Potassium and magnesium foliar fertilization increase quality and soybean grain yield

Fertilização foliar de potássio e magnésio aumenta a qualidade e o rendimento de grãos de soja

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ABSTRACT

Increasing productivity sustainably is fundamental to any agricultural cultivation system. The aim of the present study was to evaluate different sources of potassium (K) and a source of magnesium (Mg), via foliar fertilization, on the agronomic performance of the soybean crop. The experiment was conducted in a randomized block design, with nine treatments and five replications, with three sources of K as pure reagents per analysis (P.A.) (K₂CO₃; K₂SO₄ and KNO₃), four commercial sources of K (A, B, C and D), a source of Mg (MgSO₄) and the control, without foliar application. The treatments were applied by foliar fertilization at the R5.1 stage.

Applications of MgSO₄ and commercial products A and D resulted in higher productivity than commercial C. Applications of commercial products A and C increased the thousand-grain mass compared to commercial B and K₂SO₄ and K₂CO₃. The application of commercial A resulted in an increase in the number of lateral branches compared to K₂SO₄ and commercial B, for the number of reproductive nodes in relation to K₂SO₄, commercial B and K₂CO₃, for the number of pods per plant in relation to commercial products B and C and K₂CO₃, and the number of grains per pod compared to commercial C and MgSO₄. The foliar application of K and Mg at the R5.1 soybean stage proved to be an efficient strategy to increase soybean grain yield and protein content in soybean grains.

Keywords: *Glycine max*, protein, spray fertilizer, plant nutrition.

RESUMO

Aumentar a produtividade de forma sustentável é fundamental para qualquer sistema de cultivo agrícola. O objetivo do presente trabalho foi avaliar diferentes fontes de potássio (K) e uma fonte de magnésio (Mg), via adubação foliar, sobre o desempenho agronômico da cultura da soja. O experimento foi conduzido em delineamento em blocos ao acaso, com nove tratamentos e cinco repetições, sendo três fontes de K na forma de reagentes puros para análise (P.A.) (K₂CO₃; K₂SO₄ e KNO₃), quatro fontes comerciais de K (A, B, C e D), uma fonte de Mg (MgSO₄) e o controle, sem aplicação foliar. Os tratamentos foram aplicados via adubação foliar no estádio R5.1. As aplicações de MgSO₄ e dos produtos comerciais A e D proporcionaram produtividade superior ao comercial C. As aplicações dos produtos comerciais A e C aumentaram a massa de mil grãos em relação ao comercial B, K₂SO₄ e K₂CO₃. A aplicação do comercial A resultou em aumento no número de ramos laterais em relação ao K₂SO₄ e comercial B, em maior número de nós reprodutivos em relação ao K₂SO₄, comercial B e K₂CO₃, em maior número de vagens por planta em relação aos produtos comerciais B e C e K₂CO₃, e em maior número de grãos por vagem em comparação com C e MgSO₄ comerciais. A aplicação foliar de K e Mg no estádio R5.1 da soja mostrou-se uma estratégia eficiente para aumentar a produtividade de grãos de soja e o teor de proteína nos grãos de soja.

Palavras-chave: *Glycine max*, proteína, adubação foliar, nutrição de plantas.
1 INTRODUCTION

Traditionally, the increase in productivity and final quality of soybeans is related, among other factors, to the increase in production cost. In this sense, it is necessary to have a greater economic return and, concomitantly, a production capacity of compensating for the initial investments in production. In modern agriculture, the use of inputs of adequate quality and quantity is required to conserve or increase crop productivity, focusing on economic criteria, and simultaneously preserving the soil in a sustainable way (Sfredo and Oliveira, 2010).

Cui and Tcherkez (2021) say that potassium (K) is the second nutrient most demanded by plants, with no structural function in plant metabolism, remaining almost entirely in the ionic form (K$^+$) in tissues. However, the nutrient acts as an enzyme activator in more than 60 enzymes, such as synthetases and kinases. These enzymes depend on K for normal activity. The nutrient also acts on changes in the conformation of molecules, increasing the exposure of active sites for substrate binding.

In general, the physiological roles of K in the plant are functioning on carbohydrate metabolism and production, starch breakdown and translocation, activity on nitrogen metabolism and protein synthesis, control, and regulation of the activity of various nutrients, neutralization of organic acids, activator of enzymes, stimulus to the growth of meristematic tissues, and the regulation of the movement to open and to close the stomata (Xu et al., 2020).

Considering its high concentration in the phloem from the old to the youngest leaves, the redistribution of K in the plants is high. The ability to maintain gas exchange, adequate levels of photosynthesis, and translocation of photoassimilates in the phloem to developing tissues under conditions of limited K supply require effective K redistribution from older to younger tissues. Therefore, the redistribution of K among plant tissues can effectively contribute to the efficient use of K (White et al., 2021).

The application of K can increase the productivity of soybeans, increase the protein content, mitigate the effects of stress, and increase the chlorophyll content. It is also reported that the foliar application of K can enhance the activity of antioxidative enzymes superoxide dismutase, ascorbate peroxidase, glutathione peroxidase, and superoxide dismutase in the leaves (Taha et al., 2020).

Magnesium (Mg) is present in many essential physiological processes and plays key roles in photosynthesis, photoprotection, and carbohydrate partitioning between plant tissues. Mg
participates in the synthesis of chlorophyll and activates several enzymes, including glutathione synthase, ribulose 1,5-bisphosphate (Rubisco), phosphoenolpyruvate carboxylase (PEPcase), RNA polymerase, protein kinases, phosphatases and ATPases, enzymes that are essential for photosynthesis and that directly influence the growth and development of plants (Rodrigues, 2021).

Given the above, this study aimed to evaluate the efficiency of different sources of K and a source of magnesium (Mg) applied by foliar application, in the agronomic performance of the soybean crop.

2 MATERIAL AND METHODS
2.1 EXPERIMENTAL SITE

The experiment was carried out in the field, at geographical coordinates 17º46'06" South, 51º01'58" West, and 846 m altitude. The climate in the region is Aw according to the Köppen classification, with an average temperature of 23.3 °C and an average annual rainfall of 1.663 mm (Climate-data, 2019). The rainfall index during the experiment was approximately 833 mm, and the average air temperature in the experimental period was 23.9 °C.

The soil in the experimental area was classified as dystrophic Red Oxisol (Ferralsol). For crop planting, a physical and chemical analysis of the soil was carried out (Table 1).

<table>
<thead>
<tr>
<th>pH</th>
<th>OM</th>
<th>P</th>
<th>Ca</th>
<th>Mg</th>
<th>K</th>
<th>Al</th>
<th>H+Al</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.13</td>
<td>20.63</td>
<td>27</td>
<td>2.71</td>
<td>0.92</td>
<td>0.19</td>
<td>0.05</td>
<td>3.67</td>
<td>53</td>
<td>5</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 1 Physicochemical properties of the experimental soil (0-20 cm depth).

| pH: in solution of CaCl₂ 0.01 mol L⁻¹; OM: organic matter; P: extraction with Mehlich-1; Ca, Mg, K: extracted with KCl 1 mol L⁻¹; Al, H+Al: extracted with 1.0 mol L⁻¹ calcium acetate.

The levels of K and Mg in the soil, interpreted according to Sousa and Lobato (2004), were within the range considered adequate. The planting fertilization in the experimental area was carried out using 200 kg ha⁻¹ KCl, 250 kg ha⁻¹ of monoammonium phosphate, and 30 kg ha⁻¹ of a fertilizer containing 8% Zn, 4% B, 4% Cu, 8% Mn, and 0.3% Mo.
2.2 CONDUCTING THE EXPERIMENT

The M7739 IPRO® Monsoy™ soybean cultivar was sowing using 1 L ha⁻¹ Nitrogin® (inoculant containing *Bradyrhizobium*).

The experimental design was a randomized block, with nine treatments, and five replications, totaling 45 plots. Each experimental plot consisted of 8 rows spaced at 0.50 m with 6 meters in length. For the evaluations, the useful plot was used, discarding two rows on each side of the plot, and 1.5 m at each end, totaling a 6 m². The treatments were applied on the leaves and consisted of 3 sources of K as pure reagents per analysis (P.A.), 4 commercials sources (A – K thiosulfate with 36.5% K₂O and 24.8% S; B – 40% K₂O and 10% N; C – 25% K₂O, 1% N and 5.08% amino acids; D – K carbonate with 35% K₂O), a source of Mg (MgSO₄·7H₂O), and the control - without foliar application. Doses were adjusted to 1 kg ha⁻¹ K₂O supported by Muraro et al. (2017), and 540 g ha⁻¹ Mg, according to Altarugio et al. (2017).

The foliar application of the treatments was carried out when soybean plants were at the R5.1 stage, using a CO₂ pump (20 psi pressure and spray volume corresponding to 150 L ha⁻¹), and application bar equipped with four XR 110.02 fan nozzles, spaced 0.5 m apart. The amounts applied from each source for the respective treatments were 1.47 kg ha⁻¹ K₂CO₃, 1.85 kg ha⁻¹ K₂SO₄ (T3), 2.51 kg ha⁻¹ KNO₃ (T4), 2.74 L ha⁻¹ commercial product A (T5), 2.65 kg ha⁻¹ commercial product B (T6), 3 L ha⁻¹ commercial product C (T7), 1.91 L ha⁻¹ commercial product D (T8), and 5.55 kg ha⁻¹ MgSO₄·7H₂O (T9). Each treatment received 200 mL ha⁻¹ vegetable oil as an adjuvant for greater adherence and absorption of the products.

During crop development, all crop treatments were carried out following the recommendations of the technical bulletin for commercial standard crops (Embrapa, 2013).

2.3 VARIABLES EVALUATED

Plants in the three central rows were manually harvested 122 after days of the crop cycle. We disregarded 1 meter at each end of the line, thus making up 6 m² useful areas harvested per plot.

Were evaluated yield, thousand-grain mass (TGM), plant height, number of lateral branches, number of reproductive nodes, number of pods per plant, number of grains per plant, number of grains per pod, nitrogen, and protein content in the grains.
The soybean yield was evaluated after threshing on a stationary threshing machine, after which the grain mass in each plot was determined. Moisture was analyzed in triplicate for each plot and after calculating the average, the yield was adjusted to a moisture content of 13%.

For the variables TGM, plant height, number of lateral branches, number of reproductive nodes, number of pods per plant, and number of grains per plant, 5 plants were randomly sampled in the useful plot. After analysis, the grain mass of the 5 plants was added to the soybean yield calculation.

To determine TGM, 5 samples of 100 grains were weighed for calculations using the formula: \( TGM = \frac{\text{sample weight} \times 1,000}{\text{total number of grains}} \).

Plant height was evaluated using a graduated ruler, considering the height of the plants from the collar stem to the apex of the last reproductive node.

The number of lateral branches, reproductive nodes, pods per plant, and grains per plant were manually counted. The number of grains per pod is a ratio of the number of grains per plant to the number of pods per plant.

The grain N content was determined by the Kjeldahl method, in which an aliquot of 0.2 grams was weighed for each plot and subsequently digested with sulfuric acid and heated in a digester block. After this step, the released ammonia was distilled and collected in a boric acid solution after a reaction with sodium hydroxide. The titration was performed with a hydrochloric acid solution, obtaining the N content in the samples.

Hence, with the N content, the protein content of the grains was calculated, using the factor 6.25 (Silva and Queiroz, 2002).

2.4 STATISTICAL ANALYSIS

The normality and homoscedasticity of residual variances were checked by Shapiro-Wilk and Bartlett tests, respectively. Thus, without the need for data transformation, the analysis of variance was run and, when significant by the F-test (p<0.05), mean values were compared by t-test (LSD) (p<0.05). Orthogonal contrasts (C) were also used since some treatments have similarities and differences such as compound type, nutrient, and sources, being relevant to the comparison of treatment groups, which were verified the significances by t-test (p<0.05): C1 = (-7)Control + (1)K₂CO₃ + (1)K₂SO₄ + (1)KNO₃ + (1)Com. A+(1)Com. B + (1)Com. C + (1)Com. D; C2 = (-3)Control + (1)K₂CO₃ + (1)K₂SO₄ + (1)KNO₃; C3 = (-4)Control + (1)Com. A+(1)Com.

3 RESULTS AND DISCUSSION

The yield of plants that received MgSO₄ was higher than plants treated with K₂CO₃, the control, and the commercial product C (Figure 1A). By the orthogonal contrasts C5, C6, C7, and C8, in addition to the higher grain yield compared to the control, the application of MgSO₄ resulted in higher yield compared to all P.A. K sources and commercial products containing K. The same results of these orthogonal contrasts were found for the number of grains per pod (Table 2).

Figure 1. Productivity (A), numbers of side branches (B), weight of 1000 grains (C) and numbers of reproductive nodes per plant (D) in function of sources of potassium and magnesium sulfate. Means followed by the same letter do not differ by the LSD test (α = 0.05).
Table 2 Comparisons among groups of means by orthogonal contrasts for the analyzed variables in the function of sources of potassium and magnesium sulfate.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Analyzed variables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Productivity (kg ha⁻¹)</td>
</tr>
<tr>
<td>Control (T1)</td>
<td>4663.20</td>
</tr>
<tr>
<td>K₂CO₃ (T2)</td>
<td>4870.80</td>
</tr>
<tr>
<td>K₂SO₄ (T3)</td>
<td>5054.40</td>
</tr>
<tr>
<td>KNO₃ (T4)</td>
<td>4911.00</td>
</tr>
<tr>
<td>Com. A (T5)</td>
<td>5004.00</td>
</tr>
<tr>
<td>Com. B (T6)</td>
<td>5004.60</td>
</tr>
<tr>
<td>Com. C (T7)</td>
<td>4120.20</td>
</tr>
<tr>
<td>Com. D (T8)</td>
<td>5156.40</td>
</tr>
<tr>
<td>MgSO₄ (T9)</td>
<td>5511.60</td>
</tr>
<tr>
<td>Means</td>
<td>4921.80</td>
</tr>
</tbody>
</table>

| Contrasts         |                        |                      |                        |                        |                      |                      |                        |                      |                    |
|--------------------|------------------------|----------------------|------------------------|------------------------|----------------------|----------------------|------------------------|----------------------|                    |
| C1                 | 3.52                   | -0.01                | -1.39                  | ns                     | -1.91                | -0.01                | 1.81                   | 7.73*                | 4.83*               |
| C2                 | 4.70                   | -0.03                | -2.03                  | ns                     | -2.92                | -0.00                | -0.65                  | 7.79*                | 4.87*               |
| C3                 | 2.64                   | 0.00                 | -0.91                  | ns                     | -1.15                | -0.01                | 3.66                   | 7.69*                | 4.81*               |
| C4                 | 2.07                   | -0.03                | -1.12                  | ns                     | -1.77                | 0.01                 | -                      | 0.11                 | 0.07                |
| C5                 | -14.15*                | -0.3                 | -1.25                  | ns                     | -5.10                | 0.12*                | -5.22                  | -                    | -6.28*              |
| C6                 | -9.44*                 | -0.33                | -3.28*                 | ns                     | -8.02                | 0.11*                | -10.05*                | -                    | -1.41               |
| C7                 | -11.51*                | -0.30                | -2.16                  | ns                     | -6.25                | 0.10*                | -1.57                  | -2.37                | -1.48               |
| C8                 | -10.62*                | -0.31                | -2.64*                 | ns                     | -7.00                | 0.11*                | -3.41                  | -2.32                | -1.45               |

Source: the authors.

Com. = commercial product; C1 = (-7)T1 + (1)T2 + (1)T3 + (1)T4 + (1)T5 + (1)T6 + (1)T7 + (1)T8; C2 = (-3)T1 + (1)T2 + (1)T3 + (1)T4; C3 = (-4)T1 + (1)T5 + (1)T6 + (1)T7 + (1)T8; C4 = (4)T2 + (4)T3 + (4)T4 + (-3)T5 + (-3)T6 + (-3)T7 + (-3)T8; C5 = (1)T1 + (-1)T9; C6 = (1)T2 + (1)T3 + (1)T4 + (-3)T9; C7 = (1)T5 + (1)T6 + (1)T7 + (1)T8 + (-4)T9; C8 = (1)T2 + (1)T3 + (1)T4 + (1)T5 + (1)T6 + (1)T7 + (1)T8 + (-7)T9. ns = not significant; * = significant at 5 % by the t test.

The application of commercial product A resulted in an increase in the number of lateral branches in the plants in relation to K₂SO₄ and commercial product B (Figure 1B).

Applications of commercial products A and C increased TGM compared to commercial B, K₂SO₄, and K₂SO₄. Commercial product C increased TGM compared to the control (Figure 1C). The C4 orthogonal contrast indicated that the application of K with the commercial products
provided greater TGM compared to the P.A. products containing K. The orthogonal contrast C6 indicated that the application of MgSO₄ provided greater TGM compared to all P.A. sources of K (Table 2).

For the number of reproductive nodes, plants that received commercial product A and MgSO₄ had a higher number of nodes than plants treated with commercial product B, K₂CO₃, and K₂SO₄ (Figure 1D). The orthogonal contrasts C6 and C8 pointed out that the application of MgSO₄ resulted in a greater number of reproductive nodes compared to all P.A. sources of K and all sources of K combined (Table 2).

Plants receiving commercial product A showed a greater number of pods per plant than the control, P.A. sources of K and commercial products B, C, and D. There was no significant difference between commercial product A and MgSO₄ (Figure 2A).

Figure 2. Numbers of pods per plant (A), numbers of grains per pod (B), nitrogen content in grains (C) and protein content in grains (D) in function of sources of potassium and magnesium sulfate. Means followed by the same letter do not differ by the LSD test (α = 0.05).
The application of MgSO$_4$ caused a decline in the number of grains per pod in the plants compared to the control, K$_2$CO$_3$, K$_2$CO$_5$, and commercial products A, B, and D. On the other hand, plants showed a higher value for this variable when they received the commercial product A compared to K$_2$SO$_4$ and commercial product C (Figure 2B).

The N content (Figure 2C) and the protein content (Figure 2D) in the grains presented a significant increase in the plants for all treatments compared to the control. That is, the application, at the R5.1 stage, of all K sources evaluated and MgSO$_4$ provided an increase in the N and protein content in the grains.

The orthogonal contrasts C1, C2, and C3 indicate an increase in the N and protein content in the grains with the application of all sources of K, whether P.A. or commercial, compared to the control. The C5 orthogonal contrast evidenced an increase in the N and protein content in the grains with the application of MgSO$_4$, compared to the control (Table 2).

For plant height, there was no significant difference between treatments (p<0.05) (Table 2).

The application of MgSO$_4$ provided an increase in soybean yield by 848 kg ha$^{-1}$ grains compared to the control, corresponding to an increase of 18%. Compared to the experiment carried out by Altarugio et al. (2017), the application of the same dose of MgSO$_4$ used here promoted an increase of 324 kg ha$^{-1}$ compared to the control. Vrataric et al. (2006) tested 1.9 kg ha$^{-1}$ Mg and obtained similar results with an increase of up to 9% in soybean yield with foliar application of Mg.

As observed by Muraro et al. (2017) and Passos et al. (2008), the foliar application of KNO$_3$ also did not result in significant increases in grain yield in relation to the control.

In agreement with the results of the present study, Altarugio et al. (2017) found no significant differences in TGM when applying MgSO$_4$ at the R5.1 stage compared to the control. Muraro et al. (2017) also obtained no significant difference in TGM compared to the control when potassium nitrate was applied to leaves at the R5.2 stage, as well as Passos et al. (2008).

Physical and chemical variables such as the deliquescence point and the point of efflorescence of salts can play a key role in the uptake of nutrients by leaves. In a study carried out by Schönher and Luber (2001), the highest rates of foliar absorption of salts containing K were associated with compounds with a low deliquescence point. In the present study, among the K salts applied as a reagent for analysis, K$_2$CO$_3$ is the most soluble (10.94 mol L$^{-1}$, at 25 ºC) and
with the lowest deliquescence and efflorescence points at 25 °C (45 % and 35 %, respectively) (Bahamonde et. al., 2023). However, K₂CO₃ was the only salt in the form of reagent (P.A.) that resulted in a significantly lower yield compared to the best treatment (MgSO₄). Therefore, assuming that higher yields were due to the greater uptake of nutrients applied via foliar, the results obtained here differ from those obtained by those authors, emphasizing the importance of further research to characterize the main factors affecting the absorption mechanisms and the efficiency of foliar fertilization.

The literature brings that the leave uptake of potassium by soybean plant depends on the source according to the following order: potassium carbonate > potassium acetate > potassium formate > potassium nitrate > potassium sulfate. The transport speed in vascular tissues after uptake also follows the same pattern, indicating the importance of the counter-ion (Corrêa et al., 2021). The counter-ion can also influence the efficiency of foliar fertilization due to its nutritional function. The positive influence of foliar application of elemental sulfur on soybean yield is reported, as well as, to a lesser extent, of foliar application of nitrogen during the grain filling phase (Bagale, 2021). In the present study, the foliar application of K₂CO₃ obtained lower results in terms of yield and the number of pods per plant among the pure salts (P.A.). In this case, physiological responses to the counter-ion (CO₃²⁻) are not expected since the C assimilated by plants comes from atmospheric CO₂ (Slattery and Ort, 2019).

The higher concentration of N and protein due to potassium foliar application compared to the control can be because potassium is directly and indirectly involved in the metabolism of vegetable proteins, being crucial in most stages of protein synthesis. The higher transport of essential amino acids in response to the foliar application of potassium is also reported in the literature, especially for developing seeds (Pande et al., 2014).

Foliar Mg supplementation increases the net photosynthetic rate and stomatal conductance and reduces leaf transpiration under light-saturated conditions in soybean plants. The increase in photosynthesis leads to an increase in the concentration of sugars in the leaves before grain filling. In addition, foliar fertilization with Mg can also increase antioxidant metabolism, reducing the environmental stress that plants may face under tropical climate conditions (Rodrigues et al., 2021). Therefore, these would be justifications for the higher productivity observed due to the foliar application of MgSO₄ compared to the control.
The antagonistic effect of K on Mg is stronger than that of Mg on K in uptake, transport, distribution, and utilization by plants. Root absorption and transport of Mg$^{2+}$ to shoots are inhibited by the increase in K supply, an inhibition that can have harmful effects on the yield and nutritional quality of harvested grains (XIE et al., 2021). In the present study, a dose of 116 kg ha$^{-1}$ K$_2$O was applied at planting. Considering the existing antagonistic effect of K on Mg, the dose of K applied may have been sufficient to negatively interfere with the uptake and use of Mg by the plants, thus justifying the greater yield of soybean plants fertilized with MgSO$_4$ via foliar application.

Considering that the protein content in the grains has been decreasing in commercial soybean crops, largely due to the genotypic characteristics of the available cultivars, our findings show that the application of K and Mg during the grain filling period can increase the N content and consequently the protein content in the grains (Pipolo et al., 2015).

4 CONCLUSIONS

P.A. sources of K (K$_2$CO$_3$, K$_2$SO$_4$, and KNO$_3$), commercial sources (A, B, C, and D), and MgSO$_4$ increased the nitrogen and protein content in soybean grains.

The application of commercial product A allowed the plants to increase the number of pods per plant, the number of grains per pod, the number of reproductive nodes, the number of grains per plant, and the number of lateral branches. Commercial product C allowed the increase in the thousand-grain mass of the plants.

Soybean plants subjected to the foliar application at the R5.1 stage of 540 g ha$^{-1}$ Mg as MgSO$_4$ had an increase in grain yield compared to the control.

The foliar application of K and Mg at the R5.1 soybean stage proved to be an efficient strategy to increase soybean grain yield and protein content in soybean grains.

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