Similar to total aboveground N uptake, total aboveground K uptake ranged from 22.0 g m^{-2} from ECST to 35.4 g m^{-2} from CPST and averaged 27.5 g m^{-2} overall among fertilizer-P sources, while total Mg uptake ranged from 9.6 g m^{-2} from the UC to 15.5 g m^{-2} from TSP and averaged 12.2 g m^{-2} among fertilizer-P sources (Table 5).

Total Plant Dry Matter and Nutrient Uptake

As the sum of the belowground and aboveground dry matter and grain yield, and similar to total aboveground dry matter, total plant dry matter and N, P, K, and Mg uptakes were unaffected ($P > 0.05$) by fertilizer-P source, while only total plant Zn uptake differed ($P < 0.03$) among fertilizer-P sources (Table 5). Contrary to expectation, total plant dry matter did not differ ($P = 0.21$) among fertilizer-P source, which ranged from 3.21 kg m^{-2} from ECST to 4.92 kg m^{-2} from TSP and averaged 4.08 kg m^{-2} overall among all fertilizer-P sources (Table 5). In contrast to total plant dry matter, total plant Zn uptake was numerically largest from TSP, which did not differ from CPST, DAP, and the UC (Table 5). Total plant Zn uptake from TSP, DAP, and the UC was at least 1.5 times greater than from ECST, which was numerically smallest among all fertilizer-P sources, but was also similar to that from CPST (Table 5).

Similar to total plant dry matter, total plant N, K, and Mg uptakes did not differ ($P > 0.12$) among fertilizer-P source (Table 5). Total plant N uptake ranged from 33.2 g m^{-2} from ECST to 48.1 g m^{-2} from TSP and averaged 39.8 g m^{-2} (Table 5). Similar to total aboveground K uptake, total plant K uptake ranged from 22.4 g m^{-2} from ECST to 36.1 g m^{-2} from CPST and averaged 29.9 g m^{-2} overall among fertilizer-P sources, while total Mg uptake ranged from 11.4 g m^{-2} from the UC to 17.6 g m^{-2} from TSP and averaged 13.9 g m^{-2} among fertilizer-P sources (Table 5). However, contrary to expectations and in contrast to total aboveground dry matter P uptake which differed among treatments, total plant P uptake did not differ ($P > 0.07$) among fertilizer-P source, which ranged from 3.8 g m^{-2} from the UC to 6.2 g m^{-2} from TSP and averaged 4.8 g m^{-2} among fertilizer-P sources (Table 5).

Implications

Recovering P from agricultural and/or municipal wastewaters to produce struvite could potentially remediate ecosystems affected by eutrophication from excess P and/or N by decreasing the amount of P and/or N released into the environment from agricultural runoff and/or WWTP effluent. Additionally, struvite has the potential to decrease global agriculture's dependence on unsustainable sources of RP-derived fertilizer with a more sustainable fertilizer-P source. However, being only in the crystalline form thus far as an experimental material, ECST would need to be pelletized, like CPST, to make ECST compatible with current fertilizer-spreading technology for wide-spread use in production agriculture. Moreover, because struvite is a relatively new fertilizer-P source, producing, distributing, and applying struvite in a manner that is economically viable and sufficient for global use will be necessary critical advancements prior to viable, large-scale use.

Conclusions

This study evaluated the effects of two struvite materials, ECST and CPST, on below- and aboveground plant response of a hybrid rice cultivar grown in the greenhouse in a P-deficient, silt-loam soil under simulated furrow-irrigation compared to other common fertilizer-P sources. As hypothesized, both ECST and CPST treatments produced similar rice responses for every measured plant property, except for aboveground Zn uptake and belowground and grain Zn concentration. Furthermore, for numerous rice properties, both ECST and CPST treatments produced at least a numerically greater rice response than a commonly used, commercially available fertilizer-P source. Based on the results of this greenhouse study, it can be concluded that struvite, namely ECST, is a viable fertilizer-P source that could be used as an alternative to RP-derived fertilizers for simulated furrow-irrigated rice production in a P-deficient, silt-loam soil.

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Table 1. Summary of initial physical and chemical property means (n = 5) and standard errors (SE) for the soil used in the greenhouse experiment.

Soil Property	**Mean (± SE)**
Sand ($g\ g^{-1}$)	0.09 (< 0.01)
Silt ($g\ g^{-1}$)	0.79 (< 0.01)
Clay ($g\ g^{-1}$)	0.12 (< 0.01)
Electrical conductivity ($dS\ m^{-1}$)	0.167 (< 0.01)
pH	7.5 (0.01)
Extractable soil nutrients ($mg\ kg^{-1}$)	
P	11.4 (0.1)
K	46.1 (0.9)
Ca	2005 (4.2)
Mg	276.3 (2.3)
S	11.9 (0.4)
Na	29.8 (0.6)
Mn	244.3 (5.1)
Fe	303.8 (7.8)
Cu	1.6 (< 0.1)
Zn	2.5 (0.1)
Soil organic matter ($g\ kg^{-1}$)	25.7 (0.2)
Total C ($g\ kg^{-1}$)	11.4 (0.2)
Total N ($g\ kg^{-1}$)	1.1 (< 0.1)
C:N ratio	10.0 (0.1)

Table 2. Analysis of variance summary of the effect of fertilizer-phosphorus treatment [i.e., electrochemically precipitated struvite (ECST), chemically precipitated struvite (CPST), diammonium phosphate (DAP), triple superphosphate (TSP), and unamended control (UC)] on below ground dry matter and belowground dry matter elemental concentrations and uptake for rice grown in the greenhouse under simulated furrow-irrigated conditions.

Plant Property	***P*-value**	**ECST**	**CPST**	**DAP**	**TSP**	**UC**	**Overall Mean**
Root DM (kg m^{-2})	0.26	0.76 a	1.11 a	1.13 a	1.29 a	1.24 a	1.11
Root concentration							
N (%)	0.61	0.79 a	0.80 a	0.85 a	0.72 a	0.67 a	0.77
P (%)	0.27	0.11 a	0.11 a	0.89 a	0.11 a	0.08 a	0.26
K (%)	0.29	0.05 a	0.05 a	0.09 a	0.08 a	0.04 a	0.06
Mg (%)	0.45	0.13 a	0.15 a	0.13 a	0.16 a	0.14 a	0.14
Zn (mg kg^{-1})	< 0.01	82.3 bc	60.4 d	94.0 a	92.5 ab	72.5 c	80.3
Root uptake							
N (g m^{-2})	0.45	5.80 a	8.87 a	9.91 a	9.32 a	8.48 a	8.48
P (g m^{-2})	0.61	0.83 a	1.24 a	0.99 a	1.43 a	1.06 a	1.11
K (g m^{-2})	0.21	0.38 a	0.57 a	1.19 a	0.99 a	0.58 a	0.74
Mg (g m^{-2})	0.38	1.03 a	1.71 a	1.53 a	2.00 a	1.76 a	1.61
Zn (mg m^{-2})	0.10	64.7 a	66.7 a	104.3 a	118.1 a	89.6 a	88.7

Table 3. Analysis of variance summary of the effect of fertilizer-phosphorus treatment [i.e., electrochemically precipitated struvite (ECST), chemically precipitated struvite (CPST), diammonium phosphate (DAP), triple superphosphate (TSP), and unamended control (UC)] on aboveground dry matter and aboveground dry matter elemental concentrations and uptake for rice grown in the greenhouse under simulated furrow-irrigated conditions.

Plant Property	*P*-value	ECST	CPST	DAP	TSP	UC	Overall Mean
Dry matter (kg m^{-2})	0.24	1.31 a	1.90 a	1.57 a	2.16 a	1.54 a	1.70
Dry matter concentration							
N (%)	0.38	0.54 a	0.53 a	0.60 a	0.65 a	0.55 a	0.57
P (%)	0.03	0.02 c	0.02 c	0.04 ab	0.05 a	0.02 bc	-
K (%)	0.02	1.42 bc	1.66 ab	1.31 bc	1.19 c	2.07 a	-
Mg (%)	0.15	0.72 a	0.65 a	0.68 a	0.64 a	0.55 a	0.65
Zn (mg kg^{-1})	0.01	63.0 c	73.6 bc	85.0 ab	75.3 bc	103.9 a	-
Dry matter uptake							
N (g m^{-2})	0.24	7.08 a	10.02 a	9.68 a	14.06 a	8.58 a	9.88
P (g m^{-2})	0.10	0.24 a	0.34 a	0.58 a	0.90 a	0.27 a	0.47
K (g m^{-2})	0.10	18.6 a	31.1 a	19.8 a	25.6 a	31.3 a	25.3
Mg (g m^{-2})	0.10	9.25 a	11.95 a	10.59 a	13.83 a	8.53 a	10.8
Zn (mg m^{-2})	0.03	81.9 b	136.1 a	133.2 a	163.3 a	156.7 a	-

Table 4. Analysis of variance summary of the effect of fertilizer-phosphorus treatment [i.e., electrochemically precipitated struvite (ECST), chemically precipitated struvite (CPST), diammonium phosphate (DAP), triple superphosphate (TSP), and unamended control (UC)] on grain yield and grain elemental concentrations and uptake for rice grown in the greenhouse under simulated furrow-irrigated conditions.

Plant Property	*P*-value	ECST	CPST	DAP	TSP	UC	Overall Mean
Grain yield (kg m^{-2})	0.44	1.13 a	1.42 a	1.11 a	1.47 a	1.19 a	0.44
Grain concentration							
N (%)	0.36	1.82 a	1.63 a	1.75 a	1.68 a	1.59 a	1.69
P (%)	0.02	0.26 a	0.26 a	0.27 a	0.27 a	0.20 b	-
K (%)	0.42	0.31 a	0.30 a	0.30 a	0.33 a	0.30 a	0.31
Mg (%)	0.04	0.11 a	0.11 a	0.12 a	0.12 a	0.09 b	-
Zn (mg kg^{-1})	0.11	32.4 a	34.2 a	36.5 a	40.5 a	34.7 a	35.6
Grain uptake							
N (g m^{-2})	0.54	20.3 a	23.1 a	19.5 a	24.6 a	18.9 a	21.3
P (g m^{-2})	0.10	2.98 a	3.72 a	3.05 a	3.87 a	2.39 a	3.20
K (g m^{-2})	0.19	3.51 a	4.32 a	3.32 a	4.70 a	3.60 a	3.89
Mg (g m^{-2})	0.09	1.30 a	1.59 a	1.36 a	1.72 a	1.08 a	1.41
Zn (mg m^{-2})	0.11	36.6 a	48.8 a	40.5 a	57.5 a	41.0 a	44.9

Table 5. Analysis of variance summary of the effect of fertilizer-phosphorus treatment [i.e., electrochemically precipitated struvite (ECST), chemically precipitated struvite (CPST), diammonium phosphate (DAP), triple superphosphate (TSP), and unamended control (UC)] on total aboveground and total plant nutrient uptake and total aboveground and total plant nutrient elemental concentrations and uptake for rice grown in the greenhouse under simulated furrow-irrigated conditions.

Plant Property	***P*-value**	**ECST**	**CPST**	**DAP**	**TSP**	**UC**	**Overall Mean**
Total aboveground dry matter (kg m^{-2})	0.18	2.44 a	3.33 a	2.69 a	3.63 a	2.73 a	2.96
Total aboveground dry matter uptake							
N (g m^{-2})	0.26	27.4 a	33.2 a	29.3 a	38.7 a	27.6 a	31.2
P (g m^{-2})	0.02	3.23 bc	4.08 ab	3.68 ab	4.78 a	2.68 c	-
K (g m^{-2})	0.11	22.0 a	35.4 a	23.2 a	22.0 a	34.9 a	27.5
Mg (g m^{-2})	0.09	10.5 a	13.5 a	12.0 a	15.5 a	9.6 a	12.2
Zn (mg m^{-2})	0.04	118.6 b	184.9 a	173.8 a	220.9 a	197.7 a	-
Total plant dry matter (kg m^{-2})	0.21	3.21 a	4.45 a	3.83 a	4.92 a	3.97 a	4.08
Total plant dry matter uptake							
N (g m^{-2})	0.32	33.2 a	42.1 a	39.4 a	48.1 a	36.2 a	39.8
P (g m^{-2})	0.07	4.07 a	5.33 a	4.67 a	6.22 a	3.79 a	4.82
K (g m^{-2})	0.12	22.4 a	36.1 a	24.3 a	31.3 a	35.5 a	29.9
Mg (g m^{-2})	0.12	11.6 a	15.3 a	13.5 a	17.6 a	11.4 a	13.9
Zn (mg m^{-2})	0.03	183.7 b	251.7 ab	278.2 a	339.2 a	287.9 a	-

Figure 1. Sieved soil in tubs arranged in a randomized complete block design on A single greenhouse bench prior to seeding. Picture was taken on 4 May, 2021.

Figure 2. Tub of soil immediately after seeding. Holes where rice seeds were placed are visible. Picture was taken on 15 May, 2021.

Figure 3. Polyvinyl chloride base collars, which were manually installed 20 days after seeding the rice to a depth of approximately 10 cm in all tubs, that were used for the trace gas emissions measurements as part of the broader study encompassing the current study. Picture was taken on 7 July, 2021.