

# Enhanced-Efficiency Phosphorous Fertilizer Impacts on Corn and Common Bean Crops and Soil Phosphorus Diffusion

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## Abstract

Phosphorus (P) supply to crops is a major constraint on the quantity and quality of food production in tropical soils, which are often characterized by highly weathered soils having low phosphorus use efficiency. Increasing P fertilizer use efficiency is a good tool for increasing food production to feed an increasing world population. Enhanced efficiency P fertilizer is used to achieve this goal. The lack of information about soil P diffusive flux and corn and common bean yield response with increased efficiency P fertilizers justify studies to evaluate the performance of this type of fertilizer. The aims of this study were to evaluate P diffusive flux and corn and common bean crop response to P sources and rates. A laboratory trial was carried out to evaluate soil P diffusive flux in response to P sources (MAP and Policote coated MAP). Field trials were carried out to evaluate corn and common bean yields in response to P sources (MAP and Policote coated MAP) and rates. Policote, an additive based on water-soluble polymers, is an anionic copolymer with iron an aluminum affinity. Increasing contact time between P-fertilizers and soil reduced phosphorus diffusive flux. Policote coated P-fertilizer resulted in higher phosphorus diffusion than conventional phosphorus fertilizer. Phosphorus fertilization increased corn and common bean yields. Policote coated phosphorus fertilizer resulted in higher agronomic P efficiency use, corn, and common bean yields than conventional phosphorus fertilizer. Policote coated P fertilizer can be used as an enhanced efficiency fertilizer and is a more efficient way to deliver required phosphorous to plants. Reducing farm investment, increasing agricultural profits, preserve phosphatic rocks reserves, and avoid the overuse of phosphate fertilizer could be realized through the rational use of enhanced efficiency fertilizers and fertilizer rate use reduction.

**Keywords:** agronomic efficiency, Policote, fertilizer technology developing

## 1. Introduction

Sub-optimal P nutrition can lead to crop yield losses in the range of 10% to 15% of the maximal yields (Shenoy & Kalagudi, 2005). Tropical regions are often characterized by highly weathered soils having low P stocks (Roy et al., 2016), high capacity for P sorption (Vitousek et al., 2010; Roy et al., 2016) and irreversible P fixation, favored by high contents of (hydr)oxides of Fe and Al (Abdala et al., 2015; Novais & Smyth, 1999). These regions are widely expected to play a growing role in the world population feed. Amelioration attempts by the addition of P-fertilizers are economically and ecologically unsound as the efficiency of added P-fertilizers is very low (Shenoy & Kalagudi, 2005). This scenario increases the pressure to increase P use efficiency. Currently, most commercial P fertilizers are water-soluble and P sorbs rapidly onto soil minerals, causing low P use efficiency and low residual values of these fertilizations (Everaert et al., 2017). The low efficiency of P fertilization has been reported (Dorahy et al., 2008; Takahashi & Anwar, 2007; Sanders et al., 2012; Dhillon et al., 2017; Dhillon et al., 2019). It is estimated that the plants absorb only 15 to 25% of P applied via fertilizer (Zanão et al., 2020). For this reason, much of the input P fertilizer is not used by crops. These P chemisorption processes greatly reduce the rate of P diffusion through the soil matrix to the root surface (Santner et al., 2015). Diffusion is considered the main mechanism for P transport in soils and is affected by a number of soil and solute parameters (Villani et al., 1998). P-fertilizer diffusion in the soil affects applied P efficiency by influencing the probability of root/P-fertilizer contact as well as soil/P-fertilizer contact (Eghball et al., 1990).

The high P adsorption capacity of Al- and Fe-oxhydroxydes in strongly weathered soils helps to maintain low levels of available phosphate (Johnson & Loeppert, 2006; DeLong et al., 2013; Fink et al., 2014) and reduces its diffusive flux to the soil solution, thereby hindering or delaying approach of this anion to plant roots (Raghothama & Karthikeyan, 2005).

Corn is the second-largest crop in Brazil's agricultural production, being surpassed only by the soybean crop that leads the grain production in the country. Common bean (*Phaseolus vulgaris* L.) is a food-secure and nutritious crop, playing a big dietary role, as supplying proteins, carbohydrates, essential elements and vitamins to both rural and urban households (Margaret et al., 2014). Brazilian producing areas are concentrated in the tropical regions, whose soils are highly weathered with low plant available phosphate. It is estimated that the world population will increase by 33% until 2050, from the current 7.2 billion to 9.6 billion people (Nalley et al., 2017). To provide adequate food, fiber, and renewable energy resources to meet this growth in population, we will need to dramatically increase crop yields (Heiniger et al., 2014), requiring, among several strategies, increasing the use of plant nutrients such as P applied in the form of fertilizers.

Developing new technologies to reduce P losses and increase its effectiveness is necessary to improve P management in tropical soils. For decades now, scientists and engineers have been working to understand what makes an agricultural system P efficient (Weeks Jr. & Hettiarachchi, 2019) and several strategies have been used to increase P fertilization efficiency (Zanão et al., 2020). There are a number of potential options to improve P fertilizer use efficiency by plants (McLaughlin et al., 2011; Withers et al., 2014). One approach being heavily explored to improve P use efficiency is to limit the association of this nutrient with reactive components of the soil (Weeks Jr. & Hettiarachchi, 2019) by using increased efficiency fertilizers. These fertilizers contain aggregate technologies that control the release of nutrients or stabilize their chemical transformations in the soil, increasing their availability to the plant (Pelá et al., 2019). This type of technology has long been used in nitrogen (N) fertilizers, but its use in P fertilizers is small (Zanão et al., 2020). One of the used strategies in enhanced efficiency fertilizers is the addition of additives capable of inhibiting the transformation of nitrogen into the soil in some undesirable way (AAPFCO, 1997). A similar strategy could be applied with additives of iron and aluminum affinity, elements responsible for P fixation in the soil because it's possible to increase fertilizer agronomic efficiency by using these additives to cover it. Increasing P fertilizer efficiency with P fertilizer coated with anionic polymers (Policote) was demonstrated P by Reis Jr and Silva (2012), 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).

The lack of information about soil P diffusive flux and corn and common bean yield response with increased efficiency P fertilizers justify studies to evaluate the performance of this type of fertilizer. The aims of this study were to evaluate P diffusive flux and corn and common bean crop response to P sources and rates.

## 2. Material and Methods

Experiments were carried out to evaluate soil P diffusive flux and corn crop response to P sources (MAP and Policote coated MAP). Policote, an additive based on water-soluble anionic copolymers marketed by Wirstchat Polímeros do Brasil, with iron and aluminum affinity.

### 2.1 Soil P Diffusive Flux

A trial was carried out in Unipam Laboratory (Patos de Minas, MG, Brazil). The experiment was laid out in a Yellow-Red Oxisol, whose soil chemical and physical properties were pH (H<sub>2</sub>O) = 5.59; organic matter = 2.0 g dm<sup>-3</sup>; Prem = 7.62 mg L<sup>-3</sup>; P-Mehl = 0,22 mg dm<sup>-3</sup>; K = 54.9 mg dm<sup>-3</sup>; Ca = 13 mmol<sub>c</sub> dm<sup>-3</sup>; Mg = 13.0 mmol<sub>c</sub> dm<sup>-3</sup>; Al = 1.2 mmol<sub>c</sub> dm<sup>-3</sup>; H+Al = 27 mmol<sub>c</sub> dm<sup>-3</sup>; CEC = 54.4 mmol<sub>c</sub> dm<sup>-3</sup>; base saturation = 50 %; clay = 650 g kg<sup>-1</sup>. The treatments were arranged entirely at random with four replicates, in a factorial (3 × 9), using two P sources [Control; MAP (11% N, 52% P<sub>2</sub>O<sub>5</sub>) and Policote coated MAP (10% N, 49% P<sub>2</sub>O<sub>5</sub>)] and nine incubation times (3; 6; 9; 12; 18; 24; 36; 48 and 60 days). The experimental unit was formed by a Ger-box chamber with a capacity of 0.3 dm<sup>3</sup> of soil. The experimental plots were filled to half of their volume with the soil, followed by the application of fertilizers at rate of 1,000 mg dm<sup>-3</sup> P (corresponding to the maximum capacity of adsorption of P in the soil), except for Control, in the center of the experimental plot. Subsequently, a 0.5 cm layer of soil was deposited and anion exchange resin sheets (AER; 2 × 2 cm) were installed over, followed by the application of the rest of the soil until the plot capacity experimental. After the application of P sources, the soil moisture was maintained at 80% of the field capacity. After each incubation time, the AERs were removed from the experimental plot and washed with water (to remove adhered soil) and dried on filter paper. Subsequently, P was extracted from the AERs with a solution of NH<sub>4</sub>Cl 0.8 mol L<sup>-1</sup> and HCl 0.2 mol L<sup>-1</sup>, after stirring at 200 rpm for one hour, according to the methodology described by Rajj et al. (1987), and determination of the P content

(Braga & Defelipo, 1974). The phosphorus diffusive flux (PDF) in the soil has been directly estimated by the use of AER (Amer et al., 1995) and by the use of filter paper impregnated with iron and aluminum oxides (Van der Zee et al., 1987; Menon et al., 1989), also called anionic paper. The AER adsorb the P from the soil solution, in its vicinity, similar to the behavior of a root, creating a gradient of concentration of P as it moves away from the AER. It is an indirect measure of PDF because it determines the P that reaches a known surface of AER, as it could be from a root, for a given period. Thus, the estimation of the diffusive flow, for each incubation time, was performed by quantifying the P adsorbed to the AER. With observed PDF after each incubation time (amount accumulated in the incubation period), the daily diffusive flow of phosphorus (DDFP) in the subsequent incubation time was calculated, according to the equation below, and the accumulated PDF was calculated.

$$\text{DDFP} = \frac{\text{PDF}_{\text{final}} - \text{PDF}_{\text{initial}}}{\text{Time (days)}} \quad (1)$$

## 2.2 Corn Crop

A corn trial was carried out in Lagoa Formosa, MG, Brazil (18°30'58.4"S, 46°12'34.6"W and average altitude around 886 m), whose climate is classified as Aw, with average temperature of 22.2 °C and average precipitation of 1462 mm. The experiment was laid out in a Yellow-Red Oxisol, whose 0-0.2 m layer soil chemical and physical properties were pH (H<sub>2</sub>O) = 6.41; organic matter = 30.0 g dm<sup>-3</sup>; Prem = 4.93 mg L<sup>-3</sup>; P-Mehl = 0.26 mg dm<sup>-3</sup>; K = 50.7 mg dm<sup>-3</sup>; Ca = 18 mmol<sub>c</sub> dm<sup>-3</sup>; Mg = 8.0 mmol<sub>c</sub> dm<sup>-3</sup>; Al = 0.1 mmol<sub>c</sub> dm<sup>-3</sup>; H+Al = 33 mmol<sub>c</sub> dm<sup>-3</sup>; CEC = 60.3 mmol<sub>c</sub> dm<sup>-3</sup>; base saturation = 45 %; clay = 550 g kg<sup>-1</sup>. The soil P availability is classified as "Very Low" (CFSEMG, 1999).

The treatments, applied in the planting furrow, were arranged in an incomplete factorial (2 × 4) + 1, using two P sources (MAP and Policote coated MAP), four P rates (40, 80, 120 and 160 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub>) and control (without P application). A complete block design, with four replication, was used. Each experimental plot had five rows, spaced 0.5 m, and seven meters long. The SHS7990 Pro cultivar was sown, after nitrogen (total 40 kg ha<sup>-1</sup> N; urea), potassium (50 kg ha<sup>-1</sup> K<sub>2</sub>O; KCl) and treatments applications in the sowing furrow, at December, 8<sup>th</sup>, 2017. Nitrogen and potassium (70 kg N + 70 kg K<sub>2</sub>O ha<sup>-1</sup> on V4 stage and 50 kg ha<sup>-1</sup> N on V6 stage; urea and KCl) were applied on top surface soil. Weed, pest and disease controls were made. The number of row/ear ratio, number of grain/row ratio and yield (corn spikes were manually cut, followed by manual threshing and moisture content correction to 13%, humid base) were evaluated on the three central rows of the experimental plot at harvest (April 25, 2018).

## 2.3 Common Bean Crop

A common bean trial was carried out in Patos de Minas, MG, Brazil (18°42'45.2"S, 46°31'51.5"W and average altitude around 840 m), whose climate is classified as Aw, with average temperature of 22.8 °C and average precipitation of 1445 mm. The experiment was laid out in a Yellow Oxisol, whose 0-0.2 m layer soil chemical and physical properties were pH (H<sub>2</sub>O) = 6.09; organic matter = 20.7 g dm<sup>-3</sup>; Prem = 3.43 mg L<sup>-3</sup>; P-Mehl = 6.22 mg dm<sup>-3</sup>; K = 1.00 mmol<sub>c</sub> dm<sup>-3</sup>; Ca = 27 mmol<sub>c</sub> dm<sup>-3</sup>; Mg = 9.0 mmol<sub>c</sub> dm<sup>-3</sup>; Al = 1.0 mmol<sub>c</sub> dm<sup>-3</sup>; H+Al = 44 mmol<sub>c</sub> dm<sup>-3</sup>; CEC = 81.0 mmol<sub>c</sub> dm<sup>-3</sup>; base saturation = 45.7 %. The soil P availability is classified as "Good" (CFSEMG, 1999).

The treatments, applied in the planting furrow, were arranged in an incomplete factorial (2 × 4) + 1, using two P sources (MAP and Policote coated MAP), four P rates (25, 50, 75 and 100 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub>) and control (without P application). A complete block design, with four replication, was used. Each experimental plot had five rows, spaced 0.5 m, and ten meters long. The Pérola cultivar was sown, after nitrogen (total 20 kg N ha<sup>-1</sup>; urea), potassium (30 kg ha<sup>-1</sup> K<sub>2</sub>O; KCl) and treatments applications in the sowing furrow, at April 20, 2018. Nitrogen (45 kg ha<sup>-1</sup> N; urea) and potassium (30 kg ha<sup>-1</sup> K<sub>2</sub>O) were applied on top surface soil at 25 days after plant emergence. Weed, pest and disease controls were made. Common bean yield was evaluated (bean pod was manually cut, followed by manual threshing and moisture content correction to 13%, humid base) on the three central rows of the experimental plot at harvest (April 25, 2018).

## 2.4 Statistical Analyses

Statistical analyses were performed with the statistical software package R (R core Team, 2016). An analysis of variance was run to test the significance of the P fertilizers and incubation time. The Shapiro-Wilk test was performed to test the residuals for normal distribution. Multiple comparisons were made using the Tukey's Test (P < 0.05). The phosphorus agronomic efficiency index (Fageria et al., 2010) was calculated with average corn and common bean yields.

### 3. Results and Discussion

#### 3.1 Soil P Diffusive Flux

Figure 1 shows the time course of P diffusion to the AER. The phosphorus diffusive flux (PDF) was significantly influenced by the phosphorus sources ( $p < 0.01$ ) and incubation times ( $p < 0.01$ ), with significant interaction between P sources and incubation times ( $p < 0.01$ ). In evaluations performed up to 36 days of incubation, the PDFs observed with MAP and Policote coated MAP were equal to each other and superior to the Control (Figure 1). In the evaluations carried out at 48 and 60 days of incubation, the PDF was statistically different between the P sources, when the Policoted coated MAP presented the highest PDF levels. The accumulated PDF increased with time, but stabilized with 24 days of MAP incubation, while it continued to increase with Policote coated MAP. Accumulated P diffusive flux with Policote coated MAP was 23.1% higher than with MAP, after 60 incubation days. Understanding the processes that influence the diffusive flow of P from fertilizer granules, especially when placed away from seeds, is important to increase its availability for plants in tropical soils.

Diffusion is the main mechanism for transporting phosphorus in the soil, which is influenced by several factors, such as the volumetric water content in the soil, the phosphorus-colloid interaction of the soil, the distance to reach the roots, the element content and soil temperature (Costa et al., 2006). The volumetric water content in the soil, the distance from fertilizer to AER (to reach the roots), the fertilizer supply (element content) and the soil temperature were the same among treatments (fertilizer source and incubation time) in this experiment. So, differences in phosphorus-colloid interaction of the soil explains the different P diffusive flux from different fertilizer source and incubation time. A reduction in P adsorption capacity of iron and aluminum oxides and hydroxides increases P diffusive flux and benefit crop P nutrition. The effect of fertilizer source and incubation time on P diffusive flux has been studied. P diffusive flux reductions with increasing incubation time were reported by Villani et al., (1988), explaining plant growth and soil available P reductions with increasing incubation time, as reported by Gonçalves et al. (1989). Different P sources [ $\text{Ca}(\text{H}_2\text{PO}_4)_2$ ,  $\text{NH}_4\text{H}_2\text{PO}_4$ ,  $(\text{NH}_4)_2\text{HPO}_4$ ,  $\text{Na}_2\text{HPO}_4 \cdot 2\text{H}_2\text{O}$ , and  $\text{K}_2\text{HPO}_4$ ] resulted in different P diffusive flux (Villani et al., 1988). Policote coated fertilizer increased P diffusive flux.

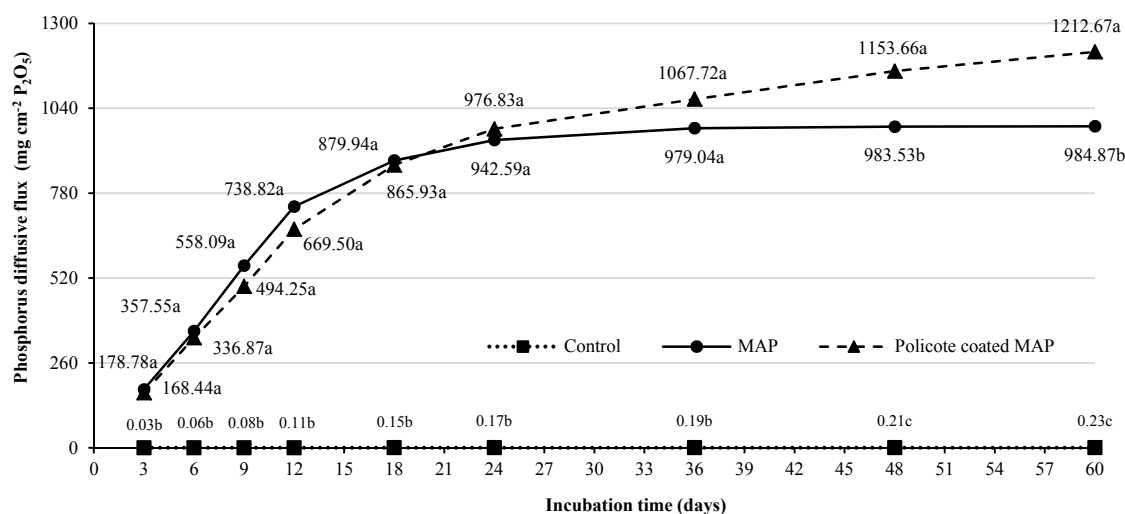


Figure 1. Accumulated phosphorus diffusive flux in response to P sources and incubation time. Means followed by the same letter in the same incubation time do not differ statistically among themselves by Tukey test ( $p < 0.05$ )

#### 3.2 Corn Crop

Fertilization increased the number of row/ear (NRE; Figure 2), the number of grain/row (NGR; Figure 3) and corn yield (Figure 4). NRE increased from 11.3 (without P fertilization) up to 14.1 ( $145.1 \text{ kg ha}^{-1} \text{ P}_2\text{O}_5$ , with MAP) and 17.3 ( $117.2 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$ , with Policote coated MAP). NGR increased from 21.1 (without P fertilization) up to 35.2 ( $134.2 \text{ kg ha}^{-1} \text{ P}_2\text{O}_5$ , with MAP) and 37.0 ( $116.1 \text{ kg ha}^{-1} \text{ P}_2\text{O}_5$ , with Policote coated MAP). Increasing NRE with P fertilization was also reported by Soares et al. (2018).

The corn yield increased from  $4,515.9 \text{ kg ha}^{-1}$  (without P fertilization) up to  $9,038.4 \text{ kg ha}^{-1}$  ( $160 \text{ kg ha}^{-1} \text{ P}_2\text{O}_5$ , with MAP) and  $9,562.3 \text{ kg ha}^{-1}$  ( $118.7 \text{ kg ha}^{-1} \text{ P}_2\text{O}_5$ , with Policote coated MAP). Higher crop yields with P

enhanced fertilizer were also reported by Sanders et al. (2012) and Noor et al. (2018). Higher corn yields with Policote coated P fertilizer were also reported by Pela et al. (2019) and Zanão et al. (2020). Coating of phosphatic fertilizers with the polymer is an innovative option to improve phosphorus use efficiency (Noor et al., 2017).

Phosphorus rate recommendation, considering soil P content availability, to corn crop is 120 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub> (CFSEMG, 1999). Corn yield with 120 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub> and MAP was 8,628.3 kg ha<sup>-1</sup>, while using the same P rate and Policote coated MAP it was 9,561.7 kg ha<sup>-1</sup>, an increase of 10.8%. The corn yield obtained with the recommended P rate based on soil analysis (120 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub> and MAP) was reached with 66.4 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub> and Policote coated MAP.

### 3.2 Common Bean Crop

P fertilization increased common bean yield (Figure 5). Common bean yield increased from 1362.0 kg ha<sup>-1</sup> (without P fertilization) up to 2,952.2 kg ha<sup>-1</sup> (96.9 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub>, with MAP) and 3,610.3 kg ha<sup>-1</sup> (86.0 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub>, with Policote coated MAP).

Phosphorus rate recommendation, considering soil P content availability, to common bean crop is 90 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub> (CFSEMG, 1999). Common bean yield with 90 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub> and MAP was 2,947.7 kg ha<sup>-1</sup>, while using the same P rate and Policote coated MAP it was 3,605.4 kg ha<sup>-1</sup>, an increase of 22.3%. The common bean yield obtained with the recommended P rate based on soil analysis (90 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub> and MAP) was reached with 39.3 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub> and Policote coated MAP. Lower P rates using polymer coated P fertilizer than conventional P fertilizer were also reported by Ali et al. (2017) to achieve the same yield. Reduced P rate using allows reducing farm investment, increasing agricultural profits, preserve phosphatic rocks reserves, and avoid the overuse of phosphate fertilizer.

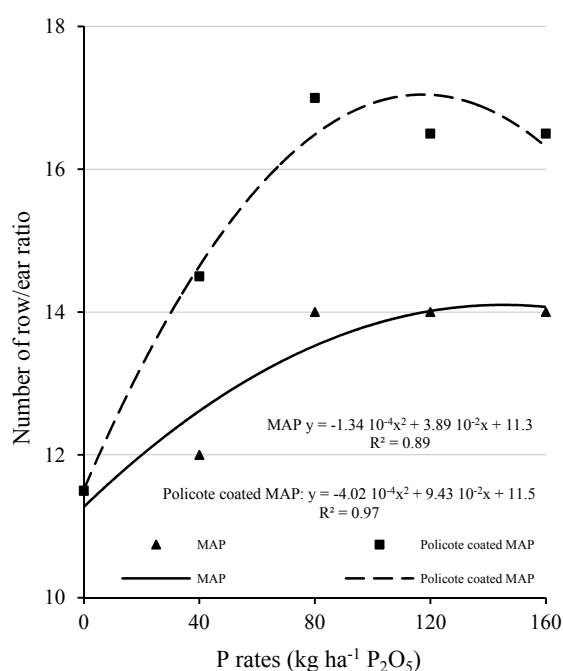


Figure 2. Number of row/ear ratio in response to P sources and rates in corn crop

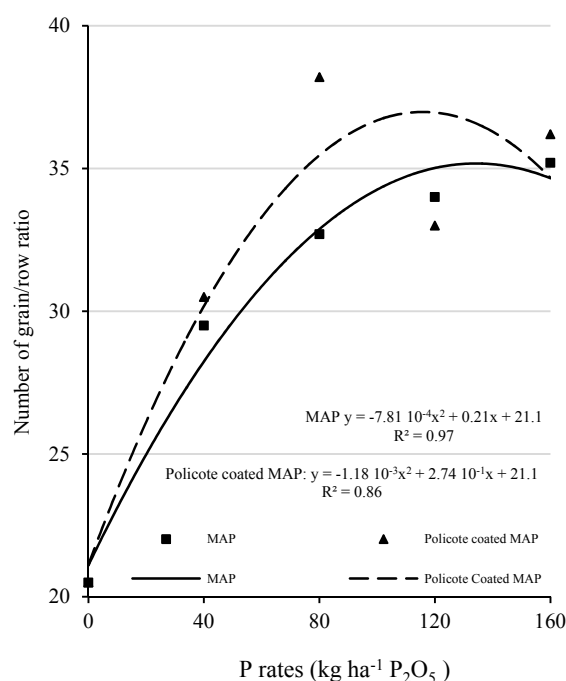


Figure 3. Number of grain/row ratio in response to P sources and rates in corn crop

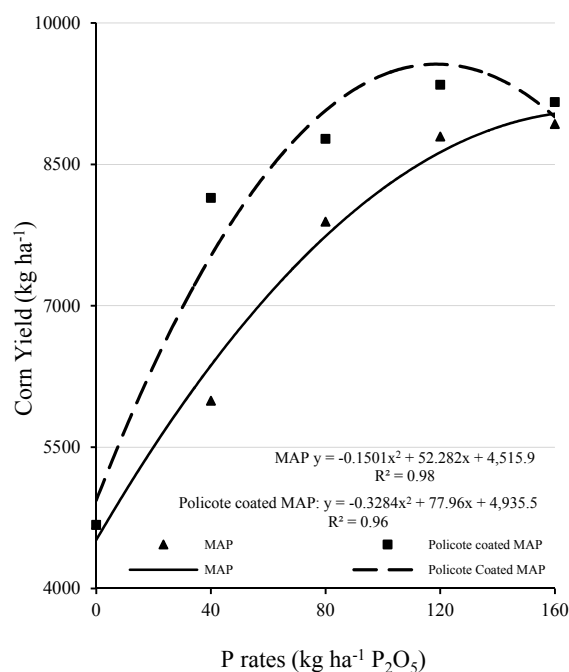


Figure 4. Corn yield in response to P sources and rates

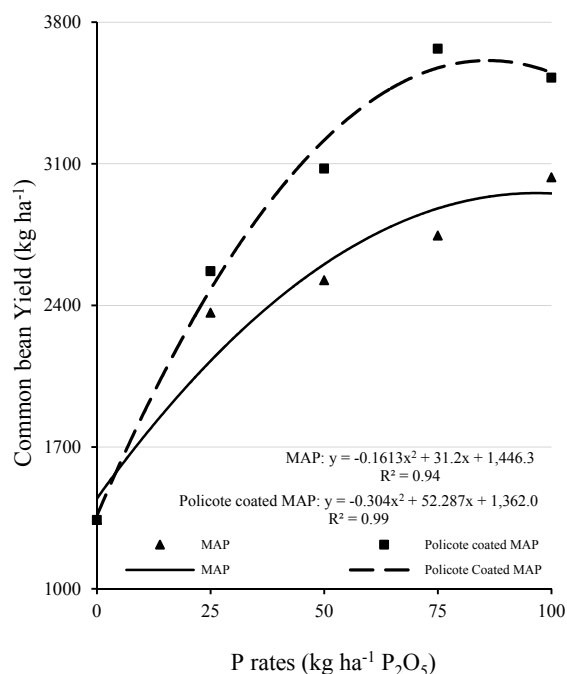


Figure 5. Common bean yield in response to P sources and rates

### 3.2 Agronomic P Use Efficiency

Table 1 shows the agronomic phosphorus use efficiency (APUE) in response to P sources and rates. Increasing P rates decreased APEU. It is explained by Mitscherlich's law of diminishing returns because there is a decreasing marginal yield as levels of the limiting factor are raised. However, Policote coated fertilizer resulted in higher APEU than conventional fertilizer. The increase in corn and common bean yields using Policote coated MAP was a consequence of the higher agronomic efficiency observed with this enhanced efficiency fertilizer. Policote coated P fertilizer is a more efficient way to deliver required phosphorus to plants. The same APEU trend was reported by Zanão et al. (2020), but with lower APUE than observed in this experiment.

Table 1. Agronomic phosphorus use index in response to P sources and rates

| $P_2O_5$ (kg ha <sup>-1</sup> ) | Corn Crop<br>(kg corn kg <sup>-1</sup> P <sub>2</sub> O <sub>5</sub> ) |                     | $P_2O_5$ (kg ha <sup>-1</sup> ) | Common Bean Crop<br>(kg common bean kg <sup>-1</sup> P <sub>2</sub> O <sub>5</sub> ) |                     |
|---------------------------------|--|---------------------|---------------------------------|--|---------------------|
|                                 | MAP  | Policote Coated MAP |                                 | MAP  | Policote Coated MAP |
| 40                              | 32.88  | 86.69               | 25                              | 41.0   | 49.1                |
| 80                              | 40.02  | 51.18               | 50                              | 23.7   | 34.7                |
| 120                             | 34.29  | 38.90               | 75                              | 18.7   | 31.0                |
| 160                             | 26.57  | 28.03               | 100                             | 16.9   | 21.8                |
| Mean                            | 33.44  | 51.19               |                                 | 25.0   | 34.1                |

Increasing P diffusive flux and agronomic P use efficiency explains increasing yields with Policote coated P fertilizer.

### 4. Conclusions

Incubation time (contact time between P fertilizers and soil) reduced phosphorus diffusive flux. Policote coated phosphorus fertilizer resulted in higher phosphorus diffusion than conventional phosphorus fertilizer.

Phosphorus fertilization increased corn and common bean yields. Policote coated phosphorus fertilizer resulted in higher agronomic P efficiency use, corn and common bean yields than conventional phosphorus fertilizer.

Increasing P difusive flux and agronomic P use efficiency explains increasing yields with Policote coated P fertilizer.

Policote coated P fertilizer can be used as an enhanced efficiency fertilizer and is a more efficient way to deliver required phosphorous to plants. Reducing farm investment, increasing agricultural profits, preserve phosphatic rocks reserves, and avoid the overuse of phosphate fertilizer could be realized through the rational use of enhanced efficiency fertilizers and fertilizer rate use reduction.

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