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Foliar application of micronutrients and potassium in soybean crop

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Abstract: Foliar fertilization can improve plant nutrition and yield of soybean crops, especially in low-fertility sandy soils. This study investigated the agronomic efficiency of using micronutrient-based foliar fertilizers during the vegetative stage combined with potassium foliar fertilization during the reproductive stage on production components and grain yield of soybean crops in sandy soils of the Cerrado. The treatments consisted of the application of five micronutrient-based foliar fertilizers during the V_4 vegetative stage [Big Red® (Cu), Maxi Zinc® (Zn), Supa Moly® (Mo), Boster® (Zn, Mo) and CMZ Infinity® (Cu, Mo, Zn)] in association or not with the application of the K-based foliar fertilizer Yantra® during the R_3 reproductive stage. An additional treatment without foliar fertilizer application was used as a control. The treatments were arranged in a randomized block design in a 5 × 2 + 1 factorial scheme with four replications. The results showed that the application of foliar fertilizers containing Zn and Mo (Boster®) and Cu, Zn and Mo (CMZ Infinity®) are the best alternatives for use in soybean crops, as they result in greater plant height, height of first pod insertion, number of pods, total pod weight and higher grain yield, regardless of the association with K-based foliar fertilizer in the reproductive stage. The application of foliar fertilizers based on micronutrients and K had no impact on the thousand-grain mass of the soybean crop. The foliar application of K at the reproductive stage resulted in higher soybean grain yield when associated with the application of Zn (Maxi Zinc®) and Mo (Supa Moly®) at the vegetative stage.

Key words: Foliar fertilization; Foliar fertilizer; *Glycine max*.

1. Introduction

Soybean [*Glycine max* (L.) Merrill.] is one of the most important crops in the world, being widely cultivated in Brazil and worldwide. Currently, Brazil is the largest soybean producer in the world, with approximately 47.5 million hectares cultivated in the 2024/25 harvest and total production of approximately 166.0 million tons, which represented an average grain yield of 3,500 kg ha^{-1} (CONAB, 2025).

The Cerrado region is the largest soybean producer in the country, accounting for approximately 60% of national production (Vilela et al., 2020). Soybean production in this region will certainly continue to be an important driver of Brazil's agricultural economic growth in the coming years. However, the soils of the Cerrado region are generally acidic and poor in essential elements, such as phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and the micronutrients molybdenum (Mo), zinc (Zn), copper (Cu), manganese (Mn) and boron (B) (Fageria & Nascente, 2014; Gomides et al., 2023). This low fertility of the Cerrado soils has limited soybean yield in this region, especially because this crop requires high amounts of nutrients to obtain high levels of grain production (Sediyama et al., 2015).

Among the alternatives to meet this high demand for mineral nutrients and enhance the grain yield of soybean crops in the Cerrado region is the foliar application of mineral fertilizers (Fageria et al., 2009; Nava et al., 2011; Oliveira et al., 2019). Foliar fertilization has been an agronomic practice widely used in recent years and its purpose is to complement or supplement the mineral nutrient requirements of agricultural plants (Fageria et al., 2009).

Foliar fertilizers can be applied from the beginning of the vegetative stage to the reproductive stage of soybean plants. In general, during the vegetative development stage, foliar fertilizers based on micronutrients have been commonly applied to improve the nutritional, physiological and biochemical metabolism of plants and, consequently, crop development (Gonçalves et al., 2017; Oliveira et al., 2022). In turn, during the reproductive stage of flowering and grain filling, the application of foliar fertilizers based on macronutrients, especially nitrogen (N) and K, has been more frequent (Mandić et al., 2015; Oliveira et al., 2019). Foliar fertilization between the flowering and grain filling stages (R_1 to R_5) has been justified due to the reduction in root activity and nutrient absorption capacity by plant roots, precisely at a time that coincides with the greatest demand for nutrients by the soybean crop, when there is a high rate of nutrient translocation from the leaves to the grains (Fageria et al., 2009; Veiga et al., 2010; Sediyama et al., 2015; Oliveira et al., 2019). Therefore, foliar fertilization can be an essential factor in improving plant development and grain yield in soybean crops.

Positive responses to foliar micronutrient fertilization have been reported in agronomic studies with soybean crops. Oliveira et al. (2017) showed that foliar application of Zn at the vegetative stage resulted in greater growth and development of soybean plants and increased grain yield of the crop. Oliveira et al. (2022) reported that foliar Mo fertilization was efficient in improving nitrogen assimilation and metabolism and plant response to carbon fixation, resulting in increased grain yield of soybean and corn crops. Rossi et al. (2012) also showed that foliar application of Mo at the V_4 vegetative stage resulted in increased production components and grain yield of soybeans. Bedin et al. (2020) found that foliar Cu fertilization resulted in increased soybean grain yield, especially due to reduced severity of Asian rust. However, Gonçalves et al. (2017) found that foliar application of Cu resulted in increased content of this micronutrient in soybean leaves; but had no significant impact on grain yield.

These studies demonstrated the importance of foliar application of micronutrients during the vegetative phase in increasing grain yield in soybean crops. Furthermore, the effects of foliar fertilization with micronutrients can be enhanced by the association of foliar application with macronutrients during the reproductive stage. Lana et al. (2002) reported that foliar application of K at the reproductive stage had a positive effect on soybean grain yield. However, there are few studies evaluating the agronomic efficiency of foliar application of micronutrients in combination with foliar application of K.

This study was conducted to evaluate the agronomic efficiency of the use of micronutrient-based foliar fertilizers during the vegetative stage combined with foliar application of potassium during the reproductive stage on the production components and grain yield of soybean crops in the Cerrado region.

2. Material and Methods

2.1 Characterization of the Study Site

The field experiment was carried out in the municipality of Cassilândia, Mato Grosso do Sul, Brazil during the 2019/2020 growing season. The climate of the region, according to the Köppen classification, is tropical rainy (Aw), with a rainy summer and dry winter between the months of May and September (rainfall in winter less than 60 mm). The annual rainfall and the average annual temperature are 1,520 mm and 24.1 °C, respectively. The rainfall and temperature data recorded during the experiment are shown in Figure 1. The accumulated rainfall during the soybean crop development period was 520 mm. The monthly rainfall after soybean sowing was 7, 143, 108, 149 and 72 mm, respectively, for the months of November, December, January, February and March (Figure 1).

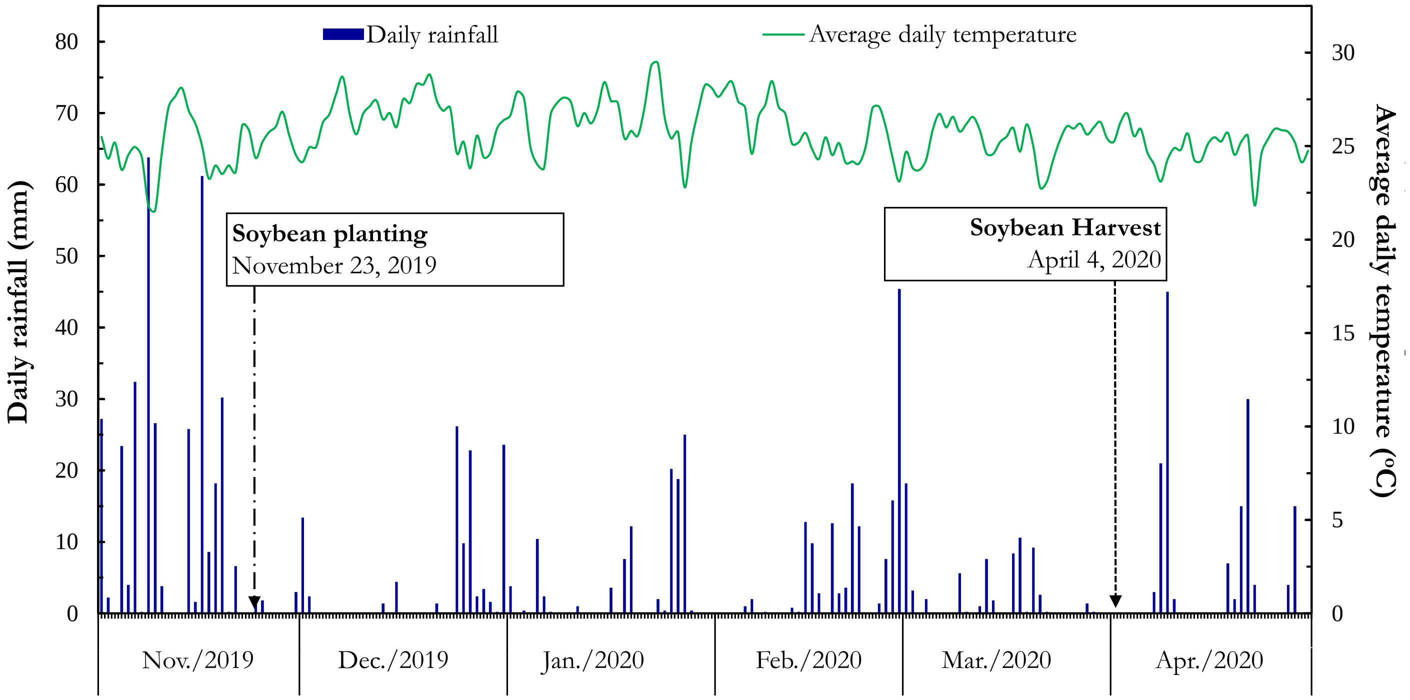

Figure 1. Daily rainfall (mm) and average daily temperature (°C) during soybean cultivation in the municipality of Cassilândia, MS, Brazil.

The soil of the experimental area was classified as dystrophic Red Latosol, deep, well-drained and of medium texture (230 g kg^{-1} of clay, 80 g kg^{-1} of silt and 690 g kg^{-1} of sand) (Santos et al., 2018). Before the start of the experiment, the experimental area had been cultivated in a no-tillage system for 2 years, with soybean [*Glycine max* (L.) Merrill.] in the spring/summer period and corn (*Zea mays* L.) in the fall/winter period. Before the implementation of the experiment, soil samples were collected in the surface layer of 0.0–0.20 cm depth, and the main chemical characteristics of the soil are shown in Table 1. The results of the chemical analysis indicate that the soil in the experimental area has low acidity and medium fertility. Ideal indicators for foliar fertilization bioassays.

Table 1. Some of the chemical characteristics of the soil in the 0.0–0.20 m depth layer before soybean sowing.

pH	P	MO	H + Al	Al	K	Ca	Mg	CTC	V
	mg dm^{-3}	g dm^{-3}	--------------------------------		cmol$_c$ dm^{-3}	------------------------------------			%
5.4	13.8	19.8	3.9	0.05	0.15	3.9	2.1	10.0	61

pH in 0.01 mol L-1 $CaCl_2$ solution. Mehlich-1 P extractant.

2.2 Experimental Design and Treatments

The experimental design used was a randomized block design in a 5 × 2 + 1 factorial scheme with four replicates. The treatments consisted of the application of five micronutrient-based foliar fertilizers during the V_4 vegetative stage [Big Red® (Cu), Maxi Zinc® (Zn), Supa Moly® (Mo), Boster® (Zn, Mo) and CMZ Infinity® (Cu, Mo, Zn)] in association or not with the application of the K-based foliar fertilizer Yantra® during the R_3 reproductive stage. An additional treatment without foliar fertilizer application was used as a control. The description of the chemical composition, doses and phenological stage in which the foliar fertilizers were applied are shown in Table 2.

Each experimental unit was 5.0 m long and 2.25 m wide (5 soybean sowing lines with 0.45 m spacing). The three central lines were considered for evaluating the production components and grain yield, disregarding 1.0 m from the ends of the plant rows, totaling a useful area of 4.05 m^2 (3.00 × 1.35 m).

Table 2. Chemical composition of foliar fertilizers based on micronutrients and potassium applied to soybean crops during the vegetative (V_4) or reproductive (R_3) stage in the 2019/2020 growing season.

Foliar Fertilizer	Chemical composition	Dose (mL ha^{-1})	Phenological stage
Big Red®	491 g L^{-1} de Cu	50	V_4
Maxi Zinc®	1000 g L^{-1} de Zn	400	V_4
Supa Moly®	256 g L^{-1} de Mo	100	V_4
Boster®	37 g L^{-1} de Zn; 24 g L^{-1} de Mo	200	V_4
CMZ Infinity®	105 g L^{-1} de Cu; 475 g L^{-1} de Zn; 54 g L^{-1} de Mo	400	V_4
Yantra®	449 g L^{-1} de K	1.500	R_3

Source: Agrichem do Brasil (2022).

2.3 Experiment Implementation and Management

The soybean cultivar BMX Desafio RR was sown on November 23, 2019, at a row spacing of 0.45 m, using 14 seeds per meter. The seeds were previously treated with pyraclostrobin + thiophanate methyl + fipronil (Standak Top®) at a dose of 2 mL kg^{-1} of seed and then inoculated with Bradyrhizobium japonicum strains SEMIA 5079 and SEMIA 5080, using the commercial liquid inoculant Simbiose Nod® Soja (Simbiose: Agrotecnologia Biológica), at a dose of 4 mL kg^{-1} of seed. Base fertilization was carried out by applying 350 kg ha^{-1} of the NPK fertilizer 04-20-20 in the sowing furrow.

The foliar fertilizers were applied using a CO_2-pressurized backpack sprayer with a pressure of 0.80 MPa, equipped with a flat fan nozzle, adjusted to apply a spray volume of 180 L ha^{-1}. After foliar fertilization, there was a minimum period of 72 hours without rain, allowing for better use of the foliar fertilizers.

The management of weeds, pests and diseases during the development of the soybean crop was carried out using the following products: Glyphosate, Pyraclostrobin + Epoxiconazole, Azoxystrobin + Cyproconazole, Teflubenzuron, Chlorpyrifos and Cypermethrin, according to the crop requirements and technical recommendations (Embrapa, 2011).

2.4 Measurement of Production Components and Grain Yield

Soybean harvesting was performed manually when the plants were at the R8 development stage (95% of the pods were mature). At harvest, plant height, height of first pod insertion, number of pods per plant, weight of pods per plant, weight of 1000 grains and grain yield were measured. Plant height and height of first pod insertion were measured from the soil surface to the apical meristem insertion and first pod insertion, respectively. The number of pods per plant and the weight of pods per plant were determined in a random sample of five plants from the useful area of the plot. The weight of 1000 grains were determined by weighing five random samples of 100 grains. Grain yield was standardized for a grain moisture content of 13%.

2.5 Statistical Analysis

The data were previously tested to verify the statistical hypotheses of homoscedasticity of variances (Levene's test; $p > 0.05$) and normality of residues (Shapiro-Wilk test; $p > 0.05$) using the statistical software Action Stat Pro® version 3.6 for Windows (Estatcamp – Consultoria Estatística e Qualidade, Campinas, SP). The data were then subjected to analysis of variance following a randomized block design in a 5 × 2 factorial scheme, applying the Fisher-Snedecor F test at a 5% probability level. The averages of the treatments with foliar fertilization of micronutrients and K were compared using the Tukey test at a 5% probability level. Statistical analyses were performed using the Sisvar® software version 5.6 for Windows (Ferreira, 2014).

The comparison between treatments with foliar fertilization of micronutrients and potassium with the control treatment (plants without application of foliar fertilizer) was performed using Dunnett's test at a 5% probability level (Dunnett, 1964).

3. Results and Discussion

Foliar application of micronutrients at the vegetative stage (V_4) in association or not with foliar K fertilization at the reproductive stage (R_3) significantly influenced plant height, first pod height and number of pods per soybean plant (Table 3). When there was no foliar K supplementation, the application of fertilizers containing Zn and Mo (Boster®) and Cu, Zn and Mo (CMZ Infinity®) resulted in greater plant height compared to other foliar fertilizers and control treatment. When there was K supplementation at the reproductive stage, the application of fertilizers containing Zn (Maxi Zinc®), Zn and Mo (Boster®) or Cu, Zn and Mo (CMZ Infinity®) resulted in plants with greater height compared to the application of other foliar fertilizers and control treatment (Table 3). In general, these results show that the foliar application of mineral fertilizers containing Zn in their composition had a beneficial effect on the growth of soybean plants. Souza et al. (2009) also found that foliar application of Zn resulted in greater height of soybean plants. This beneficial effect of Zn on plant growth is associated with its role in activating several enzymes and in the meristematic growth of plants by acting in the synthesis of the amino acid tryptophan, a precursor of indoleacetic acid (IAA), an auxin responsible for promoting cell elongation and regulating plant growth (Taiz et al., 2017).

Table 3. Effect of foliar micronutrient fertilization during the vegetative stage (V_4) in combination or not with foliar potassium fertilization during the reproductive stage (R_3) on plant height, first pod height and number of pods per plant for soybean crops grown in Cerrado soil during the 2019/2020 growing season.

Micronutrient-based foliar fertilizer	K-based foliar fertilizer (Yantra®)	
	No application (–K)	With application (+K)
	Plant height (cm)	
Big Red® (Cu)	73.2 bA	72.4 bA
Maxi Zinc® (Zn)	74.3 bB	77.4 aA*
Supa Moly® (Mo)	70.3 bA	73.1 bA
Boster® (Zn, Mo)	78.5 aA*	81.2 aA*
CMZ Infinity® (Cu, Zn, Mo)	79.4 aA*	80.9 aA*
Control	69.2	
	First pod insertion height (cm)	
Big Red® (Cu)	13.2 bB	15.4 abA*
Maxi Zinc® (Zn)	14.2 abA	15.5 abA*
Supa Moly® (Mo)	14.7 abA	14.5 bA
Boster® (Zn, Mo)	15.8 aA*	16.6 aA*
CMZ Infinity® (Cu, Zn, Mo)	14.0 abB	17.1 aA*
Control	13,0	

Micronutrient-based foliar fertilizer	K-based foliar fertilizer (Yantra®)	
	No application (–K)	With application (+K)
	Number of pods per plant	
Big Red® (Cu)	54 abA	55 abA
Maxi Zinc® (Zn)	51 bA	50 bA
Supa Moly® (Mo)	50 bA	51 bA
Boster® (Zn, Mo)	58 aA*	57 aA*
CMZ Infinity® (Cu, Zn, Mo)	57 aB*	62 aA*
Control	48	

[ab] Means followed by distinct lowercase letters in the columns and uppercase letters in the rows are significantly different by Tukey's test ($p < 0.05$). * Means with an asterisk differ from the control treatment (plants without foliar fertilization) by Dunnett's test ($p < 0.05$).

The application of foliar fertilizer containing Zn and Mo (Boster®) resulted in a higher height of first pod insertion compared to the application of foliar fertilizer containing Cu (Big Red®) when there was no foliar K supplementation in the reproductive stage. When there was K application in the reproductive stage, the application of fertilizers containing Zn and Mo (Boster®) and Cu, Zn and Mo (CMZ Infinity®) resulted in a higher height of first pod insertion compared to the application of the other foliar fertilizers (Table 3). Oliveira et al. (2017) reported the importance of Zn in increasing the height of first pod insertion in soybean crops. This effect is associated with the role of this micronutrient in plant growth because it is involved in auxin synthesis (Taiz et al., 2017).

The first pod insertion height of the soybean crop is an important agronomic characteristic for the mechanized harvesting of the soybean. According to Sediyama et al. (2015), the first pod insertion height should be at least 12.0 cm to reduce losses during the mechanized harvesting operation. Therefore, based on this reference value, the first pod insertion height obtained in this study is not a limiting factor for the mechanized harvesting of this soybean cultivar, regardless of the treatments with foliar fertilizer application (Table 3).

The application of fertilizers containing Zn and Mo (Boster®) and Cu, Zn and Mo (CMZ Infinity®) resulted in a higher number of pods per plant compared to the application of fertilizers containing Zn (Maxi Zinc®) and Mo Supa Moly®, regardless of the foliar application of K in the reproductive stage (Table 3). Rossi et al. (2012) found that the foliar application of Mo in the V_4 vegetative stage resulted in an increase in the number of pods in soybean plants. Similarly, Andrade et al. (1998), Rocha et al. (2011) and Lopes et al. (2016) also reported an increase in the number of pods per plant with the foliar application of Mo in common bean crops. These results indicate the importance of foliar application of micronutrients, especially Mo and Zn, during the initial development phase of legume plants to enhance the number of pods per plant.

Mo is an essential micronutrient for the shoot development of plants, especially for leguminous species, such as soybeans, which are capable of fixing atmospheric N^2. The importance of this micronutrient is due to its participation as a constituent of the enzymes nitrogenase, responsible for biological nitrogen fixation (BNF) by rhizobia, and nitrate reductase, responsible for the reduction of nitrate (NO_3^-) to nitrite (NO_2^-) (Taiz et al., 2017). Indeed, Oliveira et al. (2022) reported that foliar fertilization of Mo was efficient in improving nitrogen assimilation and metabolism and plant response to carbon fixation, resulting in an increase in the number of pods per plant and grain yield of soybean crops.

Foliar application of micronutrients at the vegetative stage (V_4) in combination or not with foliar K fertilization at the reproductive stage (R_3) significantly influenced the total pod weight per plant and the grain yield of the soybean crop (Table 4). When there was no foliar K supplementation, the application of fertilizers containing Cu (Big Red®) and Cu, Zn and Mo (CMZ Infinity®) resulted in an increase in the total pod weight per plant compared to the application of fertilizer containing only Zn (Maxi Zinc®). When there was K supplementation at the reproductive stage, the application of fertilizers containing Zn and Mo (Boster®) and Cu, Zn and Mo (CMZ Infinity®) resulted in a higher weight of pods compared to the application of fertilizer containing only Cu (Big Red®) (Table 4).

The application of fertilizers containing Zn and Mo (Boster®) and Cu, Zn and Mo (CMZ Infinity®) resulted in increased grain yield compared to the application of the fertilizer containing only Cu (Big Red®), regardless of the foliar application of K in the reproductive stage (Table 4). Garcia et al. (2009) found that the foliar application of Cu and Zn resulted in increased grain yield of soybean crops. Oliveira et al. (2017) reported that the foliar application of Zn resulted in increased grain yield of soybean. In turn, the increase in grain yield with the foliar application of Mo has been commonly reported in other studies with soybean (Rossi et al., 2012; Oliveira et al., 2022), common bean (Nascimento et al., 2009; Calonego et al., 2010; Rocha et al., 2011) and peanut (Steiner et al., 2023).

Table 4. Effect of foliar micronutrient fertilization during the vegetative stage (V_4) in combination or not with foliar potassium fertilization during the reproductive stage (R_3) on the weight of pods per plant, thousand-grain mass and grain yield of soybean crops grown in Cerrado soil during the 2019/2020 growing season.

Micronutrient-based foliar fertilizer	K-based foliar fertilizer (Yantra®)	
	No application (–K)	**With application (+K)**
	Total pod weight per plant (g)	
Big Red® (Cu)	27.5 aA	26.0 bA
Maxi Zinc® (Zn)	24.6 bB	28.0 abA
Supa Moly® (Mo)	25.3 abA	25.8 bA
Boster® (Zn, Mo)	27.4 aB	31.8 aA*
CMZ Infinity® (Cu, Zn, Mo)	29.8 aA*	30.2 aA*
Controle	24.4	
	1000 grain weight (g)	
Big Red® (Cu)	171 aA	170 aA
Maxi Zinc® (Zn)	169 aA	169 aA
Supa Moly® (Mo)	168 aA	172 aA
Boster® (Zn, Mo)	171 aA	175 aA
CMZ Infinity® (Cu, Zn, Mo)	175 aA	181 aA
Control	168	
	Grain yield (kg ha^{-1})	
Big Red® (Cu)	2,873 bA	2,993 bA
Maxi Zinc® (Zn)	3,075 abB	3,221 aA*
Supa Moly® (Mo)	2,907 abB	3,186 abA*
Boster® (Zn, Mo)	3,213 aA*	3,287 aA*
CMZ Infinity® (Cu, Zn, Mo)	3,298 aA*	3,392 aA*
Control	2,748	

[ab] Means followed by distinct lowercase letters in the columns and uppercase letters in the rows are significantly different by Tukey's test ($p < 0.05$). * Means with an asterisk differ from the control treatment (plants without foliar fertilization) by Dunnett's test ($p < 0.05$).

Bedin et al. (2020) found that foliar Cu fertilization resulted in increased soybean grain yield, especially due to reduced severity of Asian rust. Cu is a micronutrient that regulates photosynthesis processes, aiding plant respiration, balancing nutrients, activating enzymes, and contributing to biological N fixation in soybean plants (Taiz et al., 2017). In addition, it is also responsible for increasing disease resistance and plant protection (Bedin et al., 2020). However, in this study, foliar application of Cu-based fertilizer (Big Red®) resulted in grain yield equivalent to the control treatment (without foliar fertilizer application) (Table 4). Similar results were observed by Gonçalves et al. (2017), who found that foliar application of Cu resulted in increased content of this micronutrient in soybean leaves, but did not alter grain yield of the crop.

The thousand-grain weight was not significantly influenced ($p > 0.05$) by the application of micronutrient-based foliar fertilizers and K (Table 4). Some studies have reported the importance of foliar application of K during the reproductive phase of soybean for increasing the weight and grain yield of soybean crops (Lana et al., 2002; Pereira et al., 2016; VARGAS et al., 2018). In this study, the foliar application of K in the reproductive phase resulted in increased soybean grain yield when associated with the application of Zn (Maxi Zinc®) and Mo (Supa Moly®) in the vegetative phase (Table 4).

The higher grain yield with the application of K during the reproductive stage is associated with the fact that this foliar fertilization aims to maintain and/or increase the concentration of K in the leaves during the grain filling period, because in this phase the absorption of K by the plant roots is practically zero, and this nutrient is essential for grain filling (Silas et al., 2016). Therefore, the foliar application of K can improve the redistribution of this nutrient from the leaves to the pods during the grain filling phase and this can reflect in the increase in grain yield, as observed by Lana et al. (2002).

4. Conclusions

Foliar fertilizers containing Zn and Mo (Boster®) and Cu, Zn and Mo (CMZ Infinity®) are the best options to be applied in commercial soybean fields. These fertilizers can be applied by Brazilian farmers to obtain crops with greater plant height, height of first pod insertion, number of pods per plant, total pod weight and higher grain yield, regardless of the association with K-based foliar fertilizer in the reproductive stage.

The application of foliar fertilizers based on micronutrients and K had no impact on the thousand-grain weight of soybean crops.

Foliar application of K at the reproductive stage resulted in higher soybean grain yield when associated with the application of Zn (Maxi Zinc®) and Mo (Supa Moly®) at the vegetative stage.

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6. Additional Information

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6.3 Conflicts of Interest

The authors declare that there is no conflict of interest.