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Fertilizing effect of wastewater-derived granular struvite on contrasting Manitoba soils

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Abstract

Wastewater-derived struvite is a promising phosphorus (P) fertilizer but more information on its behaviour in soil is needed to guide management practices for this slow-release fertilizer. After 20 days of incubation in two contrasting low-P soils in Petri dishes at two temperatures, the Olsen-P concentrations in soil surrounding struvite granules were 30–122 mg kg⁻¹, which were much lower than after amendment with monoammonium phosphate (MAP) (435–1063 mg kg⁻¹). Olsen-P concentrations further from the granule showed that MAP fertilized a larger volume of soil than struvite. Thus, the fertilizing effect of struvite may be very localized in soil.

Key words: struvite, phosphorus, fertilizer, soil

Introduction

Most phosphorus (P) fertilizers are sourced from mined mineral apatite processed to create highly soluble formulations such as ammonium phosphates. Fertilizers with high solubility can satisfy crop P demands but can also increase off-site transport of P and associated negative environmental impacts, including eutrophication of surface waters. Efforts to reduce reliance on finite P reserves and limit P loading to the environment have led to the development of processes to recover P from wastewater for use as a fertilizer, for example, by precipitation of struvite (NH₄MgPO₄·6H₂O). Struvite is only slightly soluble in water but crop response to struvite can be similar to that of soluble P fertilizers under certain conditions (Hertzberger et al. 2020). However, granular struvite dissolves slowly in soil, and the released P may diffuse only a short distance from the granule, especially in alkaline soils (Degryse et al. 2017). The slow dissolution of struvite and limited P movement may reduce the risk of P loss to the environment relative to soluble fertilizers (Everaert et al. 2018) but may also limit crop P supply.

Struvite is an effective P source for at least some crop species in Manitoba (Thiessen Martens et al. 2022), but we currently know little about struvite dissolution and diffusion dynamics in the soils and growing conditions of the Canadian Prairie region. Soils in this region are typically formed from calcareous glacial till and lacustrine parent materials under grassland ecosystems, creating soils with neutral to alkaline pH and a wide range of textures. With the short growing season afforded by the extreme continental climate, soils are often cold at the time of spring sowing, restricting P supply to crop seedlings and potentially compromising crop productivity (Grant et al. 2001). Understanding the factors that

contribute to P release from struvite and movement through soil during this critical seedling stage is especially important for guiding recommendations for fertilizer placement, application rate, and timing.

In this study, we conducted a pair of short-term soil incubations at different temperatures to compare the soil-fertilizing capabilities of struvite and the soluble fertilizer monoammonium phosphate (MAP) in two low-P but otherwise contrasting soils from Manitoba. We used the Olsen-P concentration and recovery (proportion of added P extracted) in soil collected from concentric rings around a single fertilizer granule incubated in the soil as indicators of the net effects of fertilizer dissolution, P diffusion, and P transformations in soil on soil P supply. The two incubation temperatures provided a preliminary exploration of soil P dynamics associated with struvite in cold and warm soils representative of early- and late-spring soil temperatures, respectively.

Materials and methods

Soils were collected from the surface layer (0–15 cm) of farm fields near Libau (50.241258, -96.728878) and Thalberg (50.414696, -96.489661), MB. The Libau soil was a Dencross clay (Gleyed Rego Black Chernozem) with 5.7 mg kg⁻¹ Olsen-P, 665 mg kg⁻¹ total P, pH 8.1, and 5.6% total organic matter. The Thalberg soil was a Wampum sandy clay loam (Gleyed Grey Luvisol) with 10 mg kg⁻¹ Olsen-P, 308 mg kg⁻¹ total P, pH 7.0, and 3.2% total organic matter. The fertilizers used were granular struvite (Crystal Green®, 5-28-0-10Mg guaranteed minimum analysis, approx. 3 mm diameter; Ostara Nutrient Recovery Technologies Inc., Vancouver, BC) and MAP (11-52-0 guaranteed minimum analysis, CropKing Inc., Lodi,

Table 1. Effects of fertilizer type, soil type, and distance from the granule on Olsen-P concentration and Olsen-P recovery in soil incubated with struvite or MAP at 4 °C or 22 °C.

Factor	4 °C incubation temperature		22 °C incubation temperature	
	P concentration mg kg ⁻¹	P recovery* %	P concentration mg kg ⁻¹	P recovery* %
Fertilizer				
Struvite	16 (0.4)	0.7 (0.10)	19 (1.7)	1.2 (0.37)
MAP	89 (2.2)	9.6 (0.41)	86 (8.0)	9.1 (0.97)
Soil				
Libau	28 (0.7)	1.7 (0.21)	30 (2.7)	2.4 (0.70)
Thalberg	52 (1.3)	4.3 (0.30)	55 (5.1)	4.6 (0.76)
Distance from the granule				
0–8 mm	181 (7.9)	6.1 (0.51)	197 (19.5)	6.9 (1.2)
8–17 mm	28 (1.2)	1.7 (0.31)	30 (3.0)	2.0 (0.75)
>17 mm	11 (0.5)	1.9 (0.24)	11 (1.1)	2.6 (0.54)
Source of variation				
			<i>p</i> values	
Soil (S)	<0.0001	<0.0001	0.001	0.07
Fertilizer (F)	<0.0001	<0.0001	<0.0001	<0.0001
S × F	0.07	0.52	0.13	0.81
Distance (D)	<0.0001	<0.0001	<0.0001	0.001
S × D	<0.0001	<0.0001	0.04	0.35
F × D	<0.0001	0.002	<0.0001	0.003
S × F × D	<0.0001	0.003	<0.0001	0.0002

Note: Values presented are back-transformed least-squares means for main effects with the back-transformed standard error of the mean in parentheses. The highest order significant interactions are plotted in Fig. 1. Abbreviation: MAP, monoammonium phosphate.

*P recovery is the estimated proportion of the P added in fertilizers that was recovered as Olsen-P in the sampling rings.

OH). Total P concentrations of the fertilizers were confirmed by laboratory analysis.

Separate experiments were conducted for the cold and warm incubation temperatures, each using a completely randomized design with three replicates. Treatments included the factorial combination of the two soil types and the two fertilizers, giving four treatments, and twelve experimental units in each experiment.

Each soil type was sieved, air-dried, and mixed thoroughly. For each experimental unit, the air-dry equivalent of 78 g of oven-dry soil was spread evenly in a Petri dish (87 mm diameter) and wetted to field capacity (0.44 and 0.29 g water g⁻¹ soil for Libau and Thalberg soils, respectively) using deionized water. Individual granules of struvite (65 mg) and MAP (35 mg) containing 8 mg of P were placed in a 5 mm deep hole in the centre of each dish and covered with soil. Each dish was covered and wrapped with Parafilm to avoid moisture loss. The dishes for each experiment were randomized and incubated at 4 ± 1 °C (cold) or 22 ± 1 °C (warm) for 20 days, re-randomizing their positions within the incubators every 7 days. The 20 day period approximates the crop germination and seedling establishment period during which crop P supply is critical (Grant et al. 2001).

Soil was collected from each dish in three concentric rings representing the distance from the granule: 0–8 mm (first), 8–17 mm (second), and >17 mm (third) from the centre of the dish. Undissolved struvite granule remnants were removed from the samples to avoid overestimation of Olsen-P in the soil (Gu et al. 2021). No remnants of MAP granules were detected. Soil samples were air-dried, sieved to pass a

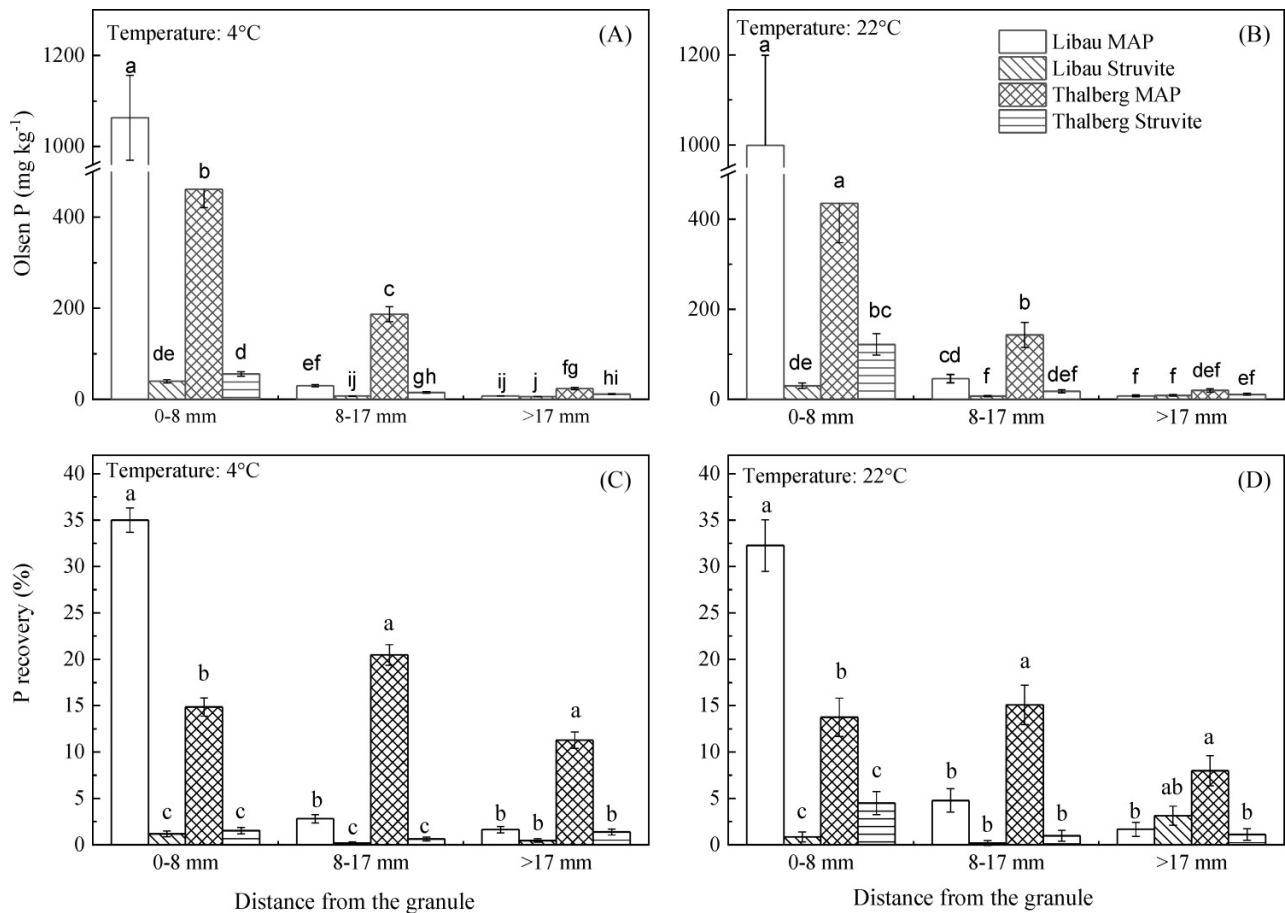
2 mm screen, and analyzed by a commercial lab (Farmers Edge, Winnipeg, MB) using a 0.5 mol/L sodium bicarbonate extraction with colorimetric determination (Schoenau and O'Halloran 2008) to determine the Olsen-P concentration in each sampling ring. The proportion of added P that was recovered in Olsen-P extracts in each ring was calculated as:

$$(1) \quad P_{\text{recovered}} = (P_{\text{content}} - P_{\text{baseline}}) / P_{\text{added}}$$

where P_{content} is the product of Olsen-P concentration and the mass of soil in each ring (calculated based on the proportions represented by each ring), P_{baseline} is the calculated Olsen-P content of the unfertilized soil in each ring based on a sub-sample of the same soil used to fill the Petri dishes, and P_{added} is the total quantity of P added to the dish as fertilizer (8 mg). A study using the same soils showed that the Olsen-P in unfertilized soils remained within 2.5 mg kg⁻¹ of Olsen-P in baseline samples throughout 28 days of incubation (Thiessen Martens, unpublished data, 2022); thus the baseline Olsen-P was an acceptable proxy for that of unfertilized incubated samples.

Analysis of variance was conducted for each experiment using PROC GLIMMIX of SAS software (Version 9.4, SAS OnDemand for Academics, SAS Institute), with soil type, fertilizer type, and distance from the granule as fixed effects; distance from the granule was treated as a repeated measurement. Data for soil P concentration were analyzed as a log-normal distribution, and resulting means and standard errors were back-transformed to the original scale. Homogeneity of vari-

Fig. 1. Interactive effects of fertilizer type, soil type, and distance from the granule on Olsen-P concentration (A, B) and Olsen-P recovery (C, D) at two incubation temperatures. Bar heights represent back-transformed least-squares means ($n = 3$); error bars represent back-transformed standard error of the mean. Lowercase letters indicating mean groupings are applied across all treatments and sampling distances for Olsen-P concentration and across treatments within each sampling distance for Olsen-P recovery. Abbreviation: MAP, monoammonium phosphate.



ance and normal distribution of residuals were assessed by visual assessment of residual plots and the Shapiro–Wilk test (W -statistic > 0.9). Data for P recovery were analyzed as a β distribution and expressed as a percentage. Means were compared using Tukey’s multiple comparison procedure. Effects were considered significant at $\alpha = 0.05$.

Results and discussion

Soil Olsen-P concentration and recovery were affected by the interaction of fertilizer type, soil type, and distance from the granule at both temperatures (Table 1). The two experiments showed similar patterns (Table 1; Fig. 1), suggesting that the P dynamics associated with these fertilizers did not vary substantially with temperature. These findings indicate that the soil and fertilizer characteristics, rather than temperature, are dominant in determining P dissolution when fertilizer is mixed with soil. However, additional research investigating the role of temperature in struvite dissolution and subsequent P transformations in soil is needed to determine whether different struvite management practices would be beneficial for application to cold vs. warm soils.

Soil Olsen-P concentrations were much lower for struvite than for MAP in both soil types in both experiments, especially in the first and second sampling rings (Figs. 1A and 1B). These results, together with the presence of struvite granule remnants in soil, show that the P in struvite dissolved and diffused through soil to a lesser extent than MAP. Nonetheless, Olsen-P concentrations near the granule in the struvite treatments (30–122 mg kg⁻¹) were several times greater than the baseline soil concentrations (5.7–10 mg kg⁻¹) in both experiments, indicating that the P in struvite dissolved and remained in labile forms in both soil types to some degree. Past research using a similar incubation approach with concentric sampling has reported greater soil solution P concentrations with struvite than with MAP in the centre sampling ring, but included the struvite granule remnant in the analyzed sample (Degryse et al. 2017), likely overestimating the quantity of soluble P (Gu et al. 2021).

The trends in Olsen-P concentration and recovery among the sampling rings demonstrate the effect of soil type on the P dynamics associated with the two fertilizers. For struvite, Olsen-P concentration was higher in the Thalberg soil than the Libau soil in the first ring of the 22 °C incubation (Fig.

1B) but not the 4 °C incubation (Fig. 1A). Struvite was expected to be more soluble in the neutral pH Thalberg soil than in the alkaline Libau soil, as observed with Australian soils amended with struvite (Degryse et al. 2017), but the cold temperature may have reduced differences in solubility. Differences between soil types in the second and third rings of struvite treatments in the 4 °C incubation (Fig. 1A) were likely mainly due to the different baseline Olsen-P concentrations (i.e., 5.7 mg kg⁻¹ for Libau soil and 10 for Thalberg soil), as little to no P from struvite appeared to have diffused more than 8 mm from the granule in either experiment. These results are consistent with previous findings on diffusion of P from granular struvite (Degryse et al. 2017). As P diffusion is governed in part by the dissolved P concentration gradient in soil solution, a low concentration of dissolved P in struvite-amended soil would create very little potential for diffusion away from granules, causing P released from struvite to stay very near the granules.

For MAP, P concentration and recovery were greater in the Libau soil than in the Thalberg soil in the first ring, but the opposite was true in the second and third rings, though differences between means were not always significant (Fig. 1). Based on Olsen-P in the third ring, P diffusion past 17 mm from the granules appears to have occurred only in the Thalberg soil treated with MAP. The lower concentration and recovery of Olsen-P in the first sampling ring of the MAP treatments in the Thalberg soil relative to the Libau soil were likely due to the movement of dissolved P out of this ring to the outer two rings.

These results indicate that the soil-fertilizing effect of struvite in the first weeks after application was significantly less than that of MAP. Only about 1%–5% of the P applied as struvite was recovered as soil Olsen-P and most of this was in a very small zone, compared to roughly 40% of added P from MAP. Under field conditions, this P supply from struvite could be exhausted by plant uptake relatively quickly. Over a longer period, however, especially with plant uptake providing a P sink, the struvite would continue to dissolve and contribute P to the plant-available pool, whereas the MAP was already completely dissolved after 20 days.

Elevated Olsen-P concentration in surface soil is a risk factor for P loss in runoff in Manitoba (Liu et al. 2021). Thus, the more moderate Olsen-P concentrations observed with struvite relative to MAP could reduce the risk of P losses shortly after application. The relatively slow dissolution of struvite in soil can also help prevent seedling injury in sensitive crops such as canola (*Brassica napus*; Katanda et al. 2019) and a low P supply during the seedling stage may encourage mycorrhizal colonization of crop roots (Grant et al. 2001).

Conclusions

Our results demonstrate that struvite dissolves in plant-free soil to some degree at both warm and cold temperatures but that the movement of P away from struvite granules is minimal. This research highlights the need for a better understanding of how the slow-release properties of struvite affect management practices such as fertilizer placement to opti-

mize crop P supply early in the growing season while minimizing the risk of P loss.

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Data availability

Data are not publicly available.

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Competing interests

The authors declare there are no competing interests.

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