

Agronomic and economic evaluation of soybean under beneficial microorganism and cover crop management

Avaliação agronômica e econômica da soja cultivada com microrganismos benéficos e plantas de cobertura

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ABSTRACT - Soybean, the main oilseed crop cultivated in Brazil, faces challenges related to sustainability and dependence on chemical inputs. The use of beneficial microorganisms and cover crops may be an alternative to increase productivity and reduce costs. The objective of this study was to evaluate the effect of combining cover crops with multifunctional microorganisms on soybean development and to assess its financial viability. The experiment was conducted using a randomized block design in a 5 × 3 factorial scheme, with four replications. Treatments consisted of the combination of five cover crops [1] fallow; 2) *Fagopyrum esculentum*; 3) *Pennisetum glaucum*; 4) Mix 1 (*Avena strigosa*, *A. sativa*, *Crotalaria ochroleuca*, *C. juncea*, *Raphanus sativus*, and *Eleusine coracana*); and 5) Mix 2 (*A. strigosa*, *C. spectabilis*, *Raphanus sativus*, and *F. esculentum*)] with three microbiological management strategies (1. Embrapa: *Serratia marcescens*, *Bacillus* sp., *Azospirillum brasilense*, and *Trichoderma koningiopsis*; 2. Commercial: microbial consortium + Penergetic; and 3. Standard management). The evaluated variables were cover crop biomass production, 100-grain weight, yield, and economic analysis. Pearl millet showed the highest biomass production (8.52 t ha⁻¹). The Commercial and Embrapa management strategies provided the highest average soybean yields (4.48 and 4.34 t ha⁻¹, respectively), both higher than the Standard management (4.26 t ha⁻¹). Economic analysis indicated the highest financial return for the Commercial management (\$799.49 ha⁻¹). It is concluded that the adoption of plant growth-promoting microorganisms, combined with the use of cover crops, is a sustainable and economically viable practice for soybean cultivation.

Keywords: *Glycine max*. Rural economics. Production. Cover crops. Sustainability.

Conflict of interest: The authors declare no conflict of interest related to the publication of this manuscript.



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RESUMO - A soja, principal oleaginosa cultivada no Brasil, enfrenta desafios relacionados à sustentabilidade e à dependência de insumos químicos. O uso de microrganismos benéficos e plantas de cobertura pode ser alternativa para aumentar a produtividade e reduzir custos. O objetivo deste estudo foi avaliar o efeito da combinação de plantas de cobertura com microrganismos multifuncionais no desenvolvimento da soja e verificar sua viabilidade financeira. O experimento foi conduzido em delineamento de blocos ao acaso, em esquema fatorial 5 × 3, com quatro repetições. Os tratamentos consistiram da combinação de cinco coberturas vegetais [1] pousio; 2) *Fagopyrum esculentum*; 3) *Pennisetum glaucum*; 4) Mix 1 (*Avena strigosa*, *A. sativa*, *Crotalaria ochroleuca*, *C. juncea*, *Raphanus sativus* e *Eleusine coracana*); e 5) Mix 2 (*A. strigosa*, *C. spectabilis*, *Raphanus sativus* e *F. esculentum*)] com três manejos microbiológicos (1. Embrapa: *Serratia marcescens*, *Bacillus* sp., *Azospirillum brasilense* e *Trichoderma koningiopsis*; 2. Comercial: consórcio microbiano + Penergetic; e 3. Manejo Padrão). As variáveis avaliadas foram produção de biomassa das coberturas, massa de 100 grãos, produtividade e análise econômica. O milho apresentou maior produção de biomassa (8,52 t ha⁻¹). Os manejos Comercial e Embrapa proporcionaram as maiores produtividades médias da soja (4,48 e 4,34 t ha⁻¹, respectivamente), ambos superiores ao Padrão (4,26 t ha⁻¹). A análise econômica indicou maior retorno financeiro para o manejo Comercial (\$ 799,49 ha⁻¹). Conclui-se que a adoção de microrganismos promotores de crescimento, associada ao uso de plantas de cobertura, constitui prática sustentável e economicamente viável para o cultivo da soja.

Palavras-chave: *Glycine max*. Economia rural. Produção. Plantas de coberturas. sustentabilidade.

INTRODUCTION

Soybean (*Glycine max* (L.) Merr.) is a global commodity and the main oilseed crop cultivated worldwide, serving as an important source of protein and lipids for a wide range of products, including animal feed and foods for human consumption (VOGEL et al., 2021). Brazil stands out as the world's largest soybean producer and exporter. In the 2023/2024 growing season, national production was estimated at 147.38 million tons, cultivated over 45.3 million hectares, with an average yield of 3,253 kg ha⁻¹ (CONAB, 2024).

In recent decades, Brazilian agriculture has made considerable progress toward sustainability. However, it still faces major challenges, particularly in the context of climate change. Investments in research, development, and innovation have therefore become essential to reduce the use of pesticides and fertilizers, prevent the conversion of native vegetation areas, and promote the adoption of agricultural practices with lower environmental impact (SILVA et al., 2020).

In this context, the use of multifunctional microorganisms beneficial to plants has gained increasing attention, as they contribute to a more intensive and sustainable agricultural system. These organisms provide several benefits,

including improved plant nutrition and health, enhanced plant defense mechanisms, and improved soil quality (GLICK, 2012).

These microorganisms act in the rhizosphere through rhizodeposition and root exudates, influencing nutrient cycling and availability, phosphate solubilization, the production of iron-chelating compounds, biological nitrogen fixation, phytohormone synthesis, the release of enzymes such as lipases and ACC deaminase, and biological control (SPERANDIO et al., 2017; MORENO et al., 2021). These mechanisms promote plant growth and increase tolerance to both biotic and abiotic stresses (MORENO et al., 2021).

Studies have shown that inoculation and co-inoculation with *Bradyrhizobium japonicum* or *Bradyrhizobium elkanii* associated with *Azospirillum brasilense* increase dry matter production and soybean grain yield (CHIBEBA et al., 2015). Similar results were reported by Nogueira et al. (2020), who observed greater symbiotic efficiency and higher nitrogen accumulation in soybean dry mass, and by Souza et al. (2019), who reported significant yield increases in soybean plants inoculated with plant growth-promoting microorganisms. These findings reinforce the potential of co-inoculation as a strategy to enhance the biological and agronomic efficiency of soybean cultivation.

Another important management strategy is the use of cover crops, grown either as single-species stands or in intercropping systems. During the off-season (January to May), particularly in the Cerrado region, these plants improve the physical, chemical, and biological quality of the soil, reduce thermal amplitude, stimulate microbial activity, promote nutrient recycling, increase organic matter, cation exchange capacity (CEC), and base saturation, in addition to suppressing weeds and reducing pests and diseases (LAL, 2020).

Research on cover crops has reported increased nitrogen uptake and higher yield in rice (LAL, 2020), greater phytomass production and yield in maize (CARVALHO et al., 2015), reduced weed infestation in soybean and pearl millet (OLIVEIRA et al., 2017; LAL, 2020), and agronomic gains in common bean (OLIVEIRA et al., 2017). Thus, these sustainable practices reduce the use of agrochemicals and production costs, while positively impacting crop yield (REZENDE et al., 2021).

Despite these benefits, few studies have addressed the combined use of microorganisms and crop rotation. Therefore, this study aimed to evaluate the effect of combining cover crops with multifunctional microorganisms on soybean agronomic performance and to assess the economic viability of this management system.

MATERIALS AND METHODS

The experiment under a no-tillage system was conducted in the field at Capivara Farm of Embrapa Rice and Beans, located in the municipality of Santo Antônio de Goiás, Goiás, Brazil (16°28'00" S, 49°17'00" W; altitude 823 m), over three growing seasons (2021/2022, 2022/2023, and 2023/2024). According to the Köppen classification, the region has a tropical Aw climate, with an average temperature of 23.3 °C. The mean annual rainfall is 1,428 mm. The predominant soil in the region is classified, according to the

Brazilian Soil Classification System, as Latossolo Vermelho Ácrico (SANTOS et al., 2018). During the experimental period, climatological data were monitored (Figure 1).

Before the installation of the experiments, soil chemical analyses were performed according to the methodology described by Donagema et al. (2011), yielding the following results: pH (H₂O) = 5.5; Ca²⁺ = 14.2 mmol_c dm⁻³; Mg²⁺ = 6.1 mmol_c dm⁻³; H + Al³⁺ = 27 mmol_c dm⁻³; P = 12.9 mg dm⁻³; K⁺ = 81 mg dm⁻³; Cu²⁺ = 1.4 mg dm⁻³; Zn²⁺ = 4.3 mg dm⁻³; Fe³⁺ = 21 mg dm⁻³; Mn²⁺ = 13.7 mg dm⁻³; and organic matter = 33.8 g kg⁻¹.

The experimental design consisted of a randomized complete block design arranged in a 5 × 3 factorial scheme with four replications. Thus, the treatments were composed of the combination of five crop rotations (soybean/fallow/common bean, soybean/pearl millet/common bean, soybean/buckwheat/common bean, soybean/cover crop mix 1/common bean, and soybean/cover crop mix 2/common bean) and three types of microbiological management: (1) Embrapa microorganisms (*Serratia marcescens* (BRM 32114), *Bacillus* sp. (BRM 63573), *Azospirillum brasilense* (AB-V5), and *Trichoderma koningiopsis* (BRM 53736)); (2) commercial microorganisms (*Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Paenibacillus polymyxa*, *Bacillus megaterium*, *Bacillus licheniformis*, *Trichoderma harzianum*, *Trichoderma asperellum*, and *Azospirillum brasilense* + Penegetic); and (3) standard management.

Cover crop mix 1 consisted of black oat (*Avena strigosa*), white oat (*Avena sativa*), *Crotalaria ochroleuca*, *Crotalaria juncea*, forage radish (*Raphanus sativus*), and finger millet (*Eleusine coracana*). Cover crop mix 2 consisted of black oat (*Avena strigosa*), showy crotalaria (*Crotalaria spectabilis*), forage radish (*Raphanus sativus*), and buckwheat (*Fagopyrum esculentum*). The plots measured 5 m × 10 m in length, and the usable area of each plot consisted of the three central rows (15 m²).

The cover crops were grown during the second cropping season (March to June of 2022, 2023, and 2024). The seeding rates recommended by the partner company were used: 20 kg ha⁻¹ of pearl millet, 70 kg ha⁻¹ of buckwheat, 35 kg ha⁻¹ of mix 1, and 35 kg ha⁻¹ of mix 2. Basal fertilization was performed by applying 100 kg ha⁻¹ of single superphosphate in the seeding furrow.

Common bean (winter crop) was grown after the desiccation of the cover crops, which was carried out with the herbicide glyphosate 15 days before the sowing of the legume. The cultivar BRS FC 402 was used and sown at a spacing of 0.45 m with 15 viable seeds per meter. Fertilization consisted of applying 200 kg ha⁻¹ of the formulated fertilizer 4-30-16. After the harvest of the common bean crop, glyphosate was applied at a rate of 5 L ha⁻¹, 20 days before soybean sowing.

Soybean sowing was carried out in October of each year (10/15/2021, 10/19/2022, and 10/11/2023). The cultivar NS 6906 was used, sown at a spacing of 0.50 m with 16 seeds per meter. Fertilization consisted of applying 200 kg ha⁻¹ of MAP (formulated 05-30-15), and the microorganisms were applied at sowing using a Micron precision application system, according to each treatment. In addition, all treatments received *Bradyrhizobium* inoculation at 300 mL ha⁻¹ at sowing. Crop management followed technical recommendations to keep the crop free of pests, diseases, and weeds.

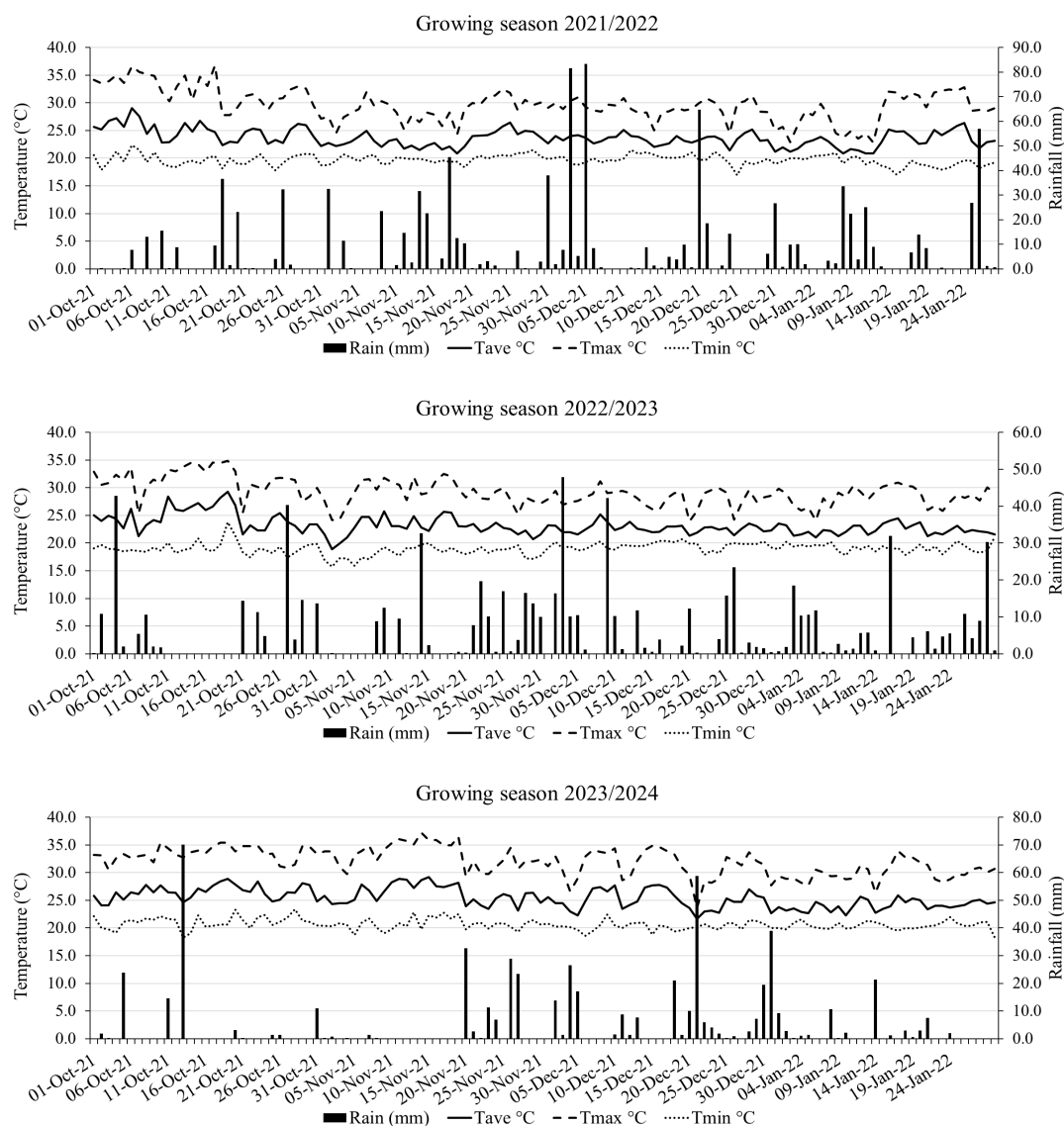


Figure 1. Temperature and precipitation during the soybean growing seasons of 2021/2022, 2022/2023, and 2023/2024 in Santo Antônio de Goiás, Goiás, Brazil. Tmax: maximum temperature; Tmin: minimum temperature; Tmean: mean temperature.

In the Embrapa management, a consortium of four beneficial microbial species was used, with 300 mL ha⁻¹ of each inoculant applied according to the corresponding treatments.

For the commercial management, the following products were used: 300 g of Penegetic Soils (a bioinoculant that enhances and balances soil microbiological activity); 200 mL of Robust Max (a microbiological nematicide composed of *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Paenibacillus polymyxa*, *Bacillus megaterium*, and *Bacillus licheniformis*, acting on root growth and the suppression of phytonematodes in the rhizosphere); 10 g of Triba (a fungicide composed of *Trichoderma harzianum*, *Trichoderma asperellum*, *Bacillus subtilis*, and *Bacillus amyloliquefaciens*, used for the control of white mold and root diseases); 100 mL of Arcadia (*Azospirillum brasilense* inoculant); 100 mL of Forts (a biostimulant composed of an amino acid complex, seaweed extract [hormonal source], and surfactants, with the product

being used as a resistance inducer and plant biostimulant); and 200 mL of Renov 1003 (*Bacillus* sp.).

The bacterial suspensions corresponding to the Embrapa management were prepared using nutrient broth and water from cultures grown for 24 hours on solid nutrient agar medium at 28 °C. The concentration was adjusted spectrophotometrically to an absorbance of 0.5 at 540 nm, corresponding to approximately 10⁸ CFU mL⁻¹.

After soybean physiological maturity, samples were collected to determine 100-grain weight (100GW) and grain yield (GY) of soybean plants grown during the 2021/2022, 2022/2023, and 2023/2024 summer seasons. The three central rows of each plot were harvested to determine grain yield, standardized at 13% moisture content. A sample from each plot was collected to determine the 100-grain weight at 13% moisture.

Aboveground dry mass was evaluated at 90 days after sowing (DAS) in all treatments. A metal quadrat with an area

of 1 m² was randomly positioned in each plot. Within this area, all aboveground dry mass of the cover crops was collected, dried in a forced-air oven to constant weight, and weighed.

The economic analysis was conducted using the partial budgeting method, according to Noronha (1987). This method accounts for the effects resulting from additional costs and revenues relative to a baseline, providing differential profit (DP) as the economic indicator, which was calculated using the following Equation (1):

$$LD = Rd - Cd \quad (1)$$

Where Rd (differential revenue) was calculated for each treatment as the product of the yield obtained in the treatment and the historical average soybean price deflated over the last five years in the state of Goiás, according to the AGROLINK platform (2024) and adjusted by the General Price Index – Internal Availability (FGV, 2023). This database was used because it was the only source available with a 05-year historical series.

To obtain the differential revenue (Rd), the average yield of each treatment within the interaction between microorganisms and cover crops (M × C) was multiplied by the deflated average price of a 60-kg bag of soybeans over the last ten years, which was \$ 24.78.

Cd (differential cost) was obtained from the price of the inputs used in each treatment, according to the respective application or non-application of microorganisms. Costs related to agricultural operations, administrative expenses, maintenance, depreciation, and the remuneration of two production factors were also included.

In the differential cost calculation, the only variable among the management strategies was the cost of applying or not applying microorganisms. For the treatments involving Embrapa microorganisms, costs associated with producing the microbial suspensions at the recommended dose of 300 mL ha⁻¹ were considered.

All values were converted to U.S. dollars using the exchange rate of May 31, 2024 (US\$ 1.00 = R\$ 5.25). Thus, differential profit (DP) was obtained from Equation (1). The data were subjected to analysis of variance, and significant means were compared using the Tukey test at the 5% significance level in Sisvar 5.6.

RESULTS AND DISCUSSION

In the evaluation, the analysis of variance revealed that the interaction between the factors microorganisms (M) and cover crops (C) was not significant for the shoot dry matter production (DM) of the cover crops grown during the second cropping seasons of 2022, 2023, and 2024 (Table 1). Significance was also observed for the cover crop factor (C) when evaluated individually, with pearl millet producing the highest amount of dry matter (8.52 t ha⁻¹), differing from the other treatments.

This greater dry matter production by pearl millet may improve soil cover, residue persistence, and nutrient cycling. Previous studies, such as those by Sousa et al. (2023) and

Soares et al. (2021), have shown that pearl millet significantly improves soil structure by increasing macroporosity and reducing soil bulk density, thereby benefiting subsequent crops. This result may be attributed to pearl millet's rapid growth and dry-mass accumulation, which are advantageous for agricultural systems seeking to improve soil structure and increase nutrient availability (SANTOS et al., 2021).

Treatments with pearl millet, buckwheat, Mix 1, and Mix 2 showed greater aboveground dry mass accumulation compared with the fallow treatment. However, this higher shoot dry matter production did not directly translate into increased soybean yield. Similar results were reported by Calonego and Rosolem (2012), who observed that the presence of cover crops improved soil physical attributes but did not result in a significant increase in soybean yield. According to the authors, the benefits of cover crops may occur over the medium and long term and are not always perceptible within a single growing season.

The 100-grain weight was not significantly affected by cover crop treatments or by microorganism application, remaining stable between 17.7 and 17.1 g (Table 1). The 100-grain weight is a trait strongly influenced by genotype, although it may also be affected by environmental and management conditions. In the present study, however, it remained stable across treatments. Previous studies support this finding, showing that applying microorganisms such as *Bradyrhizobium* and *Azospirillum brasilense* can significantly increase yield without directly affecting grain weight (CHIBEBA et al., 2015).

These results are supported by Garcia et al. (2016), who also did not observe significant changes in soybean yield parameters across different cover crop species. According to these authors, soybean response may vary depending on soil type, water regime, and the duration of system adoption. Therefore, the beneficial effects of cover crops may be more closely related to soil conservation and improvements in soil physical structure than to an immediate increase in soybean yield.

Grain yield was significantly affected by the application of microorganisms, with the commercial management resulting in the highest yield and not differing from the Embrapa management (4.34 t ha⁻¹), reaching 4.48 t ha⁻¹, compared with 4.26 t ha⁻¹ in the standard management (Table 1). This increase in yield may be due to microorganisms promoting plant growth, enhancing nutrient uptake, and improving tolerance to environmental stresses. Silva et al. (2020) demonstrated that the use of beneficial microorganisms can result in substantial increases in soybean grain yield without altering grain weight.

Although cover crops did not directly increase soybean yield, their contribution to the production system should not be disregarded. As reported by Silva et al. (2019), species such as pearl millet and *Brachiaria* contribute to soil protection, nutrient cycling, and moisture retention, which favors the performance of subsequent crops under adverse conditions. Therefore, even in the absence of immediate yield gains, the use of cover crops may contribute to the sustainability of the agricultural system in the medium term, especially in areas with well-established no-tillage systems.

Table 1. 100-grain weight (100GW) and grain yield (GY) of soybean plants grown during the 2021/2022, 2022/2023, and 2023/2024 summer seasons as a function of the application of microorganisms and cover crops.

Coverage	Mass Cov (t ha ⁻¹)	M100 (g)	PROD (t ha ⁻¹)
Fallow	5.22 b	17.16	4.39
Buckwheat	5.04 b	17.78	4.34
Pearl millet	8.52 a	17.65	4.35
Mix 1	7.51 a	17.08	4.38
Mix 2	5.87 b	17.19	4.34
Microorganisms			
Embrapa	6.16 b	17.55	4.34 ab
Commercial	6.05 b	17.62	4.48 a
Standard	7.09 a	16.94	4.26 b
Safrá			
2022	8.35 a	16.82 b	4.79 a
2023	5.02 c	17.29 ab	4.09 b
2024	5.93 b	18.00 a	4.21 b
Factors			
Coverage (C)	0.000*	0.669	0.986
Microorganisms (M)	0.007*	0.262	0.027*
Safrá (S)	0.000*	0.038*	0.000 *
C * M	0.854	0.222	0.876
C * S	0.012*	0.820	0.841
S * M	0.465	0.287	0.114
C * M * S	0.555	0.688	0.732

Means followed by the same letters do not differ according to the Tukey test ($p < 0.05$).

Embrapa: *Serratia marcescens* (BRM 32114), *Bacillus* sp. (BRM 63573), *Azospirillum brasilense* (AB-V5), and *Trichoderma koningiopsis* (BRM 53736). Commercial: *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Paenibacillus polymyxa*, *Bacillus megaterium*, *Bacillus licheniformis*, *Trichoderma harzianum*, *Trichoderma asperellum*, and *Azospirillum brasilense* + Penergetic. Mix 1: black oat (*Avena strigosa*), white oat (*Avena sativa*), *Crotalaria ochroleuca*, *Crotalaria juncea*, forage radish (*Raphanus sativus*), and finger millet (*Eleusine coracana*). Mix 2: black oat (*Avena strigosa*), showy crotalaria (*Crotalaria spectabilis*), forage radish (*Raphanus sativus*), and buckwheat (*Fagopyrum esculentum*).

Across the three growing seasons, a decreasing trend in soybean yield was observed (Table 1). The climatic variations recorded between the years (Figure 1), particularly in rainfall distribution, contributed to yield variability, which explains why the numerical difference.

The 2022/2023 and, especially, the 2023/2024 seasons showed greater rainfall irregularity throughout the crop cycle. This irregularity was reflected in reduced yields in those years and may have contributed to increased experimental variability, thereby attenuating statistical differences among treatments in the combined analysis.

Significant interactions among the factors ($C \times M$, $C \times S$, $S \times M$, and $C \times M \times S$) indicate that the effects of cover crops and microorganisms vary according to the growing season and its edaphoclimatic conditions (Table 1), primarily influencing the aboveground dry mass production of the cover crops without necessarily resulting in proportional increases in soybean yield. This highlights the importance of adopting management practices tailored to local conditions and seasonal variability to increase soil organic matter.

The soybean production costs for the different management strategies analyzed were similar, with total

values ranging from \$ 744.44 to \$ 799.49 per hectare in the 2023/2024 growing season (Table 2). The economic analysis considered exclusively the costs associated with the microbiological treatments in the 2023/2024 season, since the operational costs of the crop rotations were similar across systems and did not differ among the evaluated treatments.

However, the relative contributions of inputs to the total cost varied significantly among treatments. The commercial management, which used a combination of microorganisms + Penergetic, had the highest total cost (\$ 799.49 ha⁻¹), with 63.95% of this value corresponding to inputs (\$ 511.25 ha⁻¹). This result reflects a more intensive use of biological and chemical inputs.

In contrast, the management without microorganisms showed the lowest total cost (\$ 744.44 ha⁻¹), with 61.28% of the total (\$ 456.20 ha⁻¹) allocated to inputs. Although it represents the lowest-cost system, it does not use inoculants other than *Bradyrhizobium*, which may limit yield and long-term sustainability.

Although the standard management had lower input costs, the lower yield observed in this treatment compromises its economic viability (Table 2). The higher initial cost

associated with using microorganisms can be quickly offset by gains in yield and revenue, as demonstrated. This highlights the importance of considering not only the direct costs of inputs but also the direct benefits that biological management practices can provide throughout the production cycle.

The Embrapa management, which uses isolated microorganisms, had an intermediate cost (\$ 746.20 ha⁻¹) and an average input share across the three management strategies

(61.37%, or \$ 457.95 ha⁻¹). This indicates a more balanced distribution of costs among inputs, agricultural operations, and administrative expenses, suggesting greater efficiency in resource use.

Studies such as those by Pokhrel et al. (2021) and Cruz et al. (2025) indicate that the use of biological inputs may initially increase production costs but is offset by gains in yield and sustainability.

Table 2. Cost components and their relative contribution to soybean production costs as a function of different microbiological management strategies (Embrapa management, commercial management, and standard management) in the 2023/2024 growing season.

Component	Embrapa Management (\$ ha ⁻¹)	Participation (%)	Commercial Management (\$ ha ⁻¹)	Participation (%)	Standard Management (\$ ha ⁻¹)	Participation (%)
1. Inputs	457.95	61.37	511.25	63.95	456.20	61.28
Seeds	98.10	13.15	98.10	12.27	98.10	13.18
Inoculant (<i>Bradyrhizobium</i>)	0.89	0.12	0.89	0.11	0.89	0.12
Inoculant Own	1.75	0.23	55.05	6.89	0.00	0.00
Applications	39.52	5.30	39.52	4.94	39.52	5.31
KCl	85.90	11.51	85.90	10.74	85.90	11.54
Fertilizer MAP	146.29	19.60	146.29	18.30	146.29	19.65
Herbicides	34.57	4.63	34.57	4.32	34.57	4.64
Insecticides	22.08	2.96	22.08	2.76	22.08	2.97
Fungicides	14.86	1.99	14.86	1.86	14.86	2.00
Adjuvants	14.00	1.88	14.00	1.75	14.00	1.88
2. Agricultural Operations	86.73	11.62	86.73	10.85	86.73	11.65
Application of soil amendments	7.75	1.04	7.75	0.97	7.75	1.04
Sowing	24.75	3.32	24.75	3.10	24.75	3.32
Topdressing fertilization	6.01	0.81	6.01	0.75	6.01	0.81
Application of pesticides	18.20	2.44	18.20	2.28	18.20	2.44
Center pivot irrigation operation	11.39	1.53	11.39	1.42	11.39	1.53
Harvesting	18.63	2.50	18.63	2.33	18.63	2.50
3. Administrative Costs	109.23	14.64	109.23	13.66	109.23	14.67
Technical Assistance	12.63	1.69	12.63	1.58	12.63	1.70
Administration	12.63	1.69	12.63	1.58	12.63	1.70
Operating Interest	35.90	4.81	35.90	4.49	35.90	4.82
Taxes and Fees	48.06	6.44	48.06	6.01	48.06	6.46
A) COE (1+2+3)	653.91	87.63	707.20	88.46	652.16	87.60
4. Maintenance	2.35	0.31	2.35	0.29	2.35	0.32
Center Pivot	2.35	0.31	2.35	0.29	2.35	0.32
5) Depreciation	44.43	5.95	44.43	5.56	44.43	5.97
Machinery and Equipment	41.13	5.51	41.13	5.14	41.13	5.52
Improvements	3.30	0.44	3.30	0.41	3.30	0.44
B. COT (A+4+5)	700.69	93.90	753.98	94.31	698.93	93.89
6. Factor remuneration	45.51	6.10	45.51	5.69	45.51	6.11
Machinery and equipment	36.84	4.94	36.84	4.61	36.84	4.95
Improvements	8.67	1.16	8.67	1.08	8.67	1.17
Custo total (B+6)	746.20	100.00	799.49	100.00	744.44	100.00

*Values were converted to US dollars at the exchange rate of May 31, 2024, of \$ 1.00 = R\$ 5.25.

The efficient use of microorganisms can reduce the dependence on chemical fertilizers and pesticides, promoting soil health and improving the economic viability of the cropping system (LATAWIEC et al., 2021).

Thus, although the commercial management represents the highest direct cost, its potential agronomic and environmental returns may justify the investment, whereas the Embrapa management demonstrates good cost efficiency. In contrast, management without microorganisms, although cheaper, may compromise long-term yield and economic viability.

The differential revenue of each treatment shows that the use of the commercial microorganism in combination with

Mix 2 provided the highest revenue (\$ 1,883.69), whereas the standard management to the same cover crop resulted in the lowest revenue (\$ 1,439.31) (Table 3). This significant difference in revenue underscores the direct impact of microbial inoculation on the financial viability of soybean cultivation, demonstrating that microbial inoculation is a valuable tool for increasing economic returns. Studies such as that of Leite et al. (2023), which investigated the co-inoculation of soybean with *Bradyrhizobium* and other microorganisms, reported yield increases of up to 15%, resulting in a significant increase in profitability compared with the standard management.

Table 3. Differential revenue calculated for each treatment in relation to soybean plants grown after the second crop of cover plants, as a function of the use of cover crops and the application of Embrapa microorganisms, commercial microorganisms + Penergetic, and the standard management in the 2023/2024 growing season, calculated as the product of the yield obtained in each treatment and the historical average deflated price of a 60-kg soybean bag over the last five years.

Microorganisms	Revenue				
	Coverage				
	Fallow	Buckwheat	Pearl millet	Mix 1	Mix 2
Embrapa	\$ 1,739.97	\$ 1,719.73	\$ 1,751.12	\$ 1,819.27	\$ 1,783.33
Commercial	\$ 1,799.85	\$ 1,820.50	\$ 1,801.51	\$ 1,836.61	\$ 1,883.69
Standard	\$ 1,756.90	\$ 1,487.63	\$ 1,801.09	\$ 1,650.35	\$ 1,439.31

Embrapa: *Serratia marcescens* (BRM 32114), *Bacillus* sp. (BRM 63573), *Azospirillum brasilense* (AB-V5), and *Trichoderma koningiopsis* (BRM 53736).

Commercial: *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Paenibacillus polymyxa*, *Bacillus megaterium*, *Bacillus licheniformis*, *Trichoderma harzianum*, *Trichoderma asperellum*, and *Azospirillum brasilense* + Penergetic. Mix 1: black oat (*Avena strigosa*), white oat (*Avena sativa*), *Crotalaria ochroleuca*, *Crotalaria juncea*, forage radish (*Raphanus sativus*), and finger millet (*Eleusine coracana*). Mix 2: black oat (*Avena strigosa*), showy crotalaria (*Crotalaria spectabilis*), forage radish (*Raphanus sativus*), and buckwheat (*Fagopyrum esculentum*).

* Results obtained by multiplying the yield within the interaction of factors (M × C) by the deflated soybean price over the last five years.

** The average deflated price of a 60-kg bag of soybeans in the state of Goiás over the last five years was \$ 24.78.

***Values were converted to US dollars at the exchange rate of May 31, 2024, of \$ 1.00 = R\$ 5.25.

The higher differential revenue observed in the treatment with commercial microorganisms can be attributed to the increase in yield, which, as previously noted, was significantly higher with their application (Table 3). This yield increase offsets the additional input costs, resulting in a higher financial return than in the standard management. These findings reinforce the idea that the use of biological technologies is not only a sustainable strategy but also highly profitable for farmers seeking to maximize the return on their investments (CRUZ et al., 2025).

In addition, the differential revenue generated by using microorganisms may encourage producers who still rely on conventional inputs to adopt these practices. The positive impact on revenue provides a financial incentive to transition to more sustainable and efficient agricultural systems. Thus, the combination of cover crops and plant growth-promoting microorganisms may represent a key strategy for promoting sustainability and profitability in agribusiness.

The differential profit for each treatment highlights the management with commercial microorganisms applied to Mix

2, which generated the highest profit (\$ 1,084.20) (Table 4). In contrast, the standard management, also with Mix 2, showed the lowest profit (\$ 694.86), demonstrating a clear financial disadvantage when microorganisms are not applied.

These results confirm that although the cost of inputs may be higher with the use of microorganisms, the financial return is substantially greater, more than compensating for the initial investment. Studies such as Frasca et al. (2023) have shown that using a consortium of multifunctional microorganisms can significantly increase grain yield and revenue, highlighting their potential to improve the economic performance of agricultural systems.

The combination of higher yield and greater efficiency in input use can explain the higher profits achieved under commercial management. The application of microorganisms promotes the development of more vigorous plants, improves soil nutrient availability, and contributes to pathogen control, factors that together result in higher yields and, consequently, greater profitability.

Table 4. Differential profits (DP) for each treatment of soybean plants grown after the second crop of cover plants, as a function of the use of cover crops and the application of Embrapa microorganisms, commercial microorganisms + Penergetic, and the standard management in the 2023/2024 growing season.

Microorganisms	Profits				
	Coverage				
	Fallow	Buckwheat	Pearl millet	Mix 1	Mix 2
Embrapa	\$ 993.77	\$ 973.54	\$ 1,004.92	\$ 1,073.07	\$ 1,037.14
Commercial	\$ 1,000.36	\$ 1,021.01	\$ 1,002.01	\$ 1,037.12	\$ 1,084.20
Standard	\$ 1,012.46	\$ 743.18	\$ 1,056.65	\$ 905.90	\$ 694.86

* Results obtained by subtracting the differential cost from the differential revenue (DP = Rd – Cd).

Embrapa: *Serratia marcescens* (BRM 32114), *Bacillus* sp. (BRM 63573), *Azospirillum brasilense* (AB-V5), and *Trichoderma koningiopsis* (BRM 53736).

Commercial: *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Paenibacillus polymyxa*, *Bacillus megaterium*, *Bacillus licheniformis*, *Trichoderma harzianum*, *Trichoderma asperellum*, and *Azospirillum brasilense* + Penergetic. Mix 1: black oat (*Avena strigosa*), white oat (*Avena sativa*), *Crotalaria ochroleuca*, *Crotalaria juncea*, forage radish (*Raphanus sativus*), and finger millet (*Eleusine coracana*). Mix 2: black oat (*Avena strigosa*), showy crotalaria (*Crotalaria spectabilis*), forage radish (*Raphanus sativus*), and buckwheat (*Fagopyrum esculentum*).

In contrast, the standard management, without the addition of microorganisms, failed to optimize these factors, resulting in lower yield and, consequently, significantly lower profits. Studies by Leite et al. (2022) also demonstrate increased yield and profit in systems that use co-inoculation with beneficial microorganisms.

These data are essential to demonstrate that the use of plant growth-promoting microorganisms not only improves the sustainability of the production system but also maximizes economic returns. The adoption of biological technologies should be encouraged among producers as a practice that balances environmental and financial gains, enabling more efficient and profitable management. The differential profit observed here highlights the potential of innovative agricultural practices to improve the economic viability of major crops, such as soybeans.

CONCLUSION

The use of beneficial microorganisms increased soybean yield compared with the standard management, confirming their potential as a sustainable management practice. The commercial and Embrapa management strategies resulted in the highest soybean yields and outperformed the standard management. The commercial management provided the greatest economic return. Cover crops contributed to dry mass accumulation but did not directly affect soybean yield. Thus, the adoption of plant growth-promoting microorganisms, especially in integrated systems with cover crops, appears to be a promising strategy to increase grain yield and improve the sustainability of soybean cultivation.

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