



Economic Assessment of Potato Response to Struvite and Conventional Phosphorus Fertilizer in Eastern Canada

M. Khakbazan¹  · J. Nyiraneza² · R. Benjannet^{2,3} · A. N. Cambouris⁴ · K. Fuller⁵ · S. Hann⁶ · N. Ziadi⁴ · D. Biswas¹

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Abstract

Phosphorus (P) fertilizers are essential but potentially inefficient, especially in shallowrooted potatoes. A 3-year field experiment (2016–2018) was conducted in four distinct sites in Eastern Canada to investigate economic and environmental impacts of struvite-based slow-release and conventional P fertilizers in potato (*Solanum tuberosum* L.). Marginal return (MR = gross revenue–total operating cost) was assessed for different P treatments (0, 60, 120, 180, and 240 kg P₂O₅ ha^{−1}) from triple super phosphate (TSP) and for different mixtures of struvite (25%, 50%, and 75%) and TSP at 180 P₂O₅ kg ha^{−1}. Comparable MRs to TSP at a rate of 180 kg P₂O₅ ha^{−1} were obtained with a mixture of 75% TSP and 25% struvite across sites and years. Results demonstrated that a struvite-based mixture can be a viable alternative to conventional P fertilizers, improving profitability and lowering potential cumulative environmental costs associated with P application by \$8–\$24 ha^{−1} year^{−1} for potato production.

Keywords Potato production · Slow-release phosphorus · Cost · Marginal return

Resumen

Los fertilizantes de fósforo (P) son esenciales, pero potencialmente ineficientes, especialmente en papas de raíces superficiales. Se llevó a cabo un experimento de campo de 3 años (2016–2018) en cuatro sitios distintos en el este de Canadá para investigar los impactos económicos y ambientales de los fertilizantes de P convencionales y de liberación lenta a base de estruvita en papa (*Solanum tuberosum* L.). Se evaluó el rendimiento marginal (MR = ingresos brutos–costo operativo total) para diferentes tratamientos de P (0, 60, 120, 180 y 240 kg de P₂O₅ ha^{−1}) de superfosfato triple (TSP) y para diferentes mezclas de estruvita (25%, 50% y 75%) y TSP a 180 P₂O₅ kg ha^{−1}. Se obtuvieron MR comparables a TSP a una tasa de 180 kg de P₂O₅ ha^{−1} con una mezcla de 75% de TSP y 25% de estruvita en todos los sitios y años. Los resultados demostraron que una mezcla a base de estruvita puede ser una alternativa viable a los fertilizantes de P convencionales, mejorando la rentabilidad y reduciendo los costos ambientales acumulativos potenciales asociados con la aplicación de P en 24 ha^{−1} año^{−1} para la producción de papa.

✉ M. Khakbazan
Mohammad.Khakbazan@agr.gc.ca

¹ Brandon Research and Development Center, Agriculture and Agri-Food Canada (AAFC), P.O. Box 1000A, 2701 Grand Valley Road, R.R.#3, Brandon, MB R7A 5Y3, Canada

² Charlottetown Research and Development Center, 440 University Avenue, AAFC, Charlottetown, PE C1A 4N6, Canada

³ Soil and Agri-Food Engineering Department, Université Laval, Paul-Comtois Pavillon, 2425 rue de l'Agriculture, Quebec City, QC G1K 7P4, Canada

⁴ Quebec Research and Development Centre, AAFC, 2560 Hochelaga Boulevard, Quebec City, QC G1V 2J3, Canada

⁵ Kentville Research and Development Centre, AAFC, 32 Main Street, Kentville, NS B4N 1J5, Canada

⁶ Fredericton Research and Development Centre, AAFC, 850 Lincoln Road, P.O. Box 20280, Fredericton, NB E3B 4Z7, Canada

Introduction

Phosphorus (P) is a critical nutrient in agricultural systems, essential for the growth and productivity of crops (Malhotra et al. 2018). Despite its pivotal role, the efficiency of conventional P fertilizers is notably low, with crops utilizing only between 10% and 30% of the applied fertilizer in the year of application (Malhi et al. 2002; TrenkeL 2010). This inefficiency is particularly pronounced in crops like potatoes (*Solanum tuberosum* L.), which have shallow and less effective rooting systems reducing P use efficiency (Hopkins et al. 2014). Excess fertilizer P that is not absorbed poses significant environmental risks, potentially leading to eutrophication in aquatic environments from a higher than normal concentration of P, N or C and some microelements in the water (Sharpley and Menzel 1987; Clark 1989; Bockman et al. 1990; Sims 1998; Shaviv 2001) and the accumulation of trace contaminants (e.g., Cd, Cr, Pb, Ur and Ra) in soil over time (Mortvedt 1987; Sharpley and Menzel 1987; Shaviv 2001). The ramifications of eutrophication include compromised water quality for fisheries, recreation, industry, and consumption, incurring substantial economic costs (Khan and Mohammad 2013). In U.S. freshwaters, these costs were estimated to be approximately \$2.2 billion annually (Dodds et al. 2008). Environment and Climate Change Canada (2023) quantified the total phosphorus loading to Lake Erie between 2008 and 2022, revealing a significant contribution to eutrophication with an average annual loading of 9158.6 Mg, 1879.733 Mg of which are attributed to Canada. The economic implications on the Canadian side of Lake Erie alone are projected to be CAD \$270 million annually (Garcia-Hernandez et al. 2022).

Global P reserves are finite, and the demand of this mineral has exponentially increased since the Green Revolution to produce high crop yields for the growing population (Chen and Graedel 2016). Chen and Graedel (2016) found that during the period from 1961 to 2013, total P consumption increased fivefold. The increase in demand for a finite resource is not a sustainable trend. When assessing these setbacks, enhancing the efficiency of P fertilizer usage is imperative for both conservation and minimizing environmental impacts. The advent of slow and controlled-release P fertilizers, such as partially acidulated phosphate rock (Bolan et al. 1993; Rajan et al. 1994), dolomite phosphate rock (Yang et al. 2012; Mao et al. 2017), struvite recovered from wastewater (Shu et al. 2006; Rahman et al. 2014; Talboys et al. 2016), and polymer-coated fertilizers (Nyborg et al. 1995; Malhi et al. 2002; Pauly et al. 2002; Dunn and Stevens 2008; Ali et al. 2017), represents a promising approach to align nutrient supply more closely with crop requirements, potentially improving P use efficiency in agricultural production. Comparative studies highlight the agronomic

and environmental benefits of slow and controlled-release P fertilizers compared to conventional fertilizers. Unlike conventional P fertilizers, struvite-based slow-release P fertilizers increased yields and maintained similar plant P uptake levels while reducing root burn and P losses to the environment through greater plant P recovery (Shu et al. 2006; Rahman et al. 2014; Talboys et al. 2016; Nyborg et al. 1995; Shaviv 2001; Malhi et al. 2002). This reduced P leaching consequently lowered the risk of eutrophication (Mancho et al. 2023). Struvite-based slow-release P fertilizers have been shown to enhance plant P uptake for crops such as rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) by 7.6% to 46.4% compared to conventional fertilizer treatments (Wang et al. 2023). Talboys et al. (2016) indicated that struvite's apparent plant recovery (APR) of applied P was 38% compared to 13% from conventional fertilizers, suggesting that struvite has considerable potential residual value for succeeding crops. Kokulan et al. (2024) found that using struvite fertilizer as opposed to traditional MAP fertilizer maintained corn (*Zea mays* L.) grain yields while reducing the extractable phosphorus concentrations in soil and water.

While slow and controlled-release P fertilizers offer considerable benefits to agricultural production, including improvements in efficiency and environmental sustainability, their application is not without potential drawbacks and factors that require careful consideration. These fertilizers are designed to supply plant-available P gradually over time rather than instantaneously. This characteristic can initially lead to reduced plant performance compared to conventional P fertilizer due to the delayed availability of nutrients to match plant needs. However, as the release of P continues, plant performance may surpass that observed with conventional fertilizers, reflecting more sustained nutrient availability (Pauly et al. 2002; Qian and Schoenau 2010). The advantages of slow-release P fertilizers may not be immediately apparent and often manifest after several years of application. Specifically, fertilizers based on reactive phosphate rock, a common slow-release P source, may require up to six years to achieve yields comparable to those obtained with conventional P fertilization (Sinclair et al. 1993). Furthermore, the effectiveness and release rate of these fertilizers are influenced by environmental conditions such as temperature and moisture levels (Obreza and Sartain 2010; Roberts 2008; Lino et al. 2018), adding complexity to their management and application strategies. While one of the primary benefits of slow-release P fertilizers lies in their potential to reduce nutrient loss to the environment, thus mitigating the risk of eutrophication and other ecological disturbances, there remains a risk associated with their use. In the absence of plants, these fertilizers may continue to release nutrients, potentially leading to increased losses and detrimental environmental impacts (Oertli 1980; Shaviv 2001).

The economic implications of slow and controlled-release P fertilizers play a pivotal role in assessing the viability of their widespread application. Some slow and controlled-release P fertilizers, especially struvite, are more expensive to extract than conventional P fertilizers (Obreza and Sartain 2010; Trenkel 2010; Liu et al. 2014; Timilsena et al. 2015). Shaviv and Mikkelsen (1993) claim that slow and controlled-released P fertilizers can be 2.5 to 8 times more expensive than conventional fertilizers. However, slow and controlled-release P fertilizers are only applied once during the growing season, eliminating multiple applications that consequently reduce labor, handling, and operating costs (Shaviv 2001; Shu et al. 2006; Timilsena et al. 2015). The often prohibitively high costs of slow and controlled-release fertilizers thus have the potential to be partially offset by these cost savings (Sharma 1979), which can be combined with cost-offsetting measures such as regional beneficial management practice programs to further reduce the costs of slow and controlled-release fertilizers (Hutchinson et al. 2002). Dunn and Stevens (2008) found that the net return of rice grown in Missouri with coated Triple Superphosphate (TSP, 0–46–0) fertilizer was about \$35 per hectare greater than the net return with uncoated TSP. There is a lack of research evaluating the economic benefit of slow and controlled-release P fertilizers in Canada; consequently, the economic implications of their application remain uncertain and warrant further investigation. The aim of this study was to analyze and compare the economic aspects of using slow-release P fertilizer products against conventional P fertilizer in the context of potato rotations in Eastern Canada. We therefore hypothesized that mixes of slow-release struvite and conventional P would result in equal or higher marginal return than conventional P at the same rate. Slow-release fertilizers are widely recognized as an optimal solution to the environmental challenges posed by conventional water-soluble fertilizers (Chandra et al. 2009). Consequently, this study aims not only to determine the more economically viable option based on fertilizer costs and potato yield impacts but also to consider the environmental impacts.

Materials and Methods

Field Experiment

The experimental data used in this study and all details regarding the conduct of the experiments were previously reported by Benjannet et al. (2020) who mainly focused on agronomic aspects including soil P availability, P uptake, P recovery, total potato yields, and less emphasis on marketable yields. We used the same yield data set previously published by Benjannet et al. (2020) with slight modifications

to calculate marginal returns and economic costs. In this study, we calculated percentage yield increase in comparison to the control to avoid redundancy.

Briefly, this study encompassed twelve field trials conducted from 2016 to 2018 across four distinct sites in Eastern Canada located at Charlottetown, Prince Edward Island (PEI; 46°20'N, 63°10'W), Fredericton, New Brunswick (NB; 45°N, –66°W), Kentville, Nova Scotia (NS; 45°07'N, 64°29'W), and Cantin et Fils Farm, Sainte-Catherine-de-la-Jacques-Cartier, Quebec (QC; 46°50'N, 71°38'W). The sites are referred to as PEI, NB, NS, and QC. Planting dates varied between May and June, while the harvesting period extended from September to October. A randomized complete block design with four replicates was implemented across all sites. Each experimental unit within the replicates comprised six adjacent rows, each extending eight meters in length with a row spacing of approximately 0.91 m (3 feet). The Russet Burbank variety of potatoes was planted with a spacing of 0.38 m, and the sites relied solely on rainfall.

The struvite variant used, known as Crystal Green, contains a nutrient composition of 5% nitrogen (N), 28% phosphorus, and 10% magnesium (5–28–0 with 10% Mg) (Crystal Green 2021). This struvite is sustainably produced by Ostara Nutrient Recovery Technologies Inc., Vancouver, Canada, through a proprietary nutrient recovery technology that combines P, N, and magnesium to form pure crystalline struvite granules (<https://www.ostara.com/>).

Five distinct P treatment application rates for conventional fertilizers were evaluated: 0, 60, 120, 180, and 240 kg P₂O₅ ha^{–1}. Among these treatments, three were formulated as mixtures of struvite and triple superphosphate (TSP), with struvite constituting 25%, 50%, and 75% of the mixture by weight (Table 1). The P treatment rate of 180 kg P₂O₅ ha^{–1}, was selected for its alignment with the P sufficiency range typically recommended for soils used in potato cultivation. Nitrogen and potassium (K) supplements were uniformly applied across all treatments at a rate of 200 kg N ha^{–1} and 200 kg K₂O ha^{–1} (Table 1). No additional fertilization was applied during the potato growing season.

Economic Calculation and Assumptions

To compare the economics of P treatments, two criteria were used: first, marginal return (MR) for different P treatments was compared, and then yield and MR relative variability using the coefficient of variation (CV = standard deviation/mean × 100) was assessed. A CV for potato yields less than 10% is considered low, a CV between 10% and 20% is considered medium or moderate, and a CV greater than 20% is considered high (Seid et al. 2023). The MR over operating costs was calculated as the difference between total gross revenue and the sum of total operating costs. All values

Table 1 Fertilizer application rates, fertilizer sources, and their cost

<i>P</i> rates (kg ha ⁻¹)	Fertilizer applied (kg ha ⁻¹)			Fertilizer cost (\$ ha ⁻¹)						N (urea)	Mg (St.)	N (urea)	K ₂ O
	TSP	Struvite	N (urea)	K ₂ O	TSP	Struvite	N (St.)	Mg (St.)	N (urea)				
0	0	0	200	200	0	0	0	0	359	0	0	359	209
60	60	0	200	200	114	0	0	0	359	0	0	359	209
120	120	0	200	200	229	0	0	0	359	0	0	359	209
180	180	0	200	200	343	0	0	0	359	0	0	359	209
240	240	0	200	200	458	0	0	0	359	0	0	359	209
180: 75% St.	45	135	200	200	86	564	12	9	359	9	9	359	209
180: 50% St.	90	90	200	200	172	376	8	6	359	6	6	359	209
180: 25% St.	135	45	200	200	258	188	4	3	359	3	3	359	209

P Phosphorus (P₂O₅), *St* Struvite (5–28–0), *TSP* Tripple Superphosphate (0–46–0), *Mg* Magnesium, *K₂O* Potassium oxide, *N* Nitrogen (46–0–0)

were expressed in CAD \$ ha⁻¹ for potato and treatments, and prices are also in CAD \$. Operating costs included fertilizers, seed, pesticide, machinery operations, hired labor, interest on operating costs, and other costs. Gross revenue was calculated by multiplying the marketable potato yield by the price. The grading and quality aspects of potato were described by Benjannet et al. (2020). The 2022 potato processing price (\$303 Mg⁻¹) was taken from the Manitoba Potato Production Cost (Manitoba Agriculture 2022). This price, although from a Manitoba source, represents potato processing prices in our studied provinces. The average for all types of potatoes (seed, table, and processing) from 2019 to 2023 in the three provinces was \$350 per tonne (Agriculture and Agri-Food Canada 2024), and our assumed price represents processing potatoes well, as processing potato prices are less than seed or table potatoes. The cost of fertilizer was calculated by multiplying the nutrient prices as reported by Manitoba Agriculture (2024) by the fertilizer rates used in the experiment, as shown in Table 1. The prices for actual TSP, actual N, and K₂O were assumed to be \$1.91, \$1.795, and \$1.043 kg⁻¹, respectively (Manitoba Agriculture 2024).

Assessing the cost of struvite-based slow-release fertilizers within the Canadian context required direct inquiries with suppliers due to the lack of publicly accessible pricing data. Communications were established with several suppliers. Agro Source Ltd. provided a quotation of \$1,400 per Mg for 5–28–0 with 10% Mg, and Taurus quoted an average price of \$1,500 per Mg for their struvite-based fertilizers. This pricing information was crucial for evaluating the economic feasibility of struvite as a sustainable fertilizer option. Throughout the analysis, a struvite cost of \$1,400 per Mg was utilized, as the differences between \$1,400 and \$1,500 per Mg were minor and did not significantly impact the results. Excluding the N and Mg portions, the price of struvite P was \$4.18 kg⁻¹. The variability in cost arises exclusively from fertilizer, with some scenarios involving struvite, others involving conventional fertilizers, and some involving a mixture of both.

Environmental Costs and Assumptions

Analyses estimated the environmental cost, and it was not included in the MR analysis for different *P* treatments. Smith et al. (2019) and Environment and Climate Change Canada (2023), estimated the annual economic cost of eutrophication to be around \$272 million CAD, with the average total *P* loading around 1,879.73 Mg per year in Lake Erie. Hence, using these numbers, the estimated annual economic damage cost along the Canadian shoreline of Lake Erie is calculated to be about \$144.7 kg⁻¹. The figure \$144.7 kg⁻¹ will be used to calculate the environmental impact.

The total percentage P loss for TSP fertilizer banding was adapted from Smith et al. (2016) and assumed to be 0.142%. The findings of Leon et al. (2023) were also used to calculate the total percentage of P loss of struvite and assumed to be 0.0002. The total environmental cost for each fertilizer treatment was calculated by multiplying the P loss with the environmental cost per kg (\$144.7 kg⁻¹).

Statistical Analysis

Data on marginal returns and relative potato yield were checked for outliers and normality. Since data were not normally distributed and available data transformations did not improve the distribution, statistical analysis was conducted using data from NB (2016), NS (2016), PEI (2017 and 2018), and QC (2016, 2017, and 2018) in order to meet the normality assumptions and equality of variance. Statistical analysis was conducted for each site separately and across sites and also for each year separately and across years. Data on marginal returns and relative yields were subjected to analysis of variance using a Mixed model with the ‘nlme’ R statistical package R software version 4.2.2 (R Core Team 2022; R version: 4.4.1). In the model, the phosphorus (P) rate was considered as a fixed effect, and replication was considered as a random effect. In addition, coefficient of variation analysis was conducted for marginal returns. Least squares means of treatments were compared with Tukey’s HSD test using the ‘emmeans’ and ‘multcompview’ R packages when the F-test was significant ($P < 0.05$). A p-value of less than 0.05 indicates statistical significance.

Results

Relative Potato Yield

The effects of P treatment on percent relative change in potato yield were not significant for NB and NS but significant for PEI, QC, and across sites (Table 2). Potato yields in the PEI site were 64%, 96%, 103%, and 88% higher than the control for 120, 180, and 240 kg P₂O₅ ha⁻¹ and 180 kg P₂O₅ ha⁻¹ with 25% struvite, respectively. The potato yields in QC increased by 48%, 49%, and 43% compared to the control for the treatments of 240 kg P₂O₅ ha⁻¹, 180 kg P₂O₅ ha⁻¹, and 180 kg P₂O₅ ha⁻¹ with 25% struvite, respectively (Table 2). Both P rates of 180 and 240 kg ha⁻¹ and the P rate of 180 kg ha⁻¹ with 25% struvite showed statistically similar and higher yield increases relative to the control across all sites.

The effects of P rates were not significant for 2016 but were significant for 2017, 2018, and across years (Table 3). Although P rates were not significant in 2016, potato yields

Table 2 Percentage change of potato yields compared to the control (zero P rate) for each site and across sites

P rates	NB	NS	PEI	QC	Across sites
(kg ha ⁻¹)	% Change	% Change	% Change	% Change	% Change
0	0	0	0 ^c	0 ^c	0 ^c
60	-22	1	45 ^{cd}	15 ^{bc}	9 ^{bc}
120	20	9	64 ^{bc}	37 ^{ab}	29 ^{ab}
180	35	1	96 ^{ab}	49 ^a	36 ^a
240	37	-6	103 ^a	48 ^a	38 ^a
180: 75% St.	30	-14	22 ^{de}	29 ^{ab}	13 ^{abc}
180: 50% St.	17	-13	47 ^{cd}	33 ^{ab}	17 ^{abc}
180: 25% St.	16	2	88 ^{ab}	43 ^a	32 ^{ab}
P value	0.099	0.891	<0.001	<0.001	<0.001

P Phosphorus (P₂O₅), St Struvite, Fredericton, New Brunswick (NB); Kentville, Nova Scotia (NS); Charlottetown, Prince Edward Island (PEI); Sainte-Catherine-de-la-Jacques-Cartier, Quebec (QC). Means followed by the same letter in a column for each section suggests not significant ($P > 0.05$). Zero P rate is control treatment. The effects of treatments on marketable potato yield were presented by Benjannet et al. (2020). We used the same data set with slight modifications to calculate % yield change in comparison to the control

Table 3 Percent change in potato marketable yield in different P treatments relative to control in each year and across years

P rates	2016	2017	2018	Across years
(kg ha ⁻¹)	%change	%change	%change	%change
0	0	0 ^c	0 ^d	0 ^d
60	-8	24 ^{abc}	53 ^{bc}	20 ^c
120	12	40 ^{ab}	77 ^{abc}	40 ^{ab}
180	10	47 ^a	112 ^a	51 ^a
240	16	50 ^a	114 ^a	55 ^a
180: 75% St.	5	20 ^{bc}	47 ^{cd}	22 ^c
180: 50% St.	4	26 ^{abc}	69 ^{abc}	30 ^{bc}
180: 25% St.	15	41 ^{ab}	101 ^{ab}	48 ^a
P value	0.393	<0.001	<0.001	<0.001

P Phosphorus (P₂O₅), St Struvite, Fredericton, New Brunswick (NB); Kentville, Nova Scotia (NS); Charlottetown, Prince Edward Island (PEI); Sainte-Catherine-de-la-Jacques-Cartier, Quebec (QC). Means followed by the same letter in a column for each section suggests not significant ($P > 0.05$). Zero P rate is control treatment. The effects of treatments on marketable potato yield were presented by Benjannet et al. (2020). We used the same data set with slight modifications to calculate % yield change in comparison to the control

increased by 15% and 16% relative to the control for 180 kg P₂O₅ ha⁻¹ with 25% struvite and 240 kg P₂O₅ ha⁻¹, respectively (Table 3). All treatments in 2017 produced higher yields compared to 2016, with 120, 240, 180, and 180 kg P₂O₅ ha⁻¹ with 25% struvite increasing by 40%, 50%, 47%, and 41% higher than the control, respectively (Table 3). P treatments of 180, 240, and 180 kg P₂O₅ ha⁻¹ with 25% in 2018 produced the highest yields at an 112%, 114%, and 101% increase compared to the control, respectively (Table 3). P rates of 180 and 240 kg ha⁻¹ and 180 kg ha⁻¹

with 25% struvite showed statistically similar and higher relative yields than a P rate of 60 kg ha⁻¹ and P rates of 180 kg ha⁻¹ with 75% struvite and 180 kg ha⁻¹ with 50% struvite across years.

There were significant strong quadratic relationships between marketable potato yield and P rates across sites and years (Fig. 1a, c).

Total Operating Cost and Environmental Cost

Total operating cost increased with the increase in P rates. However, total operating cost was the highest for the P rate of 180 kg ha⁻¹ with 75% struvite because of the higher cost of struvite fertilizer (Fig. 2a). P rate of both 180 kg ha⁻¹ with 25% struvite (\$6720 ha⁻¹) and 240 kg ha⁻¹ with conventional P fertilizer (\$6725 ha⁻¹) had similar operating costs. The operating cost of 180 kg ha⁻¹ with 25% struvite was about 2% higher than the 180 kg ha⁻¹ with conventional P fertilizer.

Environmental cost increased as P rate increased with conventional P fertilizer (Fig. 2b). Struvite decreased

environmental cost, but its extent depended on the percentage of struvite used in the P treatments. Environmental cost was the highest for the P rate of 240 kg ha⁻¹ (\$48.94 ha⁻¹ year⁻¹) and the lowest for the control or 75% of the struvite mixture at 180 kg P ha⁻¹ (\$13 ha⁻¹ year⁻¹) across sites and years (Fig. 2b). Both P rates of 180 kg ha⁻¹ with 25% struvite and 120 kg ha⁻¹ with conventional fertilizer had similar environmental costs.

Marginal Returns

The effects of P treatments on marginal returns were not significant for NB and NS but were significant for PEI, QC, and across sites (Table 4). In PEI, a notable enhancement in potato MR was observed for all treatments relative to the control, with the exception of the treatment entailing an application rate of 180 kg P₂O₅ ha⁻¹ and 75% struvite. In PEI, P rates of 180 and 240 kg ha⁻¹ and a P rate of 180 kg ha⁻¹ with 25% struvite displayed equally the highest MRs among the P treatments. The higher MRs of these treatments

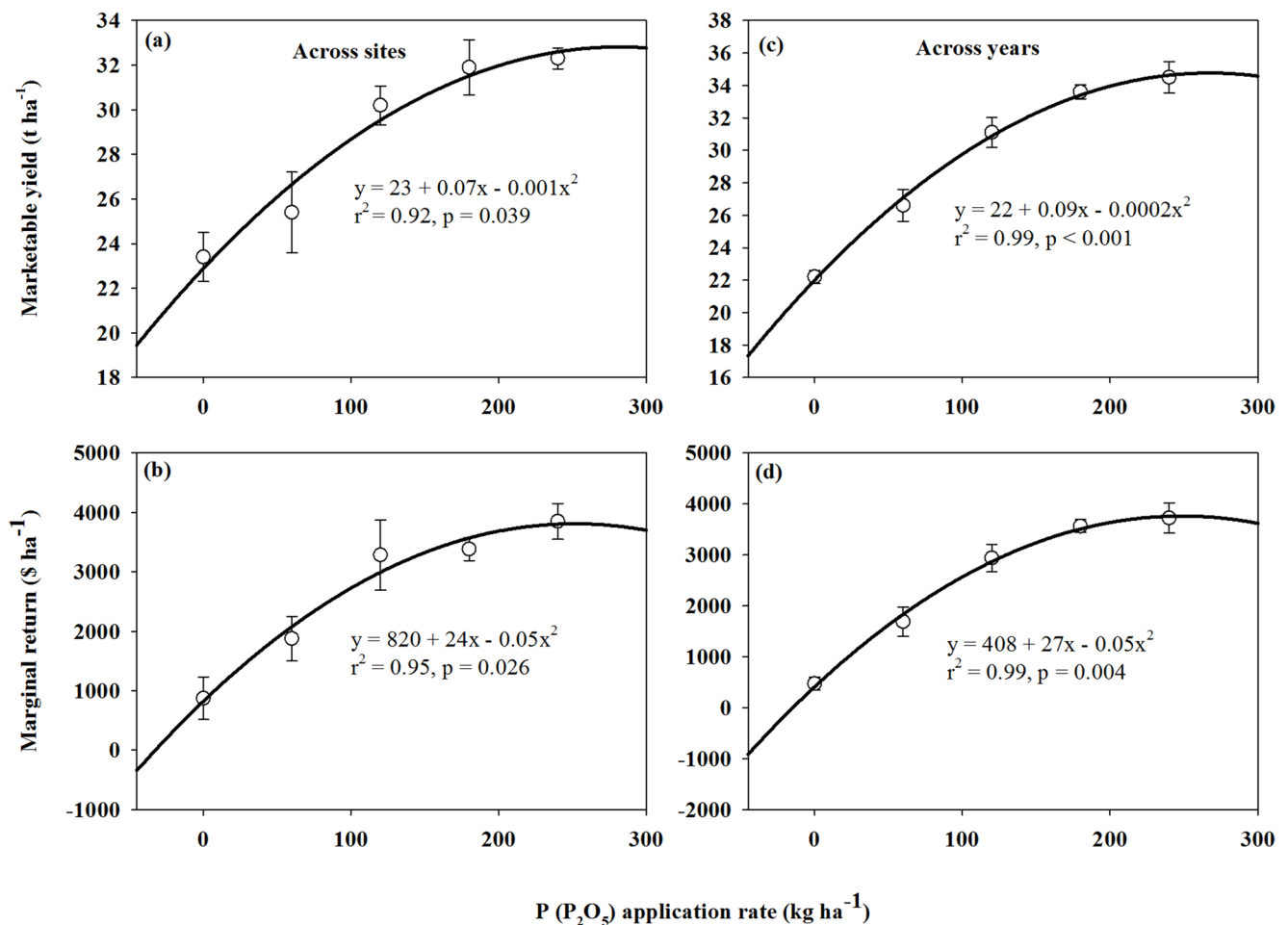


Fig. 1 The relationships between marketable potato yield/marginal return and P (P₂O₅) application rates from triple superphosphate (TSP) across four sites and across three years

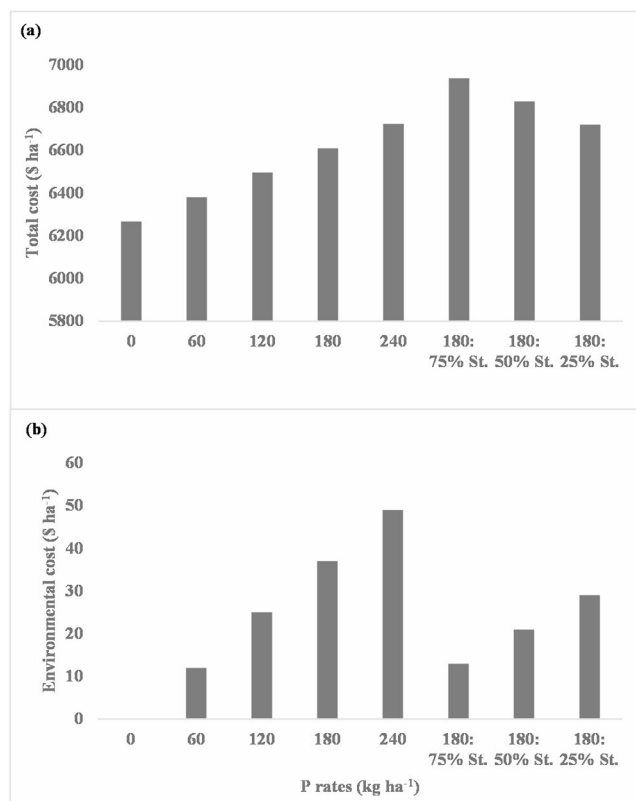


Fig. 2 Effects of P rates and source on total operating cost and environmental cost. P rates of 60, 120, 180, and 240 kg ha⁻¹ applied with conventional P fertilizer (TSP). A rate of 180 kg ha⁻¹ also applied with a mixture of TSP and different percentages (75%, 50%, and 25%) of slow-release struvite (St.)

were the results of higher potato yields compared to the control treatment. Although costs were higher for the 180 kg P₂O₅ ha⁻¹ with 25% struvite, its MR remained statistically similar to the conventional 120–240 kg P₂O₅ ha⁻¹ application. Moreover, a P rate of 180 kg ha⁻¹ with 25% showed the highest MR stability (CV=18%) among the P rates that showed the most profitable. P treatment at 180 kg ha⁻¹ had a higher CV compared to 240 kg ha⁻¹ and 180 kg P₂O₅ ha⁻¹

with 25% struvite (Table 4). The treatment with an application rate of 180 kg P₂O₅ ha⁻¹ with 75% struvite did not significantly increase the overall average potato MR and had higher MR variability compared to the control.

In QC, treatments with application rates of 120, 180, and 240 kg P₂O₅ ha⁻¹ and mixtures of conventional and 25% or 50% struvite at 180 kg P₂O₅ ha⁻¹ significantly surpassed the control in terms of overall MR (Table 4). All treatments generated higher and statistically similar MRs except the control and the treatment with an application rate of 60 kg P₂O₅ ha⁻¹. Results at this site showed that the CV values for both conventional fertilizers and the mixture of conventional with struvite were generally low, suggesting low variability and higher stability. P rates of 180–240 kg ha⁻¹ and 180 kg ha⁻¹ with 25% struvite showed statistically similar and higher MR than P rate of 60 kg ha⁻¹ and control, but the former showed higher stability than the later.

In NB and NS, no significant differences were observed among treatments for MR. In NS, the treatment applying 120 kg P₂O₅ ha⁻¹ generated the highest MR numerically. Despite the statistical insignificance of differences, the 180 kg P₂O₅ ha⁻¹ treatment with 25% struvite increased in MR compared to most P treatments, highlighting the effectiveness of the struvite mixture as a viable alternative to conventional fertilizers. The higher MR was a consequence of an increase in numerical potato yield. The CV values of MRs for NS were higher than the CVs of PEI and QC, with the highest being 124% and the lowest being 40% at 180 kg P₂O₅ ha⁻¹ with 50% struvite and 120 kg P₂O₅ ha⁻¹, respectively (Table 4). Notably, the 120 kg P₂O₅ ha⁻¹ treatment produced numerically the highest MR with one of the lowest CVs and costs compared to the other treatments within NS (Table 4). The CV values were relatively high for both conventional and struvite fertilizer mixtures, suggesting high variability.

Across sites, P treatments of 120, 180, and 240 kg ha⁻¹ and the P rate of 180 kg ha⁻¹ with 25% struvite exhibited statistically similar and higher MRs than the control. However,

Table 4 Potato marginal returns (MR) and coefficient of variation (CV) for each site and across sites

P rates (kg ha ⁻¹)	NB		NS		PEI		QC		Across sites	
	MR (\$ ha ⁻¹)	CV%	MR (\$ ha ⁻¹)	CV%	MR (\$ ha ⁻¹)	CV%	MR (\$ ha ⁻¹)	CV%	MR (\$ ha ⁻¹)	CV%
0	-613	-	3596	68	-585 ^d	-	872 ^c	82	817 ^c	82
60	-1942	-	3572	75	1844 ^{bc}	67	1875 ^{bc}	40	1337 ^{abc}	40
120	286	506	4210	40	2818 ^{ab}	22	3281 ^{ab}	36	2648 ^{ab}	36
180	1046	175	3315	107	4479 ^a	24	3381 ^{ab}	11	3055 ^a	11
240	1058	89	2589	56	4784 ^a	22	3847 ^a	16	3070 ^a	16
180: 75% St.	463	325	1578	100	2 ^{cd}	-	2275 ^{abc}	19	1080 ^{bc}	19
180: 50% St.	-176	-	1768	124	1517 ^{bc}	31	2726 ^{ab}	25	1458 ^{abc}	25
180: 25% St.	-181	-	3389	85	3939 ^a	18	3516 ^a	20	2666 ^{ab}	20
P value	0.198		0.745		<0.001		<0.001		<0.001	

P Phosphorus (P₂O₅), St Struvite; Charlottetown, Prince Edward Island (PEI); Fredericton, New Brunswick (NB); Kentville, Nova Scotia (NS); Sainte-Catherine-de-la-Jacques-Cartier, Quebec (QC). Means followed by the same letter in a column for each section suggests not significant ($P > 0.05$)

a P rate of 180 kg ha⁻¹ showed the highest stability among the P treatments across all sites.

P treatment on MRs was not significant for 2016 regardless of sites but significant for 2017, 2018, and across years (Table 5). All treatment groups in 2016 reported similar MR values, with the highest being the 180 kg P₂O₅ ha⁻¹ with 25% struvite treatment and 120–240 kg P₂O₅ ha⁻¹ (Table 5). In 2016, while P treatments had no significant effect on MRs, P rates of 120 (48%), 180 (30%), and 240 (52%) kg ha⁻¹ and a P rate of 180 kg ha⁻¹ with 25% struvite (43%) showed considerable increases in MRs relative to the control among the P treatments. The CV values of MRs in 2016 were high for all treatments, except for the treatments with application rates of 120 and 240 kg P₂O₅ ha⁻¹. The high CV values in 2016 indicate higher variability and lower stability.

In 2017, the results suggest that treatments with application rates of 240 and 180 kg P₂O₅ ha⁻¹ had the highest MRs compared to all treatments, although they were statistically comparable to treatment with 180 kg P₂O₅ ha⁻¹ with 25% struvite. The treatments of 120 kg P₂O₅ ha⁻¹ and 180 kg P₂O₅ ha⁻¹ with 25% struvite trailed closely behind. In 2017, P rates of 120, 180, and 240 kg ha⁻¹ and the P rate of 180 kg ha⁻¹ with 25% struvite showed statistically similar and higher MRs than the control. A P rate of 180 kg ha⁻¹ with 75% struvite generated less MR than 120–240 kg ha⁻¹ treatments in 2017. A P rate of 180 kg ha⁻¹ showed the highest MR stability as shown by the lowest CV (10%) among the P rates of 120–240 kg ha⁻¹ and 180 kg P₂O₅ ha⁻¹ with 25% struvite. The CV values in 2017 were low for conventional and struvite mixtures, except for the application rate of 180 kg P₂O₅ ha⁻¹ with 75% struvite. The CV values were generally lower for conventional P than for the struvite mixture, suggesting that in the year 2017, conventional fertilizers provided higher stability and consistency compared to conventional and struvite mixtures.

In 2018, all treatments except the control produced significantly higher MR compared to the previous 2016 and 2017

MRs. Examination of the overall average MR indicated no significant differences among treatments with application rates of 120, 180, and 240 kg P₂O₅ ha⁻¹ and 180 kg P₂O₅ ha⁻¹ with 25% and 50% struvite, all of which manifested similar overall average MRs. Furthermore, all treatments demonstrated a substantial MR improvement over the control. In 2018, P treatments of 180 and 240 kg ha⁻¹ and the P rate of 180 kg ha⁻¹ with 25% struvite displayed statistically similar and higher MRs than the P rate of 180 kg ha⁻¹ with 75% struvite and the control. The CV values in the year 2018 were moderate, suggesting reasonable variability, as some CV values were higher or lower than in previous years. A P rate of 240 kg ha⁻¹ had higher stability on MRs than a P rate of 180 kg ha⁻¹ and a P rate of 180 kg ha⁻¹ with 25% struvite, which showed the same stability as documented by their CVs.

Over the years, treatments with application rates of 120, 180, 240 kg P₂O₅ ha⁻¹ and 180 kg P₂O₅ ha⁻¹ with 25% struvite produced significantly higher overall MR compared to the control or other treatments. Across years, P rates of 180 and 240 kg ha⁻¹ and the P rate of 180 kg ha⁻¹ with 25% struvite showed statistically similar and the highest MRs among the P treatments. However, a P rate of 180 kg ha⁻¹ resulted in the greatest stability on MR among the P treatments that provided the highest MRs.

There were significant strong quadratic relationships between MRs and P rates without struvite across sites (Fig. 1b, d).

Discussion

When applying conventional P fertilizers, plants with shallow root systems, such as potatoes, only take up between 10% and 30% of the application (Malhi et al. 2002; Trenkel 2010; Hopkins et al. 2014). The excess P fertilizer could lead to negative environmental consequences such as

Table 5 Marginal returns (MR) and coefficient of variation (CV) in each year and across years

P rates	2016		2017		2018		Across years	
(kg ha ⁻¹)	MR (\$ ha ⁻¹)	CV%	MR (\$ ha ⁻¹)	CV%	MR (\$ ha ⁻¹)	CV%	MR (\$ ha ⁻¹)	CV%
0	1607	75	338 ^c	170	-534 ^d	-	470 ^d	53
60	823	213	1827 ^{abc}	36	2410 ^{bc}	51	1686 ^c	35
120	2375	28	2775 ^a	14	3649 ^{abc}	32	2933 ^{ab}	19
180	2086	75	3092 ^a	10	5510 ^a	28	3563 ^a	7
240	2439	30	3206 ^a	33	5513 ^a	25	3720 ^a	16
180: 75% St.	1307	54	984 ^{bc}	138	1492 ^{cd}	92	1261 ^{cd}	14
180: 50% St.	1376	128	1495 ^{abc}	39	2844 ^{abc}	19	1905 ^{bc}	27
180: 25% St.	2298	46	2584 ^{ab}	36	4786 ^{ab}	28	3223 ^a	19
P value	0.525		<0.001		<0.001		<0.001	

P Phosphorus (P₂O₅), St Struvite, Fredericton, New Brunswick (NB); Kentville, Nova Scotia (NS); Charlottetown, Prince Edward Island (PEI); Sainte-Catherine-de-la-Jacques-Cartier, Quebec (QC). Means followed by the same letter in a column for each section suggests not significant ($P > 0.05$)

eutrophication and the economic consequences of spending money on unused P fertilizer (Shaviv 2001). An alternative is struvite-based slow-release P fertilizers that have shown enhanced plant P uptake, reduction in root burn, and increase in yields, reducing negative environmental and economic consequences (Wang et al. 2023; Mancho et al. 2023; Shu et al. 2006; Rahman et al. 2014; Talboys et al. 2016; Nyborg et al. 1995; Shaviv 2001; Malhi et al. 2002). While there are benefits, there are two main drawbacks of this method. First, the increased crop performance is attained over a longer timeline due to the slow-release aspect of this method, which may be undesirable for some farmers (Pauly et al. 2002; Qian and Schoenau 2010). Secondly, the release of the P is dependent on environmental conditions like temperature and precipitation (Obreza and Sartain 2010; Roberts 2008; Lino et al. 2018).

A risk involved with struvite is when plants do not absorb it, the residue can affect the soil pH due to the heavy metal components (Rahman et al. 2014; Yang et al. 2012; Trenkel 2010). With regard to economics, struvite is more expensive to extract than conventional P fertilizer but can save on labor, handling, and operating costs from the application of P fertilizer (Shaviv 2001; Shu et al. 2006; Timilsena et al. 2015) unless fertilizer is applied with seeding.

Potato MRs did not show a consistent trend between all sites, but a mixture of struvite and conventional P is still considered a viable solution. Our results showed that NS and NB have no significant difference among P treatments for MR. Despite the statistical insignificance of differences, the 180 kg P_2O_5 ha⁻¹ treatment with 25% struvite increased in MR, highlighting the effectiveness of the struvite mixture as a viable alternative to conventional fertilizers. Potato yields were unreasonably low in some years at some sites; therefore, for statistical reasons we had to remove some of the data from the analysis. For NB, for example, Statistics Canada has reported 34.19, 32.93, and 34.44 Mg ha⁻¹ potato yields for 2016, 2017, and 2018, respectively; however, the potato yields from the experimental site were 21.82, 4.45, and 10.07 Mg ha⁻¹ for 2016, 2017, and 2018, respectively (Government of Canada 2024). We removed NB data in 2017 and 2018 from the analysis. Similarly, Statistics Canada reported a 33.26 Mg ha⁻¹ potato yield for 2016 in PEI and 30.26 Mg ha⁻¹ for 2017 in NS, but the experimental yield for 2016 in PEI was 19.41 Mg ha⁻¹ and 23.19 Mg ha⁻¹ in 2017 for NS.

In PEI, the treatments of 180 and 240 kg P_2O_5 ha⁻¹ and 180 with 25% struvite showed statistically similar and the highest MRs among the P treatments. Similarly, treatments of 240 P_2O_5 ha⁻¹, and a P rate of 180 kg with 25% struvite significantly surpassed a P rate of 60 kg ha⁻¹ and the control treatment in QC. The higher MRs of those treatments were the results of higher potato yields. The results

indicated that while a mixture of conventional P and struvite had no effect on MRs in NB and NS, a P rate of 180 kg ha⁻¹ with 25% struvite provided higher MRs in PEI and QC. However, P treatments of both 180 and 240 kg ha⁻¹ displayed higher MRs than the P rate of 180 kg ha⁻¹ with 75% struvite and control across all sites. This implies that the effects of a mixture of struvite and conventional P on potato yield and MRs are site specific and depend on the P and struvite used. This might be due to site-specific weather conditions and soil P deficiency level causing differential impacts of the mixes of struvite and conventional P on potato yields (Benjannet et al. 2020). While P treatment was not significant for MRs in 2016, a P rate of 180 kg ha⁻¹ with 25% struvite showed a higher increase in MR relative to control than the same P rate from a conventional source (triple super phosphate). Moreover, a P rate of 180 kg ha⁻¹ with 25% struvite provided statistically similar and higher MRs with P treatments of both 180 and 240 kg ha⁻¹ in 2017, 2018, and across years. This suggested that a P rate of 180 kg ha⁻¹ with 25% struvite was as beneficial as a high rate of conventional P used for high potato yields and hence high MRs, and its effect was consistent across years. Both potato yield and MR response to P rates showed a quadratic relationship, indicating that a supply of P rate of 180 kg ha⁻¹ optimized both yield and MRs across sites and years.

Environmental costs are impacted differently depending on the application rates (Fig. 2b). Analyses separately estimated the environmental costs for different P treatments. Following the analysis of environmental costs, the additional environmental expenditures were identified to be approximately \$12.23, \$24.67, \$36.7, and \$48.94 ha⁻¹ year⁻¹ for 60, 120, 180, and 240 kg ha⁻¹ of conventional P fertilizer, respectively, and \$28.82, \$20.94 and \$13.05 ha⁻¹ for treatments with application rates of 180 kg ha⁻¹ with 25% struvite, 50% struvite, and 75% struvite, respectively. As expected, the higher application rates correlated with increased P loss and, consequently, higher environmental costs. The inclusion of struvite in the fertilizer decreases the environmental cost compared to conventional fertilizer at the same rate. Specifically, the cost reductions were approximately \$7.88 ha⁻¹ year⁻¹, \$15.76 ha⁻¹ year⁻¹ and \$23.65 ha⁻¹ year⁻¹ for application rates of 180 kg ha⁻¹ with 25%, 50%, and 75% struvite, respectively. These findings underscore struvite's dual benefit of not only potentially providing long-term agricultural advantages but also reducing the environmental impact, thereby positioning struvite as a viable alternative to conventional fertilizers. An application of 180 kg ha⁻¹ of P_2O_5 with 25% of P_2O_5 coming from struvite and 75% coming from TSP could potentially reduce the environmental costs by 22% compared to 180 kg ha⁻¹ of P_2O_5 only from TSP.

Conclusion and summary

This study provides an analysis of potato yield and MR across different P treatment applications in Eastern Canada, emphasizing the potential of struvite as a viable alternative to conventional fertilizers. The research was conducted across multiple field trials in PEI, NB, NS, and QC from 2016 to 2018. Results showed that a mixture of 75% conventional P fertilizer and 25% struvite at the application rate of 180 kg ha⁻¹ provided similar economic results as conventional P fertilizer at the same or higher rate in PEI and QC. In PEI, the application of 180 kg ha⁻¹ with 25% struvite demonstrated the lowest CV, suggesting the highest MR stability. In contrast, no significant differences in MR among treatments were noted in NB and NS, with high CV values suggesting high variability and low consistency and stability in MR. Potato marketable yields and MRs' response to different P rates showed a strong quadratic relationship, indicating that a supply of P at the rate of 180 kg ha⁻¹ optimized both yield and MR across sites and years. This further confirms that a P rate of 180 kg ha⁻¹ with 25% struvite was equally effective as a conventional P source for both high yield and MRs across sites and years. Estimating the environmental cost revealed that struvite reduced costs compared to conventional fertilizers, enhancing its appeal as a sustainable alternative. Struvite fertilizers offer potential long-term benefits, such as improvements in efficiency, reduced root burn, and significant environmental advantages by reducing P runoff and lowering the cumulative environmental costs associated with eutrophication. The findings affirm the viability of struvite as a sustainable fertilization alternative for potato growers, emphasizing the effectiveness of slow-release P fertilizer in aligning with farm profitability and environmental stewardship. This study establishes a fundamental basis for further investigations into the long-term benefits and optimal application strategies of struvite-based fertilizers in various agricultural settings. The limitation of data on struvite application and P loss prevents the full environmental assessment of the experiment, emphasizing the importance of correct data collection and management. Additionally, a longer duration for the experiment could have provided more reliable data and, in turn, have seen statistically significant results.

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Data Availability The datasets during and/or analyzed during the current study are available from the corresponding authors on reasonable request. Code availability Not applicable.

Code Availability Not applicable.

Declarations

Ethical Approval The study was performed in accordance with the ethical standards as outlined by AAFC ethical standard protocols.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Conflict of interest The authors declare no competing interests.

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