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RECYCLED NUTRIENTS SUPPLY PHOSPHORUS AND IMPROVE RYEGRASS YIELDS ON PHOSPHORUS DEPLETED SOIL

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Abstract

Recycling phosphorus (P) within the food system is fundamental to long-term sustainability. This greenhouse study compared three sources of recycled P – struvite precipitated from municipal wastewater, black soldier fly frass from food waste, and anaerobic digestate of food waste – to mono-ammonium phosphate (MAP), compost, and a control. Italian Ryegrass (*Lolium multiflorum*) was harvested four times during a 123 day trial from a P-depleted soil. In nitrogen (N) sufficient conditions, all amendments significantly increased cumulative ryegrass yields compared to the control, and were not significantly different from MAP. Relative P supply was frass=MAP>struvite>= compost>=digestate>>control. The recycled nutrient sources tested show promise as sustainable P sources.

Keywords: Organic management, phosphorus, recycled nutrients, nutrient cycling, circular economy

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Introduction

Phosphorus (P) plays a pivotal and paradoxical role at the food-energy-water nexus; it is an essential nutrient for the crop growth, but also a harmful pollutant causing eutrophication of water bodies when it leaves the agricultural system (Jarvie et al. 2015). Mined phosphate rock, used to make phosphorus fertilizers and applied directly in organic systems, is a non-renewable resource that may be depleted in 70-140 years (Li et al. 2018). Recycled sources of P must become the norm in order to ensure long-term food system sustainability. Recycled nutrients may be especially important on Canadian organic farms, which often suffer from P depletion due to negative P balances (Schneider et al. 2017). Nutrients derived from recycled sources remain understudied compared to conventional mined fertilizers or manures, particularly in terms of their P properties.

The present greenhouse study assessed nutrient availability from three recycled sources commercially available in Canada – struvite, frass, and anaerobic digestate – applied to a low-P Prairie soil. Struvite is a phosphate mineral that is extracted from animal or municipal wastewater. The struvite used in the study is municipal in origin, with a median granule size of 0.9 mm. Reviews have found that struvite has good P availability compared to conventional fertilizers, but that it may be less effective in high-pH soils due to its low solubility at high pH (Möller et al. 2018; Hertzberger et al. 2020). Struvite is currently allowed as an organic amendment in Canada when it is sourced from animal or plant wastes. Inclusion of municipal waste struvite will likely be reviewed in the future.

The frass used in this study was the waste product of black soldier fly (BSF) larvae (*Hermetia illucens*) fed a diet of pre-consumer urban food waste. Few studies exist on the fertilizer potential of BSF frass. Kebli and Sinaj (2017) conducted a pot study on three soils

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using lettuce and ryegrass, and found that frass applied based on a nitrogen rate consistently improved yields over the control in a sandy, low pH soil. Yields were similar to or greater than the mineral fertilizer. The present study is the first, to our knowledge, to focus specifically on the P fertilizer attributes of frass.

The anaerobic digestate in this study is a dried and pelletized solid fraction of food retail and food processing waste digested in the absence of oxygen. Most studies on the fertilizer properties of digestate use animal waste or sewage sludge digestates and/or focus on N supply. Brod et al. (2015) characterized P fractions of liquid and solid food waste digestate, and used a ryegrass pot study to test P uptake. They found a higher proportion of HCl-soluble recalcitrant P in the solid digestate; a lower P recovery of solid digestate compared to liquid digestate or synthetic P; and lower ryegrass yields for solid digestate compared to liquid digestate or synthetic P at the earliest harvest time. This indicates lower P availability in solid P digestate compared to mineral fertilizer, and a high proportion of HCl-soluble recalcitrant P, which suggests the availability of digestate P may be limited at high pH.

We hypothesized that nutrient from recycled sources would improve ryegrass yields and P uptake compared to the control, and that they would have similar yields and P uptake compared to a conventional fertilizer under conditions of N-sufficiency. A secondary hypothesis was that nutrient sources with a lower N:P ratio (e.g. struvite) would yield less than those with high N:P ratio (e.g. frass) when N was not supplied and amendments were applied at a constant P rate, due to N supply from the amendment itself. We assessed these hypotheses by comparing the nutrient sources with or without the addition of non-limiting N fertilizer.

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Materials and Methods

Nutrient Sources

Struvite, frass, and digestate were compared to a common conventional (monoammonium phosphate, MAP) and a common organic (aerobic compost, predominantly horse manure and bedding) nutrient source. Total nutrient concentrations for MAP (110 g kg^{-1} N, 230 g kg^{-1} P) and struvite (50 g kg^{-1} N, 120 g kg^{-1} P) were based on manufacturer specifications. Analyses for the organic-matter-based amendments, digestate (38 g kg^{-1} N, 28 g kg^{-1} P, 4.0 g kg^{-1} K, 350 g kg^{-1} C, 80 g kg^{-1} water), frass (32 g kg^{-1} N, 8.7 g kg^{-1} P, 8.7 g kg^{-1} K, 400 g kg^{-1} C, 90 g kg^{-1} water), and compost (7.1 g kg^{-1} N, 2.3 g kg^{-1} P, 5.0 g kg^{-1} K, 89 g kg^{-1} C, 180 g kg^{-1} water), were conducted by Agvise Laboratories, ND, USA.

Experimental Setup

The greenhouse study was conducted using a P-deficient soil with Italian Ryegrass (*Lolium multiflorum*) as a bioassay crop. The soil was a Gleyed Rego Black Chernozem, collected from the 0-15 cm layer at a site under long-term organic management, with a clay texture, 35 kg ha^{-1} nitrate-N, 3 mg kg^{-1} Olsen-P, 312 mg kg^{-1} K, 40 kg ha^{-1} Cl, 27 kg ha^{-1} S, 1.3 mg kg^{-1} B, 0.6 mg kg^{-1} Zn, 18.7 mg kg^{-1} Fe, 1086 mg kg^{-1} Mn, 0.96 mg kg^{-1} Cu, 1086 mg kg^{-1} Mg, 6622 mg kg^{-1} Ca, 54 g kg^{-1} organic matter, and a soil pH value of 8.1 based on analysis by Agvise Laboratories, ND, USA. The soil was coarse-sieved (approx. 15 mm), homogenized in a cement mixer, and added to 15-cm diameter pots at a rate of 1914 g dry soil per pot.

The experiment used a two factor fully-factored randomized complete block design with four replicates. The first factor was phosphorus source, with 5 amendments and a non-amended control. The second factor was nitrogen fertilization, with pots receiving N fertilizer (identified as +N) and pots not receiving N fertilizer (identified as –N). Amendments were thoroughly

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mixed with the top 5 cm of the soil to ensure early root access to the amendments. They were applied at a rate equivalent to 20kg P ha^{-1} based on the surface area of the pots. Amendment addition per pot was: 0.16 g MAP, 15.6 g compost, 0.29 g struvite, 4.0 g frass, and 1.3 g digestate. N:P ratios of the amendments varied, such that different amounts of N were supplied to each pot via the amendment treatments. The N addition from each amendment was equivalent to 9.4 kg ha^{-1} for struvite, 73 kg ha^{-1} for frass, 28 kg ha^{-1} for digestate, 63 kg ha^{-1} for compost, and 10 kg ha^{-1} for MAP based on the surface area of the pots. The +N pots received 90 kg N ha^{-1} as urea dissolved in 100 mL reverse osmosis water at the beginning of the experiment and after each biomass harvest to eliminate N-deficiency. The –N pots received no nitrogen, but an equivalent amount of water. Based on the soil analysis, other nutrients were not expected to be limiting in this soil, and so no additional nutrient solution was added.

Pots were seeded with 25-30 Italian Ryegrass seeds at an approximate depth of 0.5-1 cm and were later thinned to 10 plants per pot. Pots were watered by weight up to a target of 80% free-drained container water capacity using reverse osmosis water. Subsequently, pots were watered every 1-3 days. Approximately once per week they were watered to their target weight and re-randomized within their blocks. Other waterings were done by weighing 3-5 randomly selected pots and watering based on the lower end of water use. Following the second biomass harvest (70 days after planting) +N and –N pots were watered separately due to substantially higher water use of the +N pots. Pots were initially housed in a naturally lit greenhouse with ventilation but no cooling system, and experienced water stress on sunny days. After the first biomass harvest, pots were transferred to a naturally lit greenhouse with a cooling wall (mean temperature 19°C - 23°C), which alleviated water stress.

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Sample Collection and Analysis

Four aboveground biomass harvests were conducted 42, 70, 95, and 123 days after seeding (DAS) (25-28 days between harvests) by cutting ryegrass plants just above the soil surface. Biomass was dried for a minimum of 48 hours at 65°C and weighed. Biomass samples were ground using a coffee grinder (Black and Decker, CBG100SC) for tissue P and Kjeldhal N determination. Sulfuric acid-peroxide wet-oxidation digestion was conducted on 0.4g of each sample, and phosphorus was determined colorimetrically using the molybdate-blue ascorbic acid method, as described by Akinremi et al. (2003). Kjeldhal N in the digested samples was determined using a Technicon AutoAnalyzer II.

Statistical Analysis

Two-way Analysis of Variance (ANOVA) was conducted using the GLIMMIX and MIXED (α=0.05) procedures of SAS software version 9.4, applying Tukey-Kramer means separation where the ANOVA results were significant (SAS Institute, 2017). Analysis of both cumulative and individual harvest date biomass, P uptake, and N uptake was performed; in the case of individual harvest dates, repeated measures analysis was used. Uniformity of variance was tested using COVTEST and comparison of AIC values for different models, and non-homogenous variance was incorporated into models as applicable using a Random _residual_/group statement. By default, PROC GLIMMIX was used, but in some cases PROC GLIMMIX was unable to run when non-homogenous variance was required. In these cases, PROC MIXED was used. Normality of residuals produced by the ANOVA was tested using PROC UNIVARIATE, with a threshold value of 0.9 for the Shapiro-Wilk statistic. Assessment of normality for nitrogen uptake revealed two outliers at biomass harvest #2, a frass –N pot with

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very high N uptake and a MAP +N pot with very low nitrogen uptake. We concluded that their nitrogen applications had likely been switched and they were removed from analysis.

Results and Discussion

A significant ($p<0.001$) amendment x nitrogen x harvest time effect was found for dry matter yield of ryegrass (Figure 1). Yields at the first harvest date were significantly greater overall for the +N treatments, though the difference within amendment was not significant for any of the individual P source amendments. After the first harvest, biomass yields in the –N pots plummeted for all treatments, presumably due to N depletion. Biomass yields in the +N amended pots remained steadily high or increased at subsequent harvests. In the +N pots, biomass yields were numerically higher for all treatments, and statistically higher for struvite and frass compared to the control at harvest times 1 and 2. At the third and fourth harvests, all amended +N pots had statistically greater yield than the control.

Significant amendment, nitrogen, and amendment x nitrogen effects were found for cumulative biomass, P uptake, and N uptake (Table 1)**Error! Reference source not found.**. All amendments significantly increased biomass yields in the +N pots. The increase was between 49% for digestate and 72% for frass. Frass yielded significantly more than the digestate and compost treatments, while MAP and struvite were statistically similar to all amended treatments. P uptake was significantly increased in all +N amendments compared to the control, ranging from 70% with digestate to 130% with frass. Unlike biomass, where all amendments were not significantly different from MAP, only frass was not significantly different from MAP based on P uptake. Struvite and digestate had lower P uptake than MAP, and were not significantly different from the compost comparison treatment. This aligns with previous studies that found solid food waste digestate had lower P availability than mineral fertilizers (Brod et al. 2015) and

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that struvite P availability is reduced compared to conventional fertilizers at high pH (Hertzberger et al. 2020). These results support our hypothesis that circular nutrient sources would increase P uptake and improve yields compared to a control in a P-depleted soil, when N was non-limiting.

In the –N pots all amendments except digestate produced increased cumulative biomass (Table 1). Our secondary hypothesis was that high-N:P amendments would yield more than low-N:P amendments in N-limited conditions. The result for frass, which had the highest N:P ratio and the greatest N uptake and yield among the –N treatments appears to support the hypothesis. However, MAP and struvite, which had low N:P ratios, produced yield and N uptake not significantly different from compost, a high-N:P amendment. Digestate had an intermediate N:P ratio but produced yields and N uptake not significantly different from the control. The N in compost and digestate appears to be of low plant availability compared to that of frass. However, as non-limiting P was not supplied to the –N pots, we cannot conclusively determine whether yield differences were due to N supply; they may also be the result of P supply during early growth, before N was depleted.

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Conclusions

All three recycled nutrient sources used in this study showed a capacity to supply phosphorus and substantially increase yields above an unamended control. In conditions of sufficient nitrogen, uptake of phosphorus was frass=MAP>struvite>=compost>=digestate>>control. Notably, all circular amendments produced biomass yields not significantly different from the soluble MAP fertilizer under greenhouse conditions for this ryegrass crop. Frass may also play an important role as a nitrogen source under N-limiting conditions. This research supports the role of these recycled materials as

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P sources. Further investigation and validation of these findings is needed under field conditions and with a variety of crop species on Prairie soils.

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Table 1 Average cumulative biomass yields, tissue P uptake, and Kjeldhal N uptake for ryegrass per pot. Standard error of the mean is given in brackets.

		Cumulative biomass (g)		Cumulative Tissue P (mg)		Cumulative Tissue N (mg)	
	+ Nitrogen	12.8 (0.2)	a	18.3 (0.3)	a	396 (4)	a
	- Nitrogen	5.5 (0.1)	b	16.8 (0.3)	b	97 (0.6)	b
	Control	6.6 (0.2)	d	10.8 (0.3)	e	180 (4)	d
	Struvite	9.4 (0.2)	bc	18.3 (0.3)	c	243 (4)	bc
	Digestate	8.9 (0.2)	c	16.1 (0.3)	d	236 (4)	c
	Compost	9.2 (0.2)	bc	17.5 (0.3)	c	232 (4)	c
	Frass	10.7 (0.2)	a	23.0 (0.3)	a	269 (4)	a
	MAP	9.9 (0.2)	b	19.5 (0.3)	b	260 (5)	ab
+ Nitrogen	Control	8.6 (0.3)	c	10.0 (0.4)	f	271 (8)	d
	Struvite	13.4 (0.3)	ab	19.5 (0.4)	b	387 (8)	abc
	Digestate	12.8 (0.3)	b	17.3 (0.4)	cd	379 (8)	bc
	Compost	12.9 (0.3)	b	18.3 (0.4)	bc	367 (8)	c
	Frass	14.8 (0.3)	a	23.2 (0.4)	a	426 (8)	a
	MAP	14.1 (0.4)	ab	21.6 (0.4)	a	424 (10)	ab
- Nitrogen	Control	4.7 (0.2)	g	11.6 (0.4)	f	89 (1.5)	g
	Struvite	5.4 (0.2)	ef	17.1 (0.4)	cd	98 (1.3)	f
	Digestate	5.1 (0.2)	fg	15.0 (0.4)	e	93 (1.3)	fg
	Compost	5.5 (0.2)	ef	16.7 (0.4)	d	97 (1.3)	f
	Frass	6.6 (0.2)	d	22.8 (0.4)	a	112 (1.5)	e
	MAP	5.8 (0.2)	e	17.3 (0.4)	cd	97 (1.5)	fg
ANOVA p-values	Amendment	<.0001		<.0001		<.0001	
	Nitrogen	<.0001		<.0001		<.0001	
	Amd *Nit	<.0001		<.0001		<.0001	

* Treatment means within a column and effect (nitrogen, amendment, and nitrogen x amendment) followed by the same letter are not significantly different based on Tukey-Kramer means separation (α=0.05).

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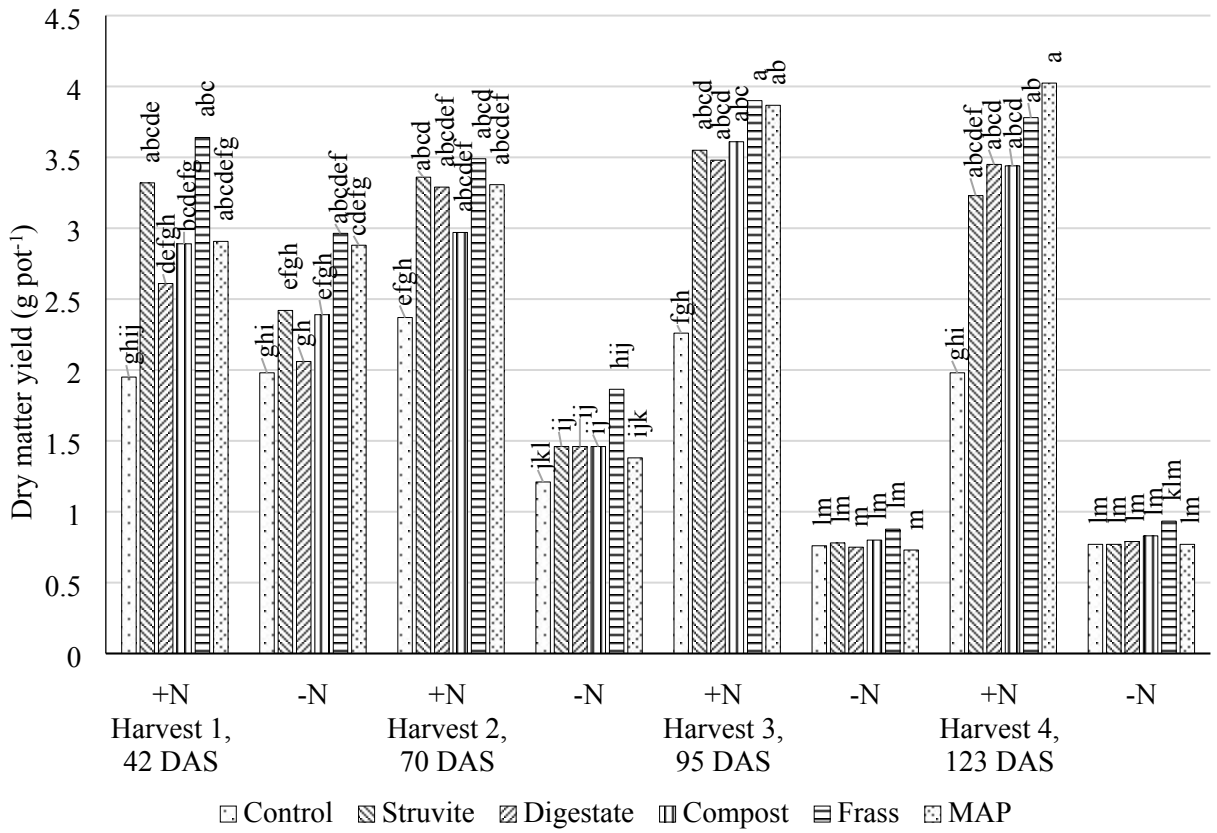


Figure 1 Mean ryegrass dry matter biomass produced at four harvests 42, 70, 95, and 123 days after seeding (DAS). Six amendment treatments were included with or without nitrogen (N) addition. Bars with at least one letter in common are not significantly different based on repeated measures analysis using Tukey-Kramer means separation (α=0.05).

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