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REVIEW & ANALYSIS

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A review and meta-analysis of the agricultural potential of struvite as a phosphorus fertilizer

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Abstract

The low water solubility of struvite is thought to limit its agronomic utility as a phosphorus (P) fertilizer compared with highly soluble P fertilizers. Furthermore, struvite's fertilizer potential is complicated by its hypothesized soil pH-dependent solubility, crop-specific interactions, and limited availability of struvite-derived N, which may explain conflicting reports of crop responses to struvite compared with conventional P fertilizers. A systematic literature review and meta-analysis was conducted to evaluate the effects of soil pH, soil test P (STP), P rate, struvite particle size, and struvite-derived N on crop aboveground biomass, P concentration, P uptake, and N uptake. Struvite-fertilized plants yielded higher biomass, P concentration, and P uptake compared with ammonium phosphates, and superphosphates in soils with pH < 6 and crop responses decreased with increasing pH. Crop responses to struvite were inversely related to experiment duration to soil mass ratios (d kg^{-1}) used in greenhouse studies, opposite to the hypothesized benefit of more roots per unit soil on struvite dissolution. The proportion of total N applied derived from struvite increased with increasing struvite-P application rate and was inversely related to total N uptake, likely due to the increased crop reliance on slowly available struvite-N. Crop responses were potentially overestimated by high STP and/or P rates and underestimated due to N limitation from large proportions of total N applied derived from struvite. Evaluations of struvite collectively indicate its efficacy as a P fertilizer is affected by soil pH and its contribution to total N application.

1 | INTRODUCTION

The mining of nonrenewable rock phosphate to manufacture phosphorus (P) fertilizers (e.g., ammonium phosphates and superphosphates) to support agricultural intensification is estimated to have doubled the total P input flux of the global P cycle in less than a century (Filippelli, 2008). After fertilizer P application, preharvest P losses can occur directly from the field, and postharvest losses can occur from processing plants or livestock operations and eventually from population centers where P is consumed and excreted (Metson, MacDonald, Haberman, Nesme, & Bennett, 2016). Points of P losses are opportunities for P recycling, the largest of which in the United States are livestock manure and crop processing (e.g., oil production, milling, etc.), followed by P excreted by humans (Margenot et al., 2019; Metson et al., 2016). Currently, P is primarily removed from municipal wastewater and incorporated into excess sewage sludge produced during biological treatment (Duan et al., 2017). The P that is not removed is released to surface waters. Aqueous P point sources, such as municipal wastewater treatment plants and

Abbreviations: STP, soil test phosphorus; TSP, triple superphosphate.

industry, combined with P losses from agricultural systems were estimated to contribute 37.9 Tg P to surface waters in 2013 (Chen & Graedel, 2016). Abundant losses from the global P cycle are the major contributors to the eutrophication of fresh waters and coastal areas, especially in large drainage basins such as the United States Mississippi River Basin, which flows to the Gulf of Mexico, where hypoxia is a major problem (Correll, 1998; MacDonald et al., 2016).

The disjointed cycle of anthropogenic P usage could be realigned by developing strategies to reuse P from waste streams as agricultural fertilizers. Struvite ($MgNH_4PO_4 \cdot 6H_2O$) is a P mineral that can be precipitated from aqueous waste streams (Doyle & Parsons, 2002) by increasing the pH of wastewater and maintaining a stoichiometric ${PO_4}^{3-}$ to Mg^{2+} molar ratio (Cerrillo, Palatsi, Comas, Vicens, & Bonmati, 2014; Hallas, Mackowiak, Wilkie, & Harris, 2019; Uysal & Kuru, 2013). A pH of 9.0 and Mg^{2+} to ${PO_4}^{3-}$ molar ratio of 1 was found to maximize precipitation of struvite from swine slurry in batch assays (Cerrillo et al., 2014), although the same molar ratio but with a pH of 9.5 was found when precipitating struvite from potato (*Solanum tuberosum* L.)-processing wastewater (Uysal & Kuru, 2013). Because struvite precipitation occurs under alkaline conditions, dissolution rates are greatest under acidic conditions and decrease as pH increases to 9.0, leading to the possibility of its application to soils as a fertilizer source (Bhuiyan, Mavinic, & Beckie, 2007; Booker, Priestley, & Fraser, 1999). Although struvite dissolution is greatest under acidic conditions, struvite solubility in water is low compared with commonly used P fertilizers. The solubility product constant values for various struvite samples evaluated in the literature are relatively low, ranging from 4.37×10^{-14} to 3.89×10^{-10} (Rahaman, Mavinic, Bhuiyan, & Koch, 2006). Struvite is nonetheless a promising candidate agricultural P fertilizer due to the myriad of abiotic and biotic processes found in soil that could aid in its dissolution, described by the following:

$$MgNH_4PO_4 \cdot 6H_2O \rightarrow Mg^{2+}_{aq} + NH^{+}_{4aq} + PO^{3-}_{4aq} + 6H_2O_l$$

There are possible benefits of the low water solubility and high citrate solubility of struvite, which was first mentioned in 1858 as a plausible replacement of P fertilizers that were "too soluble" (Murray, 1858). The slow release of nutrients could reduce their susceptibility to losses under intense precipitation, and root exudate (e.g., citrate, malate, oxalate)–aided dissolution could improve the timing of nutrient release. Presumably, fertilizer P and N recovery efficiency would be greater compared with rapidly solubilized conventional P fertilizers, such as ammonium phosphates and superphosphates, producing similar or increased crop response to fertilization. Struvite-P dissolution may be accelerated in acidic soils because struvite is most thermodynamically stable at alkaline pH. Struvite dissolution is further complicated by the potential pH increase of up to two pH units in acidic soils that has been observed from struvite application due to the consumption of protons with its dissolution (Talboys et al., 2016). The congruent release of P and N from struvite and the effect of soil properties (e.g., pH, texture) on its dissolution make it difficult to quantify individual effects of the multiple factors driving crop response to struvite.

Core Ideas

- We performed a literature review and meta-analysis of struvite as a P fertilizer.
- Crop responses to struvite were evaluated relative to that of ammonium phosphates and superphosphates.
- Crop responses of aboveground biomass, P concentration, and P uptake to struvite increased with decreasing soil pH.
- Crop responses in field and greenhouse studies were potentially overestimated by high soil test P and excessive P application rates.
- Crop responses were underestimated due to N limitation from large proportions of total applied N derived from struvite.

Studies to date have reported highly variable crop responses to struvite compared with conventional P fertilizers. A recent qualitative review of struvite research identified extreme variability in crop growth with struvite across 33 studies from a 28% decrease in the biomass of canola (*Brassica napus* L.) compared with a monoammonium phosphate–fertilized control to a 488% increase in the dry biomass of arugula (*Eruca sativa* Mill.) compared with a no-P control (Ahmed, Shim, Won, & Ra, 2018). Another recent review on struvite, limited to studies conducted in the European Union or geographic areas with similar soils to the European Union, categorized struvite with other secondary precipitated P salts (calcium phosphate and dittmarite) to test plant biomass response (log response ratios) and apparent P use efficiency relative to mined (i.e., phosphate rock) and synthetic reference P fertilizers (Huygens & Saveyn, 2018). These response ratios were compared across coarsely binned groups (i.e., noncontinuous) within pH, soil texture, granule size, plant species, and soil test P (STP) as well as experimental duration, scale, and balance. Similar crop responses to precipitated P salts and acidulated or ammoniacal fertilizers were found for all predictors. Variable data across studies resulted in few significant differences and are likely an artifact of differences in the crop grown, soil pH, STP, experimental duration, and soil mass used in greenhouse experiments as well as whether struvite N is credited in crop N requirements, raising the possibility of N-limited crop responses. In commonly used greenhouse settings, longer experimental durations would theoretically allow for greater solubilization of struvite, and lower soil masses could result in an elevated root density around struvite granules. A larger experiment duration to soil mass ratio would then increase the potential for plant root restriction in the pot due to long growing durations and/or insufficient soil mass. Under root-restricted conditions, lower available soil nutrients could accentuate relative differences in crop response between rapidly solubilizing reference P fertilizers compared with struvite.

The objectives of this review were (a) to perform a comprehensive analysis of the current body of research on the potential of struvite as a P fertilizer and (b) use continuous variable metadata to test soil, struvite, and experimental design factors hypothesized to influence crop response to struvite. Based on the cited literature, we hypothesized that (a) a complete substitution of ammonium phosphates or superphosphates with struvite would reduce crop aboveground biomass, P concentration, and total P uptake because the low water solubility of struvite will cause a lag between crop P demand and struvite-P release; (b) the relative crop response to struvite would be dependent on the reference fertilizer of ammonium phosphates versus superphosphates because they differ in pH and chemical composition (i.e., ammonium phosphates but not superphosphates contain N); (c) crop responses to struvite would be sensitive to experiment duration and/or soil mass used in greenhouse studies because crop biomass increases over the experiment duration and requires increased soil mass to prevent unrealistic root densities that favor struvite solubilization; (d) crop response to struvite would be inverse to soil pH because struvite dissolution is hypothesized to be greatest in acidic conditions; (e) crop species would differ in response to struvite due to crop-specific root exudation quantity and speciation and/or crop-specific rhizosphere acidification because struvite dissolution is hypothesized to be affected by pH and organic acid concentrations; (f) high STP and P application rates would overestimate the apparent availability of struvite P; (g) crop responses would be inversely related to struvite particle size because of the surface area–specific dynamics of struvite dissolution; and (h) the slow dissolution of struvite would limit the availability of N derived from struvite, potentially to the point of N limitation if struvite-N was credited as available N.

2 | MATERIALS AND METHODS

2.1 | Data collection

A systematic literature review was conducted between May 2018 and February 2019 using Google Scholar. To identify studies that included agronomic evaluations of struvite, the search terms were a combination of "struvite" with "agriculture," "fertilizer," "crop response," or "recycled P fertilizers." Eighty-two publications were identified, 59 of which were selected for a total of 1037 individual observations using struvite, conventional P fertilizers, and other recycled P materials (Supplemental Table S1). Selection criteria included field or greenhouse assessments of struvite used as a soil-applied fertilizer. From the 59 selected studies, struvite treatments accounted for 378 of the 1037 observations. The remainder were reference P fertilizers of ammonium phosphates (monoammonium and diammonium phosphate; $n = 88$) and superphosphates (single superphosphate and triple superphosphate [TSP]; $n = 125$) as well as other recycled and conventional P products (e.g., sewage sludge, urine, manure; $n = 313$) and no-P fertilization controls ($n = 133$). To eliminate the potential variability in reference P fertilizers to which struvite treatment responses would be compared, only paired observations for ammonium phosphates or superphosphates with struvite were selected for the final set of observations ($n = 213$ struvite observations). In 2017, ammonium phosphates and superphosphates accounted for approximately 63% of world commercial P fertilizer usage (IFA, 2019),

For each individual observation, experimental design parameters and crop response variables were systematically extracted to test factors hypothesized to affect struvite efficacy. Experimental design parameters were experimental scale (e.g., greenhouse, field), experimental duration, the mass of soil used in greenhouse experiments, and crop species. Extracted soil variables were pH, textural class and/or particle size fractions, and STP concentration along with the method used (e.g., Mehlich III, Bray, Olsen). Fertilizer information included the name and formulation, water-extractable P, total P and N, particle size, and P and N application rate. The percent of the total N input applied as struvite-N was calculated by dividing the N derived from the struvite application by the total N rate for the experiment. Crop responses included in the dataset were aboveground and/or belowground dry biomass, aboveground plant-P concentration, and total P and N uptake.

2.2 | Statistical analyses

All statistics were calculated in SAS v9. with (SAS, 2013) the procedures MEANS for descriptive statistics, GLIMMIX for lsmeans and mean comparisons using approximate t tests, and REG for regression coefficients and trend lines.

2.3 | Descriptive analysis

Descriptive statistics were calculated for all field and greenhouse trials to assess the experimental parameters most likely to affect struvite efficacy. The range, median, and mean were calculated for experiment duration (d), and, for greenhouse observations only, the soil mass in each pot (kg) as well as the experiment duration normalized to soil mass (d kg^{-1}) were calculated. Experiment duration, soil mass, and experiment duration normalized to soil mass were also separated by the cropping groups of maize (*Zea maize* L.), small grains (amaranth [*Amaranthus* L.], barley [*Hordeum vulgare* L.], buckwheat [*Fagopyrum esculentum* L.], oats [*Avena sativa* L.], rye [*Secale cereale* L.], sorghum [*Sorghum bicolor* (L.) Moench], triticale [× *Triticosecale* L.], wheat [*Triticum* L.]), legumes (alfalfa [*Medicago sativa* L.], broad bean [*Vicia faba* L.], chickpea [*Cicer arietinum* L.], lupine [*Lupinus* L.], soybean [*Glycine max* (L.) Merr.]), grasses (rye forage, fescue [*Festuca* L.]), vegetables (cabbage [*Brassica oleracea* var. *capitate* L.], chard [*Beta vulgaris* L.], garden cress [*Lepidium sativum* L.], lettuce [*Lactuca sativa* L.], purslane [*Portulaca oleracea* L.], spinach [*Spinacia oleracea* L.], tomato [*Solanum lycopersicum* L.]), and oilseeds (canola [*Brassica napus* L.], sunflower [*Helianthus* L.]).

Soil textural classes for struvite treatment observations from field and greenhouse experiments were plotted in the USDA soil textural triangle (Shirazi & Boersma, 1984) to compare texture distributions within and among experimental scales. If not reported, soil textural classes were calculated from reported particle size fractions of sand, silt, and clay. Studies that reported soil textural class but not individual particle size fractions were assigned to the approximate center of each textural polygon.

To describe the distribution of soil pH values in the dataset, struvite observations from field and greenhouse studies for which there was a comparison to ammonium phosphates or superphosphates were visualized as a function of soil pH and the number of observations at each soil pH. Observations were also contextualized by the soil P availability curves adapted from Havlin, Tisdale, Nelson, and Beaton (2014) (Supplemental Figure S1).

2.4 | Struvite response ratios

Struvite treatment crop response variables (aboveground biomass, P concentration, P uptake, and N uptake) were compared with reference P fertilizers (ammonium phosphates and superphosphates) corresponding to the same within-experiment parameters (e.g., P rate, crop species, soil texture, pH). Struvite response ratios were calculated by normalizing struvite crop response (i.e., biomass, P concentration, and P uptake) to the ammonium phosphate and superphosphate fertilizer response (Equation 1).

$$\frac{\text{Struvite response}}{\text{Reference fertilizer response}} = \text{Response ratio} \qquad (1)$$

A response ratio >1.00 indicates that the effect of struvite on the response variable is greater than that of the reference P fertilizer response, and vice versa for a response ratio of <1.00. A response ratio of 1.00 indicates a similar crop response to struvite as to the reference P fertilizer of ammonium phosphate or superphosphate. Response ratios were modeled as first-order functions of the continuous variables of experiment duration normalized to soil mass, pH, P application rate, struvite particle size (diameter), and proportion of total N applied as struvite. Values of continuous predictor variables were used rather than grouping or binning these, which requires assumptions that may bias analyses. Significant *p* values for linear regressions (<.05) indicate that the slope is different from zero. Interactions of predictor variables were constrained by sample size due to the irregularity of reported variables across research.

2.5 | Soil test phosphorus and phosphorus application rate analysis

To determine the potential of STP and P application rates to confound P responses, a comprehensive analysis of these variables was performed for struvite observations in the dataset. Observations were separated by experimental scale (field or greenhouse) and by three crop subgroups: maize, the dominant United States crop with 37.1 million ha planted in 2019 and used in 35% of recorded struvite observations (USDA-NASS, 2019); small grains, the second largest collection of species group in the dataset (31% of struvite observations); and all other crops, each with an insufficient sample size to separate into separate groups (alfalfa, canola, chickpea, lettuce, soybean, sunflower, tomato, and grasses excluding maize). The percentage of total struvite observations (n = 179) represented by each group was calculated for experimental scale, crop subgroup, STP classification, and P application rate classification. Soil P availability was grouped into one of three STP levels categorized as low, optimal, and high based on crop-specific recommendations from CDFA (2011), North Dakota State University (2018), Ojo, Kintomo, Akinrinde, and Akoroda (2007), University of California (2013), Wortmann, Ferguson, Hergert, Shapiro, and Shaver (2013), and University of Minnesota Extension (2019). Similarly, two P application rate categories (non-excessive vs. excessive) were determined based on crop P requirements for each crop species (CDFA, 2011; North Dakota State University, 2018; Putnam, Oplinger, Doll, & Schulte, 1989; University of California, 2013; University of Minnesota Extension, 2019; Wortmann et al., 2013) (Supplemental Table S2). Although all STP methods were reported using the same units (mg P kg^{-1}), STP values are not directly comparable across STP methods because methods can extract different amounts of P (Mallarino, 1997). Conversions were

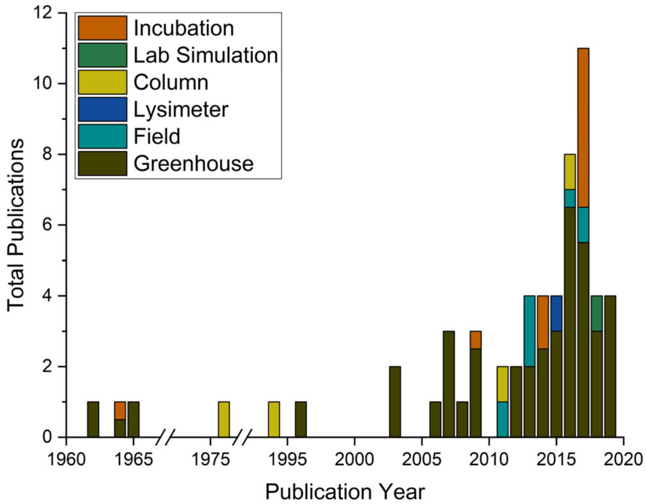

FIGURE 1 Temporal distribution of experimental evaluations of struvite as a P fertilizer and the experiment type from 56 peer-reviewed publications and three other non–peer-reviewed publications.

made for the purpose of comparing STP values of one method to the crop specific recommended STP levels of another: Bray to Olsen (Mallarino, 1995), Mehlich III to Olsen (Ige, Akinremi, Flaten, & Kashem, 2006), Olsen to water-extractable P (Ige et al., 2006), Mehlich III to Morgan (Cornell University, 2019), Mehlich III to double lactate (Zbiral & Nemec, 2002), and Olsen to double lactate (Zbiral & Nemec, 2002) (Supplemental Table S2). Phosphorus application rates reported in lb ac^{-1} or kg ha^{-1} were converted to mg P kg^{-1} assuming a soil volume of 1 ha at 15.24 cm depth or an acre furrow slice and, if not reported otherwise, a bulk density of 1.3 g cm^{-3}.

3 | RESULTS

3.1 | Dataset descriptive statistics

3.1.1 | Origin of dataset studies

The first extensive evaluation of struvite as a P fertilizer identified was published in 1962 when plants were grown in struvite directly, without soil (Bridger, Salutsky, & Starostka, 1962) (Figure 1), but three additional experimental evaluations occurred over the next three decades until 1994. Forty-three of the 59 publications (73%) occurred after 2010. Until 2009, only greenhouse studies were used to evaluate struvite, and in 2011 the first field experiment was reported (Gell, de Ruijter, Kuntke, de Graaff, & Smit, 2011). Over this 57-yr period, greenhouse studies accounted for 70% of publications, whereas field studies accounted for 8%. Struvite publications originated largely in Europe and Central Asia ($n = 33$). European Union member countries accounted for approximately half of all struvite publications ($n = 28$). Germany accounted for the most publications ($n = 8$), followed by the United States ($n = 7$), Korea ($n = 5$), Belgium ($n = 4$), and Spain ($n = 4$).

3.1.2 | Crop species and experimental parameters

Across the 59 publications, the 307 struvite observations with crop responses were generated largely at the greenhouse scale (78%) and to a lesser degree at the field scale (22%). All field-scale observations were limited to maize, legume, or small grains, whereas greenhouse studies entailed greater crop diversity. In greenhouse experiments, soil mass ranged from 0.2 to 15 kg and was greatest for nongrain grasses (mean, 8.7 kg) and maize (mean, 3.8 kg). Experiment duration varied widely, from 11 d (grass, garden cress, purslane) to 140 d (grass). Grasses were grown the longest on average (87 d), followed by small grains, maize, oilseeds, vegetables, and legumes (64–39 d). As a proxy of root-restricted growing conditions, experiment duration normalized to soil mass (d kg^{-1}) was greatest for legumes and small grains, with means of 69 and 55 d kg^{-1}, respectively. Maize, which is the crop species with generally the greatest biomass of crops used in struvite evaluations, was grown using lower duration/soil mass (23 d kg^{-1}) than legumes and small grains (mean, 62 d kg^{-1}).

3.2 | Soil texture

Soil textures from struvite-fertilized observations were constrained to textural classes having <500 g clay kg^{-1} and <800 g silt kg^{-1}. Greenhouse studies were most frequently conducted in sandy textured soils with >500 g sand kg^{-1} (136 observations, 83%), whereas field studies were conducted mostly in loam, silt loam, and silty clay textured soils (60 observations, 90%). Clay content, regardless of experimental scale, did not influence crop dry matter, P concentration, or P uptake responses to struvite compared with ammonium phosphate or superphosphate (Supplemental Figures S2–S4).

3.3 | Crop responses

Aboveground dry matter was the most commonly measured crop response variable in evaluations of struvite as a P fertilizer. Only two studies evaluated grain yield, and there were limited observations reporting belowground responses of biomass ($n = 11$), P concentration ($n = 13$), or total P uptake ($n = 2$). At the field scale, the mean aboveground biomass response ratio comparing struvite with reference P fertilizers was 0.94 and was significantly lower than 1.00 ($p = .0005$) (Table 2). However, plants that received struvite had similar P concentration and P uptake (response ratios of 0.99 and 0.98, respectively) to plants receiving reference P

TABLE 1 Descriptive statistics of struvite observations from field and greenhouse experiments by crop group

Crop group	Observations		Soil mass			Experiment duration			Experiment duration/soil mass	
	Field scale	Greenhouse scale	Range	Median	Mean	Range	Median	Mean	Range	Mean
			kg			d			d kg^{-1}	
Total (307)	22% (68)	78% (239)	0.2–15	1.4	3.1 ± 3.5 (233)	11–140	51	57 ± 31 (215)	4.0–180.0	44 ± 40 (215)
Maize (109)	37% (40)	63% (69)	1–15	3.0	3.8 ± 3.7 (68)	28–135	51	54 ± 30 (48)	5.7–54.0	23 ± 14 (48)
Small grains[a] (96)	3% (3)	97% (93)	0.2–10	1.0	2.4 ± 2.9 (93)	12–115	74	64 ± 34 (94)	4.0–180.0	55 ± 38 (93)
Legumes[b] (37)	65% (24)	35% (13)	0.2–2	1.3	1.0 ± 0.6 (13)	30–45	42	39 ± 6 (13)	22.5–150.0	69 ± 54 (13)
Grasses[c] (9)	11% (1)	89% (8)	1–15	10.5	8.7 ± 6.5 (8)	11–140	98.5	87 ± 56 (8)	9.3–57.0	15 ± 16 (8)
Vegetables[d] (36)	(0)	100% (36)	0.25–10	2.0	2.8 ± 3.2 (31)	11–84	42	45 ± 20 (32)	8.4–168.0	48 ± 57 (31)
Oilseeds[e] (20)	(0)	100% (20)	1–8	2.0	3.5 ± 2.8 (20)	42–56	56	50 ± 7 (20)	5.4–42.0	24 ± 13 (20)

Note. Values following ± are SD. Values in parentheses indicate the number of observations.
[a]Amaranth, barley, buckwheat, oats, rye, sorghum, triticale, wheat.
[b]Alfalfa, broad bean, chickpea, lupine, soybean.
[c]Rye forage and fescue.
[d]Cabbage, chard, garden cress, lettuce, purslane, spinach, tomato.
[e]Canola and sunflower.

fertilizers ($p = .057$ and 0.198 for P concentration and uptake, respectively). At the greenhouse scale, the mean struvite response ratio for aboveground biomass was 0.91, which was also significantly lower than 1.00. Mean aboveground P concentration and P uptake response ratios for greenhouse studies were not significantly different from 1.00 (1.10 and 1.02, respectively). Mean responses of the three aboveground P variables to struvite were within 10% of the mean for plants receiving ammonium phosphates or superphosphates across experimental scales (i.e., response ratios >0.90 and <1.10). Greenhouse crop responses varied widely compared with field experiments across all three response ratios. Despite marked differences in growing conditions (Table 1) and soil texture (Figure 2) by experimental scale, greenhouse response ratios were not significantly different from field-scale ratios for any aboveground measurement, although response ratios at the field scale were more narrowly distributed than at the greenhouse scale (not shown).

3.4 | Greenhouse experiment duration and soil mass

In general, aboveground biomass, aboveground P concentration, and aboveground P uptake response ratios declined with increasing experiment duration to soil mass ratios for ammonium phosphate and superphosphate treatment comparisons (Figure 3). The response ratio of aboveground biomass was ≈1.00 (combined ammonium phosphate and superphosphate comparisons) for experiments of short duration and/or using larger soil masses (duration/soil mass <20 d kg^{-1}) and <1.00 with experiment duration to soil mass ratios >20 d kg^{-1} (Figure 3a). As experiment duration normalized to soil mass increased, the biomass response ratio of struvite relative to ammonium phosphates decreased ($p = .001$) and was similar compared with superphosphates ($p = .23$) (Figure 3a). Aboveground P concentration was relatively higher for struvite relative to ammonium phosphates at lower experiment duration/soil mass ($p = .03$) (Figure 3b). Aboveground P concentration response ratios for struvite compared with superphosphate was constant (slope $p = .66$) across experiment duration/soil mass. Mean aboveground P uptake response ratios were >1.00 for experiment duration/soil mass <15.7 d kg^{-1}, regardless of the reference P fertilizer (Figure 3c), but declined sharply as experiment duration/soil mass ratio increased for both reference P fertilizers ($p = .0001$ and .001 for ammonium phosphates and superphosphates, respectively). Aboveground P uptake from struvite was equal to the reference P fertilizers at an experiment duration/soil mass of 15.7 d kg^{-1}, which was nearly threefold less than the mean experiment duration/soil mass of 44 ± 40 d kg^{-1} soil (median, 29 d kg^{-1}) for all cropping groups (Table 1).

TABLE 2 Mean and range of response ratios of aboveground biomass, P concentration, and P uptake, with *p* values comparing struvite response ratio to reference P fertilizers of ammonium phosphate and superphosphate (response ratio of 1.00) at the field and greenhouse scales

	Aboveground biomass	Aboveground P concentration	Aboveground P uptake
Field scale (66)			
Struvite mean response ratio	0.94 (15)[a]	0.99 (59)	0.98 (66)
Struvite response ratio range	0.85–1.00	0.80–1.06	0.72–1.38
Model P fertilizer comparison *p* value	.0005a	.0572	.1984
Greenhouse scale (186)			
Struvite mean response ratio	0.91 (173)	1.10 (68)	1.02 (104)
Struvite response ratio range	0.10–1.52	0.57–1.56	0.06–2.02
Model P fertilizer comparison *p* value	.0035	.1556	.7529

[a]Values are significantly different from 1.00 at α = .05. The numbers of observations for each mean response ratio are in parentheses

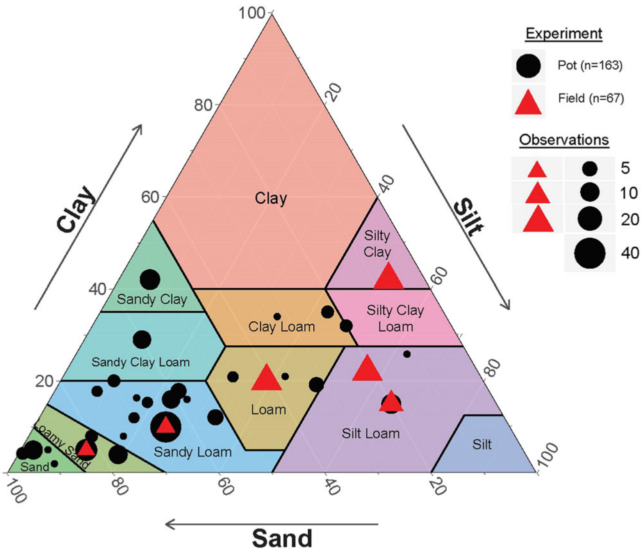

FIGURE 2 Soil textures (USDA) identified in field (red triangles) and greenhouse experiments (black circles) evaluating the agronomic potential of struvite. Symbol size corresponds to the number of observations.

3.5 | Soil pH

Struvite experiments were conducted in soils with a wide range of soil pH (from 4.5 to 8.5). Forty-one (21%) struvite observations were generated in experiments using acidic soils (pH < 6.0), in which aluminum and iron P fixation potential is greatest, 116 (58%) observations were generated in the soil pH range of 6.0 to 7.0 where P availability is greatest, and 42 (21%) observations were generated when struvite was applied to alkaline soils and where calcium P fixation potential is greatest (Supplemental Figure S1). Soil pH had a significant effect on aboveground biomass, P concentration, and P uptake response ratios (Figure 4a–c). Response ratios varied widely within crop group and experimental scale and differed depending on the reference P fertilizer (Figure 4a–c).

Averaged across all experimental scales and crop groups, aboveground biomass of struvite treatments relative to all other fertilizer-P sources decreased significantly as soil pH increased (p = .013) (Figure 4a). When aboveground biomass response ratios were separated by the reference P fertilizer, mean struvite response ratios appeared to be greater relative to superphosphates than ammonium phosphates (Figure 4d). Mean aboveground P concentration response ratios were >1.00 in soils with acidic pH and <1.00 for soils with alkaline pH. Aboveground P concentration response ratios decreased with increasing pH, similar to the biomass response (p = .002) (Figure 4b). Struvite response ratios for P concentration did not significantly differ from 1.00 relative to superphosphates across the pH range of 5.2 to 7.6 (Figure 4e). When compared with ammonium phosphates, P concentration response to struvite decreased significantly with increasing pH, with responses >1.00 in acidic soil pH and <1.00 at alkaline pH. Overall, aboveground P uptake response ratios also decreased with increasing pH (Figure 4c). Similar to biomass and P concentration, aboveground P uptake response ratios relative to superphosphates did not significantly differ from 1.00 across the soil pH range of 4.5 to 8.0 (Figure 4f). Mean response ratios relative to ammonium phosphates approached 1.00 at acidic soil pH and declined with increasing pH. Depending on the crop response of interest, struvite treatments performed equally as well as reference P fertilizers (response ratio = 1) at different soil pH. Struvite aboveground biomass response was similar to reference fertilizers at pH 4.5. Response ratios were similar for P concentration and P uptake at pH 6.4 and 5.7, respectively, with these pH values occurring in the lowest 50% of pH levels across struvite observations. Despite the textural difference between the sandy-textured soils used in pot studies and the silty-textured soils in field studies, mean response ratios were similar between field and greenhouse studies (not shown), and response ratio trends were similar across the pH range in the dataset (Supplemental Figures S5–S7).

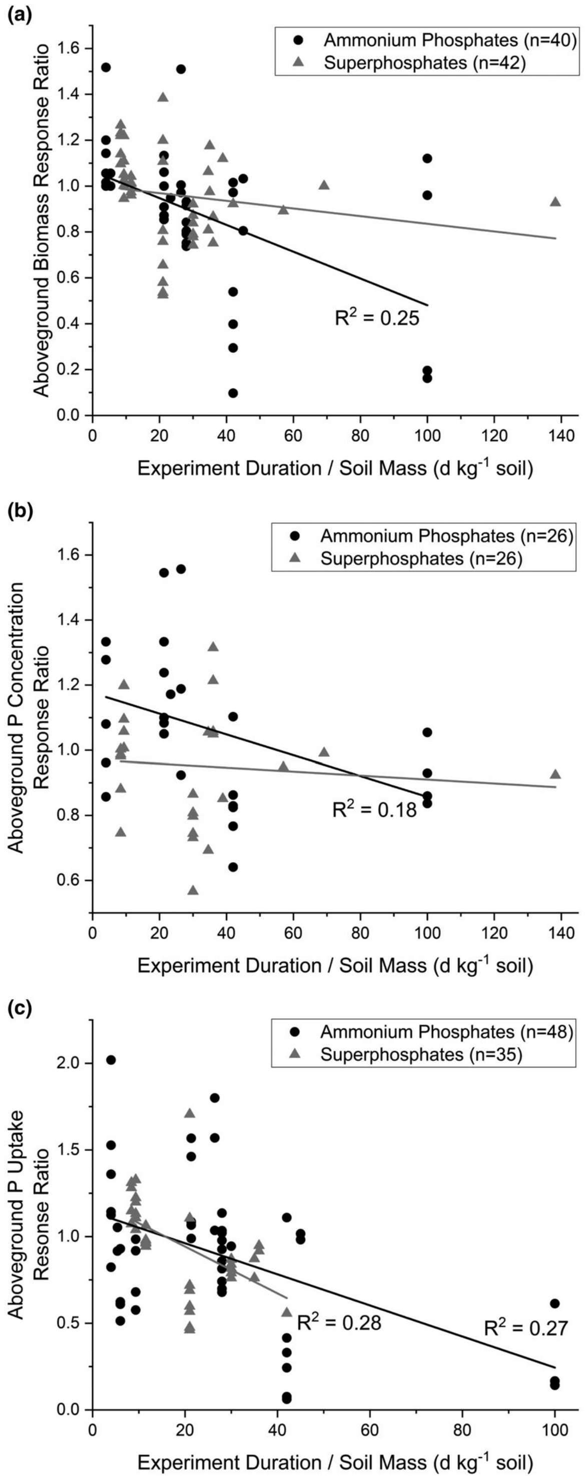

FIGURE 3 Relationship of the experiment duration to soil mass ratio (total days of experiment divided by the soil mass used) used in greenhouse studies (d kg^{-1}) with (a) aboveground biomass response ratio, (b) aboveground P concentration response ratio, and (c) aboveground P uptake response ratio. Data were separated by struvite comparisons to the reference P fertilizer of ammonium phosphates (circles) and superphosphates (triangles). Slope p values for ammonium phosphate comparisons were (a) .0012, (b) .0304, and (c) .0001. Slope p values for superphosphate comparisons were nonsignificant (a and b) and .001 ($\alpha = .05$) (c).

3.6 | Phosphorus application rates and soil test phosphorus

Field and greenhouse experiments in the dataset exhibited wide ranges of STP and P application rates (Table 3). Maize was grown in field experiments predominantly (90% of observations) in soils with a STP level classified as low, and the other 10% of the observations were from soils with a STP level classified as high. Phosphorus application rates considered high to excessive accounted for 39% of field maize observations. Although small grains were mostly grown in greenhouse experiments (95% of total observations), limited observations at the field scale ($n = 3$) were generated using soils with high STP and high to excessive P application rates. Although field evaluations of all other crops were generally conducted using soils with low STP, nearly two-thirds of these observations used high to excessive P application rates.

Greenhouse-scale studies differed from field-scale studies by using soils with high STP (29 vs. 15% of observations) and often high to excessive application rates (58 vs. 50% of observations) (Table 3). Soil test P and application rates in greenhouse-scale observations differed by crop. For example, 76% of greenhouse observations for maize were generated using soils with STP considered adequate for maize, and a similar proportion of observations were generated using high to excessive P application rates. Observations for small grain crops, which were predominantly from greenhouse experiments (Table 2), tended to use soils with either high STP (39%) or low STP (35%) and used high to excessive P rates (83%). In greenhouse experiments, all other crops were most often grown in low STP soils (44%), followed by optimal STP (38%) and high STP (19%). For other crops, high to excessive P rates were used in 59% of greenhouse observations.

Linear relationships between P application rates and aboveground biomass, P concentration, and P uptake response ratios were not significant overall, but differences in response ratios were observed when data were grouped by reference P fertilizer (Figures 5a–c). Aboveground biomass response to ammonium phosphates was consistently greater than the response to struvite (mean response ratio, 0.911) and did not have a linear relationship across a 56-fold range of fertilizer-P application rates of 4 to 228 mg P kg^{-1} (Figure 5a) ($p = .84$). Aboveground P concentration response ratios were statistically similar to that of superphosphates ($p = .36$) and ammonium phosphates ($p = .27$) across P rates (Figure 5b). Aboveground P uptake response ratios were constant across fertilizer-P rates relative to superphosphates ($p = .25$) and ammonium phosphates ($p = .68$) (Figure 5c). Struvite-ammonium phosphate P uptake response ratios were consistently less than 1.00 across fertilizer-P rates. Aboveground biomass response ratios of control (P-unfertilized) treatments to ammonium phosphates and superphosphates had an overall mean of 0.59

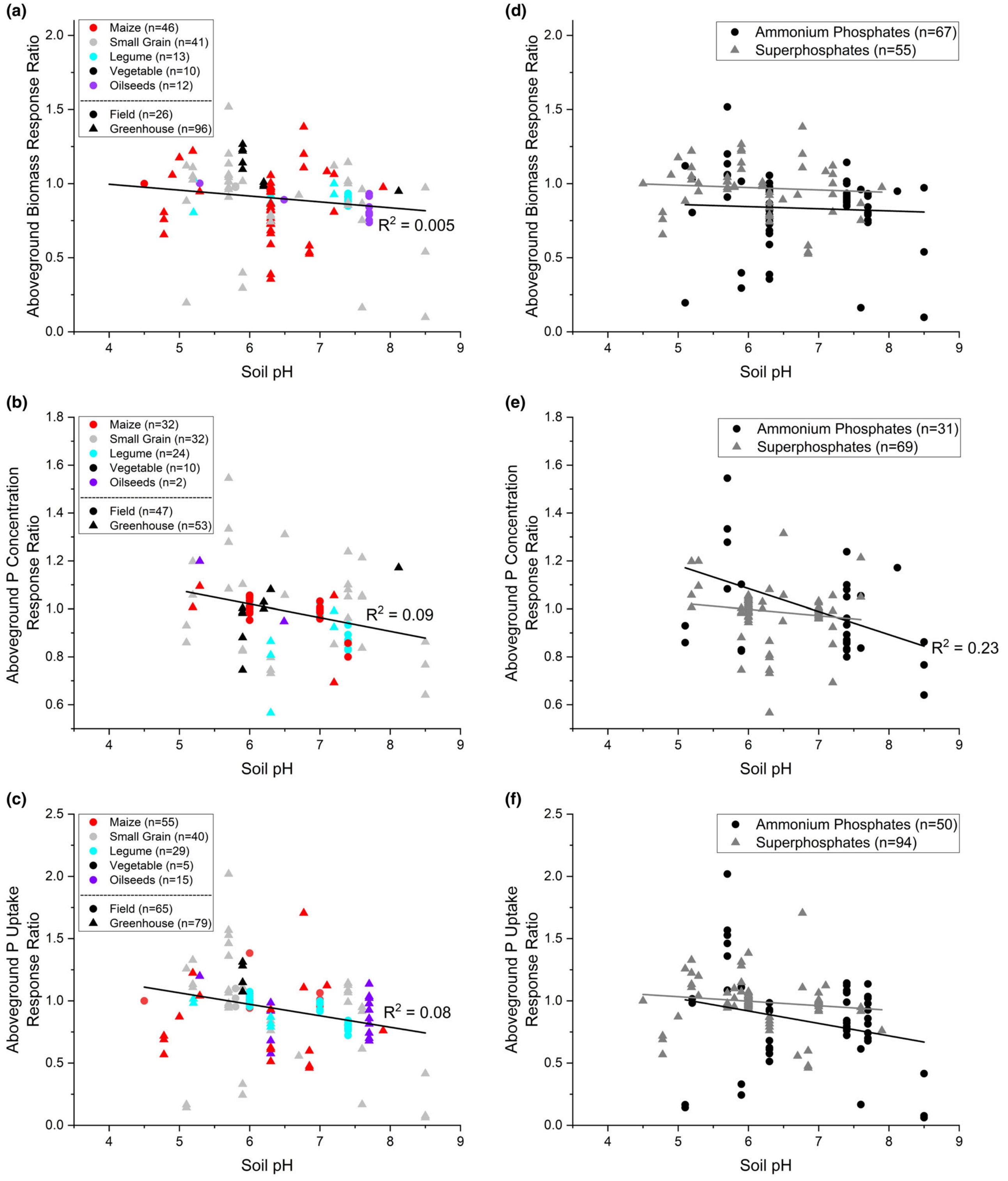

FIGURE 4 Soil pH effects on (a) aboveground biomass response ratios, (b) aboveground P concentration, and (c) aboveground P uptake response ratios identified by crop species and field or greenhouse scale, and (d–f) separated by the reference P fertilizer to which struvite was compared: ammonium phosphate and superphosphate. Slope *p* values were (a) .126, (b) .0023, and (c) .0005. Slope *p* values for ammonium phosphate comparisons were nonsignificant (d and f) and .0071 (e). Slope *p* values for superphosphate comparisons were nonsignificant (d–f; $\alpha = .05$).

TABLE 3 Percent of struvite observations classified as high, optimal, or low soil test P (STP) and non-excessive or excessive P application rates in field and greenhouse experiments for maize, small grains, and all other crops (vegetables, oilseeds, legumes, and non-maize grasses)

	Maize (n = 39)		Small grains (n = 3)		All other crops (n = 24)	
	Non-excessive P application	Excessive P application	Non-excessive P application	Excessive P application	Non-excessive P application	Excessive P application
	%					
	Field experiments (n = 66)					
High STP	5.1	5.1	0.0	100.0	0.0	0.0
Optimal STP	0.0	0.0	0.0	0.0	0.0	0.0
Low STP	56.4	33.3	0.0	0.0	37.5	62.5
	Greenhouse experiments (n = 113)					
	Maize (n = 29)		Small grains (n = 52)		All other crops (n = 32)	
High STP	6.9	17.2	5.8	32.7	0.0	18.8
Optimal STP	20.7	55.1	1.9	25.0	6.3	31.3
Low STP	0.0	0.0	9.6	25.0	34.4	9.4

Note. Soil test P and P application rate designations were determined for each crop separately from agronomic literature. See Materials and Methods and Supplemental Table S2 for details.

(Supplemental Table S3). For observations in which STP was considered high, control treatments had a mean aboveground biomass response ratio of 0.81. Mean aboveground biomass response ratios were 0.65 and 0.47 for control treatment observations with low and unreported STP, respectively.

3.7 | Struvite particle size

Struvite particle size was reported for 34% of the struvite observations, and particle diameters were limited to either <1.0 or >2.3 mm, with a maximum diameter of 3.0 mm. Struvite particle size did not influence mean aboveground biomass (p = .17) or P uptake (p = .43) response ratios (Figure 6b). Mean aboveground P uptake was similar for struvite as for ammonium phosphates and superphosphates regardless of struvite particle size (not shown).

3.8 | Struvite-derived nitrogen

Struvite P application rate was strongly correlated ($p < .0001$) with the proportion of total N applied in each experiment as struvite NH_4–N. In general, as P application rate increased, the proportion of total N applied as struvite also increased (Figure 7). Observations for which struvite N accounted for 100% of N applied were generated from experiments using ammonium phosphates as reference P fertilizers and spanned fertilizer-P application rates from <10 mg P kg^{-1} to >228 mg P kg^{-1}. A fertilizer-P application rate of 10 mg P kg^{-1} does not provide sufficient N for most crops (i.e., 4.0 mg N kg^{-1} from struvite, 4.3 mg N kg^{-1} from monoammonium phosphate) and would therefore require additional N input.

Aboveground biomass response ratios were consistently <1.00 across all proportions of total N derived from struvite, with a nonsignificant slope (p = .57) (Figure 8a) and a mean response ratio of 0.89, which was not significantly different from 1.00. Mean aboveground N uptake response ratios were highly variable, and observations were available only for the extremes of <20% and 100% of total N applied derived from struvite (Figure 8b). Aboveground biomass response ratios comparing struvite with ammonium phosphates were well below 1.00 regardless of the proportion of struvite-derived N (Figure 8c). When compared with superphosphates, aboveground biomass response ratios were consistently <1.00 across all proportion of struvite-derived N (Figure 8c), and N uptake response ratios were <1.00 when the proportion of struvite-derived N was >0.1, or 10% of total N applied (Figure 8d). The only N uptake observations (n = 8) in which struvite was compared with ammonium phosphates were conducted with no additional N input, signifying that 100% of the total N rate was from the P source. Within this subset of observations, aboveground N uptake consistently decreased for struvite treatments compared with ammonium phosphates with increasing P application rate (p = .02) (Figure 8e).

4 | DISCUSSION

4.1 | Historical trends in research on struvite as a phosphorus fertilizer

The potential of struvite as a "perennial" P fertilizer was first proposed in 1858 due to its lower water solubility, which was hypothesized to be an advantage over "annual" phosphate fertilizers that were "too soluble" (Murray, 1858). It was

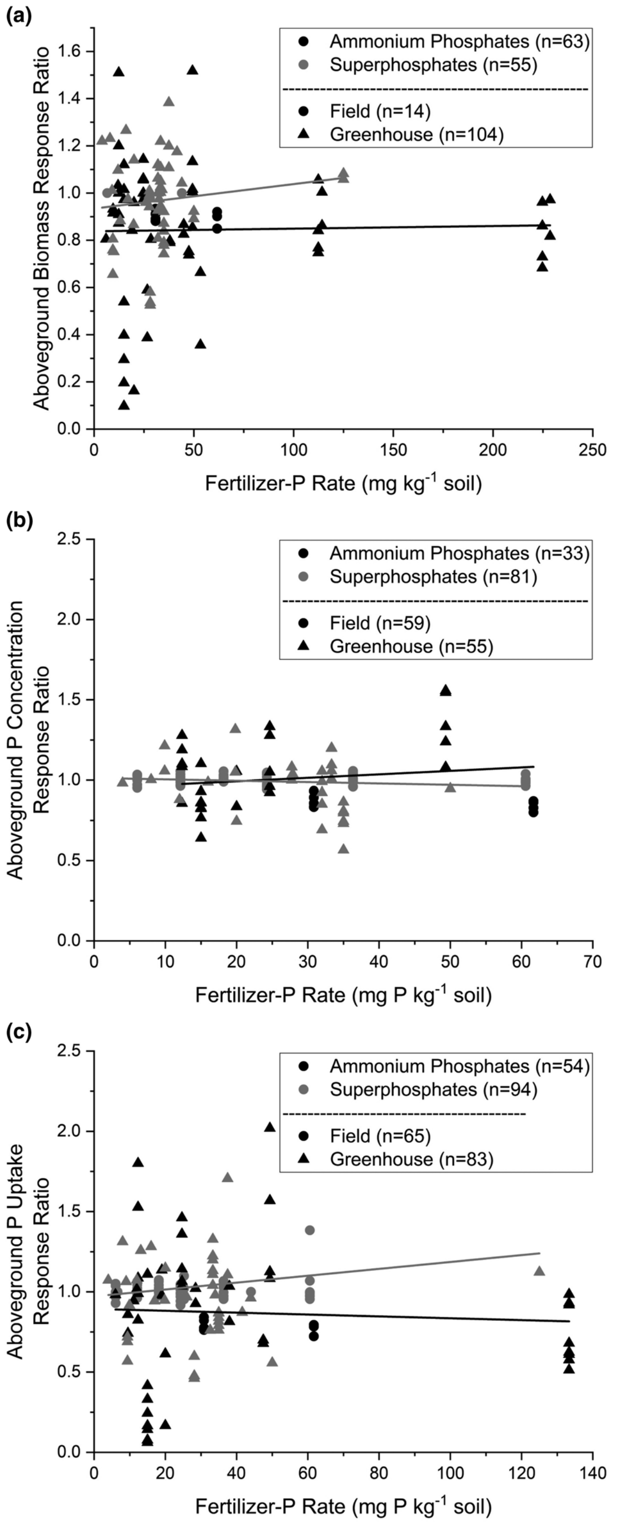

FIGURE 5 Fertilizer-P application rate (mg P kg^{-1}) compared with crop response ratios of (a) aboveground biomass, (b) aboveground P concentration, and (c) aboveground P uptake. Observations were separated by struvite comparison to ammonium phosphate or superphosphate and by experimental scales greenhouse and field. Values originally reported as field-based rates (lb ac^{-1} or kg ha^{-1}) were converted to mg kg^{-1} to enable comparison of observations across studies. All slope *p* values were nonsignificant (α = .05).

not until 1933 that "magnesium ammonium phosphate" was again mentioned as a potential fertilizer (Bartholomew & Jacob, 1933; Illoyskaya, Podolskaya, & Dmitriev, 1933). Despite this, additional experimental evaluations of struvite did not occur until 1962, coinciding with the tripling in global P fertilizer consumption during 1961 to 2006 from approximately 5 million tons P to approximately 17 million tons P annually (Bridger et al., 1962; Cordell & White, 2011). These P fertilizers are ultimately derived from mined phosphate rock, largely as acidulated (i.e., superphosphate) or ammoniacal (e.g., monoammonium phosphate) forms (Mikkelsen, 2019; Roberts, 2019).

Research on struvite as a fertilizer remained relatively stagnant, with few studies conducted until the 1990s and 2000s, coinciding with several potential landmark events related to P usage and environmental concerns. European governmental interest in sustainable P management led to the creation of P point and non-point regulations in 1991 with the European Union Urban Waste Water Treatment Directive, providing a foundation for future regulation. Eventually, the European Commission delivered a detailed report to the European Parliament in which they called for more sustainable P use in 2011. The report stated the need to reduce reliance on rock phosphate reserves, to engineer approaches to recycle and reuse P, and to develop strategies to limit P losses, estimated to be 1217 Gg P in 2005 (51% of total P inputs), at multiple steps of the anthropogenic P cycle (European Commission, 2011, 2013; van Dijk, Lesshen, & Oenema, 2016).

The European Sustainable Phosphorus Platform, a collection of over 150 organizations devoted to P sustainability, was created in 2013 to promote the exchange of knowledge and experience in the management and sustainability of nonrenewable P resources (ESPP, 2019). This may explain why the majority of publications on agronomic evaluations of struvite (28/55) originated from the European Union. Concurrent with the rise in European Union efforts on P stewardship, the "Peak Phosphorus" concept was proposed in 2011. Peak Phosphorus is defined as the point of maximum phosphate rock production after which production declines as finite reserves of phosphate rock are not be able to meet P demand and was forecasted to occur in 2033 (Cordell & White, 2011). Although the Peak Phosphorus concept has been contested for not accounting for changes in P pricing based on supply-demand dynamics (Vaccari & Strigul, 2011) and for using modeling techniques found to be inaccurate (Scholz & Wellmer, 2013), its implication of eventual global P limitation has spurred interest in intensifying recycling of P in the human trophic chain (Ulrich & Schnug, 2013). Struvite has the potential to alleviate reliance on imported phosphate rock or its manufactured products (e.g., P fertilizers) by enabling recirculation of P.

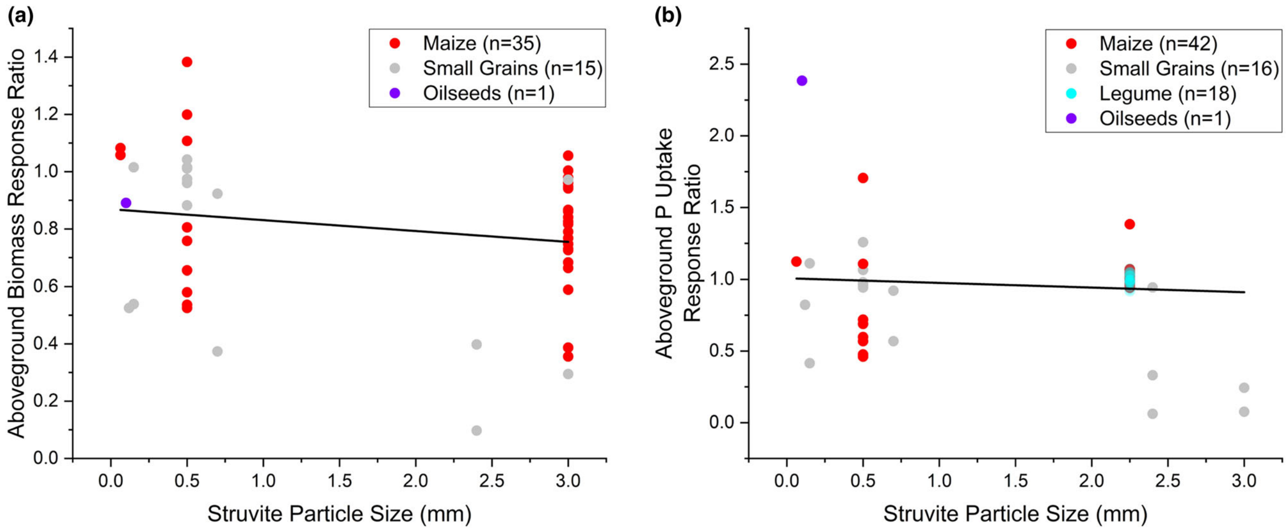

FIGURE 6 The relationship of struvite particle diameter size to (a) aboveground biomass and (b) aboveground P uptake response ratios. Struvite response ratios are a combination of ammonium phosphate and superphosphate comparisons. There were insufficient observations for aboveground P concentration response ratios. Slope *p* values were nonsignificant (α = .05).

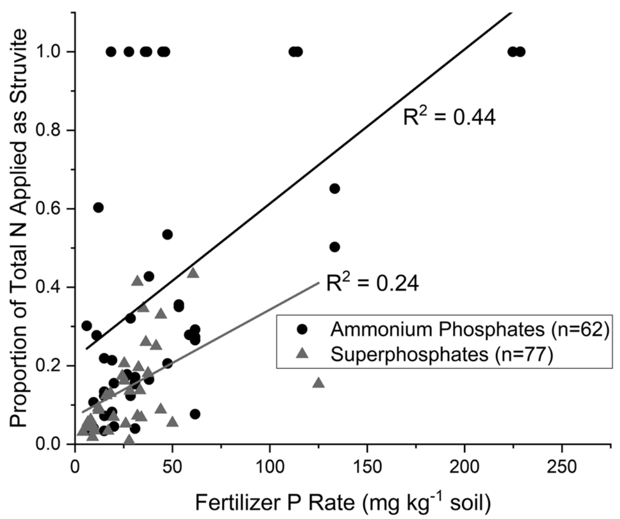

FIGURE 7 Relationship of struvite P application rate (mg P kg^{-1}) and the percent of total N applied as struvite separated by the reference P fertilizer of ammonium phosphates and superphosphates. Slope *p* values were <.001 for ammonium phosphates and superphosphates (α = .05).

4.2 | Struvite solubility

Struvite solubility is generally greater in citrate-based solubility assays compared with water alone (Ostara Nutrient Recovery Technologies Inc., 2019; Rech, Withers, Jones, & Pavinato, 2019), but the reported solubility varies by struvite source and/or study. The struvite product marketed by Ostara Inc. as Crystal Green is reported to be 4% water soluble and 96% citrate soluble (Ostara Nutrient Recovery Technologies Inc., 2019). However, citrate solubility can differ depending on the source and purity of struvite and the method of determining citrate solubility. Citrate solubility of struvite produced from poultry manure, swine manure, and municipal wastewater (Crystal Green) has been reported to be 18, 28, and 29%, respectively, whereas water solubility was lower and more constrained at 2–3% (Rech et al., 2019). This is comparable to the water solubility and combined neutral ammonium citrate + water solubility of monoammonium phosphate (21.9 and 23.5%, respectively) (Maluf, Silva, de Morais, & de Paula, 2018) but vastly different from that of TSP (82 and 97%, respectively) (Prochnow, van Raij, & Kiehl, 2002). Citrate solubility means struvite dissolution could be driven by organic acids exuded by plant roots, consistent with in vitro dissolution experiments using pure organic acids (Talboys et al., 2016). In situ, variation in exudate type and concentration by crop species creates a potential for crop-specific response to struvite. Responses of maize, *Sargassum vulgare*, amaranth, and cereal rye (species also found in the dataset analyzed here) to struvite and TSP were previously tested and showed no significant difference in aboveground biomass between the two P sources (Vogel, Nelles, & Eichler-Lobermann, 2015). There was, however, a significant difference in P uptake for all crop species attributed to crop-specific exudation of organic acids. Substantial variation in the amounts of organic acids (e.g., up to three orders of magnitude) as well as the type of organic acids (e.g., citrate as 10–100% of total organic acid exudates) has been identified for maize, wheat, canola, lupine, soybean, broad bean, chickpea (Lyu et al., 2016).

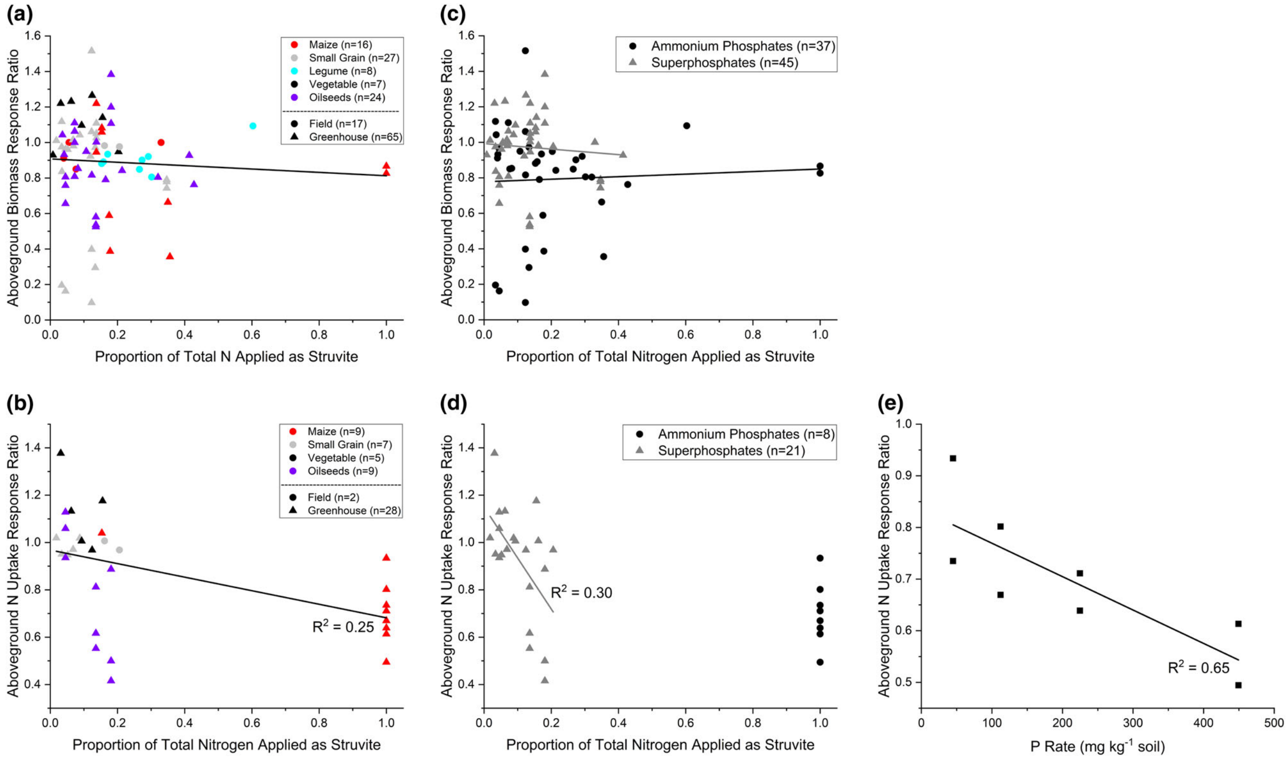

FIGURE 8 The relationship of the proportion of total N applied as struvite compared with (a) aboveground biomass and (b) aboveground N uptake response ratios. Response ratios were evaluated by crop species and experimental scale. (c and d). Data were also separated by reference P fertilizers of ammonium phosphate and superphosphate. (e) The relationship of aboveground N uptake response ratios to P application rate for the observations comparing struvite to ammonium phosphates in which 100% of the total N was derived from the P application rate. Slope *p* values were (a) nonsignificant, (b) .0061, (d) .0097, and (e) .0152. Slope *p* values were nonsignificant for ammonium phosphate and superphosphate comparisons (c; α = .05).

4.3 | pH and struvite particle size

A significant and inverse relationship between pH and struvite response ratios supports the hypothesis that struvite dissolution and thus crop availability is favored by acidic soil pH values. Aboveground biomass response ratios were less affected by pH compared with P concentration and P uptake in the aboveground biomass, indicating that crop biomass was affected by factors beyond P source, such as STP. At soil pH 4.5, struvite yielded the same aboveground biomass as the reference P fertilizers, indicating that, analogous to phosphate rock (Margenot, Singh, Rao, & Sommer, 2016; Szilas, Semoka, & Borggaard, 2007), strongly acidic soils are more amenable to full substitution of highly water-soluble P fertilizers with struvite. Shorter experiment durations may mute differences in biomass response across the pH gradient because less total amount of P is needed during early growth (Bender, Haegele, Ruffo, & Below, 2012). Conversely, early-season P limitation may be observed due to limited root volume and P movement in cool soils.

Phosphorus-specific plant response variables of P concentration and total uptake were most affected by differences in pH likely because of the known differences in struvite P dissolution as a function of pH (Bhuiyan et al., 2007; Booker et al., 1999). Struvite solubility in the circumneutral pH range can vary by several orders of magnitude because the monoprotic to diprotic pK_a of phosphoric acid is 7.2 (Doyle & Parsons, 2002). Degryse, Baird, da Silva, and McLaughlin (2017) found nearly ninefold lower struvite dissolution rates in soils with alkaline pH up to 8.5 than in soils with acidic pH as low as 5.9 in the absence of plants (0.005 and 0.43 mg d^{-1}, respectively). Aboveground biomass of wheat grown in these two soils exhibited greater P concentration and total P uptake with monoammonium phosphate granules compared with 3-mm-diameter struvite granules, but finely ground struvite (<0.15 mm) led to similar wheat P uptake as finely ground monoammonium phosphate. This suggests struvite dissolution is a function not only of pH but also particle size, although the inverse relationship of struvite particle size and dissolution rate in situ does not necessarily reflect dissolution rates measured in soil incubations due to differences in soil–struvite surface area contact (Achat et al., 2014; Cabeza, Steingrobe, Romer, & Claassen, 2011). However, aboveground biomass and P uptake were not significantly affected by struvite particle size. This may have been a result of a non-normal particle size distribution because there were no observations in which struvite particle sizes were between 1 and 2.25 mm diameter. This likely reflects the binary particle size distribution of struvite observations as either finely ground or as granules given that most granulated P fertilizers have a mean diameter of 3 mm (Incitec Pivot Fertilisers, 2016). Response ratios corresponding to observations in which struvite granules of 3 mm outside diameter were used varied widely (0.29–1.06) and were limited to one study using a single soil with pH 6.2. The inverse relationship of struvite particle size and the small grain response ratios are consistent with previous greenhouse evaluations of wheat (Degryse et al., 2017).

4.4 | Experimental design and confounding parameters

Experimental designs were inconsistent across studies and thus complicated predictor variable–crop response relationships. Experiment duration in conjunction with the mass of soil used in greenhouse experiments may account for the absence of crop group–specific trends. Crop-specific rates of P uptake can change across crop growth stage as P allocation shifts from biomass to grain production (Bender et al., 2012). For example, approximately 50% of the total P uptake by maize occurs by the beginning of its reproductive stages (Bender et al., 2012). Therefore, maize experiments with short durations limited to nonreproductive growth are unable to offer insight on crop P demand that would occur in a field setting. Because there were insufficient grain or seed yield data, response ratios were limited to aboveground growth and at vegetative stages rather than grain yield, which is the preferred metric of fertilizer performance.

Experiment duration normalized to soil mass (d kg^{-1}) was not an accurate predictor of root restriction because it did not exhibit the hypothesized positive trend with crop response ratios (Figure 3). Instead, the metric identified substantial variability among studies in the database, potentially further exacerbated by coarse-textured soils used at the greenhouse scale that could promote P availability and vertical movement compared with the fine-textured soils in field studies. Pot dimensions and plant density per pot could benefit from standardization to constrain root–fertilizer interaction caused by increased root density on crop responses in pot studies. Maize, which is the crop with the largest biomass production potential in the present meta-analysis, was grown using 23 d kg^{-1} on average, whereas lower-biomass grasses were generally grown using 15 d kg^{-1}. Soil masses required for greenhouse studies to avoid root restriction are dependent on the size of the crop species and experiment duration, although there is a lack of research on crop-specific soil masses to avoid artificially high root densities. Overly dense root concentrations could overestimate struvite dissolution rates due to the high concentration of root exudates near the fertilizer granule, although this could mimic soil–struvite–root interactions in the zone of fertilizer banding (i.e., struvite placement directly in the seed furrow). Shallow-banding triple superphosphate has been found to improve maize yield over broadcast and deep banding for no-till, conventional tillage, and deep tillage treatments (Alam et al., 2018).

Soil test P levels and P application rates may have confounded results from experiments in the dataset. By supplying sufficient P from a nonstruvite source, high soil test P values may have artificially increased apparent plant response to struvite and could explain apparent nonsignificant differences in plant response to struvite relative to ammonium phosphates and superphosphates. For example, a field-scale evaluation of barley, forage rye, and sorghum in a soil with slightly high STP (55 mg double lactate P kg^{-1}) reported equal crop growth with struvite and superphosphate, although the unfertilized control treatment yielded 90, 79, and 72% of the biomass of barley, forage rye, and sorghum obtained for superphosphate, respectively (Vogel, Nelles, & Eichler-Lobermann, 2017). Another study recorded a 15% apparent P fertilizer recovery in a sandy loam (Olsen P 28 mg L^{-1}) classified as “medium P level” for maize, but Olsen P levels as low as 12–15 mg kg^{-1} are often considered sufficient for maize (Johnston & Richards, 2003; University of Minnesota Extension, 2019). The best growth results reported were for mung bean [*Vigna radiata* (L.) R. Wilczek] using struvite-P rates as high as 250 mg P kg^{-1}, corresponding to an unrealistic field rate of 560 kg P ha^{-1} compared with an agronomically appropriate rate of 56 kg P ha^{-1} as diammonium phosphate (Prabhu & Mutnuri, 2014). The positive confounding effect of high STP for struvite relative to the reference P fertilizers is especially likely in greenhouse studies because P application rates at this experimental scale were generally excessive (Table 3). A similar confounding effect was identified in a meta-analysis of AVAI, a long-chain dicarboxylic acid copolymer P use efficiency additive designed to chelate P-fixing ions. The addition of AVAIL to P fertilizer was found to increase yields when STP values were low but did not significantly increase yields when STP levels were high (Hopkins, Fernelius, Hansen, & Eggett, 2017). Additionally, yield increases under both STP conditions compared with the control of P fertilization without AVAIL were not significantly different. When P application rate was categorized as low or high for vegetable production, normalized yield increases from AVAIL were significantly greater under low P application rates compared with high P rates. This demonstrates the potentially significant confounding effect of using soils with high availability of P derived from the preapplication soil test P pool and/or application rates.

4.5 | Struvite-derived nitrogen

Unlike N sourced from monoammonium phosphate and diammonium phosphate, the majority of struvite N is presumably not immediately available for plant uptake due to its low water solubility. An increase in the proportion of total N applied as struvite NH_4–N may increase the risk of early-season N limitation due to the slow dissolution of struvite. Greater P and N uptake was reported for maize and annual ryegrass (*Festuca perennis*) using struvite with additional N or ammonium phosphates compared with struvite without additional N (Szymanska et al., 2019). Lower plant N uptake with the application of struvite without additional N compared with ammonium phosphate may be due to relatively low dissolution rate of N, congruent with P (Bhuiyan, Mavinic, & Beckie, 2009), from struvite compared with ammonium phosphates (Szymanska et al., 2019).

This meta-analysis suggests that low availability of struvite N and thus the management of additional N inputs may influence apparent P-based crop responses to struvite. To the extent N limitation affects crop growth, the apparent crop P responses to struvite could be confounded by greater physiological need for N (1.5% dry mass basis) compared with P (0.2%) (Havlin et al., 2014). Struvite comparisons to superphosphate could be confounded by N limitation if struvite-N is credited to plant growth at sufficient or suboptimal rates because the N applied in superphosphate treatments to balance the total N rate is likely to be from a fertilizer source that is readily available (e.g., urea, ammonium nitrate). Greater proportions of total N application derived from struvite negatively affected aboveground N uptake, which is consistent with the hypothesis of lower availability of struvite N. That overall aboveground biomass responses were not correlated with P application rate suggests that biomass was not driven by P availability. The only struvite N uptake responses compared directly with ammonium phosphates were for a limited set of maize observations (Figure 8e), which could not be evaluated across a gradient of struvite-derived N because 100% of the total N was derived from the P source. Maize N uptake from struvite relative to monoammonium phosphate decreased as P rate increased, consistent with greater availability of ammonium phosphate N relative to struvite N. To prevent crop reliance on struvite N and to eliminate the potentially confounding N limitation, struvite comparisons to ammonium phosphates and superphosphates should entail a total N rate that does not include struvite N.

5 | RECOMMENDATIONS AND FUTURE DIRECTION

5.1 | Experimental design recommendations

Weak and often nonsignificant correlations between explanatory variables and response ratios may be in part due to variability in experimental designs and unintentional confounding parameters. Measurements of yield, belowground biomass and/or belowground P uptake, and changes in STP were limited, but would have enabled a more thorough assessment of struvite as a P fertilizer. A field evaluation of maize and soybean fertilized with struvite and TSP over 4 yr measured both yield and changes in STP (Thompson, Mallarino, & Pecinovsky, 2013). Similar yields and changes in STP (15.6 and 18.9 mg Mehlich-3 P kg^{-1} for TSP and struvite applied at 120 kg P ha^{-1}, respectively) between struvite and TSP were observed at fertilizer rates from 12 to 120 kg P ha^{-1} for both crops. Radiolabeling struvite, as well as reference P fertilizers, with ^{32}P or ^{33}P offers differentiation of P uptake from struvite versus non-struvite sources (i.e., soil, seed reserves). For example, although there was no significant difference in overall P uptake by a mixture of ryegrass and fescue (40% *Lolium perenne*, 60% *Festuca rubra*) between TSP and struvite, radiolabeling (^{32}P) revealed soil-P as the largest proportion (< 60%) of total P uptake in both treatments, followed by fertilizer-P (Achat et al., 2014).

Greenhouse studies could be designed to better mimic in situ conditions to increase comparability with field-scale studies. The high sand content of soils and the low root per unit soil ratio common in greenhouse studies can result in high P availability, which is further exacerbated by high STP and/or unrealistically high P application rates. Soil masses should be calculated based on experiment duration and crop-specific traits (e.g., belowground biomass, root proliferation, P scavenging ability) to avoid root restriction, overestimation of struvite efficacy from high concentrations of root exudates, and overestimation of apparent struvite efficacy from overreliance on soil-derived P. It would not be feasible for greenhouse soil masses to match the soil mass accessible to root systems of most crops grown to maturity in the field. Assuming a maize plant population of 75,000 ha^{-1} (Abuzar et al., 2011), a maize rooting depth of 2.4 m (Baker, Ochsner, Venterea, & Griffis, 2007), a 120-d growing season, and a soil bulk density of 1.3 g cm^{-3} would be equivalent to 416 kg per plant and an experimental duration to soil mass ratio of 0.29 d kg^{-1}, or nearly 80-fold less than the mean experiment duration/soil mass for greenhouse maize in the dataset (23 d kg^{-1}). The vast reduction in soil masses used in greenhouse studies compared with field-scale studies

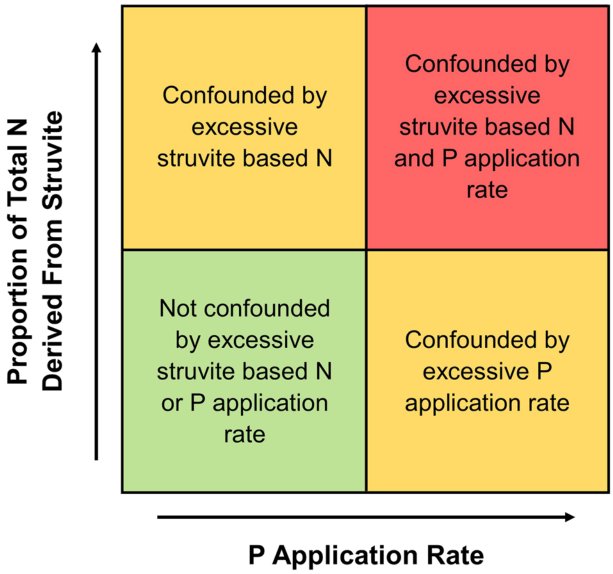

FIGURE 9 Conceptual diagram of the possible results confounding effects of P application rates and the proportion of total N derived from struvite.

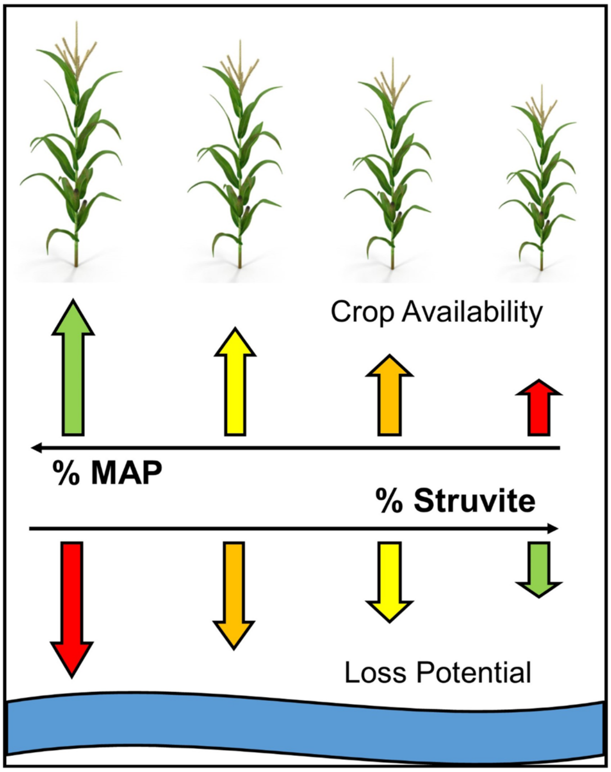

FIGURE 10 Concept of the differences in crop availability and loss potential between monoammonium phosphate (MAP) and struvite.

suggests an unrealistically high root density. Compensation for this mismatch in soil masses would be difficult but could be managed by shortening experimental durations and/or increasing soil mass. There is a need for additional field evaluations of struvite that evaluate yields, in particular for economically important grain crops.

Although a range of soil pH values and different crop species were well represented in the dataset, results were likely overestimated by other parameters such as high STP and application rates. Phosphorus-responsive soils (i.e., less than optimal STP) should be used to avoid a positive confounding effect of inherently high available P that can compensate for low availability of P from struvite. Soil test P levels should be considered on a crop-specific basis, especially if the same soil is used to evaluate multiple crop species. Struvite application rates should be calculated based on STP levels and crop requirement. Ensuring that P application rates are not excessive and/or that N rates do not include struvite N avoids the confounding effect of struvite N on crop response identified in this meta-analysis (Figure 9). Specifically, struvite-derived N should not be credited toward total N application, which should be sufficient to avoid N limitation.

5.2 | Struvite blends

The consistently lower aboveground biomass from struvite treatments relative to ammonium phosphate treatments indicates that a full replacement of conventional P fertilizers by struvite is not agronomically viable. However, benefits from partial struvite substitution for conventional P fertilizers may offer environmental benefits because these highly water-soluble P fertilizers carry a greater risk for off-farm losses (Sharpley, McDowell, & Kleinman, 2001). Ahmed et al. (2016) identified less cumulative P and N leaching from struvite compared with conventional fertilizers such as superphosphates across 10 studies, highlighting the potential of struvite to lower loss risk compared with conventional P fertilizers. Blends of struvite and ammonium phosphate has the potential to maintain the soil available P levels throughout the growing season while benefiting from the hypothesized lower loss risk of P and N from struvite (Figure 10). However, little has been done at the field scale to quantify the hypothesized potential of struvite to mitigate off-farm P losses in agricultural landscapes (Margenot et al., 2019). Only three studies (not included in this meta-analysis due to lack of crop response variables) assessed the effects of struvite blended with ammonium phosphates or superphosphates (Ahmed et al., 2016; Guertal, 2015; Talboys et al., 2016). Greater P uptake by wheat (greenhouse scale) occurred with 20:80 and 10:90 blends of struvite and diammonium phosphate, compared with 100:0, 30:70, and 0:100 blends (Talboys et al., 2016), which is consistent with the recommendation by the commercial struvite supplier Ostara Nutrient Recovery Technologies Inc. to maintain struvite proportions <35% in P blends. Similar evaluations of rock phosphate and triple superphosphate blends in an acidic soil (pH $CaCl_2$ = 4.7) found that even 20% rock phosphate blends yielded significantly less maize biomass due to lower plant P uptake (Franzini, Muraoka, & Mendes, 2009). Struvite blends may be more successful than phosphate rock because struvite P is generally more citrate soluble than most phosphate rock P (Supplemental Table S3). Optimizing struvite blends with highly water-soluble P fertilizers to maintain yields based on crop species, cropping rotations, and soil context requires additional research.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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