Root and aerial growth of corn subjected to different biological managements in seed treatment with *Bacillus aryabhattai*

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Abstract

Plant growth-promoting rhizobacteria (PGPR) can be an option to mitigate the impact of abiotic constraints in different cropping systems in the tropical semi-arid region. Therefore, the objective of this study was to evaluate the biometric growth parameters and root system of corn plants subjected to the use of *Bacillus aryabhattai* via seed treatment and furrow application. The trial was conducted in a commercial area in the southwestern region of Goiás, Brazil. The experiment was set up in a randomized block design with four treatments (T1 – Control; T2 – *B. aryabhattai* (4 mL kg^{-1} of seed) via seed treatment; T3 – *B. aryabhattai* (200 mL ha^{-1}) via furrow application; T4 – *B. aryabhattai* (300 mL ha^{-1}) via furrow application) and five replications, totaling 20 experimental plots. Root parameters (maximum root length (cm); root dry mass (g); root volume (cm^3)) and biometric parameters (plant height (cm); ear insertion height (cm); stem diameter (mm); prolificacy (number of ears per plant); number of leaves) were evaluated. The application of *Bacillus aryabhattai* led to increases in root system volume and stem diameter in corn plants.

Keywords: *Bacillus aryabhattai*, rhizobacteria, root system, corn, semi-arid.

Crescimento radicular e aéreo do milho submetido a diferentes manejos biológicos no tratamento de sementes com *Bacillus aryabhattai*

Resumo

O uso de rizobactérias promotoras do crescimento de plantas (PGPR) pode ser uma opção para mitigar o impacto de restrições abióticas em diferentes sistemas de cultivo na região semiárida tropical. Portanto, o objetivo deste trabalho foi avaliar os parâmetros biométricos de crescimento e o sistema radicular de plantas de milho, submetidas ao uso de *Bacillus aryabhattai* via tratamento de semente e sulco de plantio. O ensaio foi conduzido em área comercial no sudoeste do estado de Goiás. O experimento foi instalado em delineamento em blocos casualizados com 4 tratamentos (T1 – Controle; T2 – *B. aryabhattai* (4 mL kg^{-1} de semente) via tratamento de semente; T3 – *B. aryabhattai* (200 mL ha^{-1}) via sulco de plantio; T4 – T3 – *B. aryabhattai* (300 mL ha^{-1}) via sulco plantio) e 5 repetições, totalizando 20 parcelas experimentais. Foram avaliados os parâmetros radiculares (maior comprimento radicular (cm); massa seca radicular (g) e; volume de raízes (cm^3)) e biométricos (altura de planta (cm); altura de inserção da espiga (cm); diâmetro do colmo (mm); prolificidade (número de espigas por planta); número de folhas. Os manejos com *Bacillus aryabhattai* promoveram incrementos no volume do sistema radicular e no diâmetro do colmo de plantas.

Palavras-chave: *Bacillus aryabhattai*, rizobactérias, sistema radicular, milho, semiárido.

1. Introduction

Corn (*Zea mays* L.) originates from the Americas and belongs to the Poaceae family (Pirnajmedin et al., 2024). It is an annual, monoecious species that falls into the C-4 plant group, meaning it has a high net photosynthesis rate and a strong affinity for CO_2 (Conte et al., 2024). Besides its importance in terms of production, corn cultivation stands out for its diverse applications, allowing for the production of a wide range of products (Miranda, 2018). In the 2023/24 season, the cultivated area was 21,058.5 thousand hectares, representing a 5.4% decrease compared to the previous season, with an estimated production of 115,722.8 thousand tons, 12.3% lower than the previous growing cycle (CONAB, 2024).

Bioinputs can be defined as products or substances of biological origin used in agriculture to promote plant growth, improve soil health, and sustainably control pests and diseases. The use of bioinputs provides greater food security, increased crop sustainability, and cost reduction. Their application aims to maximize the benefits of biological interactions, mitigate environmental damage, and can be incorporated throughout the entire production process (Figueiredo et al., 2016; Nunes et al., 2024).

In the soil, plants interact with microorganisms present in their surroundings, offering a highly specific environment for the natural development and growth of microbial communities (Paul et al., 2024). Throughout evolution, these communities have developed skills and strategies that enable their interaction with plants (Deng et al., 2022). These interactions may bring benefits without harming plants, or they may be detrimental when pathogenic microorganisms cause biochemical and physiological imbalances, leading to various types of diseases (Korenblum et al., 2020; Lazcano et al., 2021).

The rhizosphere has a complex and dynamic biological system in which microorganisms degrade almost all organic compounds, thereby recycling them (Nannipieri et al., 2017). Plants interact with microorganisms present in the rhizosphere, creating a favorable environment for the growth and multiplication of microbial communities. Throughout evolutionary processes, microbial communities have developed strategies and abilities that allow their interaction with plants (Deng et al., 2022). These interactions can have both beneficial and harmful effects. Plant Growth-Promoting Microorganisms (PGPMs) are microorganisms that colonize various plant organs and, through the production of metabolites, substances, and molecules, alter plant metabolism, potentially optimizing plant growth and development (Sheirdil et al., 2019).

Bacillus aryabhattai is a gram-positive rhizobacteria, capable of colonizing the root system of a wide range of plant species (Steiner et al., 2024). The species *B. aryabhattai*, commonly found in the rhizosphere of mandacaru (*Cereus jamacaru*) plants in the northeastern region of Brazil, has been associated with a potential biological alternative to enhance the growth of corn and soybean crops (Mun et al., 2024). Studies show that plants treated with *Bacillus aryabhattai* experienced growth promotion through mechanisms such as phytohormone regulation, mineral nutrient solubilization, and antagonistic action against plant pathogens (Mariano, 2022; Castelo Sousa et al., 2023). In addition to promoting vegetative growth, it significantly increases the levels of abscisic acid, indoleacetic acid, jasmonic acid, and gibberellins, contributing to enhanced drought tolerance compared to control plants in the experiment (Park et al., 2017; May et al., 2019).

Therefore, the objective of this study was to evaluate the biometric growth parameters and root system of corn plants subjected to the use of *Bacillus aryabhattai* through seed and furrow treatment.

2. Materials and Methods

2.1 Experimental area, climate, and soil analysis

The trial was conducted in a commercial area in the southwestern region of Goiás, Brazil. The climate of the region is classified according to Köppen & Geiger (1928) and Alvares et al. (2013) as *Aw* (tropical), with rainfall occurring from October to May and a dry season from June to September. Rainfall was observed up to 50 days after the experiment was sown. Before the experiment was set up, disturbed soil samples were collected for physicochemical characterization at a depth of 0–20 cm. The collected soil was classified as Dystroferric Red Latosol (LVdf), Cerrado phase, with a clayey texture (Santos et al., 2018) (Table 1).

Table 1. Physicochemical characteristics of Dystroferric Red Latosol, at the 0-20 cm layer.

Depth	pH	O.M	P	K	Ca	Mg	Al	H+Al	CEC	V
		$g.kg^{-1}$	--- $mg.dm^{-3}$ --		--------------- $cmol_c.dm^{-3}$ ---------------					%
0-20	5.0	23.8	8.9	26	1.5	0.9	<0.1	4.0	6.4	37.9
Depth	m	S	B	Cu	Fe	Mn	Zn	Clay	Silt	Sand
	-- % --	--------------------- $mg.dm^{-3}$ ---------------------						----- $g.kg^{-1}$ -----		
0-20	0	8.0	0.1	3.1	32	12.0	0.8	420	105	475

Note: P (Phosphorus) = Mehlich, K (Potassium), Na (Sodium), Cu (Copper), Fe (Iron), Mn (Manganese), and Zn (Zinc) = Mehlich; Ca (Calcium), Mg (Magnesium), and Al (Aluminum) = KCl 1 $mol.L^{-1}$; S (Sulfur) = $Ca(H_2PO_4)_2$ 0.01 $mol.L^{-1}$. OM = Organic Matter = Colorimetric method; B (Boron) = hot water. CEC = Cation Exchange Capacity. V = base saturation; m = Aluminum saturation. Source: Authors, 2024.

2.2 Corn sowing and agricultural cultural practices

The corn was sown on 02/20/2023, using a 5-row seed drill with a horizontal disc seed distribution system. The row spacing was 0.45 m with 3 seeds per linear meter, resulting in 66,666 seeds per hectare. The planting system used was no-till, with soybean being the predecessor crop in the 2022/23 season. Cultural practices were carried out for the corn crop in the study area with fungicides, herbicides, and insecticides.

2.3 Experimental design

The experiment was set up in a randomized block design with 4 treatments and 5 replications, totaling 20 experimental plots. The useful area of the experimental plots consisted of 10 rows, each 5 meters long (Table 2).

Table 2. Description of the treatments.

Treatments	Practice
T1	Control – Without application
T2	*Bacillus aryabhattai* (4 mL kg^{-1} seeds) / Through Seed Treatment
T3	*Bacillus aryabhattai* (200 mL ha^{-1}) / Through Furrow
T4	*Bacillus aryabhattai* (300 mL ha^{-1}) / Through Furrow

2.4 Evaluations

Root system: At 40 days after sowing, two plants per replication were extracted to measure the following root parameters: maximum root length (cm); root dry mass (g); and root volume (cm^3). Growth Biometrics: At 80 days after sowing (DAS), two plants per replication were collected to assess: Plant height (PH – cm); Ear insertion height (EIH – cm); Stem diameter (SD – mm); Prolificacy (number of ears per plant), and Number of leaves (NL). A semi-analytical scale was used to determine the mass (g), and an electric oven with air circulation, and a tape measure were used to determine the length.

2.5 Statistical analysis

The data were subjected to analysis of variance using the *F-test* ($p < 0.05$) to determine significance between the evaluated factors. When a significant effect was found, the *Tukey* test ($p < 0.05$) was applied to compare the means between treatments, using the statistical software SISVAR® (Ferreira, 2011).

3. Results

3.1 Final plant population

The plant population per hectare did not show any statistical difference between the treatments, with an average population of 49,750 plants per hectare (Table 3).

Table 3. Final plant population per hectare, for each biological management, off-season 2023, Rio Verde – GO, Brazil.

Agricultural Management	Plant Population per Hectare
T1	47.000 a
T2	50.000 a
T3	48.000 a
T4	54.000 a

Note: Identical letters in the same column do not differ by the *Tukey* test at 5% probability. Source: Authors, 2024.

3.2 Morphological and vegetative parameters

The treatments did not differ from each other for the variables maximum root length and root dry mass. However, the plants that received the management through seed treatment and furrow planting showed a higher root system volume compared to the Control treatment (Table 4). The managements T2 (*B. aryabhattai* (4 mL kg^{-1} of seed)/ Through Seed Treatment); T3 (*B. aryabhattai* (200 mL ha^{-1}/ Through Furrow)); and T4 (*B. aryabhattai* (200 mL ha^{-1}/ Through Furrow)) promoted an average increase of 54.84% (8.5 cm^3) compared to the Control management.

Table 4. Maximum root length, root dry mass, and root system volume, subjected to different biological managements, off-season 2023, Rio Verde – GO, Brazil.

AM	Maximum root length (cm)	Root dry mass (g)	Root system volume (cm^3)
T1	29.00 a	4.91 a	15.50 b
T2	28.40 a	6.26 a	23.00 a
T3	30.40 a	5.40 a	23.50 a
T4	32.20 a	5.87 a	25.50 a

Note: AM = Agricultural Management. Different letters in the columns indicate that the means differ from each other by the *Tukey* test at 5% probability. Source: Authors, 2024.

In the variables plant height, number of leaves, and leaf area at 40 days after sowing (DAS), the use of different *B. aryabhattai* management through seed treatment and furrow planting at different doses did not differ statistically from the Control management (Table 5).

Among the *B. aryabhattai* treatments, the seed treatment management (T2) and the furrow treatment at a dose of 200 mL ha^{-1} (T3) showed the largest stem diameters. Treatments T2 and T3 promoted an average increase of 7.66% (1.9 mm) compared to the Control management, although they did not differ statistically from each other. On the other hand, the furrow management at a dose of 300 mL ha^{-1} showed the smallest stem diameter among all the managements adopted (Table 5).

Table 5. Plant height, stem diameter, number of leaves, and leaf area at 40 days after sowing (DAS), subject to different biological managements, off-season 2023, Rio Verde – GO, Brazil.

AM	Plant height (m)	Stem diameter (mm)	Number of leaves	Leaf area (m^2)
T1	61.80 a	24.78 ab	8.00 a	0.43 a
T2	59.20 a	26.72 a	7.60 a	0.45 a
T3	54.00 a	26.64 a	8.00 a	0.43 a
T4	53.20 a	21.87 b	7.80 a	0.44 a

Note: AM = Agricultural Management. Different letters in the columns indicate that the means differ from each other by the Tukey test at 5% probability. Source: Authors, 2024.

At 80 days after sowing (DAS), no statistical differences were observed between the *B. aryabhattai* managements for the variables plant height, ear insertion height, number of leaves, stem diameter, and prolificacy of the corn crop (Table 6).

Table 6. Plant height, ear insertion height, number of leaves, stem diameter, and prolificacy of the corn crop at 80 days after sowing (DAS), subjected to different biological managements, off-season 2023, Rio Verde – GO, Brazil.

AM	Plant height (m)	Ear insertion height (m)	Number of leaves	Stem diameter (mm)	Prolificacy
T1	2.21 a	1.12 a	13.20 a	22.40 a	1.40 a
T2	2.28 a	1.12 a	13.80 a	21.60 a	1.40 a
T3	2.32 a	1.14 a	14.60 a	21.94 a	1.40 a
T4	2.25 a	1.16 a	14.80 a	22.49 a	1.40 a

Note: AM = Agricultural Management. Different letters in the columns indicate that the means differ from each other by the Tukey test at 5% probability. Source: Authors, 2024.

4. Discussion

Studies demonstrate the potential activity of *B. aryabhattai* in the development of major crops. *Bacillus aryabhattai* is involved in promoting and developing a larger root system volume, and such an effect may be related to the increase in root length and root hair number, effects attributed to the production of plant hormones or growth regulators. A larger root system volume means an advantage in soil exploration, and thus, the plant is better protected from nutrient scarcity and water deficit (Mehmood et al., 2012; May et al., 2019).

Furthermore, *B. aryabhattai* has been shown to have plant growth-promoting properties, such as the production of growth phytohormones and the solubilization of nutrients, such as phosphates, making them available to plants. This nutrient solubilization can then be absorbed by the roots, where this microorganism promotes greater root development, leading to better nutrient and water absorption, and contributing to good plant growth and development results (Melo, 2015; Lima et al., 2019). In the study by Nakatani et al. (2024), the researchers associated different *Bacillus* species, such as *B. aryabhattai*, as plant growth promoters in corn plants. In this study, *Bacillus* treatments resulted in increased nitrogen absorption by the leaves and grains, as well as in plant biomass and productivity in different regions where this group of microorganisms was tested. Additionally, *Bacillus* species associated with a 25% reduction in nitrogen provided corn plant development and productivity equivalent to those obtained with nitrogen fertilization application.

Stainer and colleagues (2024) found that different doses of an inoculant containing *B. aryabhattai* applied to seeds of hybrid corn 20A38 VIP3 did not affect seedling emergence rate. Corn plants inoculated with B. aryabhattai showed greater length and higher dry matter accumulation (biomass) in both the aerial parts and roots compared to the control plants without inoculation. Our results corroborate with Steiner et al. (2024), demonstrating that the use of an inoculant containing *B. aryabhattai* can be applied to improve the initial growth of corn seedlings and other vegetative and reproductive parameters. The optimal dose of the inoculant containing *B. aryabhattai* to be applied to hybrid corn seeds evaluated by the researchers may vary between 20 and 22 mL kg^{-1} of inoculant. The use of *B. aryabhattai* has become a promising strategy to enhance plant productivity and health in various crops, as the balanced interaction between plants and microorganisms contributes to better plant growth and development (Vacheron et al., 2015).

5. Conclusions

Management with the addition of *Bacillus aryabhattai* in seed treatment (4 mL kg^{-1} of seed) and through furrow planting at doses of 200 and 300 mL ha^{-1} were effective in promoting a larger root system volume in corn plants. The use of *B. aryabhattai* in management via seed treatment and through furrow planting at a dose of 200 mL ha^{-1} promoted the largest stem diameters in corn plants.

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7. Authors' Contributions

Diego França Mendes: project writing, experimental conduction, data analysis, article writing, publication. *Fernando Rodrigues Cabral Filho*: experimental conduction and data analysis. *Christiano Lima Lobo de Andrade*: experimental conduction and data analysis and *Matheus Vinícius Abadia Ventura*: supervisor, data analysis, project writing, post-evaluation corrections, publication.

8. Conflicts of Interest

No conflicts of interest.

9. Ethics Approval

Not applicable.

10. References

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