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Phosphorus fertilizer with increased efficiency affects soybean yields

Carlos Henrique Eiterer de Souza[1], Victor Gustavo Soares Ribeiro[1], Lara Lúcia Gonçalves[3], Mateus Gonçalves de Borba[4], Roberto dos Anjos Reis Jr[5]

[1]University Center of Patos de Minas, Patos de Minas, MG, Brazil
[2]Federal University of Viçosa, Viçosa, MG, Brazil
[3]University Center of Patos de Minas, Patos de Minas, MG, Brazil
[4]University Center of Patos de Minas, Patos de Minas, MG, Brazil
[5]Wirstchat Polímeros do Brasil, Londrina, PR, Brazil

***Corresponding author: roberto@wsct.com.br**

Abstract

Phosphate fertilization is an important tool for achieving high yields in soybean, especially in tropical soils where phosphate fertilization efficiency is low. Fertilizers with improved efficiency, such as polymer-coated fertilizers, are one of several strategies to increase P fertilization efficiency. The objective of this study was to evaluate plant growth, leaf P content, soybean yield, and P fertilization efficiency in different seasons in response to P rates and sources. A factorial experiment (2 x 4) + 1 using two P sources (monoammonium phosphate (MAP) and Policote-coated MAP), four P rates (40, 80, 120, and 160 kg P_2O_5 ha^{-1}), and the control (no P fertilization) was conducted with soybean in the 2016-2020 seasons. Phosphate fertilization increased soybean yield and was affected by P rates and sources. Soybean yield increased from 1464.7 kg ha^{-1}, 468.4 kg ha^{-1}, and 2297.3 kg ha^{-1} without P fertilization to 3,638.5 kg ha^{-1}, 3,682.1 kg ha^{-1}, and 3,856.7 kg ha^{-1}, respectively, when MAP was applied at 158.0, 125.3, and 160 kg ha^{-1} P_2O_5, while when Policote coated MAP, the maximum productivity was 3,950.3 kg ha^{-1}, 4,380.5 kg ha^{-1} and 4,343.0 kg ha^{-1} with 159.0, 160.0 and 140.1 kg ha^{-1} P_2O_5, respectively, in 2017/2018, 2018/2019 and 2019/2020 seasons. Increasing phosphate fertilizer rates decreased agronomic P use efficiency (APUE), which was mitigated by P-coated fertilizer (fertilizer with improved efficiency). Lower APUE was observed in the 2019/2020 season, likely as a result of residual effects from previous phosphate fertilizer applications.

Introduction

Tropical regions are often characterized by highly weathered soils with low phosphorus (P) stocks (Roy et al., 2016) and a high capacity for P sorption (Vitousek et al., 2010; Roy et al., 2016) and are widely expected to play an increasing role in feeding the world's population. Suboptimal P nutrition can result in yield losses on the order of 10% to 15% of maximum yields (Shenoy and Kalagudi, 2005). Lower levels of P available to plants reduce the yield potential of soybeans by leading to reduced flowering and a greater number of aborted pods (Ventimiglia et al., 1999). In these soils, P is the element that needs more attention in crop fertilization. Brazilian soils, especially in the tropical savanna (Cerrado) where soybeans are widely grown, have a high affinity for this element. Attempts to improve soils by adding phosphate fertilizers are economically and environmentally unreasonable because the efficiency of added phosphate fertilizers is very low (Shenoy and Kalagudi, 2005). For this reason, much of the added P fertilizer is not used by the plants. As part of this process, farmers started to apply high amounts of high P inorganic fertilizer (Roy et al., 2017). These applications, which for soybeans include 1.5 to 2 times the amount of P fertilizer applied in the U.S. Midwest (Riskin et al., 2013), are costly (Meade et al., 2016) and have resulted in regional dependence on imported P. In Brazil, P fertilizer imports were equivalent to 62.1% of domestic P fertilizer consumption in 2017 (FAOSTAT, 2020). The low efficiency of P fertilization has been reported in several papers (Dhillon et al., 2017; Dhillon et al., 2019). It is estimated that plants take up only 15 to 25% of the P applied via fertilizer (Zanão et al., 2020).

For decades, scientists and engineers have been working to understand what constitutes P efficiency in an agricultural system (Weeks Jr. and Hettiarachchi, 2019), and various strategies have been used to increase P fertilization efficiency (Zanão et al., 2020). One approach that is being intensively researched to improve P use efficiency is to limit the association of the nutrient with reactive components of the soil (Weeks Jr. and Hettiarachchi, 2019) by using fertilizers with increased efficiency. These fertilizers contain aggregate technologies that control the release of nutrients or stabilize their chemical transformation in the soil, increasing their availability to the plant (Pelá et al., 2019). This type of technology has long been used in nitrogen fertilizers, but its use in P fertilizers is low (Zanão et al., 2020). One of the strategies used to increase the nitrogen efficiency of fertilizers is the addition of additives that can inhibit the conversion of nitrogen to soil in an undesirable way (AAPFCO, 1997). A similar strategy could be used with additives with iron and aluminum affinity, elements responsible for P fixation in tropical soils, since it is possible to increase the agronomic efficiency of fertilizers by using these additives to cover them. In studies with P fertilizer coated with anionic polymers (Policote), Chagas et al. (2015), Chagas et al. (2016), Chagas et al. (2017), Guelfi et al. (2018), Pelá et al. (2018), Pelá et al. (2019), and Zanão et al. (2020) showed that the efficiency of P fertilizer application was increased with this type of technology in tropical soils. Studies comparing the performance of phosphate fertilizer coated with polymers with that of ordinary phosphate fertilizer have not produced conclusive results, because while many reports point to the advantages of using a polymer coating (Figueiredo et al, 2012; Machado and Souza, 2012; Zhang et al., 2006; Dunn and Stevens, 2008; Wiatrak, 2013; Chagas et al., 2015; Chagas et al., 2016), others point out the inefficiency compared to conventional fertilizer (Valderrama et al., 2009; Gazola et al., 2013; Lino et al., 2018). Thus, it cannot be assumed that every coating with polymers leads to the same response. The need to increase the efficiency of P fertilization and the lack of information on P fertilizers with increased efficiency justify studies that evaluate the performance of this type of fertilizers. Considering the importance of the interaction between different soils, regions, and crop years and P fertilization, the objectives of this study were to evaluate plant growth, leaf P content, soybean yield, and P fertilization efficiency in different seasons in response to P rates and sources.

Results and discussion

Foliar P content

Foliar P content was significantly affected by P rates in the 2017/2018 ($p < 0.01$) and 2018/2019 ($p < 0.01$) seasons. The average foliar P content in the 2019/2020 seasons was 1.78 g kg^{-1}. P sources did not affect foliar P content. P fertilization increased foliar P content in soybean (Figure 1). Valderrama et al. (2009) found similar results in irrigated field bean, but Zanão et al. (2020) observed higher foliar P content with coated P fertilizer in soybean. Ribeiro et al. (2021) found that P sources and rates affected leaf P content, with coated P fertilizers yielding a higher leaf P content of 4.59 g kg^{-1} at a rate of 160 kg ha^{-1} P_2O_5. The range of appropriate foliar P content for soybean is 2.3-3.4 g kg^{-1} (Embrapa, 2013). Appropriate foliar P levels were obtained in this experiment with P rates above 63.3 kg ha^{-1} P_2O_5 (2017/2018 season) and 99.0 kg ha^{-1} P_2O_5 (2018/2019 season). Foliar P contents observed for the recommended P rate (120 kg ha^{-1} P_2O_5) based on soil analysis (CFSEMG, 1999) were 2.78 g kg^{-1} (2017/2018 season) and 2.43 g kg^{-1} (2018/2019 season). These foliar P contents were considered adequate (Embrapa, 2013). Phosphate fertilization is an important tool for achieving high yields in soybean because the absence of P reduces foliar P content, resulting in nutritional imbalance.

Leaves and stem dry matter

Leaf (LDM) and stem (SDM) dry matter were significantly affected by P fertilization only in 2017/2018 ($p < 0.01$) and 2018/2019 ($p < 0.01$) seasons. Mean LDM and STM in 2019/2020 seasons were 19.8 g $plant^{-1}$ and 14.8 g $plant^{-1}$, respectively. P sources did not affect leaf and stem dry matter. P fertilization increased leaf and stem dry matter in the 2017/2018 and 2018/2019 seasons. Phosphate fertilization linearly increased leaf and stem dry matter up to 14.6 and 8.93 g $plant^{-1}$, respectively, in the 2017/2018 season with 160 kg ha^{-1} P_2O_5 (Figure 2). However, in 2018/19 season, phosphate fertilization increased leaf and stem dry matter up to 19.0 and 17.9 g $plant^{-1}$ with 159.7 and 132.6 kg ha^{-1} P_2O_5, respectively. Phosphate fertilization is an important tool to achieve high yield in soybean as P reduces plant growth as observed in leaf and stem dry matter.

Results of the soybean harvest

Phosphate fertilization increased soybean yield (Figure 3), which was influenced by P rates and sources. Soybean yield increased from 1464.7 kg ha^{-1}, 468.4 kg ha^{-1}, and 2297.3 kg ha^{-1} without P fertilization to 3,638.5 kg ha^{-1}, 3,682.1 kg ha^{-1}, and 3,856.7 kg ha^{-1}, respectively, when MAP was applied at 158.0, 125.3, and 160 kg ha^{-1} P_2O_5, while with Policote coated MAP the maximum productivity was 3,950.3 kg ha^{-1}, 4,380.5 kg ha^{-1} and 4,343.0 kg ha^{-1} with 159.0, 160.0 and 140.1 kg ha^{-1} P_2O_5 in 2017/2018, 2018/2019 and 2019/2020 seasons, respectively. Increasing yields with polymer-coated P fertilizer were also described by Wiatrak (2013) and Ali et al (2017).

The highest yields with MAP as source in 2017/2018, 2018/2019 and 2019/2020 seasons (3,638.5 kg ha^{-1}, 3,682.1 kg ha^{-1} and 3,856.7 kg ha^{-1}, respectively) were 158.0, 125.3 and 160 kg ha^{-1} P_2O_5. The same yields were obtained in these seasons with Policote coated MAP with 102.0, 99.0 and 53.4 kg ha^{-1} P_2O_5, corresponding to 64.5%, 79.0% and 33.4%, respectively, of the amount of phosphorus used with MAP as source to obtain the same yield. The possibility of using fertilizers with increased efficiency to reduce the amount of fertilizer applied and thus reduce many costs associated with crop production was also reported by Hutchinson et al. (2003), Wiatrak (2013), and Ali et al. (2017).

Agronomic P use efficiency

Increasing phosphate fertilizer rate decreased agronomic P use efficiency (APUE), which was mitigated by P-coated fertilizer (fertilizer with improved efficiency). The lower APUE was observed in the 2019/2020 season, likely as a result of residual effects of previous phosphate fertilizer applications (Table 2).

The higher APUE with Policote coated MAP explains the higher yields obtained with this P fertilizer with improved efficiency.

Table 1. Soil chemical and textural attributes before the installation of the experiment. Patos de Minas, July, 2016.

Layer	pH	H+Al	Al	Ca	Mg	K	P	P-rem	CTC	V	MO	Clay
m	(H_2O)	$mmol_c.dm^{-3}$				$mg.dm^{-3}$		$mg.L^{-1}$	$mmol_c.dm^{-3}$	%	$g.dm^{-3}$	$g.kg^{-1}$
0.0-0.2	5.84	26	0.8	14	14	66.7	0.22	8.48	55.7	53	28.5	464
0.2-0.4	5.59	27	1.2	13	13	54.9	0.22	7.62	54.4	50	21.9	460

pH in water; Ca^{2+}, Mg^{2+} and Al^{3+} extractor KCl 1 mol L^{-1}; P-rem solution CaCl 0.01 mol L^{-1} containing 60 mg L^{-1} of P; P-meh and K^+ mehlich1 extractor; H+Al extractor Calcium acetate 1 mol L^{-1} at pH 7.0; M.O. determined by the Walkley-Black method.

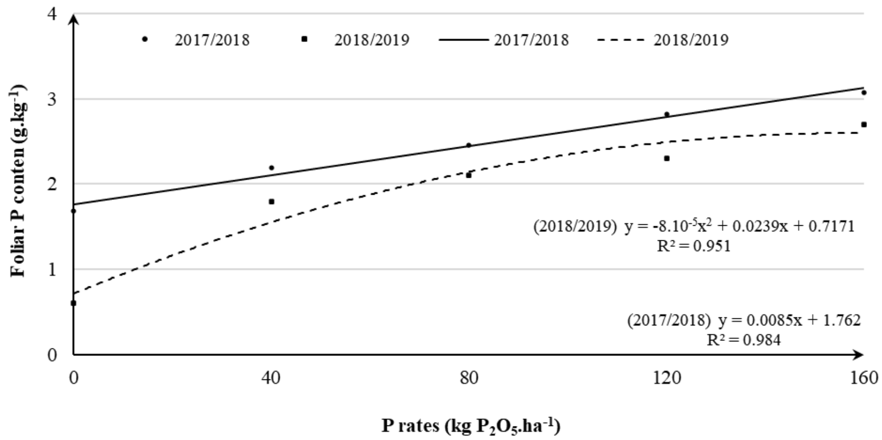

Figure 1. Foliar P content in response to phosphorus (P) rates in 2017/2018 and 2018/2019 seasons.

Table 2. Soybean agronomic P efficiency use in response to P rates and sources at 2017/2018, 2018/2019 and 2019/2020 seasons.

	Agronomic P use efficiency (kg soybean kg $P_2O_5^{-1}$)					
	MAP			Policote coated MAP		
	2017/2018	2018/2019	2019/2020	2017/2018	2018/2019	2019/2020
40	37.1	61.7	12.1	44.5	38.2	28.4
80	22.1	34.7	11.5	23.7	28.8	22.3
120	16.0	26.8	10.6	18.6	31.7	15.7
160	15.6	20.8	9.53	17.6	25.7	13.3
$Mean_{(season)}$	22.7	36.0	10.9	26.1	31.1	19.9
$Mean_{(source)}$	23.2			25.7		

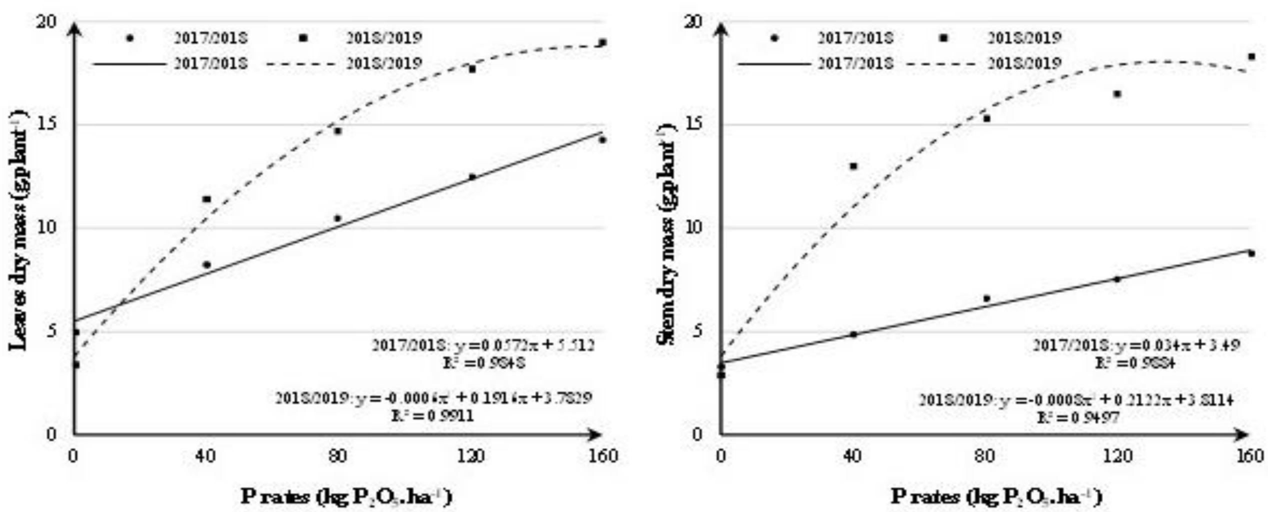

Figure 2. Leaves and stem dry matter in response to phosphorus (P) rates in 2017/2018 and 2018/2019 seasons.

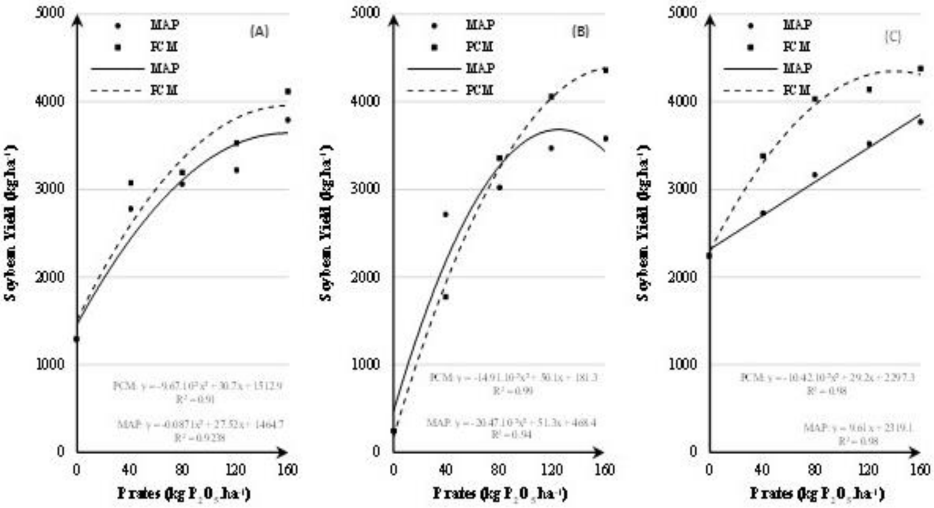

Figure 3. Soybean yield in response to phosphorus rates and sources (MAP and Policote coated MAP – PCM) in 2017/18 season (A), 2018/2019 season (B) and 2019/2020 season(C).

The increase in APUE with Policote-coated P fertilizer application was also observed by Chagas et al. (2015), Chagas et al. (2016), Guelfi et al. (2018), Pelá et al. (2019), and Zanão et al. (2020) in lettuce, coffee, and soybean, respectively. In addition, Ribeiro et al. (2021) found higher APUE values when using coated MAP.

Soybean yield as a function of recommended fertilization based on soil fertility

The recommended phosphorus rate based on soil analysis (CFSEMG, 1999) for this experiment is 120 kg ha^{-1} P_2O_5. At this rate and MAP, soybean yields in 2017/2018, 28018/2019 and 2019/2020 seasons were 3.512.8, 3,676.3, and 3,472.3 kg ha^{-1}, respectively, while with the same P rates and Policote coated MAP they were 3,805.0, 4,046.4, and 4,300.8 kg ha^{-1}, an increase of 8.3%, 10.0%, and 23.8%, respectively. Better results for plant height and wheat yield with polymer-coated fertilizers were also reported by Zhao et al. (2006). The polymer-coated fertilizers allowed plants to use them more effectively than the uncoated MAP in several cases, indicating potential for improving P fertilizer efficiency and crop production (Pauly et al., 2002). P uptake by plants can be improved by reducing the reaction with soil constituents by the Policote coating.

Materials and methods

Location

The experiment was conducted in Patos de Minas, MG, Brazil, during the 2016/2017, 2017/2018, 2018/2019, and 2019/2020 seasons, at geographic coordinates 18° 42' 45.2" S 46° 31' 51.5" W and an average altitude of approximately 832 m. According to Köppen International Classification, the climate of the region is classified as Aw, with an average temperature of 22.8 °C and precipitation of 1445 mm.

Soil characterization

The experiment was laid out on a Dystrudox (Soil Survey Staff, 1999). Soil samples (0-0.2 m and 0.2-0.4 m depth) were collected before seeding and subjected to chemical and physical analysis (Table 1). Soil P availability used in this experiment was rated "very low" according to CFSEMG standards (1999).

Experimental design

The experiment was laid out in a factorial (2 x 4) + 1 and randomized block (DBC) design using two P sources (monoammonium phosphate (MAP) - 11% N, 52% P_2O_5 and Policote coated MAP - 10% N, 49% P2O5), four P rates (40, 80, 120, and 160 kg ha^{-1} P_2O_5), and the control (no P fertilization). Policote is a water-soluble polymer-based additive distributed by Wirstchat Polímeros do Brasil. Each experimental plot consisted of five rows spaced 0.5 m apart and 7 m long.

Plant material and application of treatments

The variety SYN 13561 IPRO was sown after applying the treatments in the seed furrow on October 10, 2016 (2016/2017 season), December 9, 2017 (2017/2018 season), November 11, 2018 (2018/2019 season), and November 11, 2019 (2019/2020 season). Treatments were conducted in the same location season after season.

Conduct of the study and evaluations.

Potassium fertilizer (KCl; 120 kg K2O ha-1) was applied 25 days after plant emergence in all seasons. Cultural treatments were applied according to the technical recommendations for this crop. Leaf sampling (3rd Trifolium plus petiole) was performed at flowering (R1 stage) to evaluate P content in all seasons. Mass of 1000 grains (except in the 2019/2020 season), dry mass of leaves and stems, and yield were determined at harvest on March 27, 2017, April 10, 2018, April 3, 2019, and March 12, 2020. The dry mass of plant tissue was determined by drying in an oven at (70 °C) until constant weight. The experiment in 2016/2017 season was stopped due to climatic problems. Data were subjected to variance and regression analysis at probability level 0.05. The index of agronomic P use efficiency was calculated according to Fageria et al. (2010).

$$APUE = \frac{Gf - Gu}{Na}$$

Where: APUE: agronomic P use efficiency (kg soybean kg $P_2O_5^{-1}$), Gf: grain yield of fertilized plot (kg), Gu: grain yield of unfertilized plot (kg), Na: rate of applied P_2O_5 (kg).
Expected soybean yields for the recommended phosphorus rate were based on soil analysis (CFSEMG, 1999).

Statistical analyses
Data were subjected to the residual normality test (Shapiro-Wilk) followed by analysis of variance. Means were compared using Tukey's test ($p < 0.05$) for sources, and the regression model was fitted for P2O5 doses using the ExpDes.pt package in R Studio software (Rstudio Core Team, 2018).

Conclusions

Phosphate fertilization is an important tool for achieving high yields in soybean because P deficiency reduces foliar P content and plant growth. Yield differences among P sources were observed. Increasing phosphate fertilizer rates reduced agronomic P use efficiency (APUE), which was mitigated by the coated P fertilizer. Higher APUE with Policote coated MAP explained the higher yields obtained with this more efficient P fertilizer. The use of fertilizers with improved efficiency is a new technology to increase the phosphorus utilization of crops in the field.

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