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RELATIONSHIPS AMONG SOIL FERTILITY, RHIZOSPHERIC MICROBIOME, AND NEMATODE INCIDENCE IN COMMON BEAN PRODUCTION SYSTEMS

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Abstract

Common bean (*Phaseolus vulgaris* L.) is strongly influenced by the physical, chemical, and biological conditions of the soil, requiring management practices that promote soil health and production stability. Among these practices, cover crops and plant growth-promoting microorganisms have been adopted to enhance soil fertility and modulate the rhizospheric microbiota. This study evaluated, over three winter seasons, the effects of different cover crops and bioinputs on soil attributes, microbial and nematode communities, and the agronomic performance of irrigated common bean. The experiment followed a randomized block design in a 5 × 3 factorial scheme, combining five cover crops (fallow, millet, buckwheat, and two multispecies mixes) and three microbial managements (Embrapa, Partner, and Control), with four replications. Evaluations included cover crop biomass production, chemical and microbiological soil attributes, soil and root nematode populations, enzymatic activity, and common bean yield components. Biomass production varied significantly among cover crops, with higher values for millet and multispecies mixes. Soil analysis indicated specific effects of the inoculants on P, K, Zn, and Cu, as well as marked seasonal variations, especially associated with water availability. Microorganisms affected populations of *Rotylenchulus reniformis* and *Pratylenchus brachyurus*, whereas cover crops showed limited short-term effects on the nematode community. Common bean yield ranged from 1.24 to 2.09 t ha^{-1}, being more strongly influenced by microbial treatments and seasonal conditions than by cover crops; the Partner treatment showed the best productive performance, providing an average yield increase of 4.97% (79.6 kg ha^{-1}) compared to the control treatment. The results demonstrate that cover crops promote important environmental improvements, but immediate agronomic responses are modest. Bioinputs, in turn, exhibit specific and environment-dependent effects. The strong influence of seasonal conditions reinforces the need for multiyear evaluations to fully understand edaphic and biological dynamics.

Keywords: agricultural rhizosphere; bioinputs; cover crops; enzymatic activity; plant growth-promoting microorganisms.

RELAÇÕES ENTRE A FERTILIDADE DO SOLO, O MICROBIOMA RIZOSFÉRICO E A INCIDÊNCIA DE NEMATOIDES EM SISTEMAS DE PRODUÇÃO DE FEIJÃO-COMUM

Resumo

O feijão-comum (*Phaseolus vulgaris* L.) é fortemente influenciado pelas condições físicas, químicas e biológicas do solo, o que exige práticas de manejo que promovam a saúde do solo e a estabilidade da produção. Entre essas práticas, plantas de cobertura e microrganismos promotores do crescimento vegetal têm sido adotados para melhorar a fertilidade do solo e modular a microbiota rizosférica. Este estudo avaliou, ao longo de três safras de inverno, os efeitos de diferentes plantas de cobertura e bioinsumos sobre os atributos do solo, as comunidades microbianas e de nematoides e o desempenho agronômico do feijão-comum irrigado. O experimento foi conduzido em delineamento de blocos ao acaso, em esquema fatorial 5 × 3, combinando cinco tratamentos com plantas de cobertura (pousio, milheto, trigo-mourisco e dois mixes multiespécies) e três manejos microbianos (Embrapa, Parceiro e Controle), com quatro repetições. As avaliações incluíram a produção de biomassa das plantas de cobertura, atributos químicos e microbiológicos do solo, populações de nematoides no solo e nas raízes, atividade enzimática e componentes de produtividade do feijão-comum. A produção de biomassa variou significativamente entre as plantas de cobertura, com maiores valores para o milheto e os mixes multiespécies. A análise do solo indicou efeitos específicos dos inoculantes sobre P, K, Zn e Cu, além de variações sazonais marcantes, especialmente associadas à disponibilidade hídrica. Os microrganismos afetaram as populações de *Rotylenchulus reniformis* e *Pratylenchus brachyurus*, enquanto as plantas de cobertura apresentaram efeitos limitados, em curto prazo, sobre a comunidade de nematoides. A produtividade do feijão-comum variou de 1,24 a 2,09 t ha^{-1}, sendo mais fortemente influenciada pelos tratamentos microbianos e pelas condições sazonais do que pelas plantas de cobertura. O tratamento Parceiro apresentou o melhor desempenho produtivo, proporcionando aumento médio de produtividade de 4,97% (79,6 kg ha^{-1}) em comparação ao tratamento Controle. Os resultados demonstram que as plantas de cobertura promovem importantes melhorias ambientais, embora as respostas agronômicas imediatas sejam modestas. Os bioinsumos, por sua vez, apresentam efeitos específicos e dependentes das condições ambientais. A forte influência das condições sazonais reforça a necessidade de avaliações plurianuais para compreender plenamente a dinâmica edáfica e biológica.

Palavras-chave: rizosfera agrícola; bioinsumos; plantas de cobertura; atividade enzimática; microrganismos promotores do crescimento vegetal.

Introduction

Common bean (*Phaseolus vulgaris* L.) is one of the main legumes cultivated in Brazil, playing a fundamental role in food security and in the sustainability of agricultural systems. Its productive performance depends directly on the physical, chemical, and biological conditions of the soil, with emphasis on factors such as fertility, the rhizospheric microbiome, and the presence of plant-parasitic nematodes, which influence plant development and resource-use efficiency (Castro; Faria; Silva, 2021; Ambrosano *et al.*, 2022; Melo *et al.*, 2022). In this context, the use of cover crops constitutes an essential strategy for improving soil quality in tropical systems, since species such as millet, *Urochloa* spp., *Crotalaria* spp., and buckwheat contribute to greater biomass production, increased organic matter, improved soil structure, enhanced nutrient cycling, and modulation of the soil microbiota (Cruz; Pacheco, 2021; Torres; Pereira; Fabian, 2022; Teixeira *et al.*, 2024). The input of residues from these cover crops directly affects biogeochemical processes responsible for the availability of macro- and micronutrients and influences microbial activity.

In parallel, the use of bioinputs has received increasing attention, particularly inoculants containing rhizobia, plant growth-promoting rhizobacteria (PGPR), and beneficial fungi, which can act in phosphorus solubilization, phytohormone production, root development, improved nutrient uptake, and pathogen antagonism, thereby promoting greater plant resilience and improved biological conditions of the soil (Ambrosano *et al.*, 2022). However, responses to inoculation depend on the compatibility of the microbial strains with the soil environment, the crop, and the rhizosphere, potentially affecting both nutrient availability and the composition of beneficial and pathogenic fungi.

Another critical component of the system is the presence of plant-parasitic nematodes, such as *Meloidogyne* spp., *Pratylenchus* spp., and *Rotylenchulus* spp., which compromise the root system, reduce water and nutrient uptake, and can significantly limit common bean productivity (Castro; Faria; Silva, 2021). Recent studies have shown that the interaction between cover crops, the rhizospheric microbiome, and soil chemical attributes can modulate the incidence and impact of these nematodes, influencing both their reproduction and infective capacity (Teixeira *et al.*, 2024). Thus, integrating practices that promote soil health and microbial dynamics becomes essential for more sustainable production systems.

Given this scenario, it is necessary to investigate, in an integrated manner, how cover crops and bioinputs influence edaphic attributes, microbiological processes, and nematode dynamics, especially in irrigated tropical environments. Evaluations of cover crop biomass, chemical and

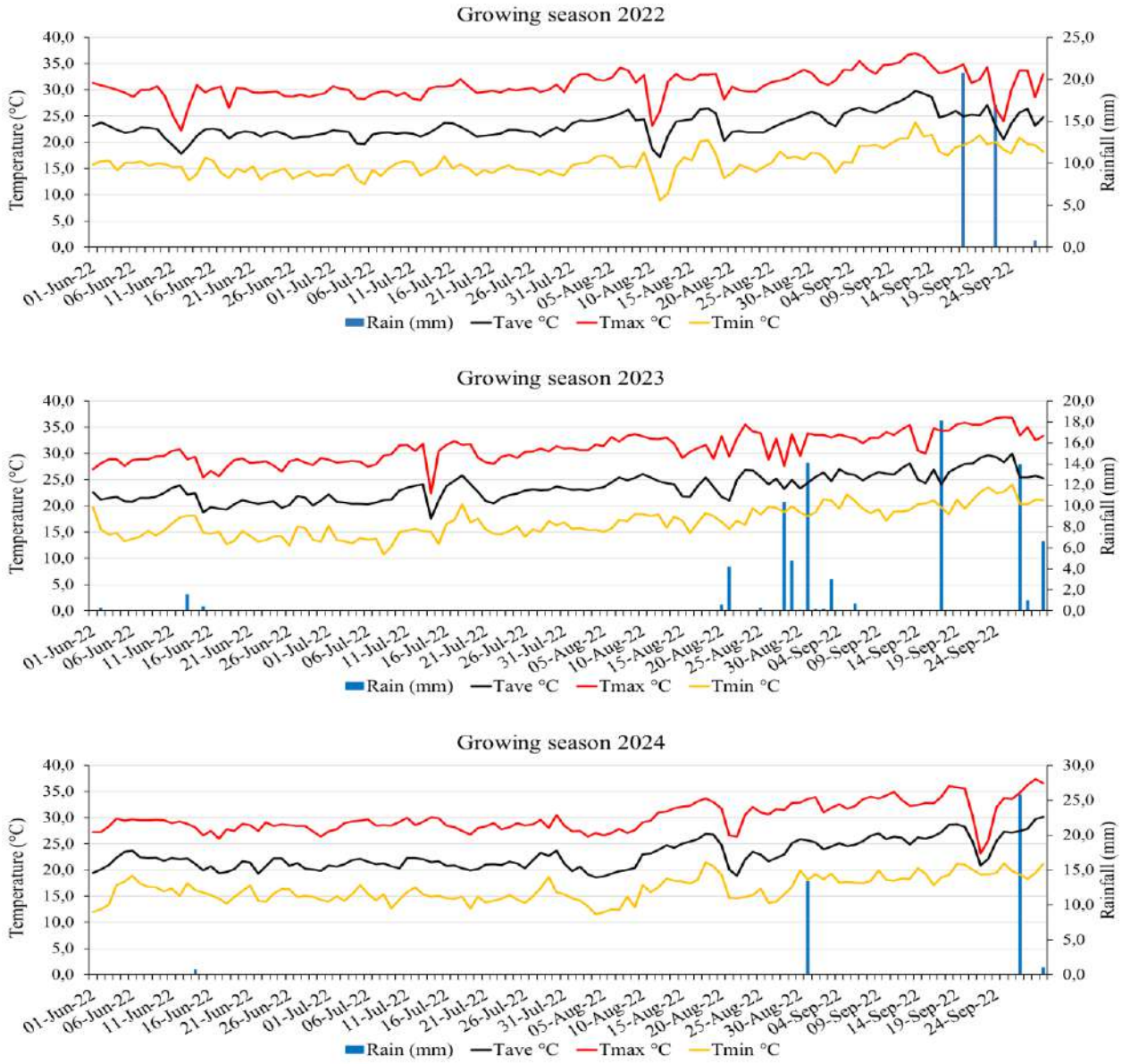
biological soil analyses, quantification of beneficial microorganisms, and surveys of nematode populations are essential tools for understanding these processes and their interactions. In this context, the present study evaluated, over three winter seasons in the Cerrado biome, the effects of different cover crops and plant growth-promoting microorganisms on cover crop biomass, soil chemical and biological attributes, fungal and nematode communities, and common bean yield components, providing insights to improve the efficiency and sustainability of agricultural systems.

Materials and Methods

Experimental Site

The experiment was conducted at Fazenda Capivara, located at the facilities of Embrapa Arroz e Feijão, in Santo Antônio de Goiás, Goiás, Brazil, at coordinates 16°28'00" S and 49°17'00" W, and at an altitude of 823 m, during the 2021/2022 growing season. According to the Köppen climate classification, the region has a Tropical Aw climate, with an average temperature of 23.3 °C and mean annual precipitation of 1,428 mm. The predominant soil type in the area is classified as Latossolo Vermelho Acrico (Santos *et al.*, 2018**),** corresponding to a Rhodic Ferralsol (IUSS Working Group WRB, 2015). To evaluate the climatic influence on crop performance, cumulative precipitation was monitored, specifically during the critical stages of flowering and grain filling (R6 to R8) (Figure 1). Prior to the installation of the experiments, soil chemical analyses were performed following the methodology described by Donagema *et al.* (2011), yielding the following results: pH (H_2O) = 5.5; Ca^{2+} = 14.2 mmolc dm^{-3}; Mg^{2+} = 6.1 mmolc dm^{-3}; H + Al^{3+} = 27 mmolc dm^{-3}; P = 12.9 mg dm^{-3}; K^{+} = 81 mg dm^{-3}; Cu^{2+} = 1.4 mg dm^{-3}; Zn^{2+} = 4.3 mg dm^{-3}; Fe^{3+} = 21 mg dm^{-3}; Mn^{2+} = 13.7 mg dm^{-3}; and soil organic matter = 33.8 g kg^{-1}.

Figure 1. Temperature and precipitation during the growing season of common bean plants cultivated after off-season maize or rice during the winter seasons of 2022, 2023, and 2024 in Santo Antônio de Goiás, Goiás State, Brazil. Tmax: maximum temperature; Tmin: minimum temperature; Tave: average temperature.



The common bean cultivar used was BRS FC 402, sown at a row spacing of 0.45 m with 15 viable seeds per meter. Fertilization consisted of 200 kg ha^{-1} of NPK fertilizer in the 4-30-16 formulation, and microorganisms were applied using a Micron® system. Three growing seasons were conducted in 2022, 2023, and 2024, all during the winter period (June–September), the most common cultivation window in the region and characterized by higher investment and technological intensity.

The experimental design was a randomized block design in a 5 × 3 factorial arrangement, with four replications. Treatments consisted of the combination of five cover crop managements selected for their functional complementarity in the Cerrado (millet for high biomass and K recycling; buckwheat for P mobilization and short cycle; and multispecies mixes for increased biological diversity and soil protection): (soybean/fallow/common bean, soybean/millet/common bean, soybean/buckwheat/common bean, soybean/cover crop mix 1/common bean, and soybean/cover crop mix 2/common bean) and three bioinput managements:

1. Embrapa microorganisms – *Serratia marcescens* (BRM 32114), *Bacillus* sp. (BRM 63573), *Azospirillum brasilense* (AB V5), and *Trichoderma koningiopsis* (BRM 53736);
2. Multispecies Consortium (Technical Management) – A complex consortium including *Bacillus subtilis*, *B. amyloliquefaciens*, *Paenibacillus polymyxa*, *B. megaterium*, *B. licheniformis*, *Trichoderma harzianum*, *T. asperellum*, and *Azospirillum brasilense* (applied at 10^8 CFU mL^{-1}), associated with a bentonite-based biostimulant (Penergetic) and a pool of amino acids and micronutrients (Co, Mo, and Zn);
3. Control, without microbial application.

Cover crops in the second season were sown in February of each year (2022, 2023, and 2024) and harvested by late May to allow chemical and physical desiccation 15 days before bean planting, including the application of 5 L ha^{-1} of glyphosate, a broad-spectrum herbicide, and the use of a knife roller.

Cover crop mix 1 consisted of black oat (*Avena strigosa*), white oat (*Avena sativa*), *Crotalaria ochroleuca*, *Crotalaria juncea*, forage radish (*Raphanus sativus*), and guinea grass (*Panicum maximum*). Mix 2 consisted of black oat (*Avena strigosa*), *Crotalaria spectabilis*, forage radish (*Raphanus sativus*), and buckwheat (*Fagopyrum esculentum*).

Cover crop seeds were sourced from Renovagro, following all sowing recommendations: millet (treatment 2) – 20 kg ha^{-1}; buckwheat (treatment 3) – 70 kg ha^{-1}; mix 1 (treatment 4) – 35 kg ha^{-1}; and mix 2 (treatment 5) – 35 kg ha^{-1}. Fertilization consisted of 100 kg ha^{-1} of single superphosphate.

For the bioinput treatments, plant growth-promoting microorganisms were applied in all soybean, cover crop, and common bean seasons. For the Embrapa management, four bacterial isolates were selected and applied at 300 mL ha^{-1} each of *Serratia* sp. (235), *Bacillus* sp. (1301), *Azospirillum brasilense* (Ab V5), and *Trichoderma koningiopsis*. For the Multispecies Consortium management, applications included 300 g ha^{-1} of chemically activated bentonite clay (Penergetic Solos), 200 mL ha^{-1} of a *Bacillus*-based pool (Robust Max), 10 g ha^{-1} of *Trichoderma* spp. (Triba),

300 mL ha^{-1} of *Bradyrhizobium* spp., 100 mL ha^{-1} of organomineral fertilizer (Arcadia), 100 mL ha^{-1} of phosphites (Forts), and 200 mL ha^{-1} of a nutrient complex (Renov 1003).

Bacterial suspensions for the Embrapa treatment were prepared in nutrient broth with cultures grown for 24 hours on nutrient agar at 28 °C. Concentrations were standardized in a spectrophotometer at A540 = 0.5 (10^8 propagules, colony-forming units). Suspensions were applied in-furrow before soybean and upland rice sowing using a Micron® furrow sprayer, following the recommendations of the microbiology laboratory at Embrapa Arroz e Feijão.

Assessments

Biomass production of cover crops was evaluated at 90 days after sowing (DAS) for all treatments. For weed assessments, evaluations were carried out at 30 and 60 DAS. Plant sampling for both crop species and weeds was performed using a 1 m^2 metallic quadrat randomly placed within each plot. Within this sampled area, the aboveground biomass of all cover crops and weeds was collected and subsequently dried in a forced-air oven at 65 °C for 72 hours until reaching constant weight.

At the end of the second-season cycle, eight soil sub-samples were collected per plot to compose a composite sample for the evaluation of macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium, and pH), micronutrients (boron, copper, iron, manganese, and zinc), enzyme activity (BioAS), and microbiological analysis. All analyses were conducted in the soil and microbiology laboratories of Embrapa Arroz e Feijão. In addition, after common bean planting, soil and root samples were collected for nematode analysis.

For yield components, common bean harvest was performed after physiological maturity by collecting three central rows (13.5 m^2) and ten individual plants. The following variables were measured: grain yield, number of pods per meter, number of grains per pod (based on grain counts from collected pods), number of filled grains in 40 pods, and 100-grain weight.

Statistical Analysis

The data were subjected to analysis of variance (ANOVA). Prior to the joint analysis of the growing seasons, the assumptions of normality (Shapiro-Wilk) and homogeneity of variances (Levene) were tested. The joint analysis was performed as the ratio between the largest and smallest residual mean squares (QMR) was less than seven, indicating homogeneity across years. Significant means were compared using Tukey's test at 5% probability, employing the Sisvar 5.6 software.

Results and Discussion

In March of 2022, 2023, and 2024, the second-season (safrinha) cycle began with the planting of cover crops. Biomass production varied significantly among the species evaluated, demonstrating the strong influence of cover crop selection on dry matter input to the soil. Millet recorded the highest biomass accumulation, reaching 8,526 kg ha^{-1}, followed by Mix 1 (7,513 kg ha^{-1}) and Mix 2 (5,879 kg ha^{-1}). In contrast, fallow (5,225 kg ha^{-1}) and buckwheat (5,049 kg ha^{-1}) showed the lowest values (Table 1).

The superior performance of millet is well documented in the literature and is attributed to its rapid growth, extensive root system, and strong adaptation to water stress conditions (Crusciol *et al.*, 2020; Silva *et al.*, 2021). These characteristics confer agronomic advantages for straw formation and soil organic matter accumulation, both essential components of conservation agriculture systems. The cover crop mixes also showed notable performance, highlighting the potential of species combinations to increase functional diversity and system resilience (Calonego *et al.*, 2023).

In contrast, the lower biomass observed in fallow and buckwheat indicates reduced residue input and lower straw persistence, which may compromise soil protection and nutrient cycling. These results align with studies documenting limitations of short-cycle species or those with sparse canopy architecture in tropical environments (Souza *et al.*, 2021).

The microorganism factor showed a significant effect on biomass production. However, inoculated treatments resulted in lower biomass compared with the control. The Control treatment yielded 7,095 kg ha^{-1}, whereas the Embrapa (6,165 kg ha^{-1}) and Partner (6,055 kg ha^{-1}) treatments produced lower values. This reduction in biomass in inoculated plants, although counterintuitive, can be attributed to the "metabolic cost" of establishing early microbial colonization and symbiosis. In the initial stages, the plant directs a significant portion of its photoassimilates to the rhizosphere to support microbial growth, which may result in a temporary reduction in shoot biomass production (Suhag, 2016; Compant *et al.*, 2019).

Table 1. Biomass of cover crops during the 2022, 2023, and 2024 second-season cycles as a function of microorganism application and cover crop species.

Cover crop	**Biomass (kg ha^{-1})**
Pousio	5225 b
Trigo Mourisco	5049 b
Milheto	8526 a
Mix 1	7513 a
Mix 2	5879 b
Microorganism	
Embrapa	6165 b
Partner	6055 b
Control	7095 a
Season	
2022	8350 a
2023	5026 c
2024	5939 b
Factor	
Cover crop (C)	0,000*
Microorganism (M)	0,007*
Season (S)	0,000*
C * M	0,854^{ns}
C* S	0,012*
S * M	0,465 ^{ns}
C * M* S	0,555 ^{ns}

Means followed by the same letters do not differ according to Tukey's 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 guinea grass (*Panicum maximum*). Mix 2: black oat (*Avena strigosa*), *Crotalaria spectabilis*, forage radish (*Raphanus sativus*), and buckwheat (*Fagopyrum esculentum*).

Although numerous studies report vegetative and physiological increases following the application of plant growth-promoting microorganisms such as *Azospirillum* spp., *Bacillus* spp., and *Trichoderma* spp. (Hungria *et al.*, 2022; Bhattacharyya; Goswami, 2020), it is also common to observe neutral or even negative responses under field conditions. Such inconsistencies may occur due to incompatibility between the microorganism and the plant species, low survival of microbial strains in the environment, or unfavorable climatic conditions, as highlighted by Compant *et al.* (2019). Therefore, the lower biomass observed in inoculated treatments suggests that there was insufficient synergy between the applied strains and the evaluated cover crop species.

The absence of a significant Cover Crop × Microorganism interaction indicates that the applied microorganisms did not alter the response pattern among cover crop species, a behavior also reported in studies conducted in tropical environments (Silva *et al.*, 2021).

The temporal analysis showed a significant effect of the growing season (Table 1) on biomass production. The highest biomass was recorded in 2022 (8,350 kg ha^{-1}), followed by 2024 (5,939 kg ha^{-1}), whereas 2023 presented the lowest value (5,026 kg ha^{-1}). This fluctuation is consistent with recent climatic variability in Brazil. In 2022, the region recorded higher cumulative precipitation during the vegetative stage (approx. 450 mm), favoring rapid growth. In contrast, 2023 was characterized by an irregular rainfall distribution associated with the El Niño phenomenon, with a 30% reduction in precipitation during the cover crop cycle, directly limiting biomass accumulation (Cunha *et al.*, 2023). Since cover crop biomass production is directly related to water availability, substantial reductions during drought years are expected and widely documented (Silva *et al.*, 2021; Calonego *et al.*, 2023).

In Table 2, soil chemical analysis showed that the use of different cover crops, the application of microorganisms, and seasonal variations among growing seasons significantly influenced several chemical attributes, especially phosphorus (P) and potassium (K). Treatments with cover crops exhibited variability in P and K contents, with the highest values found in the mixed-species treatments. Mix 1 recorded the highest P concentration (26.1 mg dm^{-3}), while the greatest K values were observed in Mix 1 (87.66 mg dm^{-3}) and buckwheat (90.84 mg dm^{-3}). These results reinforce the potential of multispecies cover crops to enhance nutrient cycling and increase macronutrient availability, particularly in no-tillage systems.

Brazilian literature highlights that species such as oats, forage radish, *Crotalaria* spp., and buckwheat promote biological decompaction, increase microbial biomass, and gradually release nutrients adsorbed to the soil matrix. Studies by Crusciol *et al.* (2020) and Calonego *et al.* (2017) demonstrate that cover crops—especially mixes—improve P and K dynamics through rhizosphere interactions and solubilization processes mediated by organic acids, corroborating the patterns observed in the present study.

Table 2. Chemical analysis of soil macronutrients under cover crops cultivated during the 2022, 2023, and 2024 second-season cycles as a function of microorganism application and cover crop species.

	pH	Ca	Mg	P	K
Cover crop	**CaCl2**	**mmolc/dm³**		**mg/dm³**	
Pousio	5,69 ab	24,7	9,4	20,9	86,43
Trigo Mourisco	5,73 a	25,5	9,5	19,6	90,84
Milheto	5,68 ab	24,7	9,6	21,7	81,96
Mix 1	5,67 ab	24,6	9,4	21,6	87,66
Mix 2	5,59 b	23,3	8,7	25,9	81,69
Microorganism					
Embrapa	5,73 a	24,74 ab	9,6	19,78 b	89,9
Partner	5,69 ab	25,51 a	9,5	29,46 a	85,69
Control	5,59 b	23,43 b	8,8	16,60 b	81,56
Season					
2022	5,93 a	24,8	9,85 a	22,70 a	80,31 b
2023	5,79 b	23,46	9,98 a	17,71 b	53,75 c
2024	5,29 c	25,5	8,10 b	25,42 a	123,09 a
Factor					
Cover crop(C)	0,084*	0,453 ns	0,356 ns	0,828 ns	0,493 ns
Microorganism (M)	0,002*	0,058*	0,049*	0,000*	0,200 ns
Season(S)	0,000*	0,074 ns	0,000*	0,000*	0,000*
C * M	0,435 ns	0,879 ns	0,719	0,464 ns	0,784 ns
C*S	0,849 ns	0,823 ns	0,951 ns	0,315 ns	0,013 ns
S*M	0,280 ns	0,663 ns	0,549 ns	0,297 ns	0,119 ns
C*M*S	0,929 ns	0,973 ns	0,981 ns	0,965 ns	0,994 ns

Means followed by the same letters do not differ according to Tukey's 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 guinea grass (*Panicum maximum*). Mix 2: black oat (*Avena strigosa*), *Crotalaria spectabilis*, forage radish (*Raphanus sativus*), and buckwheat (*Fagopyrum esculentum*).

The application of inoculants also influenced nutrient availability, as shown in Table 2. The Partner treatment exhibited the highest P content (29.46 mg dm^{-3}), whereas the Embrapa treatment showed the highest Mg concentration (9.6 mmolc dm^{-3}) and the highest K content (89.90 mg dm^{-3}). This behavior is consistent with studies involving inoculants containing *Bacillus* spp. and *Azospirillum* spp., which are recognized for their ability to solubilize phosphates, produce phytohormones, stimulate root growth, and enhance nutrient uptake.

These mechanisms are widely described in Brazilian literature. Hungria *et al.* (2016) and Santos *et al.* (2021) reported increases in assimilable P and greater nutrient accumulation in crops inoculated with growth-promoting rhizobacteria, reinforcing the physiological potential of these microbial groups.

The growing season variable showed a significant effect for most evaluated parameters, highlighting the strong influence of climatic conditions and annual soil management. In 2024, the highest K values (123.09 mg dm^{-3}) were observed, suggesting a possible interaction among water availability, crop root development, and organic matter mineralization. The sharp increase in K levels in 2024 (over 100% higher than 2023) is likely due to the high biomass produced in the previous year and the favorable rainfall in early 2024, which accelerated the leaching of K from the straw—a nutrient that is not integrated into organic structures and depends on moisture for release (Rosolem *et al.*, 2017).

On the other hand, soil pH showed a decreasing trend over the years (from 5.93 in 2022 to 5.29 in 2024), possibly due to the continuous use of intensified cropping systems. Such behavior is expected in no-tillage soils in the Cerrado, as reported by Matos *et al.* (2020) and Sá *et al.* (2017), who highlight progressive acidification resulting from straw decomposition and increased release of organic acids.

The interactions C × M, C × S, and M × S were significant for some attributes, particularly P and K, indicating that the effect of microorganisms depends on the type of cover crop and also on seasonal conditions. The significant C × M × S interaction for P reinforces the multifactorial nature of nutrient dynamics, especially in Cerrado soils, which have a high capacity for phosphate adsorption.

This behavior is supported by studies showing the dependence on combined biological, edaphic, and climatic factors for expressive responses in conservation agriculture systems, as discussed by Carvalho *et al.* (2021).

In Table 3, the dynamics of soil micronutrients varied consistently among cover crops, applied microorganisms, and growing seasons. For the cover crop factor, Mix 2 exhibited the highest levels of exchangeable Al (0.19 mmolc dm^{-3}) and H+Al (20.19 mmolc dm^{-3}), indicating greater potential soil acidification compared with fallow and buckwheat. Although diverse root systems enhance nutrient cycling, some species may intensify the release of exudates that mobilize aluminum, as reported by Crusciol *et al.* (2015) when evaluating legume–grass consortia.

Fallow, which provides minimal residue input, showed reduced acidification and comparatively lower micronutrient levels, reflecting lower biological activity and limited nutrient cycling in systems lacking soil cover.

Table 03. Chemical analysis of soil micronutrients from cover crops grown during the off-season in 2022, 2023, and 2024, as a function of microorganism application and cover crop species.

	Al	H + Al	Cu	Zn	Fe	Mn
Cover crop	**mmolc/dm³**			**mg/dm³**		
Pousio	0,08	18,69 ab	1,54 a	5,00	24,1	15,9
Trigo Mourisco	0,05	17,97 b	1,39 b	5,23	21,64	16,41
Milheto	0,05	18,66 ab	1,53 a	4,71	21,21	15,88
Mix 1	0,11	18,66 ab	1,55 a	5,09	21,31	16,64
Mix 2	0,19	20,19 a	1,58 a	5,37	21,7	17,08
Microorganism						
Embrapa	0,06	17,30 b	1,49	5,21 a	23,73	14,31 b
Partner	0,08	19,36 a	1,57	5,44 a	21,13	17,19 a
Control	0,15	19,85 a	1,49	4,60 b	21,11	17,82 a
Season						
2022	0,25 a	13,20 c	1,60 b	5,14 b	22,05 a	14,31 b
2023	0,00 b	18,41 b	1,23 c	3,56 c	25,66 a	17,19 a
2024	0,05 b	24,90 a	1,72 a	6,54 a	18,26 b	17,82 a
Factor						
Cover crop(C)	0,216 ^{ns}	0,068*	0,002*	0,165 ^{ns}	0,583 ^{ns}	0,466 ^{ns}
Microorganism (M)	0,243 ^{ns}	0,000*	0,037*	0,000*	0,155 ^{ns}	0,000*
Season(S)	0,000*	0,000*	0,000*	0,000*	0,000*	0,000*
C * M	0,647 ^{ns}	0,340 ^{ns}	0,620 ^{ns}	0,886 ^{ns}	0,351 ^{ns}	0,926 ^{ns}
C*S	0,175 ^{ns}	0,954 ^{ns}	0,216 ^{ns}	0,011*	0,658 ^{ns}	0,188 ^{ns}
S*M	0,227 ^{ns}	0,032 ^{ns}	0,520 ^{ns}	0,238 ^{ns}	0,203 ^{ns}	0,008*
C*M*S	0,988 ^{ns}	0,976 ^{ns}	0,279 ^{ns}	0,725 ^{ns}	0,474 ^{ns}	0,877 ^{ns}

Means followed by the same letters do not differ according to Tukey's 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 guinea grass (*Panicum maximum*). Mix 2: black oat (*Avena strigosa*), *Crotalaria spectabilis*, forage radish (*Raphanus sativus*), and buckwheat (*Fagopyrum esculentum*).

For metallic micronutrients, Zn content ranged from 4.71 to 5.37 mg dm^{-3}, with emphasis on Mix 2 and buckwheat, which presented the highest values. The literature indicates that buckwheat has a high capacity for Zn and Cu solubilization due to the exudation of organic acids (Cieslik *et al.*, 2019), which corroborates the results found in the present study.

Regarding the microorganism factor, the "Partner" treatment showed the highest Cu (1.57 mg dm^{-3}) and Zn (5.44 mg dm^{-3}) values, suggesting that the inoculant enhanced the solubilization and availability of these micronutrients. Microorganisms such as *Bacillus* and *Trichoderma*, included in the products used, are widely recognized for increasing the availability of Fe, Zn, and

Mn through siderophore production and rhizosphere acidification mechanisms (Silva *et al.*, 2020; Babu *et al.*, 2022). This behavior was also reflected in Mn, whose highest value was recorded in the control treatment (17.82 mg dm^{-3}), possibly due to greater oxidation of the element in the absence of bioproducts, since microbial management tends to increase the reduced form Mn^{2+}, favoring its uptake (Zhang *et al.*, 2019).

Among the cropping seasons, significant variation was observed: in 2023, Al values were close to zero, whereas in 2024 there was a substantial increase in H+Al levels (24.90 mmolc dm^{-3}). This fluctuation may be associated with annual climatic differences, especially precipitation, which influence organic matter mineralization and the dynamics of soil bases, as reported by Sanches *et al.* (2023) in no-till systems in the Cerrado.

Fe content ranged from 18.26 to 22.05 mg dm^{-3} across the seasons, with the highest value recorded in 2022. This pattern aligns with results from international studies demonstrating a strong relationship between soil aeration and Fe availability, particularly in clayey soils (Havlin *et al.*, 2014).

Factor analysis revealed that cover crops (C) and microorganisms (M) independently influenced most micronutrients. However, significant interactions (C × S and C × M × S) indicate that management effects strongly depend on environmental conditions and on the composition of plant mixtures. Brazilian literature supports this multifactorial behavior: cover crops and bioinputs modulate micronutrient availability through biological cycling, pH changes, and increased microbial activity (Nicoloso *et al.*, 2020; Moreira; Siqueira, 2006).

In summary, as shown in Table 3, the results demonstrate that diversified cover crop mixtures, associated with the use of plant growth-promoting microorganisms, increase Zn and Cu availability and influence potential soil acidity to varying degrees across seasons. These responses reinforce the importance of managing the rhizosphere in an integrated manner, especially in Cerrado environments, where nutritional efficiency depends strongly on soil biology.

In Table 4, it is observed that the values of *Fusarium* spp. propagules varied according to the cover crops, applied microorganisms, and cropping seasons. Among the cover crops, millet showed the highest number of propagules (6673 propagules g^{-1} soil), followed by Mix 1 (6277), while fallow presented the lowest values. These results corroborate studies showing that grasses with high biomass production tend to increase the density of saprophytic and phytopathogenic fungi due to the greater input of residues and the high content of structural carbon (Santos *et al.*, 2021; Brennan *et al.*, 2014).

Table 04. Microbiological analysis of the soil under cover crops cultivated during the off-season in 2022, 2023, and 2024, as a function of microorganism application and cover crop species.

	Fusarium sp	***Trichoderma spp.***	***Rhizoctonia solani***
Cover crop	**Propagules / g solo**		**%ROC**
Pousio	5362	3666	9,61
Trigo Mourisco	5648	5397	10,07
Milheto	6673	6757	9,40
Mix 1	6277	3460	9,25
Mix 2	6135	5333	6,57
Microorganism			
Embrapa	6246 ab	6173	11,13
Partner	5187 b	3825	7,95
Control	6625 a	4770	7,86
Season			
2022	7497 a	4230	9,74
2023	5922 b	5883	9,80
2024	4638 b	4655	7,40
Factor			
Cover crop(C)	0,446 ^{ns}	0,371 ^{ns}	0,538 ^{ns}
Microorganism (M)	0,043*	0,265 ^{ns}	0,907 ^{ns}
Season(S)	0,000*	0,495 ^{ns}	0,279 ^{ns}
C * M	0,528 ^{ns}	0,112 ^{ns}	0,153 ^{ns}
C*S	0,867 ^{ns}	0,768 ^{ns}	0,821 ^{ns}
S*M	0,015*	0,906 ^{ns}	0,484 ^{ns}
C*M*S	0,546 ^{ns}	0,851 ^{ns}	0,363 ^{ns}

Means followed by the same letters do not differ according to Tukey's 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 guinea grass (*Panicum maximum*). Mix 2: black oat (*Avena strigosa*), *Crotalaria spectabilis*, forage radish (*Raphanus sativus*), and buckwheat (*Fagopyrum esculentum*).

%ROC = Percentage of colonized organic residues.

For *Trichoderma* spp., recognized for its antagonistic activity against several phytopathogens, millet also provided the highest values (6757 propagules g^{-1} soil), confirming its potential to stimulate beneficial soil microbiota. This behavior has already been reported by Castro *et al.* (2020), who observed that tropical grasses favor *Trichoderma* colonization due to a more aerated environment and the accumulation of slowly decomposing residues.

For the microorganism factor, the Embrapa treatment showed greater colonization by *Fusarium* spp. and higher %ROC for *Rhizoctonia solani* (11.13%). Although bioinputs promote

agronomic benefits, some may stimulate opportunistic microbial groups depending on edaphoclimatic conditions and interactions with the host plant. This phenomenon was described by Wendling *et al.* (2022), who highlighted that formulations containing multiple microbial species can increase both beneficial organisms and some phytopathogens, particularly in environments with high inputs of plant residues.

The cropping season was the most significant factor, showing strong effects on *Fusarium* spp., *Trichoderma* spp., and *R. solani*. In 2022, the highest values of *Fusarium* (7497 propagules) and *R. solani* colonization (9.74%) were recorded, whereas 2024 presented the lowest counts. This interannual variation is often associated with fluctuations in climate—temperature, soil moisture, and precipitation—that directly influence microbial activity and the life cycle of phytopathogens (Ghini; Hamada, 2015; Scherm; Coakley, 2003).

The interaction among factors (C × M × S) was not significant for most variables, indicating that the effects depend mainly on environmental conditions and isolated management practices. This reinforces the need for multi-year assessments to understand microbial dynamics in tropical systems, as pointed out by Moreira and Siqueira (2006) and Bailey *et al.* (2022).

Accordingly, Table 4 shows that grasses and plant mixtures increase propagules of saprophytic and beneficial fungi such as *Trichoderma* spp.; microbial formulations modulate the fungal community in a specific manner, potentially favoring both antagonists and pathogens; and the cropping season is the main modulatory factor, confirming the strong influence of climatic conditions on soil fungal communities.

These findings highlight the complexity of interactions among cover crops, bioinputs, and environmental conditions, reinforcing that building a biologically balanced soil requires continuous management and microbiological monitoring.

In Table 5, soil organic matter contents did not vary significantly as a function of cover crops or applied microorganisms, with mean values between 25.7 and 26.7 g kg^{-1}. This behavior is expected since organic matter has low sensitivity to short-term changes and depends on long-term cycles of residue input and decomposition (Carvalho *et al.*, 2022).

The significant difference among cropping seasons indicates direct influence from climatic variation across the years. The year 2022 showed the highest content (27.9 g kg^{-1}) compared with 2023 (24.7 g kg^{-1}), suggesting that more favorable environmental conditions in 2022 may have reduced mineralization rates or increased residue accumulation.

Beta-glucosidase activity showed significant differences as a function of microorganisms and cropping seasons but was not influenced by cover crops ($p = 0.981$). Among the cover crops, values ranged from 33.6 to 40.2 μg p-nitrophenol g^{-1} h^{-1}, with no statistical differences. The absence of an effect from plant species is associated with the generalist nature of this enzyme,

which is involved in the carbon cycle and cellulose degradation in diverse residues (Ushio *et al.*, 2020).

The effect of the microorganism factor was evident: Control (44.0 μg pNP g^{-1} h^{-1}), Embrapa (38.7 μg pNP g^{-1} h^{-1}), and Partner (35.9 μg pNP g^{-1} h^{-1}). The greater activity in the Control suggests that the inoculants applied did not stimulate soil cellulolytic activity under the conditions of this study. Although inoculants containing *Bacillus* and *Trichoderma* can enhance enzymatic activity (Cardoso *et al.*, 2021; Hungria *et al.*, 2022), several authors report that when strains are not well adapted to the edaphic environment or to the host plant, neutral responses or even reductions in native microbial activity may occur (Compant *et al.*, 2019).

The 2023 cropping season showed much higher activity (56.9 μg pNP g^{-1} h^{-1}) compared with 2022 (22.2 μg pNP g^{-1} h^{-1}). This behavior may be associated with water stress, since drier years tend to increase the activity of hydrolytic enzymes as a microbial strategy to access carbon sources (Zhang *et al.*, 2022). Recent studies also report increases in beta-glucosidase under moderate drought conditions in tropical soils (Table 5).

Table 05. Analysis of soil enzymes collected during the 2022 and 2023 off-seasons, as a function of microorganism application and cover crop species.

	M.O.	**BETAGLICOSIDASE**	**ARILSULFATASE**
Cover crop	**g/kg**	**[ug p-Nitrofenol] g^{-1} h^{-1}**	**[ug p-Nitrofenol] g^{-1} h^{-1}**
Pousio	26,2	39,2	34,9
Trigo Mourisco	26,5	38,8	34,5
Milheto	26,5	40,2	34,5
Mix 1	25,7	39,6	33,4
Mix 2	26,7	39,9	34,0
Microorganism			
Embrapa	26,0	38,7 b	33,5
Partner	26,3	35,9 b	32,8
Control	26,7	44,0 a	36,5
Season			
2022	27,9 a	22,2 b	16,7 b
2023	24,7 b	56,9 a	51,8 a
Factor			
Cover crop(C)	0,591 ^{ns}	0,981 ^{ns}	0,984 ^{ns}
Microorganism (M)	0,384 ^{ns}	0,000*	0,187 ^{ns}

Season(S)	0,000*	0,000*	0,000*
C * M	0,746 ns	1,000 ns	0,999 ns
C*S	0,934 ns	0,996 ns	0,998 ns
S*M	0,060 ns	0,968 ns	0,990 ns
C*M*S	0,856 ns	1,000 ns	1,000 ns

Means followed by the same letters do not differ according to Tukey's 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 guinea grass (*Panicum maximum*). Mix 2: black oat (*Avena strigosa*), *Crotalaria spectabilis*, forage radish (*Raphanus sativus*), and buckwheat (*Fagopyrum esculentum*).

At the beginning of common bean planting, soil sampling was carried out for nematode detection, as presented in Table 6. The nematode community present in the soil did not show significant changes as a function of the evaluated cover crops. Populations of *Meloidogyne* sp. ranged from 7 to 17 juveniles per 100 cm³ of soil; *Pratylenchus brachyurus* ranged from 56.0 to 82.6; *Helicotylenchus* sp. from 348 to 505; *Criconemella* sp. from 32 to 55; *Rotylenchulus reniformis* from 555 to 946; and free-living nematodes ranged from 378 to 613 individuals. Although statistically similar, the observed values reflect ecological patterns consistent with the literature, which highlights the high resilience of nematode communities to short-term changes in soil management (Neher, 2023; Yeates, 2020).

The cover crop mixtures showed higher populations of free-living nematodes, especially in Mix 1 (613 individuals), suggesting greater microbial activity and organic matter decomposition in these systems. The greater plant diversity present in the mixtures tends to favor soil microbiota, creating favorable conditions for saprophytic groups, a pattern already described by Ferris (2021) in soils with high functional diversity. Conversely, species such as buckwheat and millet presented the lowest values of *Meloidogyne* sp., although not statistically significant, aligning with the suppressive potential reported for these plants in tropical agricultural environments (Wang *et al.*, 2022). Fallow areas showed relatively higher values of *Pratylenchus* and *Rotylenchulus*, reinforcing that the absence of plant cover can favor phytonematodes due to reduced biological competition and lower quality of root exudates (Neher, 2023).

Regarding the effect of microorganisms, most nematode groups did not show significant differences between inoculated treatments and the control, except for *Rotylenchulus reniformis* (Table 6). For this genus, greater density was observed in the Embrapa treatment (1307

individuals), followed by the Partner treatment (717 individuals), whereas the control showed the lowest population (322 individuals). This unexpected increase in R. reniformis in inoculated areas may be an indirect effect of the bioinputs. Growth-promoting microorganisms often stimulate the emission of fine lateral roots, increasing the total root surface area. While beneficial for nutrient uptake, this also provides more infection sites for endoparasitic nematodes, explaining the higher populations in the short term (Xiang *et al.*, 2021).

The literature attributes this type of alteration to modifications in the rhizosphere microbial community, since introduced microorganisms may compete with native microbiota, suppress natural enemies of nematodes, or alter the chemical profile of root exudates, making the environment more favorable to infestation by certain phytoparasites (Xiang *et al.*, 2021; Rashid *et al.*, 2022). Thus, the higher abundance of *R. reniformis* in the inoculated treatments suggests that the use of these bioinputs should be adopted with caution in areas with a history of this nematode.

Table 06. Analysis of soil nematodes collected during the 2023 off-season, as a function of microorganism application and cover crop species**.**

Cover crop	***Meloidogyne sp.***	***Pratylenchus brachyurus***	***Helicotylenchus sp.***	***Criconemella sp.***	***Rotylechulus reniformis***	***vida Livre***
Pousio	13	82,58	362	51	772	465
Trigo Mourisco	6	76,00	417	36	806	378
Milheto	7	56,83	348	31	830	458
Mix 1	17	77,08	505	48	946	613
Mix 2	12	56,00	485	52	555	415
Microorganism						
Embrapa	17	74	455	30 b	1307 a	513
Partner	6	58	458	56 a	717 ab	462
Control	10	77	357	45 ab	322 b	422
Factor						
Cover crop (C)	0,857 ^{ns}	0,797 ^{ns}	0,232 ^{ns}	0,496 ^{ns}	0,9275 ^{ns}	0,2449 ^{ns}
Microorganism (M)	0,393 ^{ns}	0,638 ^{ns}	0,215 ^{ns}	0,067*	0,0186*	0,5467 ^{ns}
C * M	0,395 ^{ns}	0,562 ^{ns}	0,881 ^{ns}	0,743 ^{ns}	0,9383 ^{ns}	0,5144 ^{ns}

Means followed by the same letters do not differ according to Tukey's 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 guinea grass (*Panicum maximum*). Mix 2: black oat (*Avena strigosa*), *Crotalaria spectabilis*, forage radish (*Raphanus sativus*), and buckwheat (*Fagopyrum esculentum*).

As shown in Table 6, the population of free-living nematodes also did not exhibit significant differences among treatments, although their values were higher in areas with mixtures, suggesting greater soil biological activity. These organisms are considered sensitive indicators of soil quality, as they directly reflect the availability of organic matter and the decomposer activity of the edaphic microbiota (Ferris, 2021). In the present study, this behavior reinforces that cover crops with greater biomass accumulation tend to favor biological processes related to the carbon cycle.

Overall, the results indicate that, in the short term, cover crops were not able to significantly modify the structure of the nematode community, demonstrating the stability of these organisms in response to the management practices evaluated. On the other hand, the applied microorganisms exerted a specific effect on *Rotylenchulus reniformis*, indicating that inoculants may generate differentiated responses depending on the functional group of nematodes and the interactions established in the rhizosphere. These results corroborate studies highlighting the complexity of plant–microorganism–nematode relationships in tropical environments and reinforce the need for broader and long-term assessments to understand the ecological and agronomic implications of these management practices (Neher, 2023; Wang *et al.*, 2022; Zhang *et al.*, 2022).

The analysis of nematodes present in roots collected during the 2023 growing season, as shown in Table 7, revealed that, overall, there was no significant effect of cover crops on the populations of the evaluated groups. This pattern indicates that, in the short term, the cover crops used were not capable of consistently modifying root parasitism, a pattern already documented in studies reporting the relative stability of endorhizic nematofauna in response to punctual agricultural practices (Neher, 2023; Ferris, 2021).

Populations of *Meloidogyne* sp. were extremely low, ranging from 0 to 1.25 juveniles per root system, suggesting either low presence of this nematode in the experimental area or natural soil suppressiveness. The reduced occurrence may also be associated with the characteristics of the cover species used, since plants such as millet and buckwheat are recognized as poor hosts for *Meloidogyne* spp. (Wang *et al.*, 2022). Similarly low populations of *Pratylenchus* sp. (0 to 2.33 individuals) further indicate reduced root parasitism under the evaluated conditions.

For *Pratylenchus brachyurus*, a genus of major economic importance in Cerrado agricultural systems, populations ranged from 36 to 84 individuals per root, but without statistical differences among cover crops. Even so, the lowest values were observed in fallow systems, while the highest occurred in mixtures (although not significant). This behavior reflects the opportunistic nature of *P. brachyurus*, which can develop in a wide range of hosts, including grasses and legumes commonly used a cover crops (Zhang *et al.*, 2022). As a polyphagous phytonematode, consistent reductions in its populations usually occur only under longer management cycles.

Populations of *Helicotylenchus* sp., a common ectoparasitic nematode in tropical soils, ranged from 21.45 to 33.69 individuals per root, also without significant differences among cover crops. This pattern is expected, as this group responds more strongly to rhizosphere quality and soil physicochemical conditions than to the host plant species alone (Ferris, 2021).

Analysis of the microorganism factor revealed significant differences only for *Pratylenchus brachyurus* ($p = 0.0462$) and *Rotylenchulus reniformis* ($p = 0.0178$). For *P. brachyurus*, the population was highest in the Embrapa treatment (88 individuals), followed by Partner (65), while the control showed the lowest value (40). This result suggests a possible indirect stimulation of parasitism in the inoculated treatments. The literature indicates that microbial inoculants may alter the profile of root exudates, modify the microbial structure of the rhizosphere, or increase root emission, creating microenvironments more favorable for some phytoparasitic nematodes (Xiang *et al.*, 2021).

A similar behavior was observed for *Rotylenchulus reniformis*, with higher populations in Embrapa (3.62 individuals) and Partner (1.27), whereas the control presented no detectable parasitism (0.0). This reinforces that the bioinputs used did not act as suppressive agents and, in some cases, may have created conditions more favorable for the development of phytonematodes. Recent studies show that the introduction of microorganisms not adapted to the environment can negatively affect natural antagonistic interactions in the rhizosphere, reducing the effectiveness of nematode-predating bacteria and fungi (Rashid *et al.*, 2022).

Values for *Criconemella* sp. were low (0.77 to 2.17 individuals), and no significant effect was observed for cover crops or microorganisms. As low-mobility ectoparasites, their populations tend to reflect soil physical structure more than the plant management employed (Ferris, 2021).

Overall, the results demonstrate that the root nematode community showed low abundance and high ecological stability, with specific effects associated with the use of microbial inoculants. These findings corroborate studies indicating that endorhizic nematodes tend to show little variability in response to short-term management and that bioinputs may generate divergent responses depending on the ecological balance of the rhizosphere (Neher, 2023; Zhang *et al.*, 2022). Thus, it becomes evident that continuous and long-term evaluations are essential to fully understand the impact of cover crops and microorganisms on phytonematode communities in tropical production systems.

Table 07. Analysis of nematodes present in roots collected during the 2023 off-season, as a function of microorganism application and cover crop species.

Cover crop	*Meloidogyne sp.*	*Pratylenchus sp.*	*Pratylenchus brachyurus*	*Helicotylenchus sp.*	*Criconemella sp.*	*Rotylechulus reniformis*
Pousio	0,00	0,00	76	26,78	2,17	1,67
Trigo Mourisco	1,08	0,00	36	29,02	0,77	2,28
Milheto	0,00	0,00	86	14,08	0,00	2,69
Mix 1	0,00	2,33	40	17,53	0,00	0,83
Mix 2	0,00	0,00	84	26,69	0,00	0,64
Microorganism						
Embrapa	0,00	0,00	88 a	25,32	1,76	3,60 a
Partner	0,65	1,40	65 ab	21,69	0,00	1,27 ab
Control	0,00	0,00	40 b	21,45	0,00	0,00 c
Fatores						
Cover crop (C)	0,418 ^{ns}	0,418 ^{ns}	0,135 ^{ns}	0,783 ^{ns}	0,5039 ^{ns}	0,8252 ^{ns}
Microorganism (M)	0,376 ^{ns}	0,376 ^{ns}	0,062*	0,926 ^{ns}	0,2096 ^{ns}	0,0731*
C * M	0,449 ^{ns}	0,449 ^{ns}	0,482 ^{ns}	0,991 ^{ns}	0,5683 ^{ns}	0,5698 ^{ns}

Means followed by the same letters do not differ according to Tukey's 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 guinea grass (*Panicum maximum*). Mix 2: black oat (*Avena strigosa*), *Crotalaria spectabilis*, forage radish (*Raphanus sativus*), and buckwheat (*Fagopyrum esculentum*).

The 100-grain weight (M100) and grain yield of common bean varied as a function of microorganisms and cropping seasons, whereas cover crops did not show significant effects on any of the variables. M100 values ranged from 19.99 to 21.76 g, and yield varied from 1.24 to 2.09 t ha^{-1}, reflecting the combined influence of climatic conditions and the physiological dynamics of the crop.

Although cover crops did not significantly affect M100 ($p = 0.432$) or yield ($p = 0.546$), some patterns can be observed. The highest numerical yield values were recorded for mixtures and millet, whereas fallow presented intermediate performance (1.68 t ha^{-1}). The absence of statistical differences reinforces that common bean is highly sensitive to environmental conditions—especially water availability—and does not always respond quickly to gradual improvements in physical and biological attributes promoted by cover crops (Silva *et al.*, 2020; Souza *et al.*, 2021). Still, high-biomass cover crops such as millet and plant mixtures are recognized for improving water infiltration, reducing soil temperature fluctuations, and favoring soil microbiota, contributing

to long-term yield stability even when differences are not detected in short-term evaluations (Carvalho *et al.*, 2022; Crusciol *et al.*, 2020).

The most expressive effect occurred for the microorganism factor. The 100-grain weight was significantly influenced ($p = 0.001$), with higher values in the Control treatment (21.69 g), followed by Partner (20.66 g), and lower values in the Embrapa treatment (19.99 g). Yield showed a similar pattern, being highest in Partner (1.86 t ha^{-1}), intermediate in Embrapa (1.70 t ha^{-1}), and lowest in the Control (1.60 t ha^{-1}). These results indicate that bioinputs can alter the physiological performance of the crop, but the effects depend strongly on the strains applied, rhizosphere compatibility, and climatic conditions.

Inoculants containing *Azospirillum brasilense* and *Bacillus* spp. have increased common bean yield in several Brazilian studies, mainly due to stimulation of root growth, enhanced nutrient uptake, and greater tolerance to environmental stress (Hungria *et al.*, 2022; Chagas Junior *et al.*, 2019). In many cases, yield increases of 5 to 20% are reported, especially under moderate water limitation. Accordingly, the higher yield observed in the Partner treatment is consistent with the literature, suggesting that the strains present in this inoculant were more efficient in establishing beneficial interactions with the crop.

The fact that the Embrapa treatment presented lower grain weight, despite showing intermediate yield, suggests that the inoculant may have favored an increase in pod number or final plant stand, but not necessarily greater reserve accumulation in the grains. Studies indicate that certain microorganisms can increase yield components such as pod number without increasing grain weight, due to physiological limitations associated with pod filling (Figueiredo *et al.*, 2020; Zilli *et al.*, 2021).

Cropping season was the most determining factor, influencing both M100 and yield. Yield was highest in 2023 (2.09 t ha^{-1}), followed by 2022 (1.83 t ha^{-1}), and considerably lower in 2024 (1.24 t ha^{-1}). This variation follows the climatic pattern of the region, highlighting marked differences in water distribution during the crop's critical period. In years with greater water availability, common bean tends to show better grain filling and greater final grain mass, as observed in 2022 and 2023. Sharp reductions such as those observed in 2024 are typical of water stress, which compromises photosynthesis, assimilate transport, and maintenance of leaf area (Didonet *et al.*, 2020; Cunha *et al.*, 2023).

Table 08. Hundred-grain weight (M100) and grain yield (PROD) of common bean plants cultivated during the winter cropping seasons of 2022, 2023, and 2024.

Cover crop	M100 (g)	PROD (Kg/ ha)
Pousio	20,51	1,68
Trigo Mourisco	21,06	1,66
Milheto	20,61	1,78
Mix 1	20,83	1,81
Mix 2	20,90	1,70
Microorganism		
Embrapa	19,99 c	1,70 ab
Partner	20,66 b	1,86 a
Control	21,69 a	1,60 b
Season		
2022	21,76 a	1,83 b
2023	20,08 b	2,09 a
2024	20,50 b	1,24 c
Factor		
Cover crop(C)	0,432 ^{ns}	0,546 ^{ns}
Microorganism (M)	0,000*	0,011*
Season(S)	0,000*	0,000*
C * M	0,254 ^{ns}	0,420 ^{ns}
C*S	0,420 ^{ns}	0,820 ^{ns}
S*M	0,000*	0,249 ^{ns}
C*M*S	0,960 ^{ns}	0,829 ^{ns}

Means followed by the same letters do not differ according to Tukey's 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 guinea grass (*Panicum maximum*). Mix 2: black oat (*Avena strigosa*), *Crotalaria spectabilis*, forage radish (*Raphanus sativus*), and buckwheat (*Fagopyrum esculentum*).

Additionally, common bean is a crop highly sensitive to thermal stress during flowering and grain filling. Recent Brazilian studies report yield reductions of up to 40% in years with a greater number of hot days and intermittent droughts (Farinelli *et al.*, 2021; Melo *et al.*, 2022). The sharp decline observed in 2024 reflects this pattern, suggesting climatic conditions unfavorable to crop development.

Synthesis and Technical Recommendation

The multi-year analysis reveals that although immediate yield increases are modest, the management of soil health is a cumulative process. Based on biomass input and nutrient cycling

stability, Mix 1 (Black oat, white oat, Crotalaria spp., radish, and guinea grass) and Millet are the most recommended cover crop strategies for the Cerrado. Mix 1, in particular, demonstrates superior functional diversity, which is essential for building systemic resilience against the climatic instabilities (El Niño/La Niña) observed throughout this study. The use of bioinputs should be viewed as a long-term biological structuring tool rather than a quick yield fix.

Conclusion

The results demonstrate that, in the short term, cover crops did not significantly alter common bean yield, hundred-grain weight, nematode community structure, or the chemical and biological attributes of the soil, although mixtures and millet showed greater biomass input and favored biological processes related to the carbon cycle. The applied microorganisms promoted specific effects, influencing nutrients such as P, K, Zn, and Cu, and altering populations of *Rotylenchulus reniformis* and *Pratylenchus brachyurus*, indicating responses dependent on rhizosphere compatibility and environmental conditions. The cropping season was the main modulating factor for the evaluated variables, highlighting the strong influence of climatic conditions on the agronomic and microbiological performance of the system. Technically, Mix 1 and Millet are recommended as the most promising strategies for building long-term soil resilience in the Cerrado due to their superior biomass production and nutrient cycling potential. Overall, the study reinforces that management systems based on cover crops and bioinputs — with the multispecies microbial consortium showing the highest potential for immediate yield gains — require multi-year evaluations for their structural effects on soil, microbiota, and crop productivity to be fully characterized.

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Declaration of Conflict of Interest

The authors declare that there are no conflicts of interest.

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