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Compounded Biological Soil Conditioner for Soybean Crop Production at Brazil

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Aim: To evaluate the agronomic efficiency of Bacillus-based soil conditioner on soybean crop development and productivity in different cropping areas.
Study Design: Randomized complete block design with six treatments and eight replications.
Place and Duration of Study: Municipalities of Uberlândia, Paracatú, Araxá and Guarda Mor, all in Minas Gerais State, Brazil, during the 2019/20 season.
Methodology: The treatments consisted of untreated control, 300 kg ha^{-1} of mineral fertilizer, 2.0, 2.5, 3.0, 3.5 L ton^{-1} of Bacillus-based soil conditioner applied to mineral fertilizer (BSC2.0; BSC2.5; BSC3.0; BSC3.5). Leaf and grain P and K concentration, soybean yield components (grains per pod, pods per plant, weight of a thousand grains) and grain yield were evaluated. Data were subject to ANOVA at P = 0.10. Treatments means were separated using the Duncan test at a 0.10 level of significance.

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Results: The biological soil conditioner (BSC) had a statistically superior response than mineral fertilizer in all evaluated doses. In Uberlândia, the BSC2.0 treatment was more efficient in increasing the foliar P concentration in soybean. In Araxá, BSC3.0 provided greater grain yield, as it increased the number of pods per plant and soybean yield. BSC3.5 obtained higher grain yield in Paracatú and Guarda Mor. The average soybean yield achieved in all areas was higher than that obtained in the state of Minas Gerais.
Conclusion: This study revealed that using Bacillus-based soil conditioner on soybean crops is a valuable strategy to increase the soil activity, development and crop yield.

Keywords: Bacillus; glycine max; soybean yield; mineral fertilizer.

1. INTRODUCTION

Soybean (*Glycine max* L.) is a relevant economic and strategic crop worldwide. Brazil is the current highest soybean producer, and the Brazilian soybean crop production was over 122 million tons of grain in season 2021/22, with an average grain yield of 3,016 kg ha^{-1} [1]. This mark is mainly due to advances in scientific research and technologies that increase yield for regions with different edaphoclimatic conditions, such as mineral fertilizers [2,3]. Nutritional balance is a key factor in improving seed quality and increasing crop productivity [4,5].

An intensive soybean cultivation system is required to maintain high grain productivity, and this cultivation system requires high amounts of nutrients from fertilizers, representing high economic cost and environmental challenges. Agricultural activity sustainability de-pends on reductions in inputs used, such as mineral fertilization, and improvements in nutrient use efficiency [6,7]. Thus, integrating biological fertilization techniques and cultural practices emerges as soybean crop nutritional management alternatives. In this sense, soybean producers are always looking for other options to enhance productivity, including biological soil conditioners [8-11].

The PGPR (plant growth-promoting rhizobacteria) can contribute to maintaining soil fertility and improving plant growth [12-14]. These bacteria that live naturally on the surface or in association with the plant’s root system have shown satisfactory results, positively affecting the growth of roots and shoots of plants [15] and disease resistance [16,17]. PGPR also exerts positive effects on plant nutrition and development by im-proving the absorption of phosphorus (P) (phosphate solubilization), synthesis of phytohormones (e.g., acetic indole acid), biotic nitrogen fixation, and the control of the deleterious effects of plant pathogens [18-20].

The *Bacillus* sp. genus can act as a plant growth promoter and is considered a PGRP [21-23]. This genus is one of the most important rhizobacteria to increase plant growth, improve plant performance during stressful periods, nutrient recycling and positively influence crop germination, development, and yield to produce growth-promoting substances [24-30]. Additionally, these bacteria present favorable characteristics to commercial inoculants, such as endospore production, safer handling, easy application, and the possibility to mix with other products [31,32].

Studies conducted by Jain et al. [33] showed that *Bacillus* sp. isolates could increase, in soybean, the fresh weight of shoots and roots, besides increasing the number of lateral roots. Studies aimed at evaluating the use of organic products are important since using *Bacillus* sp. as growth promoters, and biological control agents can improve the potential of crop production and the sustainability of soil activity [34].

In this context, the hypothesis is that the use of biological soil conditioner applied together with mineral fertilizers can improve the development and productivity of the soybean crop. Therefore, this study aimed to evaluate the agronomic efficiency of *Bacillus* soil conditioner based on the soil activity, development, and soybean productivity at Municipalities of Uberlândia, Paracatú, Araxá and Guarda Mor, all in Minas Gerais State, Brazil, during the 2019/20 season.

2. MATERIALS AND METHODS

2.1 Experimental Design

The experiments were implemented in different edaphoclimatic areas in the municipalities of Uberlândia (area 1), Paracatú (area 2), Araxá (area 3), and Guarda Mor (area 4), in Minas Gerais state, Brazil (Fig. 1) during the 2019/20 growing season. The experimental design was set as randomized complete blocks with six treatments: control; 300 kg ha^{-1} of mineral fertilizer (0-20-20); 300 kg ha^{-1} of mineral fertilizer treated with the biological soil conditioner at 2, 2.5, 3, and 3.5 L ton^{-1} of fertilizer (BSC2.0; BSC2.5; BSC3.0; BSC3.5), and eight replications.

The experimental plots were 3 m wide by 10 m in length each (30 m^2). The evaluations occurred only in the central two meters of each plot discarding 0.5 meters on each side at the beginning and the end of the plot (18 m^2 useful plot). The treatments were applied only once at planting using a six-line planter (0.5 m spacing between sowing lines).

2.2 Experimental Areas

The experiment in Area 1 was implemented at the Fisio-Plant Research and Development Experimental Station (road BR 050, km 83.5) in the municipality of Uberlândia, at 18°99'69.5" latitude S and 48°18'86.1" longitude W, at 842 meters altitude. The experiment began at December 2019 to April 2020. The soil is classified as a red Oxisol of sandy clay texture [35]. The climate was classified as 'Aw' according to Köppen's classification.

The soybean cultivar (KWS RK 6719 IPRO) was sown in the conventional tillage and had a population density of 15 plants per linear meter. Seedling emergence occurred seven days after sowing. The soil chemical characteristics (0-0.2 m) were as follows: 56% of sand, 4% of silt, and 40% of clay; pH (H_2O) 5.8; 23.8 g kg^{-1} of organic matter; 39 mg dm^{-3} of K; 1.06 mg dm^{-3} of P; 1.4 cmolc dm^{-3} of Ca, and 0.6 mg dm^{-3} Mg.

The experiment in Area 2 was implemented at Tia Dora Farm in the municipality of Paracatú, at 17°09'51.2" latitude S and 46°24'02.7" longitude W, at 696 meters altitude. The experiment went from December 2019 to May 2020. The soil is classified as a yellow-red Oxisol of clayey texture [35]. The climate was classified as 'Aw' according to Köppen's classification.

The soybean cultivar sown was "CZ48B32 IPRO" which was sown in the conventional planting system (tillage) and had a population density of 15 plants per linear meter. Seedling emergence occurred seven days after sowing. The soil chemical characteristics (0-0.2 m) were as follows: 60% of clay, 27% of silt, and 13% of clay; pH (H_2O) 6.4; 14 g kg^{-1} of organic matter; 21 mg dm^{-3} of K; 11 mg dm^{-3} of P; 3.9 cmolc dm^{-3} of Ca, and 0.9 mg dm^{-3} Mg.

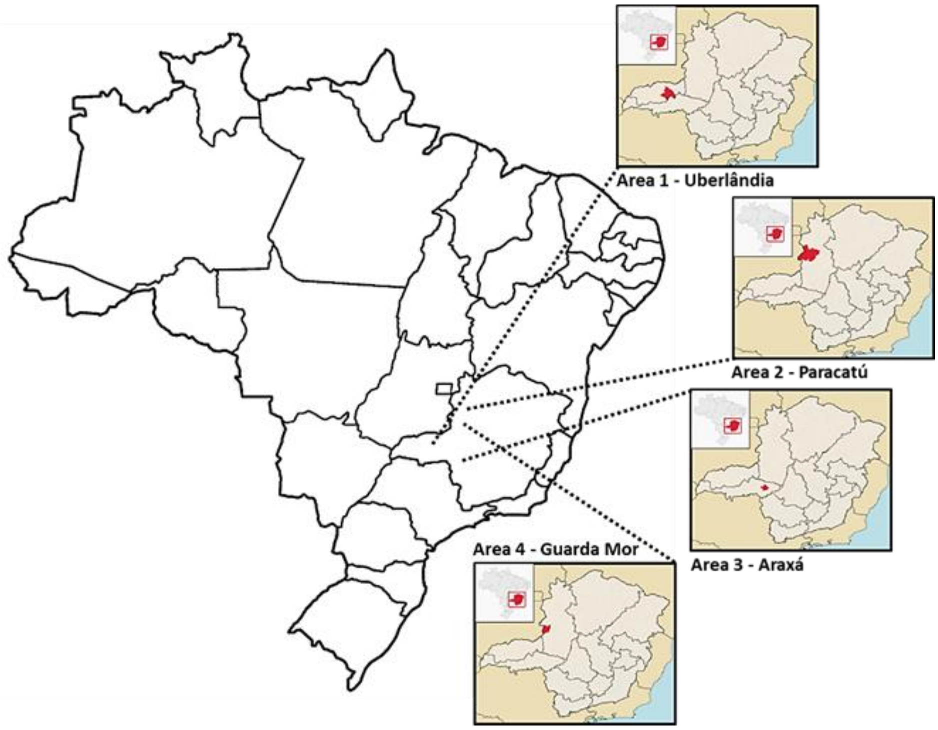

Fig. 1. Map of the location of the soybean planting areas, which are located in Minas Gerais State, Brazil

The experiment in Area 3 was implemented in the municipality of Araxá, at 19°56'89.3" latitude S and 46°98'82.5" longitude W, at 910 meters altitude. The experiment went from December 2019 to April 2020. The soil is classified as a yellow-red Oxisol of sandy texture [35,36]. The climate was classified as 'Aw' according to Köppen's classification.

The soybean cultivar sown was "8473 RSF" which was sown in the conventional planting system (tillage) and had a population density of 18 plants per linear meter. Seedling emergence occurred seven days after sowing. The soil chemical characteristics (0-0.2 m) were as follows: 24% of clay, 10% of silt, and 66% of clay; pH (H_2O) 5.8; 156 mg dm^{-3} of K; 5,5 mg dm^{-3} of P; 4.2 cmolc dm^{-3} of Ca, and 1.4 mg dm^{-3} Mg.

The experiment was implemented at São Severino Farm (road MG 188) in the municipality of Guarda Mor, at 17°39'29.0" latitude S and 47°03'18.8" longitude W, at 598 meters altitude. The experiment went from December 2019 to May 2020. The soil is classified as a red Ultisol of clayey texture (Santos et al., 2013). The climate was classified as 'Aw' according to Köppen's classification.

The soybean cultivar sown was "8473 RSF" which was sown in the conventional planting system (tillage) and had a population density of 15 plants per linear meter. Seedling emergence occurred seven days after sowing. The soil chemical characteristics (0-0.2 m) were as follows: 43% of clay, 15% of silt, and 42% of clay; pH (H_2O) 5.8; 1.9 mg dm^{-3} of K; 94 mg dm^{-3} of P; 3.9 cmolc dm^{-3} of Ca, and 1.7 mg dm^{-3} Mg.

2.3 Crop Fertilization and Biological Soil Conditioner

The recommendations for correctives (lime) and fertilizers for Minas Gerais state (Ribeiro, 1999) were defined according to each area's soil type, chemical and physical characteristics. Fertilizer application at planting for all treatments was performed with 300 kg ha^{-1} of solid formulated 0-20-20 (N, P_2O_5, K_2O - mixture of granules), except for the control treatment. The biological soil conditioner was applied in a mixture with the granular fertilizer at rates of 2, 2.5, 3, and 3.5 L ton^{-1} of fertilizer (BSC2.0; BSC2.5; BSC3.0; BSC3.5). The liquid product is sprayed onto the mixture of fertilizer granules. For example, the amount of fertilizer used at planting was 300 kg ha^{-1}, if the dose of biological soil conditioner was 2 L ton^{-1}, consequently, 0.6 L ha^{-1} was applied.

The biological soil conditioner used in this study is a liquid oil-water emulsion containing four different non-pathogenic microorganisms composed of Bacillus species with a total concentration of 3.01×10^8 propagules per milliliter, in 99% oil-based culture medium. The resulting solution presents dark brown color to black, with 6 to 7 pH and a density of 0.93 ± 0.2 g mL^{-1} (20 ºC).

The climatic data during the experimental period were obtained in an automatic station located in each experimental area (Table 1).

In addition, data on temperature, precipitation, and relative humidity were recorded during the experimental period (Table 2).

2.4 Soybean Evaluations

After the treatment's application P and potassium (K) contents were evaluated in leaves and grains, and yield components: number of grains per pod (GP), number of pods per plant (NP), weight of a thousand grains (WTG) and yield (kg ha^{-1} and bags ha^{-1} – each bag = 60 kg). The P and K contents in the leaves were determined according to the methodology proposed by [37]. For leaf analysis, ten trifoliolate leaves (newly mature, without petiole, corresponding to the third or fourth leaf from the apex of the main stem) were collected per plot when the plants were in stage 60 of the BBCH scale [38]. From the harvested grains, 100 g were sampled, dried in an oven at 60 ºC, ground, and submitted to chemical analysis to evaluate P and K contents [39].

Table 1. Dates and climatic conditions at the treatment's applications in each experimental area

Area	Date	T (ºC)	RH (%)	WS (km h^{-1})	C (%)	t_0 (h)	t_{final} (h)
Uberlândia	12/10/2019	27.5	71	0.5	100	16:00	18:30
Paracatú	12/14/2019	25.0	70	0.3	100	09:00	12:00
Araxá	12/18/2019	26.5	70	0.2	100	13:00	17:00
Guarda Mor	12/27/2019	26.0	73	0.4	100	08:00	11:00

T: temperature; RH: relative humidity; WS (km h^{-1}): wind speed; C: cloudiness; t_0: initial time of measurement; tfinal: final time of measurement

Table 2. Meteorological data recorded during the experimental period in each experimental area

Area	Air temperature (°C)			Precipitation (mm day^{-1})			Air relative humidity (%)		
	Min.	Max.	Average	Min.	Max.	Average	Min.	Max.	Average
Uberlândia	20.15	28.40	24.82	0.00	69.60	7.66	45.00	89.50	66.99
Paracatú	21.00	30.00	24.56	0.00	111.94	5.86	52.00	98.00	79.67
Araxá	19.70	26.90	23.68	0.00	104.00	9.53	57.00	83.00	69.87
Guarda Mor	18.60	26.55	23.17	0.00	99.80	7.22	46.50	88.50	74.45

Min.: minimal average data observed in one day during the experimental period; Max.: maximum average data observed in one day during the experimental period; Average: average of all data recorded during the experimental period

The WTG was determined by accounting for 1,000 seeds per plot that were weighed on a digital scale. The number of pods with one, two, three, and four grains and the total number of pods per plant were measured by counting the variables in 10 representative plants per plot. Crop yield was estimated at the end of stage 99 of the BBCH scale. The grains harvested in the 18 m² useful plot were weighed and adjusted to 13% moisture.

When necessary, the data of the evaluations were transformed and submitted to analysis of variance. The averages were compared by Duncan's test of averages ($p<0.10$) using the software SASM-Agri [40].

3. RESULTS AND DISCUSSION

The P and K concentration in soybean plant leaves in the four experiments are presented in Table 3. In none of the areas showed differences between treatments for K leaf concentration were identified. In Area 1 and Area 2, the K grain concentration did not differ ($p>0.10$). In Area 1, a significant increase in P leaf concentration was identified for plants that received soil conditioner at 2 L ton^{-1} (BSC2.0). Regarding the P grain concentration, the BSC2.5 and BSC3.5 were more efficient than the other treatments. No difference was observed for K leaf and grain concentration (Table 3).

In Area 2 and Area 3, P leaf concentration was higher for treatments that received soil conditioner compared to the control and where only mineral fertilizer was applied in Area 2. The treatments increased the P grain concentration in Area 2 compared to control; in Area 3, soil conditioner applied at 3 and 3.5 L ton^{-1} were more efficient (Table 3). In Area 3, the BSC2.0, BSC3.0 and BSC3.5 were more efficient in increasing the K level in the grains. The positive nutritional results observed in soybean leaves and grains can be justified by the bacterial activity, which can solubilize and mineralize P from organic and inorganic sources [18,19,41].

Phosphate solubilizing microorganisms play an important role in releasing inorganic forms of phosphorus present in the soil (e.g. Ca-P, Al-P, Fe-P), increasing the P content in the soil solution, and, consequently, making this nutrient available for the plant. Many plant growth promoting bacteria (PGPB) can solubilize phosphorus by acidification, chelation or enzymatic processes. Organic acids (such as gluconic acid, ketogluconic acid, ketogluconic acid, lactic acid and acetic acid) produced by these bacteria can chelate cations (e.g. Al, Fe, Ca) or make phosphorus available by the action of the glucose dehydrogenase enzyme [42,43].

The differences between the studied areas regarding P concentration may be related to soil conditions (texture and mineralogy). In the area where P leaf concentration was lower (about 2.46 g kg^{-1}), the plants were cultivated in soil with higher clay content (Area 2) compared to plants that were produced in sandy soil (Area 3) with higher average P leaf (about 5.21 g kg^{-1}). It is essential to consider this factor since clay soils have higher P adsorption capacity on soluble fertilizers via soil and consequently influence P absorption and extraction by plants. On the other hand, this behavior was not observed for K. Especially in Brazilian soils that are highly weathered, there is a predominance of exchangeable K^+ in the soil, because the type of binding is eminently by electrostatic adsorption, unlike what happens for Phosphorus. This mechanism may explain why there was no significant difference of Potassium concentration in the leaf. In these environments, the contents of non-exchangeable K^+ are very similar to exchangeable, as there is a predominance of silicate clays of the 1:1 type [44].

Table 3. Phosphorus (P) and potassium (K) content in leaves and grain as a function of treatments applied to soybean in each experimental area

Treatment	Leaf Concentration ($g\ kg^{-1}$)		Grain Concentration ($g\ kg^{-1}$)	
	P	K	P	K
-- Uberlândia --				
1. Control	3.70 bc*	17.00 a	4,38 b	17,75 a
2. Mineral fertilizer	3.93 b	16.50 a	4,55 b	17,75 a
BSC2.0	4.25 a	16.50 a	4,58 b	17,50 a
BSC2.5	3.70 bc	17.00 a	4,78 a	18,12 a
BSC3.0	3.70 bc	16.63 a	4,55 b	17,75 a
BSC3.5	3.58 c	16.38 a	4,78 a	17,62 a
CV (%)	9.47	6.86	4,86	2,53
Average	3.80	16.66	4,60	17,75
-- Paracatu --				
1. Control	1.65 c	19.25 a	3,95 b	14,58 a
2. Mineral Fertilizer	2.17 b	19.38 a	5,00 a	15,68 a
BSC2.0	2.72 a	21.25 a	4,48 a	15,15 a
BSC2.5	2.80 a	21.25 a	4,50 a	15,68 a
BSC3.0	2.65 a	20.75 a	4,63 a	15,60 a
BSC3.5	2.77 a	20.75 a	4,65 a	15,35 a
CV (%)	12.37	10.47	10,61	7,44
Average	2.46	20.43	4,53	15,33
-- Araxá --				
1. Control	4.75 b	25.63 a	3,75 d	17,50 b
2. Mineral Fertilizer	5.27 a	26.63 a	4,10 c	17,87 b
BSC2.0	5.22 a	26.25 a	4,17 c	17,87 b
BSC2.5	5.30 a	25.38 a	4,52 b	19,00 a
BSC3.0	5.40 a	25.25 a	4,95 a	19,25 a
BSC3.5	5.32 a	25.38 a	5,22 a	19,37 a
CV (%)	6.48	7.93	7,5	2,8
Average	5.21	25.75	4,45	18,47
-- Guarda Mor --				
1. Control	4.50 c	20.25 a	3,38 a	14,92 c
2. Mineral Fertilizer	4.85 b	20.75 a	4,10 a	17,50 ab
BSC2.0	4.75 b	20.75 a	3,68 a	16,95 b
BSC2.5	4.82 b	20.50 a	3,38 a	16,75 b
BSC3.0	4.85 b	21.13 a	3,45 a	16,60 b
BSC3.5	5.42 a	21.63 a	3,93 a	18,65 a
CV (%)	4.96	5.78	15,6	6,84
Average	4.86	20.83	3,65	16,89

** Means followed by the same letter in the columns do not differ by Duncan's test (p>0,10); L ton^{-1}: liters of the commercial product per ton of water; BSC: Biological Soil Conditioner; CV (%): coefficient of variation.*

High doses of fertilizers are necessary to obtain satisfactory responses in soils with higher clay content. In Area 4, only the highest dose evaluated (BSC3.5) presented higher P leaf concentration and K grain concentration of soybean (Table 3). In addition to providing P, microorganisms can also act as nutrient solubilization (e.g., Fe, K, Zn) [45] and therefore have favored the greater accumulation of K in grains.

Table 4 shows data on yield components, number of grains per pod, number of pods per plant, and weight of a thousand grains. In Area 1, pods with 1 and 4 grains were higher in plants that received soil conditioner at 3 L ton^{-1}. GP, NP and WTG are important productivity components, which can demonstrate whether the cultivar is demonstrating all its predetermined genetic potential or whether there is another variable influencing the results. However, the number of grains per pod and weight of a thousand grains did not differ among the treatments, with the number of pods per plant values ranging from 59.78 to 79.2 and the weight of a thousand grains ranging from 152.84 to 158.14 g.

The results of 3 grains per pod and NP observed in Area 3 showed that the use of soil conditioner at doses of 2.5, 3, and 3.5 L ton^{-1} was more efficient than the other treatments, although no statistical difference was found for WTG. These results are advantageous since soybean pods with 3 grains are the ones that contribute the most to increased productivity. The NP is the most important component when looking for increases in grain yield, which depends on the number of flowers emitted and fixed (not aborted) during the reproductive stage [46].

In Area 4, no significant difference (p>0.10) was observed for GP and NP. However, for WTG the soil conditioner treatment at 2.5 L ton^{-1} presented a significantly higher average (138.20 g). These results can be justified by the soil conditioner and the environment to which the plants are exposed; despite the soybean yield components being genetically predetermined, these factors (soil conditioner and environment) are determinants for the full genetic expression [47-49].

The treatment with mineral fertilizer and BSC2.5 presented significantly higher results for 1 grain per pod (Table 5). No significant differences were observed for 2 grains per pod and WTG.

Table 4. Number of grains per pod (GP), number of pods per plant (NP), and weight of a thousand grains (WTG) as a function of the treatments applied to soybean cultivated in Uberlândia, Araxá, and Guarda Mor

Treatment	GP				NP	WTG
	1 grain	2 grains	3 grains	4 grains		(g)
Uberlândia						
1. Control	1.42 bc*	10.83 a	46.18 a	1.35 c	59.78 a	152.85 a
2. Mineral fertilizer	0.77 c	12.85 a	56.18 a	1.73 bc	71.53 a	154.48 a
BSC2.0	1.35 bc	14.00 a	54.28 a	1.25 c	70.88 a	152.84 a
BSC2.5	2.00 ab	14.28 a	55.15 a	2.00 abc	73.43 a	154.03 a
BSC3.0	2.62 a	17.13 a	56.15 a	2.83 a	78.73 a	157.59 a
BSC3.5	2.10 ab	16.98 a	57.70 a	2.42 ab	79.20 a	158.14 a
CV (%)	63.49	31.74	24.97	52.48	23.01	3.98
Average	1.71	14.34	54.27	1.92	72.25	154.98
Araxá						
1. Control	3.30 a	12.00 a	25.90 b	0.175 a	41.37 b	179.94 a
2. Mineral Fertilizer	4.73 a	9.28 a	28.15 b	0.325 a	42.47 b	179.24 a
BSC2.0	3.55 a	12.13 a	26.25 b	0.275 a	42.20 b	183.31 a
BSC2.5	3.53 a	10.83 a	36.00 a	0.075 a	50.42 a	182.24 a
BSC3.0	3.05 a	12.93 a	35.45 a	0.200 a	51.62 a	184.06 a
BSC3.5	3.23 a	12.95 a	33.95 a	0.350 a	50.47 a	183.39 a
CV (%)	46.96	22.47	20.56	158.71	16.14	3.86
Average	3.56	11.68	30.95	0.233	46.42	182.02
Guarda Mor						
1. Control	4.75 a	23.75 a	33.53 a	0.134 a	62.16 a	129.83 c
2. Mineral Fertilizer	4.28 a	24.47 a	40.09 a	0.031 a	68.88 a	132.43 bc
BSC2.0	4.16 a	25.13 a	35.25 a	0.219 a	64.75 a	132.75 bc
BSC2.5	4.13 a	25.47 a	36.72 a	0.094 a	66.41 a	138.20 a
BSC3.0	4.53 a	27.38 a	36.26 a	0.165 a	68.34 a	136.06 ab
BSC3.5	4.59 a	26.94 a	40.34 a	0.125 a	72.00 a	134.77 ab
CV (%)	63.04	22.59	25.71	133.24	20.75	3.07
Average	4.40	25.52	37.03	0.127	67.08	134.01

** Means followed by the same letter in the columns do not differ by Duncan's test (p>0,10); L ton^{-1}: liters of the commercial product per ton of water; BSC: Biological Soil Conditioner; CV (%): coefficient of variation*

Table 5. The number of grains per pod (GP), number of pods per plant (NP), and weight of a thousand grains (WTG) as a function of the treatments applied to soybean cultivated in Paracatu

Treatment	GP			NP	WTG
	1 grain	2 grains	3 grains		(g)
1. Control	0.93 b*	12.94 a	14.53 b	28.40 b	140.94 a
2. Mineral fertilizer	3.56 a	12.63 a	34.21 a	50.40 a	146.49 a
BSC2.0	1.37 b	11.25 a	46.06 a	58.68 a	137.40 a
BSC2.5	2.68 a	13.28 a	42.43 a	58.40 a	140.32 a
BSC3.0	1.06 b	8.19 a	34.40 a	43.65 ab	135.68 a
BSC3.5	1.59 ab	12.53 a	44.43 a	58.56 a	140.05 a
CV (%)	46.64	49.09	39.53	37	5.96
Average	1.86	11.8	36.01	49.68	140.14

** Averages followed by the same letter in the columns do not differ by Duncan's test (p>0,10); L ton^{-1}: liters of the commercial product per ton of water; BSC: Biological Soil Conditioner; CV (%): coefficient of variation*

Table 6. Productivity due to the treatments applied to soybean crop grown in producing areas of Uberlândia, Paracatú, Araxá and Guarda Mor

Treatment	Productivity		
	(kg ha^{-1})	(sc ha^{-1})	IR (%)
Uberlândia			
1. Control	4045.66 b*	67.43 b	-
2. Mineral fertilizer	4590.06 a	76.50 a	-
BSC2.0	5104.03 a	85.07 a	11.20
BSC2.5	4717.21 a	78.62 a	2.77
BSC3.0	4668.04 a	77.80 a	1.69
BSC3.5	4623.47 a	77.06 a	0.73
CV (%)	12.62	12.62	
Average	4624.74	77.08	
Paracatu			
1. Control	1241.06 c	20.68 c	-
2. Mineral Fertilizer	2923.83 b	48.73 b	-
BSC2.0	3579.49 ab	59.66 ab	22.42
BSC2.5	3459.75 ab	57.66 ab	18.32
BSC3.0	3561.43 ab	59.36 ab	21.81
BSC3.5	3864.01 a	64.40 a	32.15
CV (%)	25.78	25.78	
Average	3104.92	51.74	
Araxá			
1. Control	4601.09 c	76.68 c	-
2. Mineral Fertilizer	4812.59 bc	80.21 bc	-
BSC2.0	5000.33 bc	83.34 bc	3.90
BSC2.5	5292.39 ab	88.21 ab	9.97
BSC3.0	5606.46 a	93.44 a	16.49
BSC3.5	5304.38 ab	88.41 ab	10.22
CV (%)	11.49	11.49	
Average	5102.88	85.05	
Guarda Mor			
1. Control	3856.73 c	64.27 c	-
2. Mineral Fertilizer	4237.15 bc	70.61 bc	-
BSC2.0	4117.18 bc	68.61 bc	-
BSC2.5	4541.48 ab	75.69 ab	7.19
BSC3.0	4568.81 ab	76.14 ab	7.83
BSC3.5	4840.98 a	80.68 a	14.26
CV (%)	14.44	14.44	
Average	4360.39	72.67	

** Averages followed by the same letter in the columns do not differ by Duncan's test (p>0,10); L ton^{-1}: liters of commercial product per ton of water; kg ha^{-1}: kilograms per hectare; bag ha^{-1}: bags per hectare (each bag = 60 kg); IR (%): increment relative compared to mineral fertilizer; BSC: Biological Soil Conditioner; CV: coefficient of variation*

There was a significant effect of the treatments in the study on soybean yield (Table 6). The treatments that received mineral fertilizer and biological soil conditioner application were more efficient than the control of soybean yield in Area 1. The average grain yield achieved in Area 1 (4,624.8 kg ha^{-1}) was higher than that obtained in the state of Minas Gerais in the 2021/2022 harvest (3,828 kg ha^{-1}), according to CONAB [1].

In Area 2, the BSC3.5 resulted in higher productivity, with increments of 2,620 and 940 kg ha^{-1} compared to the control treatments and mineral fertilizer, respectively. Thus, in this assay, soybean yield was influenced by treatments with significant increments of 18.32 to 32.15% compared to mineral fertilizer (Table 6). The average yield achieved in the trial (3,104 kg ha^{-1}) was practically equal to that obtained in the state of Minas Gerais in the 2020/21 crop season (3,016 kg ha^{-1}), according to CONAB [1].

The same response was verified in Area 4. The BSC3.5 showed productivity increments of 985 and 604 kg ha^{-1} compared to control and mineral fertilizer treatments, respectively (Table 6). The average yield achieved in the assay (4,360.2 kg ha^{-1}) was higher than that obtained in Minas Gerais in 2020/21 crop season (3,828 kg ha^{-1}), according to CONAB [1].

In Area 3, treatments affected soybean yield, which allowed gains of 3.90 to 16.49% of the use of soil conditioner compared to the mineral fertilizer (Table 6). The average yield achieved in Area 3 (5,103 kg ha^{-1}) was higher than that obtained in the state of Minas Gerais in the 2020/21 crop (3,828 kg ha^{-1}), according to CONAB [1].

It is important to emphasize that the treatments with BSC provided high levels of soybean yield, especially in Areas 1 and 3 that had low levels of Phosphorus in the soil. These results corroborate those of Jain et al. [33] and Chagas Junior et al. [50] by showing that *Bacillus* sp. isolates can increase soybean yield.

Another important aspect is that there was a positive correlation between P concentration in soybean leaves and productivity ($r = 0.68$). Lacerda et al. also found the same correlation ($r = 0.74$) for soybean in the municipality of Unaí, state of Minas Gerais [51]. These results demonstrate the efficiency of the BSC in making P available to plants, especially in areas where the Phosphorus content in the soil was low.

The efficiency of plant growth promoting microorganism correlates with the soil biological activity [50]. Additionally, the relationship of microorganisms with soil is of great importance since soil characteristics can influence the efficiency of the soil conditioner. The results observed in the present study indicated that using *Bacillus*-based soil conditioner on soybean crops is a valuable strategy for more soybean productivity and sustainability of crop production.

4. CONCLUSION

The *Bacillus*-based soil conditioner had a statistically superior response than mineral fertilizer treatment in all evaluated doses. In Uberlândia, the biological soil conditioner at 2 L ton^{-1} was more efficient in increasing the foliar P concentration in soybean. In Araxá, the biological soil conditioner at 3 L ton^{-1} provided greater grain yield, as it increased the number of pods per plant and soybean yield. The biological soil conditioner dose of 3.5 L ton^{-1} provided higher grain yield in Paracatú and Guarda Mor. The average soybean yield achieved in all areas was higher than that obtained in the state of Minas Gerais.

This study revealed that using Bacillus-based soil conditioner on soybean crops is a valuable strategy to increase the soil activity, development and crop yield.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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