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Corn and Soybean Growth as Affected by Wastewater-Derived Struvite-Phosphorus Sources and Irrigation Water Types

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Abstract

Struvite ($MgNH_4PO_4 \cdot 6H_2O$) produced synthetically from a stock solution of known phosphorus (P) and nitrogen (N) concentrations has been shown to be an effective, alternative fertilizer-P source for various crops, but little is known about the potential agronomic effectiveness of struvite created from an actual municipal wastewater source. The objective of this study was to evaluate the effects of soil [*i.e.*, Creldon silt loam (Oxyaquic Fragiudalf) and Calloway silt loam (Aquic Fraglossudalf) series], fertilizer-P source [*i.e.*, synthetically produced electrochemically precipitated struvite (ECSTsyn), real-wastewater-derived ECST (ECSTreal), chemically precipitated struvite (CPST), monoammonium phosphate (MAP), and an unamended control (UC)], and irrigation water type (*i.e.*, tapwater and struvite-removed wastewater) on corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] growth and N, P, and magnesium (Mg) uptake in a 60-day, greenhouse potted-plant study. Crop growth and N, P, and Mg uptakes for the struvite treatments (*i.e.*, CPST, ECSTsyn, and ECSTreal) were generally similar to or at least 1.2 times greater than MAP. The ECSTsyn material commonly had up to five times greater N, P, and Mg uptake in corn and soybean than any other fertilizer-P source. Struvite-removed wastewater resulted in at least 1.3 times lower dry matter and N, P, and Mg uptake than tapwater. Similar corn and soybean results from the struvite fertilizers among the various soil-water type combinations compared to MAP suggest that struvite generates similar crop responses as at least one widely used, commercially available, multi-nutrient fertilizer-P source.

Keywords

Arkansas, Corn Production, Soybean Production, Struvite, Recovered Nutrients

1. Introduction

With the current rate of human population growth, the demand for food and fertilizers will increase at a proportional rate. Crop yield demands are expected to increase annually by approximately 2.5% [1] [2]. Consequently, a larger input of phosphorus (P), an essential macronutrient, will be needed in order to grow more crops to feed the growing human population. From 2020 to 2021, the demand for P fertilizer increased by 7% [3]. However, demand for all fertilizers is expected to increase at an annual rate of only 0.9% [3], which means the raw materials to make fertilizers will increase as well.

The majority of P fertilizers are derived from mined rock phosphate (RP). Phosphorus demand is expected to outpace supply by 2040 [2] [4]. Depending on demand, economic viability, and P concentrations within the current reserves, RP reserves are likely to be depleted in the next 30 to 150 years [2] [4].

As a result of the need to produce enough food to sustain an increasing human population, there will be a concomitant increase in the production of human and animal wastes, which will further disrupt the current P cycle and balance among major P pools. Agricultural runoff and animal waste make up the majority of P discharge to surface water bodies, but approximately 15% is also due to human waste [5]. Ninety-eight percent of the N and P in the human diet is lost through waste [6], thus human waste has a large P and N concentration. Every year, 300 million Mg of human waste are produced globally, but less than a third of that quantity is reused [7]. Human waste accounts for approximately 22% of the global P economy by weight [7].

Struvite ($MgNH_4PO_4 \cdot 6H_2O$) is a white, crystalline substance, containing a 1:1:1 equimolar ratio of magnesium (Mg^{2+}), ammonium (NH_4^+), and phosphate (PO_4^{3-}), that is somewhat soluble in neutral and alkaline conditions, but more readily soluble in acidic conditions [8]. The solubility of struvite in water is generally low, around 1% to 5%, but research shows that the low solubility of struvite does not decrease its effectiveness as a fertilizer-P source for plants [9]. Consequently, struvite has been characterized as a slow-release fertilizer due to struvite's reported low solubility, although more recent research shows that struvite in powder form has a similar dissolution rate in soil as monoammonium phosphate (MAP) [10]. Struvite's reported slow-release properties may benefit crops, as the P will become available to crops over time, in a controlled-release manner [11]. Although struvite has been shown to be an effective, potential fertilizer-P source, the nutrient content of struvite varies depending on what source material was used and how the struvite was actually created.

Struvite crystallization can occur in two ways. For one method, compounds such as magnesium chloride ($MgCl_2$) or magnesium oxide (MgO) allow for struvite crystallization once the solution becomes supersaturated with Mg^{2+}, NH_4^+, and PO_4^{3-} [12]. The process of adding chemicals to an aqueous solution to precipitate struvite out of solution is known as chemical precipitation. Historically, chemical precipitation of struvite was the main method used for struvite formation. Today, there is a commercially available, chemically precipitated struvite (CPST) fertilizer material known as Crystal Green, which is produced by Ostara Nutrient Technologies, Inc. (Vancouver, British Columbia). The Crystal Green product is a slow-release fertilizer in pellet form with a fertilizer grade of 5-28-0 and 10% Mg and has low heavy metal and salt concentrations [13].

For a second method of struvite crystallization, electrochemical precipitation of struvite is achieved by electrochemically releasing Mg via a sacrificial Mg anode plate [14]. The creation of electrochemically precipitated struvite (ECST) avoids the chemical dosing that chemical struvite precipitation requires, while only an energy input for Mg dissolution is required. Kékedy-Nagy *et al.* [15] used electrochemical precipitation to more efficiently recover P from synthetic wastewater compared to chemical precipitation. Overall, electrochemical precipitation of struvite has the potential to be more energy efficient and more effective than other P-recovery methods [15]. Furthermore, with nutrient recoveries less than 100%, struvite production will result in potentially plant-available nutrients remaining in solution, which could serve as an additional nutrient source if struvite-removed water is collected and used for plant irrigation. However, plant response to fertilizer made from municipal-wastewater-recovered nutrients needs to be evaluated, particularly considering municipal wastewaters often contain a diverse array of other constituents, ones that may potentially be toxic, such as heavy metals, and pathogenic organisms [12]. In addition, the resulting pH of the fertilizer material may be initially undesirable or may render other soil nutrients less available upon dissolution.

Plant response to struvite often depends on soil pH. In many different studies [9] [16] [17] [18] [19] [20], across a variety of upland row crops, little to no difference was reported in crop response between plants fertilized with commercially available fertilizers and plants fertilized with struvite. In contrast, Robles-Aguilar *et al.* [21] grew corn (*Zea mays*) in an acidic soil to compare crop response between triple superphosphate (TSP) and struvite, where the corn treated with struvite had a larger average biomass than corn treated with TSP. Hertzberger *et al.* [22] conducted a meta-analysis and review of struvite as a potential fertilizer and reported that struvite-fertilized crops generally resulted in larger biomass, tissue-P concentration, and P uptake than plants fertilized with ammonium phosphates or superphosphates, especially in soils with pH < 6. In many studies, crop response to struvite increased as soil pH decreased, and struvite was recorded to be just as effective as commercially available fertilizers in soils with a neutral or alkaline pH [22]. For N specifically, plant-N uptake mostly depends on the soil-N concentration and availability, which can increase incrementally early in the growing season as struvite dissolves in a slow-release manner to match the timing of early season plant-N need.

The exponential population growth and the rapidly declining RP reserves will push the development and application of new and/or alternative fertilizer-P sources. Recovering nutrients in wastewater in the form of struvite may be one possible alternative. However, to date, plant response to wastewater-derived struvite has been greatly understudied. Therefore, the objective of this study was to evaluate the effects of soil [*i.e.*, Creldon (Oxyaquic Fragiudalf) and Calloway (Aquic Fraglossudalf)], irrigation water type (*i.e.*, tapwater and struvite-removed wastewater), and fertilizer-P source [*i.e.*, synthetically produced ECST (ECSTsyn), real-wastewater-derived ECST (ECSTreal), CPST, MAP, and an unamended control (UC)] on corn and soybean (*Glycine max*) growth and tissue nutrient uptake in a 60-day greenhouse potted-plant experiment. It was hypothesized that 1) corn and soybean dry matter and tissue nutrient uptakes in the struvite treatments (*i.e.*, CPST, ECSTsyn, and ECSTreal) will be similar to or greater than that for MAP, 2) corn and soybean properties will be unaffected by irrigation water type, and 3) greater crop growth and nutrient properties will occur for ECSTreal and ECSTsyn in the lower-pH soil (*i.e.*, Creldon) compared to the other fertilizer-P sources.

This study was conducted in the greenhouse for several reasons. As a current experimental material, both wastewater-derived struvite and struvite-removed wastewater have only been produced in small quantities; thus, only applicable for small-scale study, such as in small pots in the greenhouse. A greenhouse setting offers the opportunity to control environmental conditions, namely air temperature, humidity, and moisture, which can vary widely and be unpredictable under field conditions. Furthermore, results of controlled-environment experiments can guide experimental designs and expected results for field-scale studies. Greenhouse study was necessary for proof of concept that ECSTreal had potential to impact even early season crop growth before moving to more involved field-scale studies.

2. Materials and Methods

A corn and soybean potted-plant study was conducted during Summer 2022 in the greenhouse in Fayetteville, Arkansas (AR). Similar procedures to Ylagan *et al.* [23] were used, who recently, successfully evaluated corn and soybean response to various fertilizer-P-sources, including ECSTsyn and CPST, but excluding ECSTreal, in a potted-plant study in the greenhouse.

2.1. Soil Collection, Processing, and Analyses

Soil was collected from agriculturally relevant areas of southwestern Missouri and eastern Arkansas for use in the greenhouse potted-plant studies. Bulk soil was collected from a 0- to 15-cm depth at both locations. A known low-soil-test-P Calloway silt loam (fine-silty, mixed, active, thermic Aquic Fraglossudalfs) [24] was collected in early spring 2021 from within an approximate 3-m^2 area from the edge of a row-crop-cultivated field at the University of Arkansas, Division of Agriculture's Pine Tree Research Station near Colt, AR (35˚07'23"N; 90˚55'46"W). A Creldon silt loam (fine, mixed, active, mesic Oxyaquic Fragiudalfs) [25] was collected from managed pasturelands at the University of Missouri's Southwest

Research Center near Mount Vernon, MO (37˚04'45"N; 93˚53'13"W) in June 2021. Both soils represent typical agricultural areas in the mid-southern US with a low soil-test P concentration [*i.e.*, <18 mg Mehlich-3 (M3)-extractable P kg^{-1}] in the upper 15 cm that would typically receive a fertilizer-P rate recommendation to maximize crop yield. Furthermore, both soils have recently been studied for their soil response to various fertilizer-P sources [26] [27].

Two soils were moist-sieved to <6 mm and air-dried in a greenhouse at ~21˚C for ~10 days. Five sub-samples of each initial soil were collected, oven-dried, crushed, and sieved to <2 mm and extracted with M3 extraction solution in a 1:10 soil mass:extraction volume ratio [28] and analyzed for extractable soil nutrients (*i.e.*, P, K, Ca, Mg, Na, S, Fe, Mn, Zn, and Cu) by inductively coupled, argon-plasma, optical emissions spectrometry (ICAP-OES) [29] [30]. Soil pH and electrical conductivity (EC) were determined with an electrode on a 1:2 (mass/volume) soil-to-water paste. Soil organic matter (SOM) concentration was determined gravimetrically through weight-loss-on-ignition after 2 hours of combustion at 360˚C in a muffle furnace [31]. Total soil N and C were determined by high-temperature combustion with an Elementar VarioMAX CN analyzer (Elementar Americas, Inc.). Soil particle-size analyses were conducted using a modified 12-hour hydrometer method [32]. **Table 1** summarizes all measured initial soil physical and chemical properties and their differences.

2.2. Fertilizer Treatments

Corn and soybean were treated with MAP, CPST, ECSTsyn, ECSTreal, and a UC as the fertilizer-P sources. Chemical analyses for ECSTsyn, CPST, and MAP were conducted by and reported in Anderson *et al.* [33], and similar procedures in Anderson *et al.* [33] were used to chemically analyze the ECSTreal fertilizer material. Due to ECSTsyn and ECSTreal being electrochemically precipitated, both ECST fertilizers were in powder/crystalline flake form, while CPST and MAP were in pellet form. For the purposes of chemical comparison, CPST and MAP were finely ground to match the powder consistency of ECSTsyn and ECSTreal. Total-recoverable P and Mg concentrations were determined after nitric-acid digestion and heating [34] and analysis by ICAP-OES [29]. High-temperature combustion (Elementar VarioMax CN Analyzer) was used to measure the total N concentration of the fertilizer materials.

Monoammonium phosphate [fertilizer grade (%N-%P_2O_5-%K_2O): 11-52-0] is a pelletized, commonly used, commercially available P and N fertilizer that contains measured nutrient concentrations of 20.9% P, 11% N, and 1.5% Mg [35]. The CPST material is pelletized and has measured nutrient concentrations of 11.7% P, 6% N, and 8.3% Mg [36]. A synthetic wastewater source, produced to have a similar average P and N concentration as typical municipal wastewater [15], was used to precipitate ECSTsyn (18.5% P, 3.3% N, and 13.3% Mg) [33]. An actual municipal wastewater source collected from the West Side Wastewater Treatment Facility in Fayetteville, AR was used to electrochemically precipitate

Table 1. Summary of soil physical and chemical property differences between the Calloway and Creldon soil series used in the greenhouse potted-plant study.

Soil property	*P*	Calloway	Creldon
Sand ($g \cdot g^{-1}$)	<0.01	0.09b†	0.24a
Silt ($g \cdot g^{-1}$)	<0.01	0.79a	0.67b
Clay ($g \cdot g^{-1}$)	<0.01	0.12a	0.09b
pH	<0.01	7.46a	6.03b
Electrical conductivity ($dS \cdot m^{-1}$)	<0.01	0.17a	0.13b
Total C (%)	<0.01	1.14b	1.65a
Total N (%)	<0.01	0.11b	0.1a
Soil organic matter (%)	<0.01	2.6b	3.4a
Mehlich-3-extractable ($mg \cdot kg^{-1}$)			
P	<0.01	11.4b	17.0a
K	<0.01	46.1b	113a
Ca	<0.01	2006a	1115b
Mg	<0.01	276b	328a
S	0.15	12.0a	13.0a
Na	<0.01	29.8a	10.4b
Fe	<0.01	304a	112b
Mn	<0.01	244a	101b
Zn	<0.01	2.6b	4.2a
Cu	<0.01	1.6a	1.2b

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

the ECSTreal material (15.4% P, 3.3% N, and 13.6% Mg). Both ECSTsyn and ECSTreal were precipitated electrochemically by sacrificing a Mg anode plate [15].

2.3. Greenhouse Experiment Preparation and Management

A consistent mass of air-dried, sieved soil (1500 g) for both soils was added to large plastic bags, to which the appropriate amounts of ECSTreal, ECSTsyn, CPST, or MAP were added to result in the single, desired fertilizer-P application rate. The fertilizer application rate for corn was based on the mean M3-soil-test-P concentration of the initial soil and a corn yield goal of 12.5 Mg ha^{-1} [37], while, for soybean, fertilizer rates were based on the initial M3-soil-test P and soybean growth in a silt-loam soil [38]. The resulting fertilizer rates were 100.9 kg P_2O_5 ha^{-1}, 235.4 kg N ha^{-1}, and 168.1 kg K_2O ha^{-1} for corn grown in the Calloway soil; 100.9 kg P_2O_5 ha^{-1}, 235.4 kg N ha^{-1}, and 100.9 kg K_2O ha^{-1} for corn grown in the Creldon soil; 89.7 kg P_2O_5 ha^{-1}, 0 kg N ha^{-1}, and 179.3 kg K_2O ha^{-1} for soybeans grown in the Calloway soil; and 67.3 kg P_2O_5 ha^{-1}, 0 kg N ha^{-1}, and 67.3 kg K_2O

ha^{-1} for soybeans grown in the Creldon soil.

Six replications of each soil-fertilizer treatment combination for each crop were prepared, including six replications per crop of a UC treatment that received no fertilizer-P addition, but received N and K as recommended. Based on the differential N concentrations of the various fertilizer materials, uncoated urea (46% N) was used to balance the N additions at the time the soil-fertilizer mixtures were prepared. Similarly, muriate of potash (60% K_2O) was added to all soil-fertilizer combinations. The soil and fertilizer materials were manually mixed to simulate incorporation by tillage. The soil-fertilizer mixtures were added to small plastic pots (14.6 cm in diameter and 17.8 cm tall) with glass fiber filter paper placed at the bottom of each pot to prevent soil-fertilizer loss. Pots were arranged separately by crop in a randomized complete block design (RCB), with three blocks (*i.e.*, replications) that contained all treatment combinations, where each crop's pots were on separate, but adjacent greenhouse benches.

The surface of the oven-dry soil in the pots was moistened with a nominal amount of tapwater, then three seeds of each crop were initially seeded in a triangular arrangement in each pot on 21 May 2022 to a depth of 1 cm. After germination, emergence, and approximately one week of growth, the pots were thinned to only one plant per pot. Both corn and soybean plants were grown for 60 days from the date of planting, at which time the greenhouse study was terminated, the pots were disassembled, and plant samples were collected. Climate conditions in the greenhouse were maintained at a daily air temperature of ~31˚C and nocturnal air temperature of ~27˚C for the duration for the 60-day study. Only natural sunlight was used.

Three of the six replicates of soil in the pots were watered individually, exclusively with regular tapwater from the greenhouse facility approximately four times per week. The other three replicates were watered individually once a week with struvite-removed wastewater and with tapwater approximately three times per week due to the limited volume of struvite-removed wastewater available to use. The struvite-removed wastewater was prepared during Summer 2021 by electrochemically precipitating and removing struvite from a local wastewater source from a municipal wastewater treatment plant in Fayetteville, AR. The struvite-removed wastewater and tapwater were chemically characterized approximately mid-way through the 60-day plant growth period.

Similar to recent studies [23] [39] [40], multiple regression relationships [41], as part of the Soil Water Characteristics subroutine of the Soil-Plant-Atmosphere-Water (SPAW) model (version 6.02.75) [42], were used to estimate field moisture capacity for each soil using measured sand, clay, and SOM concentrations. Pots were watered approximately four times per week, where, each time, pots were watered to the estimated field moisture capacity, 35.2% (v/v) for the Calloway soil and 24.7% (v/v) for the Creldon soil. Watering was monitored using a calibrated volumetric soil moisture probe (SM-150, Dynamax, Inc., Houston, TX).

2.4. Water Sample Processing and Analyses

Two water types were used to irrigate plants. Tapwater was obtained from a spigot in the greenhouse in which the potted-plant studies were conducted. Tapwater was used out of convenience, but tapwater represents a common irrigation water source used for greenhouse plant-response studies. The second water type was struvite-removed wastewater produced in July 2021 as a result of the precipitation of the ECSTreal material described above. The purpose of using the wastewater was to evaluate its effectiveness as a potential irrigation-water type after struvite removal. The struvite-removed wastewater was refrigerated at 4˚C between production and until use, which did not occur until ~10 months later, thus necessitating cold storage to minimize potential chemical transformations. Replicate water sub-samples were collected for chemical characterization once during the 60-day experimental period and were analyzed for total soluble elemental concentrations (*i.e.*, P, K, Ca, Mg, S, Na, Fe, Mn, Zn, and Cu) using ICP-OES [30]. **Table 2** summarizes measured water properties and their differences.

2.5. Plant Sampling, Processing and Analyses

After the 60-day growth period, approximately reproductive stage 2 for soybeans and vegetative stage 12 for corn, plants were cut at the soil surface to separate the aboveground (AG) and belowground (BG) plant biomass. Roots were manually removed from the soil by washing and sieving through a 2-mm mesh screen using tapwater. All roots were washed in a similar manner and to a similar degree for consistency. A soil dispersant was not used to avoid potential effects on resulting root tissue chemical properties, thus any potential remaining soil adhered to the root samples was considered uniform across all samples after thorough cleaning.

Table 2. Summary of the nutrient concentration ($mg \cdot L^{-1}$) differences between the tapwater and struvite-removed wastewater sources used in the greenhouse potted-plant study.

Water property	***P***	Tapwater	Wastewater
P	<0.01	<0.01b†	10.6a
K	<0.01	1.25b	23.3a
Ca	0.51	24.4a	28.2a
Mg	<0.01	1.86b	45.6a
S	<0.01	7.52b	13.2a
Na	<0.01	5.85b	39.6a
Fe	<0.01	0.04b	0.28a
Mn	<0.01	<0.01b	0.16a
Zn	<0.01	<0.01b	0.02a
Cu	<0.01	<0.01b	0.03a

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

Above- and belowground plant samples were dried separately at 70˚C for approximately one week to determine dry matter (DM). Sub-samples of AG and BG DM were ground and sieved through a 2-mm mesh screen for P, N, and Mg concentration analyses. Plant tissue samples were chemically analyzed to determine total tissue N by high-temperature combustion (Elementar VarioMAX CN analyzer) and total tissue P and Mg concentrations by acid digestion [34] followed by analysis with ICAP-OES [29]. Nutrient uptakes were calculated using measured nutrient concentrations and DM for each replicate. Total plant DM and total nutrient uptake were calculated by adding the AG and BG DMs and nutrient uptakes.

2.6. Statistical Analyses

Similar to recent procedures by Ylagan *et al.* [23], separately by crop and based on a RCB design, the effects of soil, fertilizer-P source, water type, and their interaction on BG and AG DM, BG and AG tissue nutrient uptakes, and total plant DM and nutrient uptakes were evaluated by analysis of variance (ANOVA) using the GLIMMIX procedure in SAS (version 9.4, SAS Institute, Inc., Cary, NC). A one-factor ANOVA was used to determine differences in initial soil properties and mid-experiment water properties between the two soils and the two water types used, respectively. A gamma distribution was used for all plant, soil, and water property analyses due to the generally skewed, non-normal distribution of the raw data. Treatment effects were significant at $P < 0.05$ and were means separated by least significant difference.

3. Results and Discussion

3.1. Initial Soil Properties

With the exception of M3-extractable soil S, all initial properties evaluated differed ($P < 0.01$) between soils (**Table 1**). Silt and clay and soil pH and EC were larger in the Calloway than in the Creldon soil, while sand, TN, TC, and SOM were larger in the Creldon than in the Calloway soil (**Table 1**). Mehlich-3 extractable soil P, K, Mg, and Zn concentrations were larger in the Creldon than in the Calloway soil, while all other M3 nutrient concentrations were larger in the Calloway than in the Creldon soil, except S, which did not differ between soils (**Table 1**).

3.2. Initial Water Properties

All initial water properties evaluated, except for Ca, differed ($P < 0.01$) between tapwater and struvite-removed wastewater, hereafter referred to as wastewater (**Table 2**). All water properties evaluated were larger in the wastewater than in the tapwater (**Table 2**). Results clearly indicated that the wastewater, as an irrigation water type for plants, had greater concentrations of numerous essential plant nutrients that could benefit plant growth compared to tapwater.

3.3. Corn Response

3.3.1. Belowground Biomass Properties

Every measured belowground corn parameter (*i.e.*, DM and N, P, and Mg uptakes) was affected ($P < 0.05$) by one or more treatments (*i.e.*, water type, soil, and/or fertilizer-P source; **Table 3**). Belowground DM differed ($P < 0.05$) among fertilizer-P sources, but was unaffected by soil or water type (**Table 3**). Averaged across soils and water types, BG corn DM was numerically largest for MAP (13.9 g), which did not differ from ECSTreal (13.3 g), CPST (12.9 g), and ECSTsyn (12.2 g), and was numerically smallest from the UC (10.5 g), which did not differ from ECSTsyn. Belowground DM from ECSTreal, MAP, and CPST was at least 1.2 times greater than from the UC. Without receiving any fertilizer-P addition, it stands to reason that the UC treatment would have the lowest BG DM. Belowground DM also did not differ among the three struvite treatments. In contrast to the results of the current study, Ylagan *et al.* [23] reported that ECSTsyn had the numerically largest BG corn DM. However, similar to Ylagan *et al.* [23], the UC had the numerically smallest BG corn DM due to the UC being unfertilized.

Belowground N uptake differed ($P < 0.05$) among fertilizer-P sources between soils and was unaffected by irrigation water type (**Table 3**). Averaged across water types, BG N uptake was numerically largest from CPST in the Creldon soil, which did not differ from ECSTreal in the Creldon soil, and was numerically smallest from the UC in the Creldon soil, which did not differ from the UC-Calloway, CPST-Calloway, MAP-Calloway, ECSTreal-Calloway, and ECSTsyn-Calloway and -Creldon combinations (**Figure 1**). Belowground N uptake for the CPST-Creldon combination was at least 1.2 times greater than for all other soil-fertilizer-P-source combinations, expect for ECSTreal in the Creldon soil (**Figure 1**). Belowground N uptake was greater for the Creldon than the Calloway soil for CPST, MAP, and ECSTreal, while there was no difference between soils for ECSTsyn or the UC (**Figure 1**). In the Creldon soil, belowground N uptake was at least 1.3 times greater for CPST and ECSTreal, which did not differ, than for ECSTsyn, while there was no difference in among struvite sources in the Calloway soil (**Figure 1**).

In contrast to BG corn DM and N uptake, BG corn P and Mg uptakes differed ($P < 0.05$) among soil-water-fertilizer-P-source combinations (**Table 3**). Belowground P uptake differences among treatment combinations were complex, but BG P uptake was numerically largest from the Creldon-tapwater-CPST combination, which did not differ from the Creldon-wastewater-CPST combination and was numerically smallest from the Creldon-tapwater-UC combination, which did not differ from the Creldon-wastewater-UC combination (**Table 4**). Belowground P uptake differed among the struvite materials in the following order: CPST > ECSTsyn > ECSTreal for the Creldon-tapwater combination, CPST = ECSTreal = ECSTsyn for the Calloway-tapwater combination, CPST > ECSTreal = ECSTsyn for the Creldon-wastewater combination, and CPST = ECSTsyn > ECSTreal for the Calloway-wastewater combination (**Table 4**).

Table 3. Analysis of variance summary of the effects of water type (W), soil (S), fertilizer-phosphorus source (F), and their interactions on corn properties for the greenhouse potted-plant study.

Source of variation	BG† DM	AG† DM	Total DM	BG uptake			AG uptake			Total uptake		
				N	P	Mg	N	P	Mg	N	P	Mg
W	0.21	0.05	0.04	0.28	0.95	0.92	0.98	0.33	0.03	0.71	0.71	0.05
S	0.68	<0.01	<0.01	0.01	0.95	0.65	0.16	<0.01	<0.01	0.04	0.01	<0.01
F	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
W × S	0.07	0.61	0.44	0.38	0.74	0.35	0.23	0.38	0.85	0.43	0.79	0.98
W × F	0.96	0.95	0.96	0.06	0.54	0.93	0.25	0.07	0.03	0.21	0.06	0.06
S × F	0.26	<0.01	<0.01	0.01	<0.01	0.02	0.04	<0.01	<0.01	0.01	<0.01	<0.01
W × S × F	0.44	0.04	0.19	0.19	0.01	0.03	0.20	0.17	0.03	0.31	0.16	0.04

†Belowground, BG; dry matter, DM; aboveground, AG; nitrogen, N; phosphorus, P; magnesium, Mg.

Table 4. Corn properties in response to water-soil-fertilizer-phosphorus-(P)-source treatment combinations for the 60-day greenhouse potted-plant study.

Water type	Soil series	Fertilizer-P source‡	BG P†,‡ ($mg \cdot cm^{-2}$)	BG Mg†,‡ ($mg \cdot cm^{-2}$)	AG DM†,‡ (g)	AG Mg†,‡ ($mg \cdot cm^{-2}$)	Total Mg†,‡ ($mg \cdot cm^{-2}$)
Tap water	Creldon	CPST	0.28a	0.32a	116.0i	0.88fg	1.20def
		MAP	0.06gh	0.13hi	131.0a-f	0.98efg	1.11f
		ECSTreal	0.08fg	0.16d-h	124.3b-g	1.11de	1.27de
		ECSTsyn	0.15bc	0.19c-f	127.0ab	1.49ab	1.68ab
		UC	0.03i	0.12i	91.9k	0.53i	0.65h
	Calloway	CPST	0.13cd	0.18c-h	113.7f-i	1.06de	1.24def
		MAP	0.09ef	0.15e-i	133.6a-d	1.15d	1.30de
		ECSTreal	0.12cde	0.24abc	112.6e-i	1.03def	1.26def
		ECSTsyn	0.10def	0.18c-h	127.6abc	1.59a	1.77a
		UC	0.06h	0.15e-i	121.3e-i	1.02d-g	1.17def
Wastewater	Creldon	CPST	0.21ab	0.27ab	119.6hi	0.88g	1.14ef
		MAP	0.08fg	0.15f-i	124.0a-e	1.07de	1.22def
		ECSTreal	0.09def	0.21b-e	110.3d-h	1.12de	1.33d
		ECSTsyn	0.12cde	0.18c-g	129.5ab	1.34bc	1.53b
		UC	0.04i	0.13hi	95.5j	0.68h	0.81g
	Calloway	CPST	0.15bc	0.22bcd	120.2c-h	1.11de	1.33cd
		MAP	0.08fg	0.13ghi	132.9ab	1.18cd	1.31de
		ECSTreal	0.08fg	0.16d-i	132.1abc	1.36abc	1.52bc
		ECSTsyn	0.12cde	0.22bcd	128.3a	1.48ab	1.70ab
		UC	0.06h	0.14ghi	107.3ghi	1.03def	1.16def

†Means in a column with different letters are different at $P < 0.05$. ‡Chemically precipitated struvite, CPST; monoammonium phosphate, MAP; real-wastewater-derived electrochemically precipitated struvite, ECSTreal; synthetic electrochemically precipitated struvite, ECSTsyn; belowground, BG; aboveground, AG; magnesium, Mg; dry matter, DM.

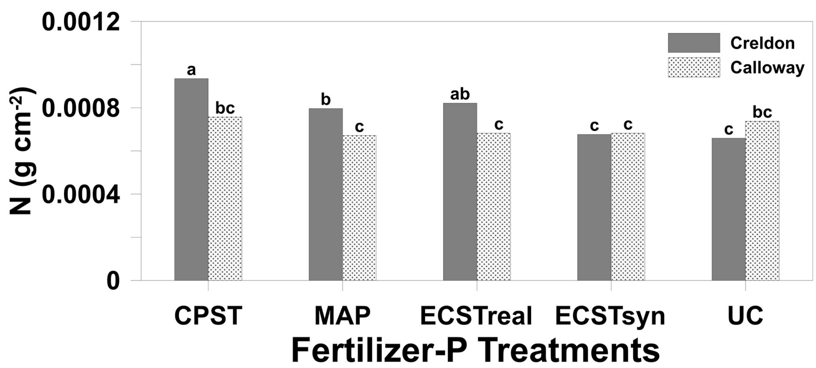

Figure 1. Belowground corn nitrogen (N) uptake in response to soil-fertilizer-P source [*i.e.*, chemically precipitated struvite (CPST), monoammonium phosphate (MAP), real-wastewater-derived electrochemically precipitated struvite (ECSTreal), synthetic electrochemically precipitated struvite (ECSTsyn) and an unamended control (UC)] combinations for the 60-day greenhouse potted-plant study. Bars with different lower-case letters are different at $P < 0.05$.

Similar to P, BG corn Mg uptake differences among treatment combinations were complex, but BG Mg uptake was numerically largest from the Creldon-tapwater-CPST combination, which did not differ from the Calloway-tapwater-ECSTreal and Creldon-wastewater-CPST combinations, and was numerically smallest from the Creldon-tapwater-UC combination, which did not differ from eight other soil-water-fertilizer-P-source combinations (Table 4). Belowground Mg uptake differed among the struvite materials in the following order: CPST > ECSTsyn = ECSTreal for the Creldon-tapwater combination, ECSTreal > CPST = ECSTsyn for the Calloway-tapwater combination, CPST = ECSTreal = ECSTsyn for the Creldon-wastewater combination, and CPST = ECSTsyn > ECSTreal for the Calloway-wastewater combination (Table 4).

For BG corn, CPST generally did not differ from the other struvite treatments or resulted in the greatest response for nutrient uptake. Specifically for N uptake, CPST was largest, which could partially have been due to struvite's slow-release behavior or the pelletized form of CPST resulting in slower dissolution, keeping CPST-derived nutrients plant-available for longer than the other fertilizer-P sources. The Creldon soil, in general, resulted in a greater plant response than Calloway, which could be explained by the greater initial N and P concentrations of the Creldon soil. In contrast, tapwater, which had a much lower initial nutrient concentration than the wastewater (Table 2), resulted in the greater plant response between the two water types. The large initial micro- and macro-nutrient concentrations in the wastewater could have caused unexpected negative interactions among the water, soils, and fertilizer-P sources, causing the greater plant response to tapwater.

3.3.2. Aboveground Biomass Properties

Similar to BG N uptake, AG corn DM differed ($P < 0.05$) among water-soil-fertilizer-P source treatment combinations (Table 3). Aboveground corn DM interactions among treatment combinations were complex, but AG corn DM was numerically largest from the Calloway-tapwater-MAP combination, which did not differ from any other water-soil-MAP, water-soil-ECSTsyn, or the Calloway-wastewater-ECSTsyn treatment combinations (**Table 4**). Aboveground corn DM was numerically smallest from the Creldon-tapwater-UC treatment combination (**Table 4**). Aboveground corn DM differed among struvite treatments in the following order: ECSTsyn = ECSTreal > CPST for the Creldon-tapwater combination, ECSTsyn > ECSTreal = CPST for the Calloway-tapwater combination, ECSTsyn > ECSTreal = CPST for the Creldon-wastewater combination, and ECSTsyn = ECSTreal > CPST for the Calloway-wastewater combination (**Table 4**). Results of the current greenhouse study differed from results of the field study of Omidire *et al.* (2022b), in which AG corn DM did not differ among fertilizer-P treatments. However, results of the current study were similar to the greenhouse study of Ylagan *et al.* [23], in which the traditional, commercially available TSP produced the largest AG corn DM.

In contrast to the results of Omidire *et al.* [43], AG N and P uptakes differed ($P < 0.05$) between soils across fertilizer treatments (**Table 3**). Averaged across water types, aboveground N uptake was numerically largest from ECSTsyn in the Creldon soil, which did not differ from ECSTsyn in the Calloway soil, ECSTreal in either soil, Creldon-CPST or -MAP (**Figure 2**). The numerically smallest aboveground N uptake was from the UC in the Creldon soil, which differed from all other treatment combinations (**Figure 2**). Aboveground N uptake was greater from the Creldon than the Calloway soil for CPST, greater with Calloway than Creldon for the UC, but similar between soils in MAP, ECSTreal, and ECSTsyn (**Figure 2**). With both Creldon and Calloway soils, aboveground N uptake was the same in ECSTreal as ECSTsyn and with the Creldon soil for CPST, which all were larger than with the Calloway soil for CPST (**Figure 2**).

Averaged across water types and unlike the results of Omidire *et al.* [43], AG P uptake was numerically at least 1.2 times larger from ECSTsyn in the Creldon soil than all other treatment combinations (**Figure 2**). Aboveground P uptake was numerically smallest from the UC in the Creldon soil, which also differed from all other treatment combinations (**Figure 2**). Aboveground P uptake was larger with the Calloway than Creldon soil for CPST, MAP, and the UC, but larger in the Creldon than Calloway soil for ECSTreal and ECSTsyn (**Figure 2**). With both soils, aboveground P uptake from ECSTsyn was larger than from ECSTreal, which was larger than from CPST (**Figure 2**).

Unlike the results of Omidire *et al.* [43], AG corn Mg uptake differed ($P < 0.05$) among water-soil-fertilizer-P source treatment combinations (**Table 3**). Aboveground Mg uptake treatment interactions were complex, but AG Mg uptake was numerically largest from the Calloway-tapwater-ECSTsyn combination, which did not differ from any other soil-water-ECSTsyn or from the Calloway-wastewater-ECSTreal treatment combinations (**Table 4**). Aboveground Mg uptake was numerically smallest from the Creldon-tapwater-UC combination,

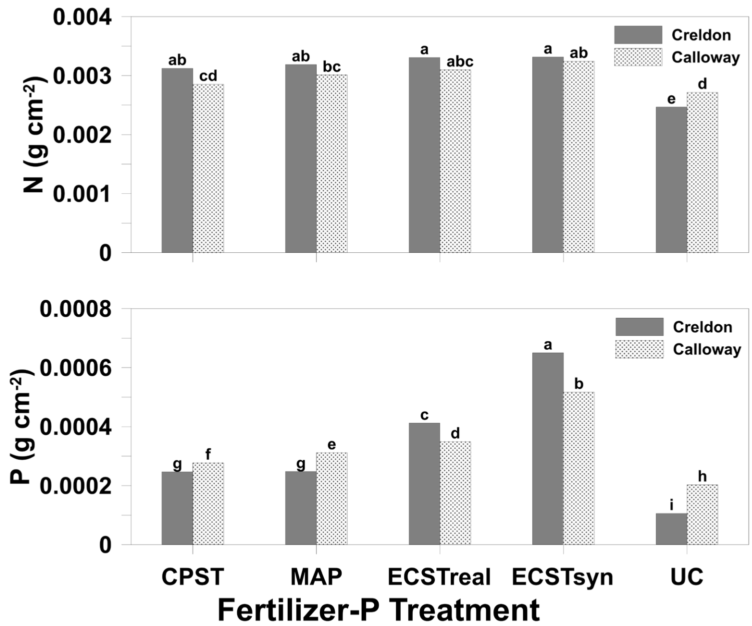

Figure 2. Aboveground corn nitrogen (N) and phosphorus (P) uptakes in response to soil-fertilizer-P source [*i.e.*, chemically precipitated struvite (CPST), monoammonium phosphate (MAP), real-wastewater-derived electrochemically precipitated struvite (ECSTreal), synthetic electrochemically precipitated struvite (ECSTsyn) and an unamended control (UC)] combinations for the 60-day greenhouse potted-plant study. Within a panel, bars with different lower-case letters are different at $P < 0.05$.

which differed from all other soil-water-fertilizer-P source treatment combinations (Table 4). Aboveground Mg uptake differed among the struvite materials in the following order: ECSTsyn > ECSTreal > CPST for the Creldon-tapwater combination, ECSTsyn > CPST = ECSTreal for the Calloway-tapwater combination, ECSTsyn > ECSTreal > CPST for the Creldon-wastewater combination, and ECSTsyn = ECSTreal > CPST for the Calloway-wastewater combination (Table 4).

In general, the UC had the smallest AG corn response among all fertilizer treatments, which was expected since the UC was unfertilized. In most cases, ECSTsyn had the largest plant response, especially for P and Mg uptake, due to its crystalline flake form and large initial P and Mg concentrations. The crystalline flake form of ECSTsyn had a larger surface area than the other pelletized fertilizer-P sources, which could have resulted in more rapid dissolution and plant uptake. Corn response in the Creldon soil was greater than in the Calloway soil in most instances, especially for ECSTsyn and ECSTreal, likely due to struvite's greater solubility under more acidic conditions (pH 7.5 for Calloway vs. pH 6.0 for Creldon; Table 1). Similar to BG corn and the reasons explained above, AG corn also had a greater response to tapwater than wastewater.

3.3.3. Total Plant Biomass Properties

Total corn DM differed ($P < 0.05$) between water types (Table 3). Averaged across fertilizer-P sources and soils, total corn DM was larger (41.5 g) from wastewater than from tapwater (39.3 g). Unlike the results of Omidire *et al.* [43], total corn DM also differed ($P < 0.05$) among fertilizer-P sources between soils (**Table 3**). Averaged across water types, total corn DM was largest from MAP in the Calloway soil and did not differ from MAP in the Creldon soil or ECSTreal and ECSTsyn in either soil (**Figure 3**). The numerically smallest total corn DM was from the UC in the Creldon soil, which differed from all other soil-fertilizer-P source treatment combinations (**Figure 3**). Total corn DM was greater with the Calloway than the Creldon soil for the UC, but did not differ between soils for all other soil-fertilizer-P source combinations (**Figure 3**). With both the Creldon and Calloway soil, total corn DM from ECSTreal and ECSTsyn did not differ, but both were greater than CPST (**Figure 3**). In contrast to result of the current study, Ylagan *et al.* [23] reported that ECSTsyn, not MAP, had the largest total corn DM. However, similar to the result of the current study, Ylagan *et al.* [23] reported that ECSTsyn had a larger total corn DM than CPST.

Total N and P uptake differed ($P < 0.05$) among fertilizer treatments between soils and were unaffected by water type (**Table 3**). Averaged across water types, total N uptake was numerically largest from ECSTreal in the Creldon soil, which did not differ from the Creldon-CPST, -MAP, or either ECSTsyn-soil combinations (**Figure 4**). The numerically smallest total N uptake was from the UC in the Creldon soil, which differed from all other soil-fertilizer-P source combinations (**Figure 4**). Total N uptake was greater with the Creldon than the Calloway soil for CPST and ECSTreal, greater with Calloway than Creldon for the UC, and did not differ between soils for MAP and ECSTsyn (**Figure 4**). With both Calloway and Creldon soils, total N uptake did not differ for ECSTreal, ECSTsyn, or Creldon-CPST, while Calloway-CPST was lower than all other soil-struvite treatment combinations (**Figure 4**).

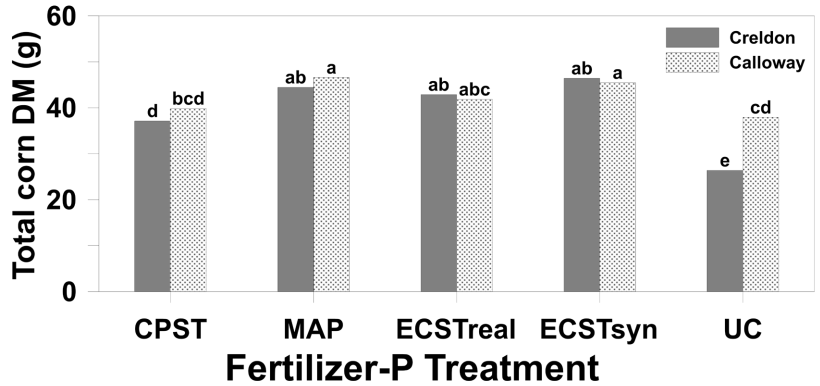

Figure 3. Total corn dry matter (DM) in response to soil-fertilizer-P source [*i.e.*, chemically precipitated struvite (CPST), monoammonium phosphate (MAP), real-wastewater-derived electrochemically precipitated struvite (ECSTreal), synthetic electrochemically precipitated struvite (ECSTsyn) and an unamended control (UC)] combinations for the 60-day greenhouse potted-plant study. Bars with different lower-case letters are different at $P < 0.05$.

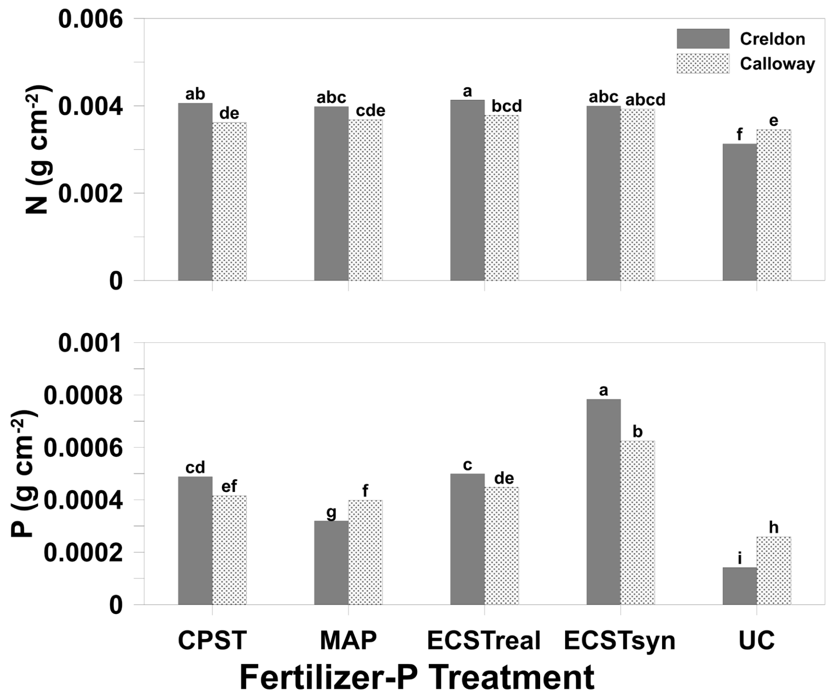

Figure 4. Total corn nitrogen (N) and phosphorus (P) uptakes in response to soil-fertilizer-P source [*i.e.*, chemically precipitated struvite (CPST), monoammonium phosphate (MAP), real-wastewater-derived electrochemically precipitated struvite (ECSTreal), synthetic electrochemically precipitated struvite (ECSTsyn) and an unamended control (UC)] combinations for the 60-day greenhouse potted-plant study. Within a panel, bars with different lower-case letters are different at $P < 0.05$.

In contrast to total N uptake, total P uptake in almost all treatment combinations differed from each other (Figure 4). Averaged across water types, total P uptake was 1.3 times larger from ECSTsyn in the Creldon soil than in all other combinations, while the numerically smallest total P uptake was from the UC in the Creldon soil, which differed from all other combinations (Figure 4). Total P uptake was greater with the Creldon than the Calloway soil for CPST, ECSTreal, and ECSTsyn, while total P uptake from the Calloway was greater than the Creldon soil for MAP and the UC (Figure 4). With both Creldon and Calloway soils, total P uptake ECSTsyn was larger than CPST and ECSTreal, which did not differ (Figure 4). Unlike the results of the current study, Omidire *et al.* [43] reported that N and P uptake was unaffected by fertilizer-P source.

In contrast to Omidire *et al.* [43], total Mg uptake differed ($P < 0.05$) among water-soil-fertilizer-P source treatment combinations (Table 3). Total Mg uptake interactions among treatment combinations were complex, but total Mg uptake was numerically greatest from Calloway-tapwater-ECSTsyn, which did not differ from any other soil-water-ECSTsyn combination (Table 4). The numerically smallest total Mg uptake was from the Creldon-tapwater-MAP, which did not differ from Creldon-wastewater-MAP, Creldon-tapwater-CPST, Calloway-tapwater-CPST, -ECSTreal, -UC, or Calloway-wastewater-UC combinations (Table 4). Total Mg uptake differed among the struvite materials in the following order: ECSTsyn > ECSTreal = CPST for the Creldon-tapwater combination, ECSTsyn > ECSTreal = CPST for the Calloway-tapwater combination, ECSTsyn > ECSTreal > CPST for the Creldon-wastewater combination, and ECSTsyn > ECSTreal > CPST for the Calloway-wastewater combination (**Table 4**).

The largest total corn DM was for MAP, which was somewhat expected considering MAP had the largest solubility of all fertilizer-P sources used in this study. The nutrients in MAP would have been released faster than the other fertilizer-P sources and caused greater foliage growth more quickly. For similar reasons to AG and BG, the greatest total corn response was, in general, to ECSTsyn or ECSTreal, in the Creldon soil, especially for the struvite treatments, and to tapwater compared to the other fertilizer-P sources, the Calloway soil, and wastewater, respectively. Since the total corn DM and uptakes were calculated from the AG and BG responses, total corn plant responses mirrored the AG corn response results.

3.4. Soybean Response

3.4.1. Belowground Biomass Properties

Similar to corn, every measured BG soybean parameter (*i.e.*, DM and N, P, and Mg uptakes) was affected ($P < 0.05$) by one or more treatments (*i.e.*, water type, soil, and/or fertilizer-P source; **Table 5**). Belowground soybean DM differed ($P < 0.05$) between soils among fertilizer-P sources (**Table 5**). Averaged across water types, BG DM was numerically largest for the UC in the Calloway soil, which did not differ from Calloway-CPST, -MAP, and both soil-ECSTreal and -ECSTsyn treatment combinations (**Figure 5**). Belowground DM was smallest for the UC in the Creldon soil, which differed from all other soil-fertilizer-P source treatment combinations (**Figure 5**). Belowground DM was greater in the Calloway than in the Creldon soil for CPST and the UC, and BG DM did not differ between soils for MAP, ECSTreal, or ECSTsyn (**Figure 5**). With both the Calloway and Creldon soils, BG DM from the struvites did not differ from each other, except for CPST in the Creldon soil, which was smaller than the other soil-struvite treatment combinations (**Figure 5**). It is unclear why the soybean BG DM was numerically greater in the unfertilized UC treatment than the other fertilizer-P source treatments. In contrast to the current results, Ylagan *et al.* [23] reported that ECSTsyn had the largest and MAP had the smallest BG soybean DM.

Belowground N and Mg uptake differed ($P < 0.05$) between soils among fertilizer-P treatments (**Table 5**). Averaged across water types, BG N uptake was numerically largest for the UC in the Calloway soil, which did not differ from any other Calloway-fertilizer-P source combination or for ECSTsyn in the Creldon soil (**Figure 6**). Belowground N uptake was numerically smallest for the UC in the Creldon soil, which differed from all other soil-fertilizer-P source treatment combinations (**Figure 6**). Belowground N uptake was larger in the Calloway than the Creldon soil for the UC and CPST and was similar between the Creldon and Calloway soils for MAP, ECSTreal, and ECSTsyn (**Figure 6**). Belowground N uptake for CPST, ECSTreal, and ECSTsyn were similar between the Calloway and Creldon soils, except for CPST, where CPST in the Creldon soil was smaller than ECSTreal and ECSTsyn (**Figure 6**).

Averaged across water types, BG Mg uptake was numerically largest for CPST in the Calloway soil, which did not differ from any other Calloway-fertilizer-P source treatment combination (**Figure 6**). Belowground Mg uptake was numerically smallest for the UC in the Creldon soil, which differed from all other soil-fertilizer-P source treatment combinations (**Figure 6**). Belowground Mg uptake was larger in the Calloway than the Creldon soil for all treatment combinations (**Figure 6**). Belowground Mg uptake did not differ between struvite treatments (**Figure 6**).

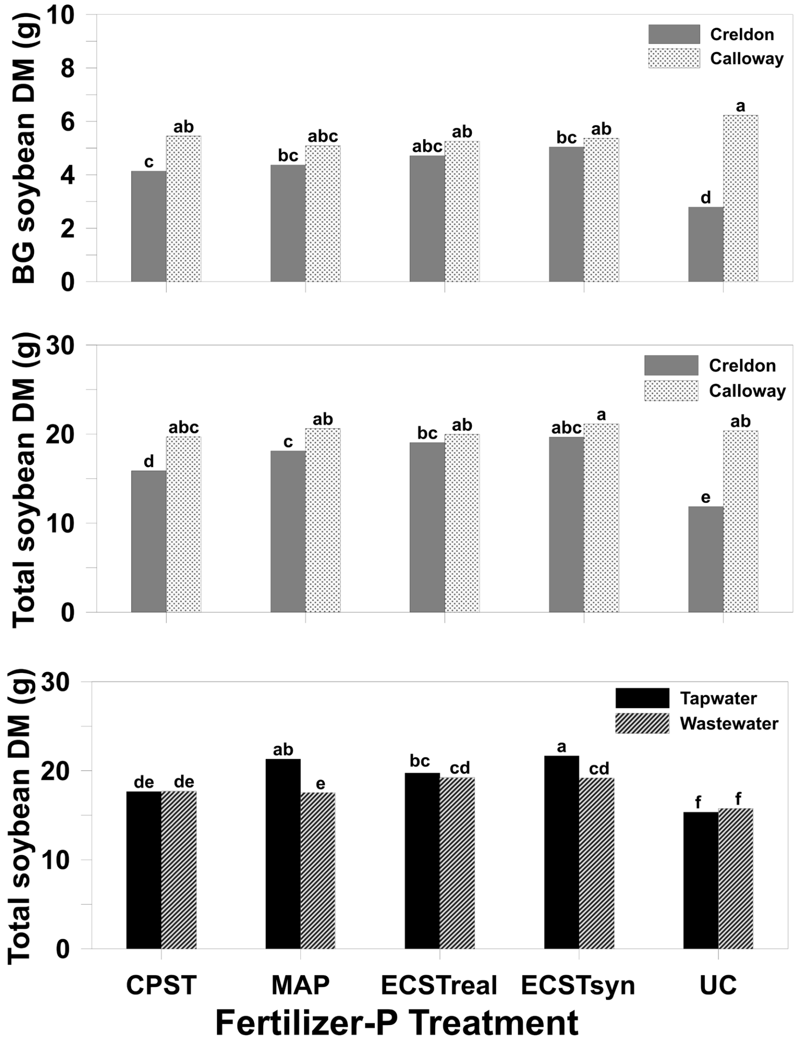

Figure 5. Belowground and total soybean dry matter (DM) in response to soil-fertilizer-P source [*i.e.*, chemically precipitated struvite (CPST), monoammonium phosphate (MAP), real-wastewater-derived electrochemically precipitated struvite (ECSTreal), synthetic electrochemically precipitated struvite (ECSTsyn) and an unamended control (UC)] combinations and total soybean DM among water-fertilizer-P source combinations for the 60-day greenhouse potted-plant study. Within a panel, bars with different lower-case letters are different at $P < 0.05$.

Table 5. Analysis of variance summary of the effects of water type (W), soil (S), fertilizer-phosphorus source (F), and their interactions on soybean properties for the greenhouse potted-plant study.

Source of variation	BG† DM	AG† DM	Total DM	BG uptake			AG uptake			Total uptake		
				N	P	Mg	N	P	Mg	N	P	Mg
W	0.06	0.01	<0.01	0.06	0.13	0.65	0.07	0.20	0.02	0.04	0.90	0.09
S	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.74	0.71	<0.01	0.13	0.05
F	0.10	<0.01	<0.01	0.10	<0.01	0.05	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
W * S	0.86	0.16	0.26	0.86	0.36	0.17	0.97	0.38	0.75	0.86	0.14	0.73
W * F	0.13	0.01	<0.01	0.13	0.06	0.06	<0.01	0.01	0.01	<0.01	0.12	0.02
S * F	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
W * S * F	0.19	0.39	0.14	0.19	<0.01	0.14	0.45	0.20	0.08	0.05	0.52	0.02

†Belowground, BG; dry matter, DM; aboveground, AG; nitrogen, N; phosphorus, P; magnesium, Mg.

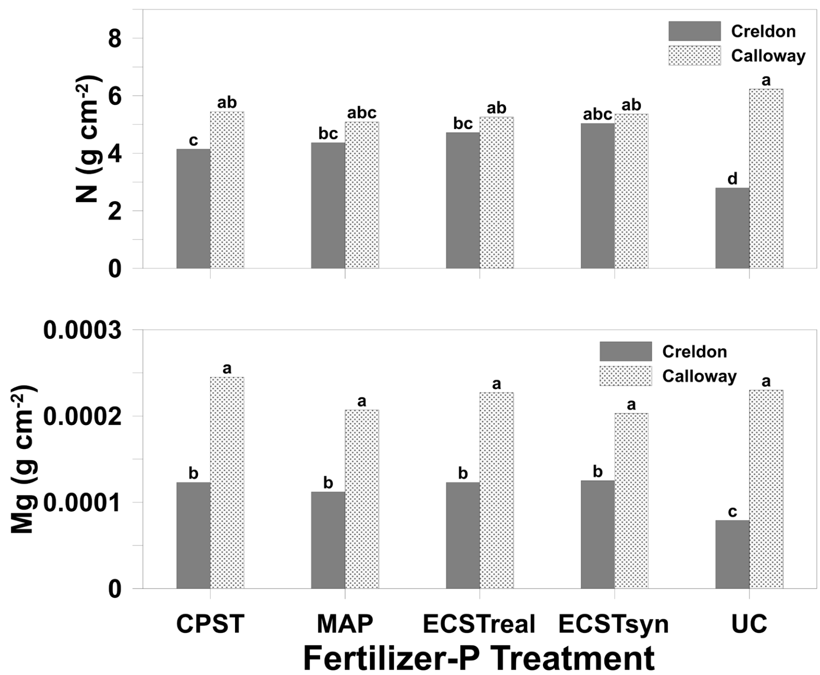

Figure 6. Belowground soybean nitrogen (N) and magnesium (Mg) uptakes in response to soil-fertilizer-P source [*i.e.*, chemically precipitated struvite (CPST), monoammonium phosphate (MAP), real-wastewater-derived electrochemically precipitated struvite (ECSTreal), synthetic electrochemically precipitated struvite (ECSTsyn) and an unamended control (UC)] combinations for the 60-day greenhouse potted-plant study. Within a panel, bars with different lower-case letters are different at $P <$ 0.05.

In contrast to N and Mg, BG P uptake differed ($P < 0.05$) among water-soil-fertilizer-P source treatment combinations (**Table 5**). Belowground P uptake interactions between treatment combinations were complex, but the numerically largest BG P uptake was from the Calloway-tapwater-CPST combination, which did not differ from 10 other soil-water-fertilizer-P source treatment combinations (Table 6). Belowground P uptake was numerically smallest in the Creldon-wastewater-UC combination, which did not differ from the Creldon-tapwater-UC or -CPST combinations (Table 6). Belowground P uptake differed among the struvite materials in the following order: ECSTsyn = ECSTreal > CPST for the Creldon-tapwater combination, ECSTsyn = ECSTreal = CPST for the Calloway-tapwater combination, ECSTsyn = ECSTreal = CPST for the Creldon-wastewater combination, and ECSTsyn = ECSTreal = CPST for the Calloway-wastewater combination (Table 6). In contrast to the results of the current study, Omidire *et al.* [44] reported that BG soybean N, Mg, and P uptakes did not differ among fertilizer-P sources.

Table 6. Soybean properties in response to water-soil-fertilizer-phosphorus-(P)-source treatment combinations for the 60-day greenhouse potted-plant study.

Water type	Soil series	Fertilizer-P source‡	BG P†,‡ ($mg \cdot cm^{-2}$)	Total Mg†,‡ ($mg \cdot cm^{-2}$)
Tap water	Creldon	CPST	6.45e	0.57fgh
		MAP	11.14abc	0.72bc
		ECSTreal	10.43abc	0.74b
		ECSTsyn	11.25abc	0.95a
		UC	5.97e	0.39i
	Calloway	CPST	13.00a	0.67b-e
		MAP	10.84abc	0.65b-f
		ECSTreal	10.55abc	0.68bcd
		ECSTsyn	12.14ab	0.90a
		UC	9.60bc	0.51h
Wastewater	Creldon	CPST	8.96cd	0.64c-f
		MAP	6.94de	0.59e-h
		ECSTreal	9.38bc	0.71bc
		ECSTsyn	9.51bc	0.91a
		UC	5.49e	0.37i
	Calloway	CPST	10.15abc	0.56fgh
		MAP	9.94bc	0.55gh
		ECSTreal	11.26abc	0.71bcd
		ECSTsyn	11.21abc	0.87a
		UC	12.01ab	0.61deg

†Means in a column with different letters are different at $P < 0.05$. ‡Chemically precipitated struvite, CPST; monoammonium phosphate, MAP; real-wastewater-derived electrochemically precipitated struvite, ECSTreal; synthetic electrochemically precipitated struvite, ECSTsyn; belowground, BG; nitrogen, N; magnesium, Mg.

Similar to the corn response, ECSTsyn had, in general, the largest soybean response among all fertilizer-P sources and tapwater had a greater soybean response than wastewater. The largest response to ECSTsyn was likely due to the crystalline flake form of ECSTsyn having a greater surface area than the other pelletized fertilizers and making greater contact with the soil for dissolution and uptake by soybean roots, promoting growth. In most cases, soybean responses in the Creldon soil were greater than in the Calloway soil for the struvite treatments, which was expected due to the increased solubility of struvite under acidic conditions. The greater response to tapwater than wastewater was likely due to the larger initial nutrient concentrations in the wastewater (**Table 2**). The large initial micro- and macro-nutrient concentrations, large pH, and potential unknown contaminants in the real wastewater could have caused unexpected, antagonistic interactions among the water, soils, and fertilizer-P sources, causing the greater plant response to tapwater. In general, soybean response to the UC was smallest, which was expected due to the UC being unfertilized.

3.4.2. Aboveground Biomass Properties

Every measured AG soybean parameter (*i.e.*, DM and N, P, and Mg uptakes) was affected ($P < 0.05$) by one or more treatments (*i.e.*, water type, soil, and/or fertilizer-P source; **Table 5**). Aboveground DM differed ($P < 0.05$) between soils across fertilizer-P sources (**Table 5**). Averaged across water types, ABG DM was numerically largest for ECSTsyn in the Calloway soil, which did not differ from ECSTsyn in the Creldon soil or ECSTreal or MAP in the Calloway soil (**Figure 7**). Aboveground DM was numerically smallest for the UC in the Creldon soil, which differed from all other soil-fertilizer-P source treatment combinations (**Figure 7**). Aboveground DM was larger in the Calloway soil than the Creldon soil for CPST, MAP, and the UC, and did not differ between soils for ECSTreal and ECSTsyn (**Figure 7**). With both the Calloway and Creldon soils, AG DM from ECSTreal and ECSTsyn did not differ, while CPST was smaller than ECSTsyn or ECSTreal (**Figure 7**). In contrast to the results of the current study, Omidire *et al.* [44] and Ylagan *et al.* [23] both reported that AG soybean DM was unaffected by fertilizer-P source.

Aboveground DM also differed ($P < 0.05$) between water types across fertilizer-P sources (**Table 5**). Averaged across soils, AG DM was largest for ECSTsyn with tapwater, which did not differ from MAP or ECSTreal with tapwater (**Figure 7**). Aboveground DM was numerically smallest for the UC with tapwater, which did not differ for the UC with wastewater (**Figure 7**). Aboveground DM was larger with tapwater than wastewater for MAP and ECSTsyn, but did not differ between water types for the other fertilizer-P source treatments (**Figure 7**). With tapwater and wastewater, AG DM from ECSTreal and ECSTsyn did not differ from each other, but both were larger than CPST (**Figure 7**).

Aboveground soybean N, P, and Mg uptake differed ($P < 0.05$) between soils among fertilizer-P sources (**Table 5**). Averaged across water types, AG N uptake was numerically largest for ECSTsyn in the Calloway soil, which did not differ from MAP in the Calloway soil (**Figure 8**). The numerically smallest AG N uptake was for the UC in the Creldon soil, which did not differ from CPST in the Creldon soil (**Figure 8**). Aboveground N uptake was larger in the Calloway than Creldon soil for CPST, MAP, ECSTsyn, and the UC, but did not differ between soils for ECSTreal (**Figure 8**). With both the Calloway and Creldon soils, AG N uptake from ECSTsyn was larger than ECSTreal, which did not differ from the Calloway-CPST combination, while the Creldon-CPST combination was smallest among the struvite treatment combinations (**Figure 8**).

Averaged across water types, AG P uptake was two times larger for ECSTsyn in both soils than in any other soil-fertilizer-P source combination, while ECSTsyn in Creldon was numerically largest and differed from all other treatment combinations (**Figure 8**). The numerically smallest AG P uptake was for the UC in the Creldon soil, which differed from all other soil-fertilizer-P source combinations (**Figure 8**). Aboveground P uptake was larger in the Creldon than Calloway soil for ECSTreal and ECSTsyn, smaller in the Creldon than the Calloway soil for the UC, and did not differ between soils for CPST and MAP. For both the Creldon and Calloway soils, AG P uptake from ECSTsyn was larger than ECSTreal, which was larger than CPST (**Figure 8**).

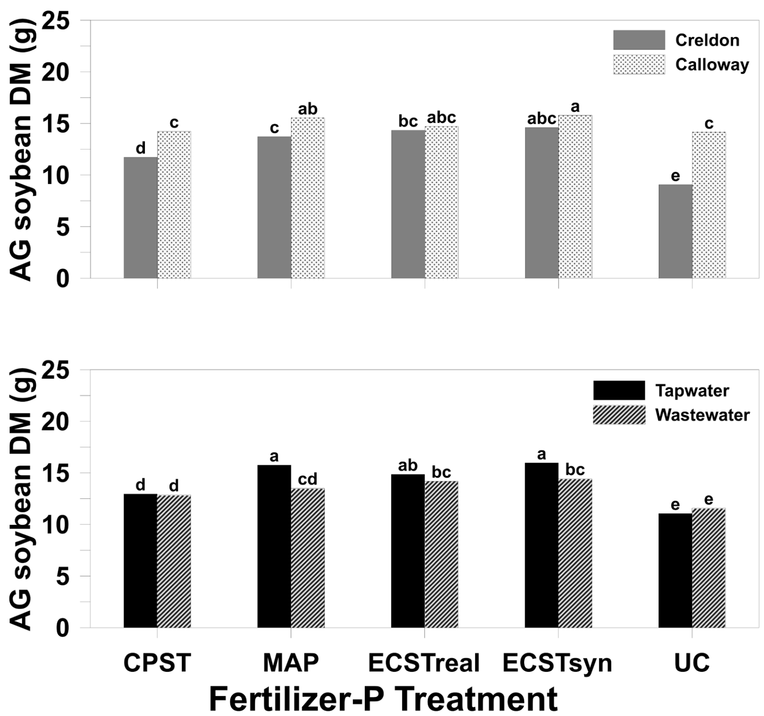

Figure 7. Aboveground (AG) soybean dry matter (DM) in response to soil-fertilizer-P source [*i.e.*, chemically precipitated struvite (CPST), monoammonium phosphate (MAP), real-wastewater-derived electrochemically precipitated struvite (ECSTreal), synthetic electrochemically precipitated struvite (ECSTsyn) and an unamended control (UC)] combinations and aboveground soybean DM among water type-fertilizer-P source treatment combinations for the 60-day greenhouse potted-plant study. Within a panel, bars with different lower-case letters are different at $P < 0.05$.

Averaged across water types, AG Mg uptake was numerically largest for ECSTsyn in the Creldon soil, which did not differ from ECSTsyn in the Calloway soil (Figure 8). Aboveground Mg uptake was numerically smallest for the UC in the Creldon soil, which differed from all other soil-fertilizer-P source combinations (Figure 8). Aboveground Mg uptake was larger for the Creldon than the Calloway soil for MAP and ECSTreal, while Mg uptake was larger for the Calloway than the Creldon soil for the UC, and Mg uptake did not differ between soils for CPST and ECSTsyn (Figure 8). With both the Creldon and Calloway soils, AG Mg uptake from ECSTsyn was larger than ECSTreal, which was larger than CPST (Figure 8).

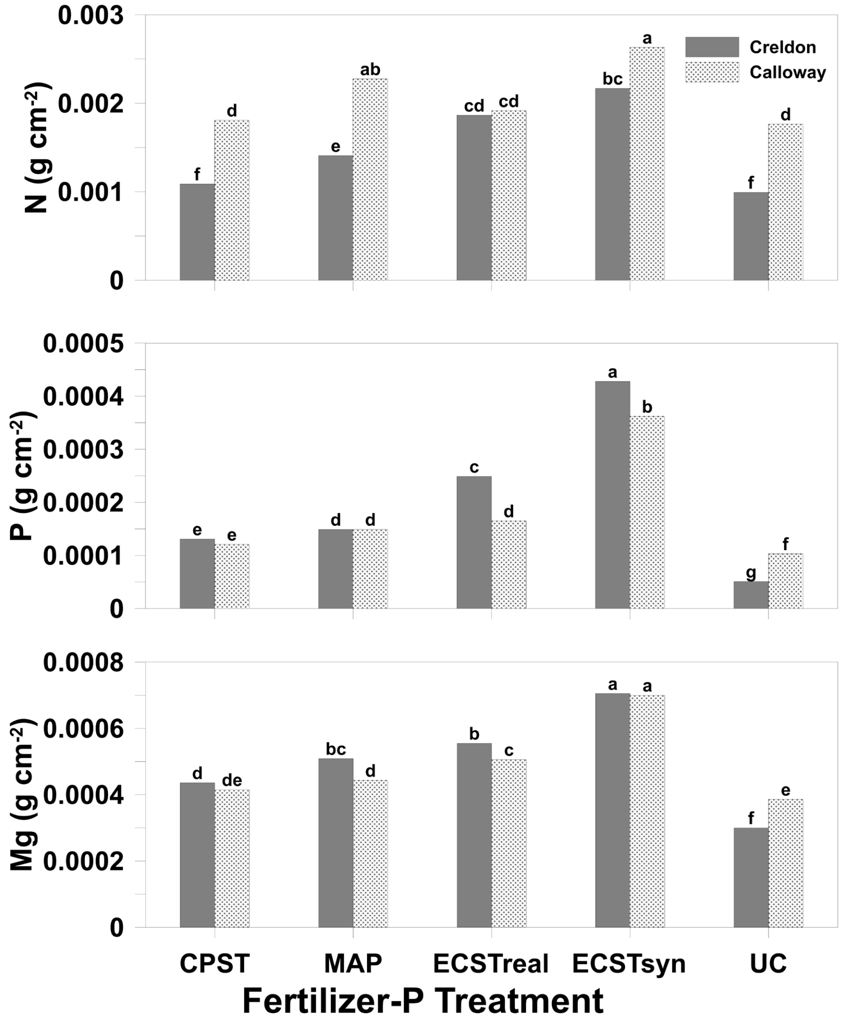

Figure 8. Aboveground soybean nitrogen (N), phosphorus (P), and magnesium (Mg) uptakes in response to soil series (*i.e.*, Creldon and Dapue)-fertilizer-P source [*i.e.*, chemically precipitated struvite (CPST), monoammonium phosphate (MAP), real-wastewater-derived electrochemically precipitated struvite (ECSTreal), synthetic electrochemically precipitated struvite (ECSTsyn) and an unamended control (UC)] combinations for the 60-day greenhouse potted-plant study. Within a panel, bars with different lower-case letters are different at $P < 0.05$.

Aboveground soybean N, P, and Mg uptakes also differed ($P < 0.05$) between water types among fertilizer-P sources (Table 5). Averaged across soils, AG N uptake was 1.3 times larger for ECSTsyn with tapwater than any other water-fertilizer-P source combination, and N uptake was smallest for the UC with tapwater, which did not differ from the UC-wastewater, either CPST-water combination, or MAP-wastewater combinations (Figure 9). Aboveground N uptake was larger with tapwater than wastewater for MAP and ECSTsyn, but tapwater and wastewater did not differ for all other fertilizer-P sources (Figure 9). With tapwater and wastewater, AG N uptake from ECSTsyn was larger than ECSTreal, which was larger than CPST (Figure 9).

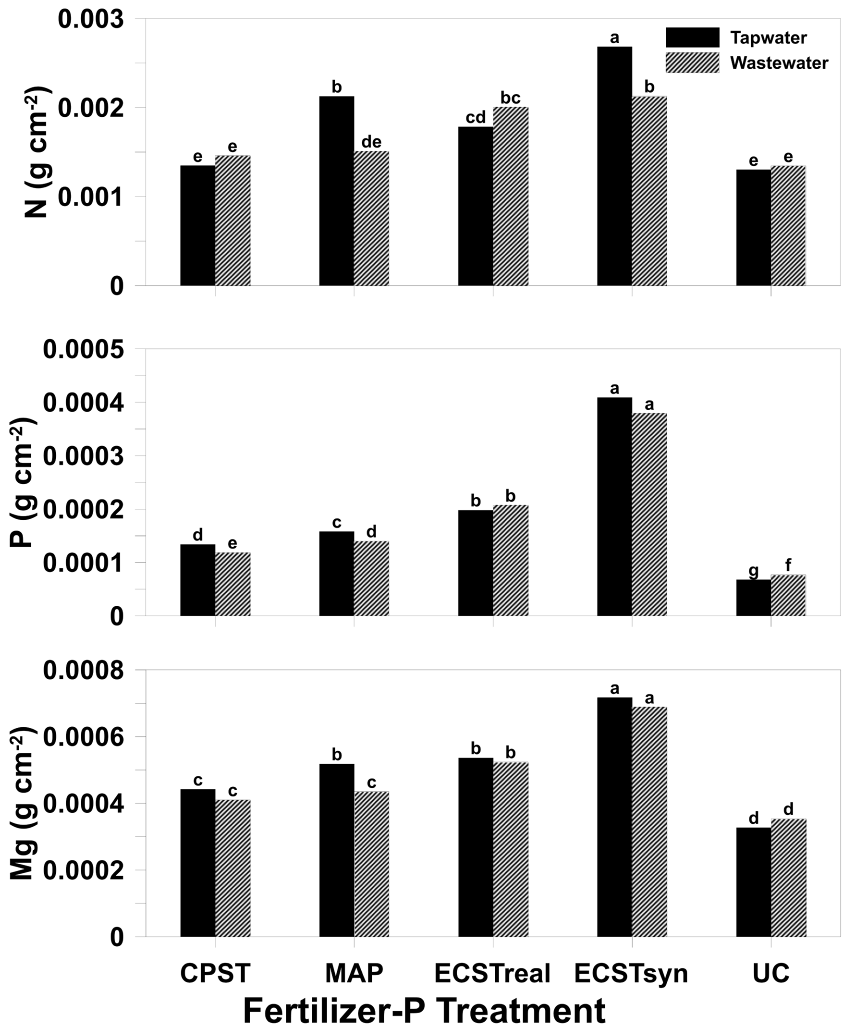

Figure 9. Aboveground soybean nitrogen (N), phosphorus (P), and magnesium (Mg) uptakes in response to water type-fertilizer-P source [*i.e.*, chemically precipitated struvite (CPST), monoammonium phosphate (MAP), real-wastewater-derived electrochemically precipitated struvite (ECSTreal), synthetic electrochemically precipitated struvite (ECSTsyn) and an unamended control (UC)] combinations for the 60-day greenhouse potted-plant study. Within a panel, bars with different lower-case letters are different at $P < 0.05$.

Averaged across water types, AG P uptake was numerically largest for ECSTsyn with tapwater, which did not differ from ECSTsyn with wastewater (**Figure 9**). The smallest AG P uptake was for the UC with tapwater, which differed from all other water-fertilizer-P source combinations (**Figure 9**). Aboveground P uptake was larger with tapwater than wastewater with CPST and MAP, larger with wastewater than tapwater for the UC, and did not differ between water types for ECSTsyn and ECSTreal (**Figure 9**). With tapwater and wastewater, AG P uptake from ECSTsyn was larger than ECSTreal, which was larger than CPST (**Figure 9**). Similar to the current study, Omidire *et al.* [44] reported that AG N and P uptake were largest for ECSTsyn.

In contrast to the results of Omidire *et al.* [44], AG Mg uptake differed among water type-fertilizer-P source combinations. Averaged across soils, AG Mg uptake was numerically largest for ECSTsyn with tapwater, which did not differ from ECSTsyn with wastewater (**Figure 9**). Aboveground Mg uptake was numerically smallest for the UC with tapwater, which did not differ from the UC with wastewater (**Figure 9**). Aboveground Mg uptake was larger with tapwater than wastewater for MAP, but did not differ between water types for all other fertilizer-P sources (**Figure 9**). With tapwater and wastewater, AG Mg uptake from ECSTsyn was larger than ECSTreal, which was larger than CPST (**Figure 9**).

Aboveground soybean responses to fertilizer-P sources, water types, and soils were due to similar reasons as corn and BG soybean responses. Generally, the largest soybean response was to ECSTsyn due to its crystalline-flake nature as described for BG soybean. The soybean properties had a greater response to the struvite treatments in the Creldon (pH 6.0) than the Calloway (pH 7.5) soil due to the greater solubility of struvite under more acidic conditions. The soybean properties also had a greater response to tapwater than wastewater in all fertilizer treatments for the same reasons explained for BG soybean properties, except the UC, which had a greater response with wastewater due to its nutrient addition. The UC had the smallest soybean response in most cases due to being unfertilized.

3.4.3. Total Plant Biomass Properties

Every calculated total soybean parameter (*i.e.*, total DM and total N, P, and Mg uptake) was affected ($P < 0.05$) by a combination of two or more treatments (*i.e.*, water type, soil, and/or fertilizer-P source; **Table 5**). Total soybean DM differed ($P < 0.05$) between soils among fertilizer-P sources (**Table 5**). Averaged across water types, total DM was numerically largest for ECSTsyn in the Calloway soil, which did not differ from ECSTsyn in the Creldon soil or any other Calloway-fertilizer-P source combination (**Figure 5**). Total DM was smallest for the UC in the Creldon soil, which differed from all other soil-fertilizer-P source treatment combinations (**Figure 5**). Total DM was larger in the Calloway than in the Creldon soil for CPST, MAP, and the UC, and did not differ between soils for

ECSTsyn or ECSTreal (**Figure 5**). For both soils, total soybean DM for ECSTsyn and ECSTreal did not differ from each other or from CPST in the Calloway soil, which were all larger than CPST in the Creldon soil (**Figure 5**). In contrast to results of the current study, Omidire *et al.* [44] and Ylagan *et al.* [23] reported that total soybean DM was unaffected by fertilizer-P source.

Total soybean DM also differed ($P < 0.05$) between water types among fertilizer-P sources (**Table 5**). Averaged across soils, total soybean DM was numerically largest for ECSTsyn with tapwater, which did not differ from MAP with tapwater (**Figure 5**). The numerically smallest total DM was for the UC with tapwater, which did not differ from the UC with wastewater (**Figure 5**). Total soybean DM was larger with tapwater than wastewater for MAP and ECSTsyn, but did not differ between water types for CPST, ECSTreal, or the UC (**Figure 5**). With tapwater, total soybean DM from ECSTsyn was larger than ECSTreal, which was larger than CPST. For wastewater, total soybean DM did not differ among struvite materials (**Figure 5**).

Total soybean N and P uptake differed ($P < 0.05$) between soils among fertilizer-P sources (**Table 5**). Averaged across water types, total N uptake was 1.3 times larger for ECSTsyn in the Calloway soil than in any other soil-fertilizer-P source combination and numerically smallest for the UC in the Creldon soil, which differed from all other soil-fertilizer-P source combinations (**Figure 10**). Total N uptake was larger for the Calloway than the Creldon soil in CPST, MAP, ECSTsyn, and the UC and did not differ between soils for ECSTreal (**Figure 10**). With the Calloway and Creldon soils, total N uptake from ECSTsyn was larger than ECSTreal, which was larger than CPST (**Figure 10**).

Averaged across water types and similar to the results of Omidire *et al.* [44], total P uptake was 1.2 times larger for ECSTsyn in the Creldon soil than in any other soil-fertilizer-P source combinations, while total P uptake was numerically smallest for the UC in the Creldon soil, which differed from all other soil-fertilizer-P source combinations (**Figure 10**). Total P uptake was larger in the Creldon than in the Calloway soil for ECSTreal and ECSTsyn, larger in the Calloway than in the Creldon soil for the UC, and did not differ between soils for CPST and MAP (**Figure 10**). With both the Calloway and Creldon soils, total P uptake from ECSTsyn was larger than ECSTreal, which was larger than CPST (**Figure 10**).

Total soybean N uptake differed ($P < 0.05$) between water types among fertilizer-P sources (**Table 5**). Averaged across soils, total N uptake was 1.4 times larger for ECSTsyn with tapwater than any other water-fertilizer-P source combination (**Figure 10**). The numerically smallest total N uptake was for the UC with tapwater, which did not differ from the UC with wastewater, MAP with wastewater, or CPST with tapwater (**Figure 10**). Total N uptake was larger with tapwater than wastewater for MAP and ECSTsyn and did not differ between water types for CPST, ECSTreal, and the UC (**Figure 10**). With tapwater, total N uptake from ECSTsyn was larger than ECSTreal, which was larger than CPST

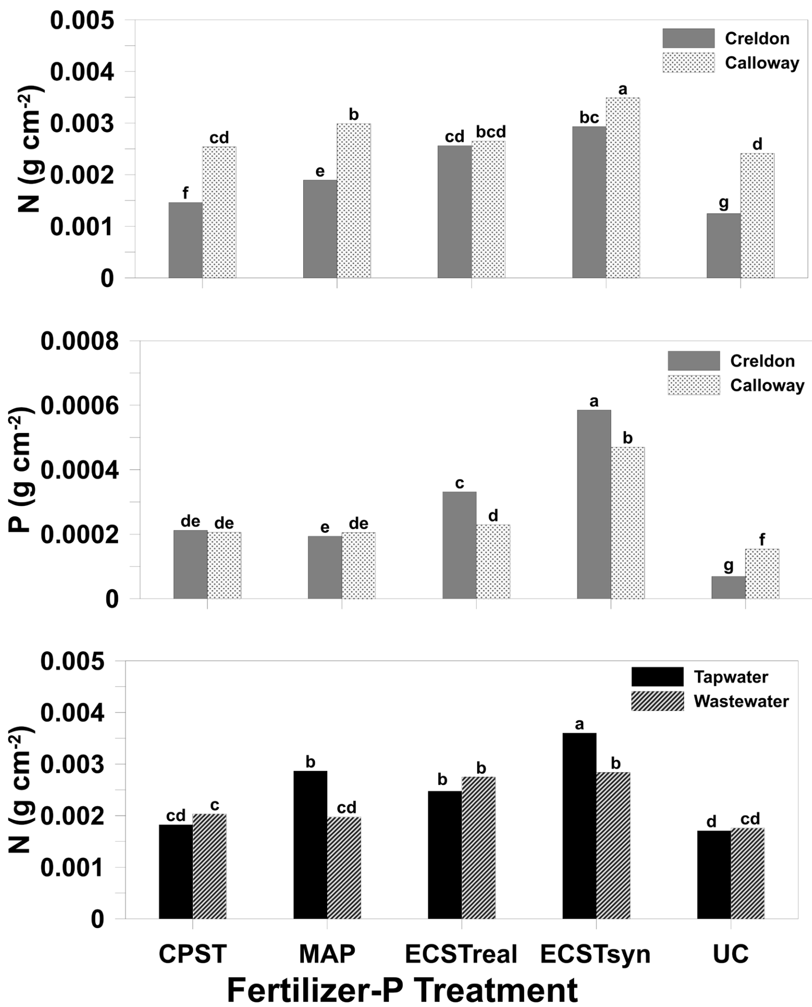

Figure 10. Total soybean nitrogen (N) and phosphorus (P) uptakes in response to soil-fertilizer-P source [*i.e.*, chemically precipitated struvite (CPST), monoammonium phosphate (MAP), real-wastewater-derived electrochemically precipitated struvite (ECSTreal), synthetic electrochemically precipitated struvite (ECSTsyn) and an unamended control (UC)] combinations and total soybean nitrogen (N) uptake among water type-fertilizer-P source combinations for the 60-day greenhouse potted-plant study. Within a panel, bars with different lower-case letters are different at $P < 0.05$.

(Figure 10). For wastewater, total N uptake from ECSTsyn and ECSTreal did not differ, but were larger than CPST (Figure 10). Omidire *et al.* [44] also reported a significant fertilizer-P-source effect, in which ECSTsyn had the largest total soybean N uptake and did not differ from CPST.

Total soybean Mg uptake differed ($P < 0.05$) among water-soil-fertilizer-P source treatment combinations (Table 5). Total Mg uptake interactions varied among treatment combinations were complex, but total Mg uptake was numerically largest for the Creldon-tapwater-ECSTsyn combination, which did not differ from any other soil-water-ECSTsyn treatment combination (Table 6). The numerically smallest total Mg uptake was in the Creldon-wastewater-UC combination, which did not differ from the Creldon-tapwater-UC combination (**Table 6**). Total Mg uptake differed among the struvite materials in the following order: ECSTsyn > ECSTreal > CPST for the Creldon-tapwater combination, ECSTsyn > ECSTreal = CPST for the Calloway-tapwater combination, ECSTsyn > ECSTreal > CPST for the Creldon-wastewater combination, and ECSTsyn > ECSTreal > CPST for the Calloway-wastewater combination (**Table 6**). In contrast to results of the current study, Omidire *et al.* (2023) reported that total soybean Mg uptake was unaffected by fertilizer-P source.

For similar reasons to BG and AG corn and soybean response, the greatest total soybean response was, in general, to ECSTsyn or ECSTreal due to their crystalline-flake nature. The greater total soybean response was also to the Creldon soil rather than the Calloway soil due to soil pH differences, especially for the struvite treatments, and to tapwater, as explained for BG and AG soybean responses. Since total soybean DM and uptakes were calculated from the AG and BG responses, total soybean responses mirrored AG results.

3.5. Implications

As demonstrated in the current study and others [23] [43] [44], struvite can perform similarly to traditional, commercially available fertilizer-P sources in terms of crop growth and yield. Struvite may also reduce the cost of extra needed urea-N inputs due to struvite containing more N than many traditional P-only fertilizer sources, namely TSP [43]. Due to ECST still being in an experimental state, ECST is more costly than traditional fertilizers to produce. According to Omidire *et al.* [44], in 2019, the cost of producing ECSTsyn was greater than the cost to produce TSP. However, depending on the source used to create struvite, ECSTsyn may contain more N and P than TSP, resulting in ECSTsyn-fertilized crops producing a greater yield than TSP-fertilized crops, and therefore ECSTsyn had the greatest value in 2019 [44]. However, as more research is conducted on both the potential crop growth efficiency and large-scale production costs, there will be opportunities to lower the cost of ECST production. The opportunity to lower ECST production costs, coupled with the growing need for sustainable fertilizer-P sources that do not rely on mined RP, makes ECST a potentially environmentally and economically viable alternative fertilizer-P source.

Despite having numerous greater initial nutrient concentrations (**Table 2**), corn and soybean responses to struvite-removed wastewater as part of the irrigation water used were often lower than for tapwater. Based on results of this study, and only using struvite-removed wastewater as an irrigation water source approximately one out of every fourth irrigation, it appears that the potential to use struvite-removed wastewater as an irrigation-water and a nutrient source is not warranted. Further research will need to be conducted to ascertain the cause of reduced corn and soybean responses using struvite-removed wastewater as an irrigation-water and nutrient source.

Results of this study showed that, as a potentially viable, alternative fertilizer-P source, struvite, particularly ECSTreal, recorded many similar corn and soybean responses as other traditional, commercially available fertilizer-P sources, namely MAP and TSP. Results of the current study also showed that, although ECSTsyn resulted in the numerically greater crop response, the response to ECSTreal was still at least similar to or greater than the response to CPST and MAP. Numerous prior studies [9] [16] [17] [18] [19] [20] corroborate results of this study, where struvite response across a variety of crops was similar to that with commercially available fertilizers. However, more research with ECSTreal in field studies and with crop yield response will provide a better understanding of the viability of ECSTreal as a potential alternative or replacement for commercially available fertilizer-P sources. Preliminary, unpublished data suggest that potential heavy metal concentrations in the CPST material, created from a municipal wastewater source, are low, which is corroborated by both corn and soybean growth that did not appear to suffer from any adverse effects that may have been related to heavy metals.

Struvite can also lower excess nutrient loads into the environment by recovering P and N from human and animal waste streams. Reduced nutrient input to the environment could also decrease eutrophication in waterways. Because corn and soybean were grown for only 60 days, the nutrient tissue concentration and uptake may have been different had a full-season greenhouse or field study been conducted, where crops were allowed to fully mature. Therefore, more economic and practical field research is needed before struvite can be considered for widespread use as a replacement for traditional fertilizer-P sources, such as TSP, MAP, and DAP. However, having a potential, alternative, renewable fertilizer-P source, such as struvite, would be beneficial for agricultural production and the environment.

4. Conclusion

This greenhouse potted-plant study evaluated the combined effects of two silt-loam soils, two water types, and five fertilizer-P sources on corn and soybean properties over a 60-day period. Along with BG and AG DM, many BG and AG N, P, and Mg uptakes responded similarly across the various soil-water-fertilizer-P source combinations. The hypothesis that the struvite materials (*i.e.*, CPST, ECSTreal, and ECSTsyn) would have the greater corn and soybean response in the lower-pH soil (*i.e.*, the Creldon soil) was partially supported, as only a sub-set of measured plant properties were larger in the Creldon than in the Calloway soil. Struvite-removed wastewater was initially studied to investigate its potential as a nutrient-supplying, irrigation-water type, but after watering corn and soybean with the wastewater only once a week throughout the 60-day period, wastewater often negatively affected corn and soybean properties, whereas tapwater resulted in larger corn and soybean N, P, and Mg uptakes, despite the wastewater having numerous greater initial nutrient concentrations than tapwater. Therefore, the hypothesis that plant properties would remain unaffected by water type was not supported. Most significantly, the hypothesis that corn and soybean properties would be greater in the struvite-P sources than in MAP was also only partially supported. In almost every fertilizer-P source treatment interaction, struvite-P sources behaved similarly to MAP, the traditional, commercially available fertilizer-P source.

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Conflicts of Interest

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

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