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# INTERACTION BETWEEN POLYMERS, MICRONUTRIENTS, AND INOCULANTS IN THE TREATMENT OF SOYBEAN SEEDS

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**Abstract:** This study evaluated the effects of different polymer formulations associated with micronutrients and inoculants in the treatment of soybean seeds (*Glycine max* L. Merrill), aiming to understand their influence on germination, initial growth, and root development of seedlings. The experiment was conducted in a greenhouse at the State University of Goiás, Palmeiras de Goiás Unit, in the first semester of 2025. The experimental design was randomized blocks, with seven treatments and thirty-six replicates (each plant being one replicate). Germination parameters, length, and fresh and dry mass of the aerial part and root system were evaluated, in addition to nodulation. The data were submitted to analysis of variance (ANOVA) and the means were compared by the Scott-Knott test at a 5% probability, using the AgroStat® program. The results showed significant differences between treatments, with T6 (Polymer + Experimental CoMo – 100) standing out, as it performed better in terms of root length and mass, in addition to promoting greater initial vigor. The association between polymers and micronutrients (Co and Mo) proved to be efficient for root growth and initial nutrition, although nodulation was reduced or absent in most treatments. It is concluded that the use of polymers associated with micronutrients represents a promising strategy for improving soybean seed treatment, although the compatibility between polymer and inoculant should be carefully evaluated.

**Keywords:** bioinputs; biological fixation; *Glycine max*; micronutrients; seed treatment.

## INTRODUCTION

Soybean (*Glycine max* L. Merrill) is one of the most important crops in global agribusiness, playing a strategic role in the production of food, animal feed, biofuels, and industrial products. Brazil is currently the world's largest producer and exporter of soybeans, followed by the United States and Argentina, consolidating its position as the leader in exports of this commodity (Conab, 2025). According to the Agro em Dados Bulletin (Goiás, 2025), the state of Goiás occupies a prominent position in national production, with more than 17% of the harvested volume. This significant productivity is directly associated with the use of technologies that aim to optimize the physiological performance of the crop and increase the efficiency of cultivation systems.

In recent years, advances in seed treatment (ST) have led to significant progress in precision agriculture and the sustainability of production systems. ST consists of the controlled application of protective products, such as fungicides, insecticides, micronutrients, and inoculants, directly on the seed, ensuring initial protection against pathogens and pests and promoting more uniform emergence (Silva *et al.*, 2021). Among the innovations employed, the use of polymers stands out. These substances are capable of forming a protective film that improves the adhesion of inputs to the seed, reduces water leaching, and minimizes the loss of inoculants.

The polymers used in seed treatment can be synthetic or biodegradable, and their physicochemical properties directly influence germination, vigor, and initial nutrition of plants (Santos *et al.*, 2021a).

When associated with micronutrients such as molybdenum, zinc, and cobalt, they can act as vehicles for the gradual release of these elements, which are essential for physiological and biochemical processes such as biological nitrogen fixation and chlorophyll synthesis (Fernandes Júnior *et al.*, 2009). Thus, polymers become important tools not only for protection but also for seed nutrition and physiological efficiency.

However, there are challenges and technical gaps in the use of polymers, especially in relation to compatibility with biological inoculants and micronutrients. Some synthetic polymers can compromise seed gas exchange and reduce germination, while naturally occurring materials such as alginates and chitosan, have greater compatibility and environmental degradation (Soares *et al.*, 2023). The study of these effects is relevant in the search for cleaner and more sustainable technologies capable of balancing productivity, biological viability, and environmental safety.

The use of polymers also directly influences the quality of rhizobium inoculation, since the coating can act both as a protective barrier against environmental stresses and as an obstacle to gas exchange and germination. Studies indicate that certain polymers increase the viability and adhesion of *Bradyrhizobium* spp. in seeds, prolonging their survival and enhancing nodule formation (Alves *et al.*, 2019; Reis *et al.*, 2020). On the other hand, the inappropriate combination of polymer and micronutrients can reduce inoculation efficiency. Thus, it is essential to evaluate the agronomic performance of plants under different treatments, considering both germination and growth aspects and biological nitrogen fixation.

In this context, the present study aimed to evaluate the initial development of soybean plants subjected to different seed treatments, with an emphasis on the use of polymers associated with inoculants and micronutrients, in order to understand their effects on germination, growth, and nodulation.

## MATERIALS AND METHODS

The experiment was conducted in a greenhouse belonging to the State University of Goiás (UEG), Palmeiras de Goiás University Unit (GO), in the first semester of 2025.

### Test Setup

The experiment was conducted under environmental conditions in December 2024. Plastic pots with a capacity of 8 L were used. The substrate used consisted of commercial substrate, sand, and organic matter (a mixture of poultry manure and carbonized rice husks) in a ratio of 2:1:2 (v/v/v). No additional chemical or h y supplementation was performed during the test. Five soybean seeds were sown in each pot, arranged equidistantly from each other.

### Treatments applied

The soybean seeds received the treatments described in Table 1. After treatment, the seeds were left in ambient conditions to dry completely (Figure 1).

The treatments involved combinations of polymers, micronutrients, and conventional chemical treatment, applied prior to sowing according to the manufacturer's recommendations. The seeds were homoge-

Identification	Description of treatments
T0	Bare seed
T1	Polymer
T2	Polymer + exp. TS (100)*
T3	Polymer + TS exp. (200)*
T4	Polymer + TS exp. (300)*
T5	Experimental CoMo (100)*
T6	Polymer + Experimental CoMo (100)*

\* Product dose (mL or g/100 kg).

Table 1. Description of treatments performed on soybean seeds for the initial development study. December (2024).

Source: Author.



Figure 1. Detail of soybean seeds treated with identification of the respective treatments. December (2024).

Source: Author.



Figure 2. Detail of the test setup. A – Germination test; B – Plants cleaned for separation of aerial parts and roots; C – Roots for measurement and other analyses.

Source: Author.

nized manually until the grains were completely covered.

## Evaluations

The following parameters were analyzed:

Germination (%): evaluated in trays containing the same substrate used in the test, with four replicates of ten seeds per treatment. Counts were performed at 3, 5, and 8 DAS (Figure 2).

Plant evaluations were performed 20 days after sowing (DAS) (Figure 2). The following were determined: Aerial part development: aerial part length (APL), fresh mass (FPM), dry mass (DMP), and leaf area (LA). Root development: root length (RL), fresh root mass (FRM), dry root mass (DRM), and number of nodules (NNod).

The plants were carefully collected, washed in running water, and segmented at the collar, separating the aerial part and root. Length was determined with a tape measure, and fresh mass was obtained with an analytical balance. For dry mass, the samples were placed in paper bags and dried in a forced-air oven at 100 °C until they reached a constant weight. The leaf area was estimated using AFSOFT software (Embrapa, 2010).

## Experimental Design

The design adopted was randomized blocks, with seven treatments and thirty-six replicates per treatment (each plant being one replicate). Six pots containing five plants/pot were used. The data obtained were submitted to analysis of variance (ANOVA), and the means were compared

using the Scott-Knott test at a 5% probability level, using AgroStat<sup>®</sup> statistical software.

## RESULTS AND DISCUSSION

The germination analysis showed significant differences between treatments throughout the evaluation period. Three days after sowing (DAS), treatment T4 had the highest germination rate, followed by T5. At 5 DAS, T0 (control) recorded the highest germination percentage, followed by T1 and T6. At 8 DAS, T0 maintained the best performance, reaching 100% germination, while T5 obtained the lowest percentage (75%), observed at 5 DAS. The average germination time (AGT) calculated was 2.4 days; T0 had an AGT of 2.8 days, and treatments T2 and T3 exhibited the lowest AGT (2.0 and 2.2 days, respectively) (Figure 3).

The variability observed suggests that the formulations applied influenced the germination kinetics, not necessarily in a linear fashion with the presence of the polymer. In particular, the superior performance of T0 at 8 DAS indicates that some formulations may delay the final emergence of seedlings, possibly by temporarily altering the inhibition or gas exchange of the seed coat (Barros Neto *et al.*, 2014). Similar results have been reported in the literature on polymeric seed coating. Studies indicate that the use of polymers can improve treatment uniformity and product adhesion to seeds; however, depending on the polymer composition and concentrations used, distinct physiological effects may occur, including changes in germination and seedling vigor (Taylor *et al.*, 2001; Avelar *et al.*, 2012). From a practical point of view, treatments that do not reduce final germination (such as T0 and T6 in part) are preferable to ensure uniform esta-

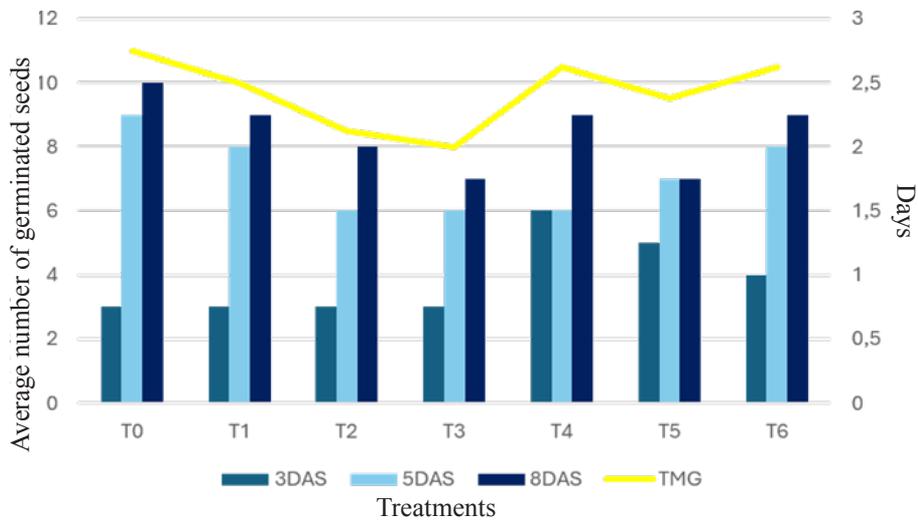


Figure 3. Average values obtained in the germination test of soybean seeds subjected to different treatments.

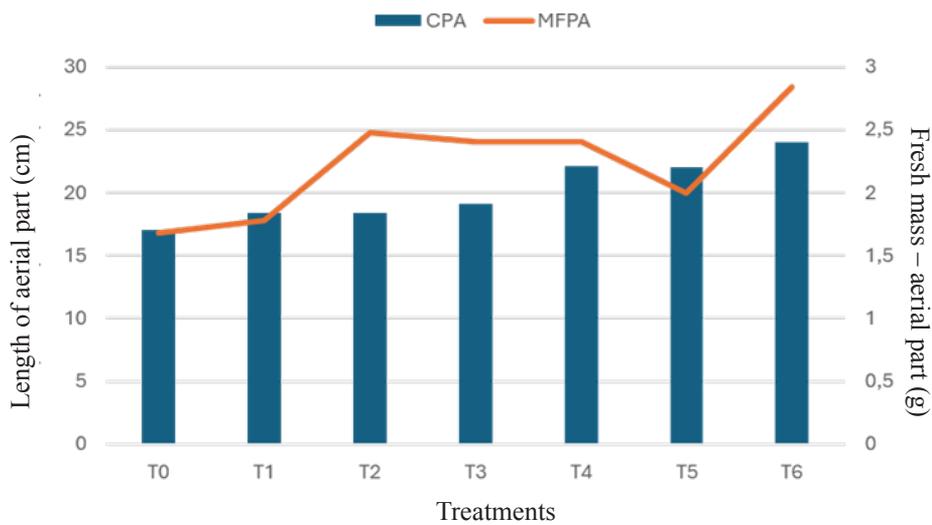


Figure 4. Mean values of shoot length and fresh shoot mass of soybean plants evaluated 20 days after sowing.

Source: Author.

blishment. However, T2 and T3, despite the lower TMG (faster), were not necessarily the best in all parameters of subsequent vigor, indicating that germination speed is not the only indicator of initial performance.

The results obtained showed significant differences between treatments for shoot length (SL), fresh shoot mass (FSSM), and leaf area (LA), while dry shoot mass (DSSM) did not show statistically relevant variation (Table 1 - Appendix).

Treatments T4, T5, and T6 promoted greater shoot elongation (Figure 4), indicating that the association of polymers with micronutrients, especially cobalt and molybdenum, may have contributed to stimulating initial seedling growth.

These elements act directly on nitrogen metabolism and physiological development in plants (Hungria; Nogueira; Araújo, 2020). Treatment T6 (Polymer + Experimental CoMo – 100) stood out for its better performance in three evaluated parameters (CPA, MFPA, and AF), followed by T5 (Experimental CoMo). This positive response suggests that the addition of the polymer (CoMo), by promoting greater adhesion and uniformity of micronutrients to the seed surface, contributed to a gradual and efficient release of essential elements (Chen *et al.*, 2023; Gubisová *et al.*, 2021) that act in important physiological processes, notably in the synthesis of enzymes related to N metabolism and photosynthetic vigor, favoring absorption during the initial stage of development. In addition, the polymer film can reduce losses due to leaching and volatilization, ensuring better nutritional utilization (Costa *et al.*, 2021).

On the other hand, the absence of a significant difference in above-ground dry

weight (AGDW) (Table 1 - Appendix) may be related to the short evaluation period (20 days), which was not sufficient for significant dry matter accumulation. Similar results were observed by Conceição *et al.* (2014), who found initial positive responses in the growth and vigor of soybean seedlings treated with micronutrient-containing polymers, but less significant differences in dry biomass during the first weeks of development. The literature corroborates that polymers associated with micronutrients can improve uniformity and initial vigor (Pereira *et al.*, 2022), but the final effect depends on the dose, type of polymer, and mode of interaction with other components of the treatment (Costa *et al.*, 2021).

The increase in leaf area (LA) observed in treatments T5 and T6 (Figure 5) indicates greater photosynthetic capacity and growth potential.

According to França *et al.* (2020), greater leaf area is indicative of metabolic efficiency, associated with better nutritional status and physiological balance of seedlings. This result reinforces the potential of polymers as a complementary technology in seed treatment, especially when associated with essential nutrients, providing adequate conditions for uniform emergence and vigorous initial establishment.

Thus, the results obtained in this study corroborate the evidence that the use of polymers in conjunction with micronutrients, especially Co and Mo, can favor the initial growth of soybean plants. However, the efficiency of this practice depends on factors such as the chemical composition of the polymer, compatibility with the inoculant, and environmental growing conditions (Reis *et al.*, 2020).

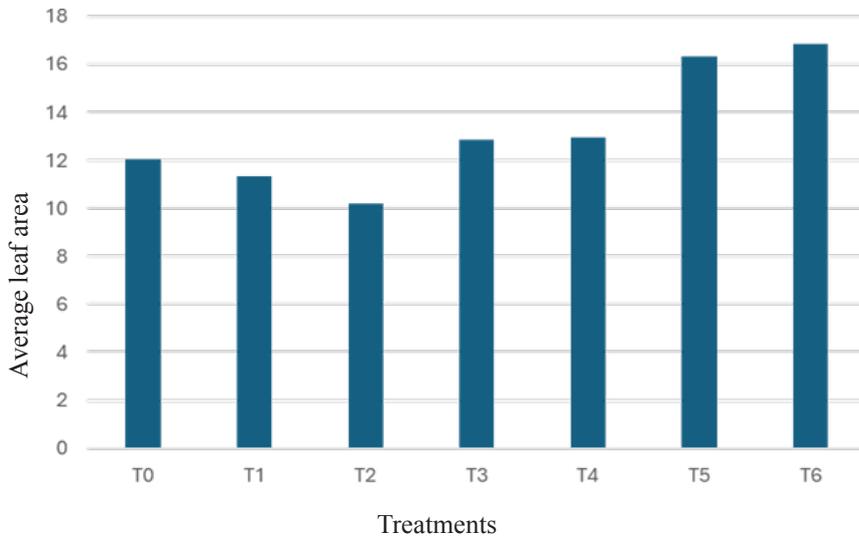


Figure 5. Mean values of the leaf area of fully expanded trifoliates of soybean seedlings evaluated 20 days after sowing.

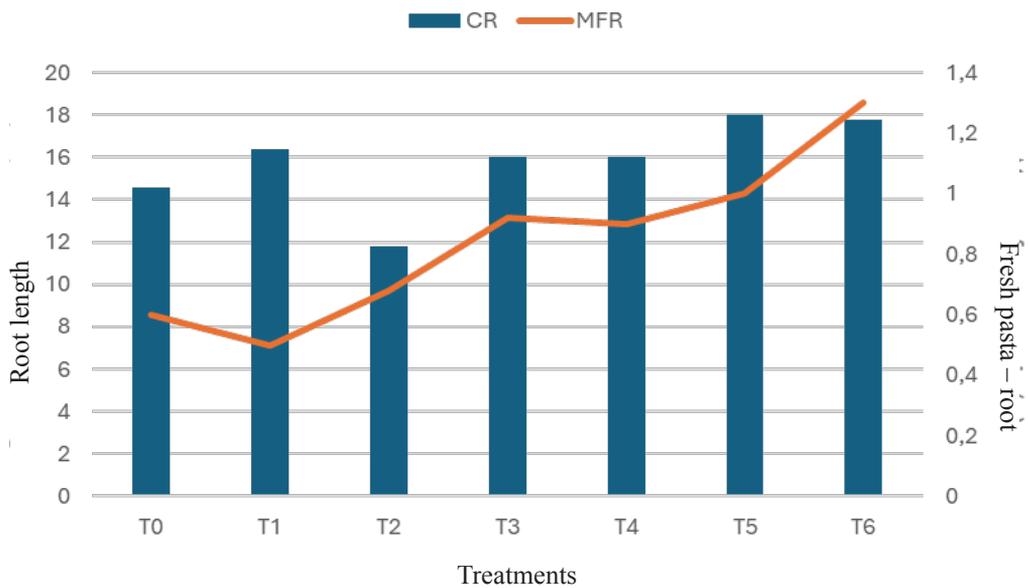


Figure 6. Mean values of root length and fresh root mass of soybean plants evaluated 20 days after sowing.

Source: Author.

Regarding the results of the root system analysis, the results showed significant differences between the treatments applied in soybean root development, both in root length (RL) and fresh mass (FFR) and dry mass (DRF) (Table 1 – Appendix). Treatment T6 (Polymer + Experimental CoMo – 100) showed superior performance in all variables, followed by T3, while nodulation was observed only in treatments T5 and T6 (Figure 6).

The superiority of T6 in root development (MFR and MSR) (Figure 7) indicates that the combined formulation of polymer + micronutrients can promote greater biomass allocation to the roots in the early stages, favoring greater soil exploration and potentially better nutrient absorption (Fernandes Júnior *et al.*, 2009).

The presence of nodulation only in T5 and T6 (Figure 7) in the first evaluation suggests a positive effect of the combination (possibly due to greater inoculant retention or the presence of Mo/Co), which is in line with reports indicating increased nodulation when compatible polymers are used as inoculant carriers (Alves *et al.*, 2019; Reis *et al.*, 2020).

The increase observed in root length and biomass in the treatments that received polymer and micronutrients is associated with better availability and utilization of essential elements, especially cobalt (Co) and molybdenum (Mo). These micronutrients play fundamental physiological roles: Mo is a component of the nitrate reductase enzyme, which acts in nitrogen assimilation, while Co participates in the synthesis of

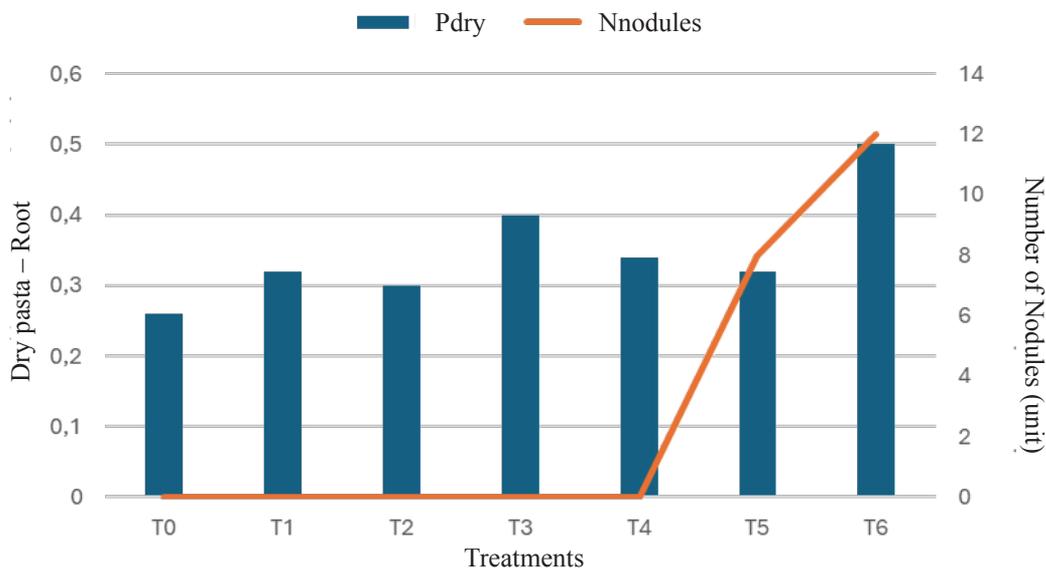


Figure 7. Mean values of root dry mass and number of nodules in soybean plants evaluated 20 days after sowing.

Source: Author.

vitamin B12, necessary for the formation of leghemoglobin and for the bacterial metabolism of rhizobia (Hungria; Nogueira; Araújo, 2020).

The use of polymers in seed treatment may have enhanced these effects, since the films formed around the seeds provide better adhesion of the inputs, as reported by Bays *et al.* (2007). In addition, the polymer creates a physical barrier that helps maintain moisture around the seed, favoring germination and initial root system development (Reis *et al.*, 2020).

Despite the promising results, nodulation was low or nonexistent in five of the treatments, and even in those that presented nodules (T5 and T6), expression was reduced. This may be related to the interaction between the polymer and the inoculant, which is not always favorable, as reported by . Depending on the formulation, the polymer can hinder gas exchange and root colonization by rhizobia, reducing symbiotic efficiency (Hungria; Campo; Mendes, 2017).

Studies on compatibility between the polymer, the inoculant, and environmental conditions are essential to ensure successful inoculation and utilization of the applied micronutrients. Rhizobium-based inoculants (such as *Bradyrhizobium japonicum* and *B. diazoefficiens*) are highly sensitive to adverse conditions of pH, temperature, humidity, and especially to the presence of reactive chemical compounds in treatment mixtures (Hungria; Nogueira; Araújo, 2020). When associated with metallic micronutrients, especially cobalt (Co) and molybdenum (Mo), osmotic or redox toxicity to microorganisms may occur, depending on the concentration and formulation (Hungria; Campo; Mendes, 2017).

In this context, the use of polymers has stood out as an alternative to minimize the deleterious effects on bacteria by forming a protective barrier that controls the release of inputs and reduces direct contact between the inoculant and potentially toxic micronutrients (Reis *et al.*, 2020). This polymer film acts as a protective microenvironment, maintaining the cellular viability of rhizobia for longer and, at the same time, favoring the adhesion of the inoculant and nutrients to the seed surface (Fernandes Júnior *et al.*, 2009).

However, the balance between protection and functionality is delicate. Studies show that the thickness and chemical composition of the polymer interfere with the germination rate, gas exchange, and diffusion of root exudates, which are essential for recognition between the plant and symbiotic bacteria (Rios *et al.*, 2014). A very thick or hydrophobic coating can reduce root emergence and colonization, delaying or even inhibiting effective nodulation (Hungria; Campo; Mendes, 2017). The compatibility between polymers and inoculants depends on physicochemical parameters such as formulation pH, viscosity, electrical charge, and the presence of preservative additives. Polymers based on polyacrylamides and vinyl acetates, for example, have shown greater biological compatibility with *Bradyrhizobium* spp. than vinyl polymers modified with fungicide additives (Costa *et al.*, 2013). On the other hand, formulations based on natural biopolymers (such as starch and chitosan) have been gaining prominence because they are more biodegradable and have less impact on microbial viability, in addition to their potential to carry micronutrients in controlled-release structures (Firmanda *et al.*, 2024).

Regarding the micronutrients Co and Mo, when applied together with the inoculant and the polymer, their availability and mobility are also altered. The polymer can reduce leaching, increasing the efficiency of nutrient use, but if the release is too slow, there may be temporary local deficiency in the early stages of root development, which compromises early nodulation (Hungria; Nogueira, 2020). Thus, the ideal formulation must balance microbial protection and nutritional availability.

When comparing the observed effects with the literature on chemical control and conventional treatments, it is possible to highlight that polymer + micronutrient-based formulations (such as T6) achieved gains in vigor and initial biomass, similar to the expected benefits of conventional treatments, with the potential advantage of favoring biological processes (e.g., nodulation) when compatibility is ensured (Campo; Araújo; Hungria, 2009). At the same time, the variability between treatments shows that not all polymers or combinations are neutral in terms of germination and establishment; some may delay emergence or impair interaction with beneficial microorganisms (Santos *et al.*, 2021b; Soares *et al.*, 2023).

Tests conducted by (Soares *et al.*, 2023) showed that the combination of acrylic polymer with liquid inoculant and micronutrients increased the viability of *Bradyrhizobium* by up to 70% 48 hours after application, compared to the treatment without polymer. On the other hand, formulations containing synthetic polymers with drying agents significantly reduced bacterial survival and nodulation. These results reinforce that the choice of polymer type and application sequence (micronutrients → polymer →

inoculant, for example) are decisive for the success of inoculation.

Therefore, the integration of polymers, inoculants, and micronutrients is a promising strategy for increasing the efficiency of soybean seed treatments, provided that the principles of microbiological compatibility, chemical stability, and controlled release are observed.

Furthermore, the short experimental period (20 days) may have limited the observation of full nodulation, since the formation of effective nodules often occurs between 20 and 30 days after emergence (Rios *et al.*, 2014). Complementary trials with longer periods and detailed physiological evaluations are recommended to confirm the effects observed in this study.

We can consider that the results obtained reinforce the potential of using polymers associated with micronutrients in the treatment of soybean seeds as a tool capable of optimizing root growth and contributing to the initial establishment of the crop, a critical stage for future productivity. Thus, adequate nutrition of essential elements tends to favor root growth and the efficiency of biological nitrogen fixation (BNF).

## FINAL CONSIDERATIONS

Treatment T6 (Polymer + Experimental CoMo – 100) showed the best results for root development, with higher values for length, fresh weight, and dry weight.

The association between polymers and micronutrients (Co and Mo) favored root vigor, indicating better absorption and nutritional utilization by soybean plants.

The low nodulation observed in most treatments suggests that the compatibility

between polymer and inoculant should be evaluated before commercial application.

The use of polymers shows promise, where rapid and efficient initial establishment is critical to the success of soybean crops.

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## ANEXO 1

Tratamento	Variáveis						
	CPA	MFPA	MSPA	Área foliar	CRaiz	MFRaiz	MSRaiz
0	17,00 C	2,00 B	0,82 A	12,04 B	14,6 B	1,00 B	0,26 C
1	18,37 B	1,78 B	1,04 A	11,36 B	16,4 A	0,50 C	0,32 C
2	18,37 B	2,48 A	0,96 A	10,22 B	11,8 B	0,68 C	0,30 C
3	19,12 B	2,40 A	0,96 A	12,88 B	16,0 A	0,92 B	0,40 B
4	22,12 A	2,40 A	1,04 A	12,94 B	16,0 A	0,90 B	0,34 C
5	22,00 A	1,68 B	1,04 A	16,32 A	18,0 A	0,60 C	0,32 C
6	24,00 A	2,84 A	1,14 A	16,86 A	17,8 A	1,30 A	0,50 A
F	11,75**	4,62**	1,04NS	2,77**	3,13**	11,16**	5,54**
Desvio Padrão	1,49	0,43	0,21	3,33	2,68	0,18	0,07
Erro Padrão	0,74	0,19	0,09	1,48	1,00	0,08	0,03
Coefficiente Variação	7,42	19,55	21,93	25,17	17,0	21,64	21,55

Médias seguidas da mesma letra na coluna não diferem entre si pelo teste de Scott&Knott. Ns não significativo; \* significativo a 5%; \*\* significativo a 1%.

Quadro 1. Valores obtidos na análise de variância e médias de diferentes tratamentos de sementes de soja para o desenvolvimento da parte aérea e sistema radicular.