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Evaluation of Antarctic strains of *Bacillus* sp. as plant growth promoting bacteria

Evaluación de cepas Antárticas de *Bacillus* sp. como bacterias promotoras del crecimiento vegetal

Avaliação de cepas antárticas de *Bacillus* sp. como bactérias promotoras de crescimento de plantas

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Abstract

In agriculture, efficient microorganisms are used, among them plant growth-promoting bacteria. This work aimed to determine, *in vitro*, the mechanism of action in strains of *Bacillus* sp. isolated from Antarctica. The analyzed characteristics of the bacterium were: catalase and hemolysis tests, Gram stain, phosphate solubilization, growth without a nitrogen source, siderophore production, and survival at different values of pH, NaCl, and temperature, which confirmed the ecological plasticity and adaptation of these strains in environments other than their origin. According to the desirable characteristics, the T5, GB-70, and B-6 strains were chosen and added to two substrates: clay and clay-compost mixture, which were sterilized and placed in 200 mL glass bottles, and a corn seed was planted in each of them. After two weeks, the following parameters were evaluated: length of root (LR), seedling height (AP), and shoot diameter (DT). The simple effect of the strains as independent variables and their interaction did not significantly affect the response variables evaluated, recording the following averages: 12.84 cm (LR), 15.28 cm (AP), and 2.26 cm (DT). Considering the substrate, the compost + clay significantly ($p<0.05$) influenced the LR and DT characteristics of the seedlings, with averages of 14.44 and 2.38 cm, respectively. The observed mechanisms of action distinguish promising strains that could be validated at the field level in agricultural production systems when inoculated in organic fertilizers.

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Resumen

En agricultura, se emplean microorganismos eficientes, entre ellos las bacterias promotoras de crecimiento vegetal. El propósito de este trabajo fue determinar, *in vitro*, el mecanismo de acción en cepas de *Bacillus* sp. aisladas de la Antártida. Se analizaron los siguientes aspectos: prueba de catalasa y de hemólisis, tinción de Gram, solubilización de fosfato, crecimiento sin fuente de nitrógeno, producción de sideróforo, y supervivencia a diferentes valores de pH, NaCl y temperatura, con lo cual se constató la plasticidad ecológica y adaptación de estas cepas en ambientes distintos al de su origen. De acuerdo con las características deseables, se escogieron las cepas T5, GB-70 y B-6 que se añadieron a dos sustratos: arcilla y mezcla arcilla-compost, los cuales fueron esterilizados y depositados en botellas de vidrio con capacidad de 200 mL, colocando una semilla de maíz en cada una. Transcurridas dos semanas, se evaluó: la longitud de raíz (LR), la altura de la plántula (AP) y el diámetro del talluelo (DT). El efecto simple de las cepas como variables independientes y su interacción, no incidieron significativamente sobre las variables respuestas evaluadas, registrándose los siguientes promedios: 12,84 cm (LR), 15,28 cm (AP), y 2,26 cm (DT). Considerando el sustrato, el Compost + Arcilla mostró diferencias significativas (p<0,05) en las características LR y DT de las plántulas, con medias de 14,44 y 2,38 cm, respectivamente. Los mecanismos de acción observados distinguen cepas prometedoras que podrían validarse a nivel de campo en sistemas de producción agrícola cuando se inoculan en fertilizantes orgánicos.

Palabras clave: microorganismos antárticos, bacterias beneficiosas, crecimiento vegetal.

Resumo

Na agricultura são utilizados microrganismos eficientes, entre eles bactérias promotoras de crescimento de plantas. O objetivo deste trabalho foi determinar, *in vitro*, o mecanismo de ação em cepas de *Bacillus* sp. isolado da Antártica. Foram analisados os seguintes aspectos: testes de catalase e hemólise, coloração de Gram, solubilização de fosfato, crescimento sem fonte de nitrogênio, produção de sideróforos e sobrevivência em diferentes valores de pH, NaCl e temperatura, o que confirmou a plasticidade ecológica e adaptação desta cepa em ambientes diferentes de sua origem. De acordo com as características desejáveis, foram escolhidas as cepas T5, GB-70 e B-6 e adicionadas a dois substratos: argila e mistura argila-composto, que foram esterilizados e acondicionados em frascos de vidro com capacidade para 200 mL mL colocando uma semente de milho em cada um. Após duas semanas foram avaliados: comprimento da raiz (LR), altura da muda (AP) e diâmetro do caule (DT). O simples efeito das deformações como variáveis independentes e sua interação não afetou significativamente as variáveis respostas avaliadas, registrando-se as seguintes médias: 12,84 cm (LR), 15,28 cm (AP) e 2,26 cm (DT). Considerando o substrato, Composto + Argila influenciou significativamente (p<0.05) as características de LR e DT das mudas com médias de 14,44 e 2,38 cm, respectivamente. Os mecanismos de ação observados distinguem cepas promissoras que poderiam ser validadas em nível de campo em sistemas de produção agrícola quando inoculadas em fertilizantes orgânicos.

Palavras-chave: microrganismos antárticos, bactérias benéficas, crescimento de plantas.

Introduction

The potential of microorganisms as biofertilizers is emerging as a promising solution to gradually reducing or eliminating synthetic fertilizers. Olanrewaju *et al*. (2017) argue that the adverse effects of synthetic chemical fertilizers, such as soil nutrient depletion and water pollution, drive the need for viable alternatives.

According to Delgado-Baquerizo *et al.* (2018), edaphic organisms are fundamental to the structure and functionality of natural and managed ecosystems (one gram of soil can contain thousands of individual microbial taxa, including viruses). Plants interact with various microorganisms, including bacteria and fungi, which can have positive, negative, or neutral effects on plants. The role of bacteria is underlined since they have various survival strategies in adverse conditions such as low temperature, ultraviolet radiation, low humidity, and nutrient deficiencies (Chattopadhyay, 2006).

Microbial communities are rich in genetic diversity and play a crucial role in adaptation and survival in challenging environments; they represent a reservoir of unknown and undescribed microorganisms, with great metabolic versatility. These microbial communities that inhabit extreme environments are essential for the maintenance of ecosystems (Castro *et al.,* 2021). The most predominant phyla in extreme (cold) environments are Pseudomonadota, Bacteroidotas, Acidobacteriota, Cloroflexota, Planctomycetota, and Actinomycetota (Kudinova *et al.,* 2021). Extremophilic microorganisms also have been used as biofertilizers (Rizvi *et al.*, 2021) since they increase nitrogen fixation and convert insoluble phosphorus into available forms for plants. Studying the mechanisms that generate and underlie microbial biodiversity is critical to predicting the response of ecosystems to environmental changes (Pincay, 2022).

Bacteria of the genus *Bacillus* have been widely studied for their ability to promote plant growth and are considered a sustainable alternative to chemical fertilizers (López-Valenzuela *et al*., 2019).

Bacillus sp. are a type of spore-forming plant growth-promoting rhizobacteria (PGPR) tolerant to adverse environmental conditions. They provide biological control against biotic and abiotic stressors that negatively affect plant growth and development (Chattopadhyay, 2006). Therefore, the concentration of *Bacillus* sp. can be adjusted to obtain optimal results in promoting the growth of *Zeamays* L. without the need for chemical fertilizers (Orozco-Mozqueda *et al*., 2021).

Plant growth-promoting bacteria benefit a host by producing siderophores, auxins, cytokinins, and gibberellins. They also play a crucial role in converting insoluble phosphorus into soluble forms, fixing nitrogen, and promoting plant growth. These bacteria are, therefore, a compelling alternative to chemical fertilizers (Yu *et al*., 2022).

There is growing interest in inoculating PGPR as biofertilizers to serve as a sustainable alternative for food production (Do Amaral *et al*., 2020). Literature references have shown that some *Bacillus* strains, particularly *B. subtilis*, have great potential as growth promoters for corn. This work aimed to determine, *in vitro*, the mechanism of action of bacterial strains isolated in Antarctica.

Material and methods

This work was conducted at the Campus of the Escuela Superior Politécnica Agropecuaria de Manabí (ESPAM)-Ecuador (0°49’8.87” S, 80°10’53.03” W, located at 15 masl). The temperature of the place varies between 20.6 and 31.11 ºC; the average annual precipitation is 624 mm, and the relative humidity is 82.42 (Valdivieso *et al*., 2021).

Eighty-three strains of *Bacillus* sp. were used, collected on the Greenwich, Dee, Barrientos, and Torres islands during the expedition carried out to the territorial space of Ecuador in Antarctica in 2014. Since then, these strains have been preserved in glycerol at -20 ºC in the Molecular Biology laboratory of ESPAM. A 100 µL sample of each strain was inoculated in Erlenmeyers with 50 mL of nutrient broth and maintained at 37 ºC, with shaking (Thermo Fisher Scientific, USA) at 180 rpm for 18 h to promote growth. Colony morphology, cell morphology (Tassadaq *et al*., 2013), and catalase test of bacterial isolates from fresh cultures were evaluated (Liu *et al*., 2016). A hemolysis test was performed on the microbial isolates that solubilize tricalcium phosphate to define the pathogenic capacity of the bacterial strains. For this, they were grown on nutrient agar at 37 °C, for 18 h. Then, they were inoculated onto a blood agar base containing 5 % sterile calf blood and incubated at 37 °C, for 24 h. To determine phosphate solubilization, each bacterial strain was inoculated in triplicate into Petri dishes containing Pikovskaya medium (PVK, Himedia, 31.3 g.L^{-1}, India) and incubated at 37 °C for 24 h and 48 h. The ability to solubilize phosphorus was observed by a transparent halo around the bacterial colony (Teng *et al*., 2018). The phosphate solubilization index (PSI) was measured and calculated according to Afzal and Bano (2008), following the equation:

$$PSI = \frac{(colony\ diameter + halo\ diameter)}{colony\ diameter}$$

The test described by Alexander and Zuberer (1991), was carried out to determine if the strains could produce siderophores. In this test, the strains that had gamma hemolysis were used. Strains (T-5, GB-70, and B-6) were punctured onto chromium azurol agar (CAS, Thermo Fisher Scientific, 0.605 mg.mL^{-1}, USA) and incubated at 37 °C for 72 h. The color change from blue to yellow-orange around the bacterial colonies of the strains was a positive indicator of the qualitative detection of siderophores. The diameters of the halos were measured in mm (Abo-Zaid *et al*., 2020).

The strains that had the best response in phosphate solubilization and produced siderophore were evaluated in a medium without a nitrogen source to determine the growth capacity under these conditions, according to Acurio *et al*. (2020). Each pure culture was punctured on Ashby agar (40,7 g.L^{-1}, Himedia, India), and incubation was carried out aerobically at 37 ºC for seven days. ASHBY semi-solid agar had the following composition (g.L^{-1}): mannitol (10.0); K_2HPO_4 (0.2); $MgSO_4$ (0.2); NaCl (0.2); $CaSO_4$ (0.1); $CaCO_3$ (5.0) and agar-agar (15.0). Nitrogen-fixing bacteria were defined as those where a 3-5 mm whitish film was produced under the surface of the culture medium. To determine some physiological characteristics of the strains, the growth of the bacterial isolates was analyzed at different pH (3, 5, 7, and 9), different temperature levels (20, 37, 50, and 60 °C), and NaCl concentration (0, 8.5, 10, 15, and 20 %). For the three evaluations, aliquots (5 mL) of each inoculum were placed in Erlenmeyer vials with 45 mL of nutrient broth (8 g, Himedia, India). The cultures were incubated at 37 °C and 180 rpm; the evaluation was carried out at 18 h for pH and NaCl. Temperature was evaluated at four time points: 0, 4, 16, and 24 h. Subsequently, serial dilutions ranging from 10^{-1} to 10^{-8} were prepared in saline solution (0.85 % NaCl). Then, 100 µL of the 10^{-8} dilution was plated on nutrient agar plates and spread with a Drigalski spatula. Plates were incubated at 37 °C for 18 h; after this, viable cells were counted as colony-forming units per milliliter (CFU.mL^{-1}).

The final test evaluated the plant growth-promoting action of the bacterial isolates with the best response in the preliminary tests. The strains were grown in nutrient broth for 18 h at 37 °C. The cells were separated by centrifugation and washed with water. Two kinds of substrates were used (a. clay alone, and b. compost + clay), and the substrates were sanitized using an autoclave (Yamato Scientific America, USA) to favor the mechanism of action of the chosen strains. The sterilized substrates were placed in glass bottles (200 mL), in which a Trueno variety corn seed was sown, considering it as an experimental unit where 3 mL of inoculum was applied. After two weeks, the following parameters were evaluated: shoot diameter (DT), seedling height (AP), and length of root (LR). The factorial experiment A (substrates: A1, A2) and B (strains: C1, C2, C3) was conducted with a Completely Randomized Design, and the INFOSTAT program was used for data analysis (Di Rienzo *et al*., 2010).

Results and discussion

Morphological Characterization of Bacterial Isolates

By Gram staining, all strains were Gram-positive bacilli. The strains showed positive reactions for catalase and presented a central endospore with an ellipsoidal shape.

The results obtained coincided with those of Ratón *et al*. (2005), who reported that all the strains isolated in their work were Gram-positive and catalase-positive, even though they were from different environments, which indicates that this type of bacteria has a cosmopolitan distribution. In this regard, Gyaneshwar *et al*. (2002) maintains that catalase acts on the toxic hydrogen peroxide produced by the mitochondrial electronic transport chain and in various oxidation and hydroxylation reactions so that it prevents its toxic effects on organisms by decomposing it to form oxygen and water.

Some genera of Gram-positive bacteria are found in different habitats, including the soil. These bacteria benefit the soil by providing nutrients or helping degrade them so that the plant can absorb them according to its needs. In addition, these bacteria can generate a positive impact by improving soil fertility, allowing plants to better use nutrients (Castro *et al*., 2021).

Solubilization of phosphate

Of the total strains used in the study, six solubilized phosphate and produced hydrolysis halos of 1.05 to 2.07 mm and 1.05 to 1.69 mm at 24 h and 48 h, respectively (table 1).

Table 1. Hydrolysis halo (phosphate solubilization index, P.S.I.) produced by the strains after 24 and 48 h of incubation.

Strain codes	P.S.I. (mm)	
	24 h	48 h
T-1	1.10	1.18
GB-70	1.19	1.18
T-5	1.12	1.13
GC-3	1.29	1.42
GB-77	2.07	1.69
B-6	1.05	1.05

The PSI values obtained were within the solubilization rates observed by Lara *et al*. (2011) in bacterial strains that produced hydrolysis halos between 1.5 and 4.2 mm, measured after three and seven days of incubation, respectively. Davis *et al*. (2005) show a directly proportional relationship between the incubation time, the size of the colony, and, therefore, its conservation, thus obtaining excellent phosphate solubilization indices (PSI).

The values reported in the present study were within the solubilization rates observed by Teng *et al*. (2018) in bacterial strains that produced P.S.I. between 1.6 and 3.1. The PSIs of isolates B-6, T-1, T-5, GB-70, and GC-3 were considered low (PSI ≤ 2), while GB-77 values were considered medium (2≤PSI<3), according to the ranges shown by Batista *et al.* (2021). Ramírez *et al*. (2008) reported slightly higher PSI values in their study on *Bacillus* sp., where they determined that this bacterial genus is an important phosphate solubilizer.

Hemolysis test

The bacterial isolates (T-1, GB-70, T-5, GC-3, GB-77, and B-6), with the capacity to solubilize tricalcium phosphate, were evaluated on blood-based agar, obtaining as results that the strains T5, GB-70, B-6 presented gamma hemolysis (no hemolytic activity, and would not affect red blood cells in humans). In contrast, strains T-1, GB-77, and GC-3 showed beta hemolysis (they produced transparent halos caused by the total lysis of red blood cells), so the latter should be discarded for agronomic use.

The percentage of strains with gamma hemolysis found in the present study (50 %) was similar to the reported by Forbes *et al*. (2007) (47 %), who maintain that the determination of this parameter is necessary to establish the commercial use of live microorganisms because it allows the identification of potentially pathogenic bacteria.

Qualitative assay of siderophore production

In this test, the strains with gamma hemolysis were used. The three strains produced siderophores with values from 1.21 to 1.60 mm, demonstrating that they have iron-fixing capacity that enhances plant growth (table 2).

Table 2. Siderophore production and growth under conditions without a nitrogen source.

Strain codes	Siderophore halo (mm)	Growth without a nitrogen source (mm)	
		Day 1	Day 5
T-5	1.21	58.23	68.00
GB-70	1.27	36.61	48.38
B-6	1.60	17.95	58.40

These results were similar to those obtained by Villarreal *et al.* (2018), who observed strains with biocontrol potential belonging to the genus *Bacillus*, which have demonstrated the ability to synthesize the siderophore, regulating the concentration of iron through its chelation (Fe^{3+}-siderophore). The selection of microorganisms with the capacity to produce siderophores enables their use in biofertilization practices, as indicated by Aguado-Santacruz *et al.* (2012), who state that bacterial siderophores have aroused great interest in recent years due to their potential for biological control of fungi and phytopathogenic bacteria, constituting a growth mechanism in plant growth-promoting rhizobacteria.

Growth of *Bacillus* sp in conditions without a Nitrogen source

The three strains subjected to this test grew under conditions without a nitrogen source. Colony measurements showed values on the first day from 17.95 to 58.23 mm, and on the fifth day from 48.38 to 68 mm (table 2). *Bacillus* can generally use cheap nutritional sources as substrates for fermentation (Gu *et al*., 2018). Furthermore, as an essential part of the heterotrophic Gram-positive bacteria, *Bacillus* has many important applications in biological manufacturing by fermentation (Xiao *et al*., 2020). The growth capacity in the absence of a nitrogen source could be related to the benefits provided by the presence of certain strains of *Bacillus* sp. in the plants (Ojuederie *et al*., 2019). *Bacillus* is a genus of bacteria that includes many species known for their beneficial effects on plants, and one of these advantages is the ability of some strains to fix atmospheric nitrogen (Orozco-Mozqueda *et al*., 2021). This capacity is crucial, since nitrogen is an essential nutrient for plant growth and its availability can limit plant productivity in soils (Fasusi, & Babalola, 2021).

Nitrogen fixation carried out by certain strains of *Bacillus* sp. involves the conversion of molecular nitrogen from the air (N_2) into forms that plants can use, such as ammonium (NH_4^+) or nitrate (NO_3^-). By supplying nitrogen to plants in this way, beneficial bacteria can improve plant growth and health, even in nitrogen-poor soils. This is especially important in environments where nitrogen is a limiting resource. In addition to nitrogen fixation, strains of *Bacillus* sp. can also promote plant growth in other ways, such as increasing the availability of other nutrients in the soil, producing plant growth-promoting compounds, and assisting in protection against pathogens. All of these factors can contribute to improving the ability of plants to grow even in the absence of available nitrogen in the soil (Bashan *et al*., 2013).

Effect of pH and temperature on the growth of strains

All strains of *Bacillus* sp. responded well to different temperatures, presenting uncountable growth (UN) due to the agglomeration of colonies. Adaptability to high temperatures and a wide pH range is of great relevance for bacteria of the genus *Bacillus* for several reasons: a) Heat resistance: Some *Bacillus* species, such as *B. subtilis* and *B. stearothermophilus*, are thermophilic, meaning they can survive and grow in relatively high temperatures. This heat resistance allows them to thrive in conditions where other bacteria might not survive, such as in composts, manure piles, or in industrial sterilization processes. b) pH tolerance: Bacteria of the genus *Bacillus* are known for their ability to grow over a wide pH range (Zalma & El-Sharoud, 2021). Some species can tolerate an acidic pH, while others thrive in alkaline conditions. This tolerance allows them to colonize different types of soil, from acidic to alkaline, and adapt to changes in the environment, such as those caused by human activity or industrial processes (Guzmán *et al*., 2015).

This level of adaptation of the strains to extreme conditions is similar to the physiological condition of *Bacillus* sp. strains studied by Calvo and Zúñiga (2010), who reported that 98 % of the strains grew at 10 ºC and temperatures between 15 and 20 ºC.

Table 3. Behavior of the strains at different temperature levels.

Strain codes	Temperature (ºC)			
	20	37	50	60
T-5	UN	UN	UN	UN
GB-70	UN	UN	$1.9\ 10^4$	UN
B-6	UN	$3.5\ 10^{10}$	UN	UN

UN, uncountable number of colonies.

Regarding pH, they observed that 100 % of the strains grew well at both pH (4 and 5.5), indicating a good growth adaptation of the strains. Similar results were found by Guzmán *et al*. (2015) when performing the isolation and selection of native bacteria from Manabí-Ecuador with cellulolytic activity (table 4).

Table 4. Growth of the strains at different pH levels (after 18 h of evaluation).

Strain codes	pH			
	3	5	7	9
T-5	UN	$2.0\ 10^{11}$	$1.6\ 10^{10}$	UN
GB-70	$1.0\ 10^{10}$	$2.0\ 10^{11}$	$4.1\ 10^{10}$	$2.0\ 10^{11}$
B-6	UN	UN	$4.1\ 10^{10}$	UN

UN, uncountable number of colonies.

Effect on NaCl concentrations for the growth of *Bacillus* sp.

Table 5 shows the behavior of the strains at different levels of NaCl. The results show that the most significant colonies occurred in the 20 % concentration with 7.4×10^8 compared to 0 % NaCl, which obtained 1.12×10^3 CFU. Salt content (NaCl) and temperature variations influence microbial development (Ikenebomeh, 1989). Alteration of NaCl concentration results in a change in the expression pattern of outer membrane proteins (Hu *et al*., 2022). Previous findings have reported that several bacterial genera, including *Pseudomonas, Bacillus, Burkholderia, Enterobacter, Microbacterium, Planococcus, and Halomonas*, could produce exopolysaccharides that guarantee their survival in salinity conditions (Qurashi & Sabri, 2012).

Table 5. Behavior of the strains at different concentrations of sodium chloride.

Strain codes	NaCl (%)				
	0	8.5	10	15	20
T-5	$1.12\ 10^3$	$6.4\ 10^3$	$1.4\ 10^5$	$1.4\ 10^6$	$7.4\ 10^8$
GB-70	$5.9\ 10^3$	$6.6\ 10^3$	$7.9\ 10^5$	$5.9\ 10^6$	$6.2\ 10^8$
B-6	$2.0\ 10^3$	$7.0\ 10^3$	$7.0\ 10^4$	$7.5\ 10^6$	$1.57\ 10^6$

Evaluation of selected bacterial strains as plant growth promoters

When evaluating the height of corn seedlings, no statistical differences were found among all the sources of variation studied (table 6). Root length and shoot diameter showed significant differences ($p<0.05$) with the type of substrate used, placing the clay + compost mixture in the best statistical category.

The compost likely played a role in providing mineral elements for the initial growth of the seedling. The ability of plants to grow without a nitrogen source may be due to the advantages provided by the presence of some *Bacillus* strains. *Bacillus* is a genus of plant growth-promoting bacteria (PGPB) that form beneficial associations with plants (Joshi *et al*., 2023). Some *Bacillus* species have the ability to fix atmospheric nitrogen and convert it into a usable form for plants and increase the efficiency of nitrogen consumption in plants even in nitrogen-deficient soil conditions (Santi *et al*., 2013).

In addition to nitrogen fixation, bacteria can promote plant growth in other ways, such as by producing plant hormones, dissolving nutrients in the soil, and inducing disease resistance. These benefits can help plants grow better even when the amount of nitrogen in the soil is limited (Glick, 2012).

Table 6. Vegetative development at 15 days of age of the corn seedlings.

Treatments	Description	Seedling height (cm)	Root length (cm)	Shoot diameter (cm)
	Factor A	**NS**	*	*
A1	Clay	16.00	11.22 [b]	2.14 [b]
A2	Clay + Compost	14.56	14.44 [a]	2.38 [a]
	Average	15.28	12.83	2.26
	Factor B	**NS**	**NS**	**NS**
C1	T-5	14.33	13.67	2.38
C2	GB-70	14.67	11.83	2.48
C3	B-6	16.83	13.00	1.92
	Average	15.28	12.83	2.26
	Factor B*Factor A	**NS**	**NS**	**NS**
A1B1	Clay + AE-1	15.67	13.67	2.00
A1B2	Clay + AE-2	17.00	10.33	1.90
A1B3	Clay + AE-3	15.33	9.67	2.53
A2B1	Clay + Compost + AE-1	13.00	13.67	2.77
A2B2	Clay + Compost + AE-2	16.67	15.67	1.93
A2B3	Clay + Compost + AE-3	14.00	14.00	2.43
	Average	15.28	12.84	2.26
	CV %	31.9	27.3	26.17

*= Significant statistical differences $p<0.05$; NS= Non-significant differences; CV= Coefficient of Variation; a and b in column = differ according to Tukey at 5 % error probabilities

Hence, the presence of specific *Bacillus* strains in soil may be related to the ability of plants to grow better under conditions of low nitrogen availability, as these bacteria provide several mechanisms that promote growth. Bacon and Hinton (2011) express that it should not be ruled out that the genus *Bacillus* contains potential microorganisms that protect the plant and could functionally be considered a biological controller because it produces antibiotic, phosphate-solubilizing substances that facilitate its availability to the plant, and because it performs functions as a siderophore. Furthermore, manipulating plant-microorganism interactions can improve plant performance in applications ranging from climate change mitigation to agricultural production (Ulrich *et al*., 2019).

Conclusion

The mechanisms of action observed in the bacterial strains isolated from Antarctic soils allowed us to distinguish promising strains as bioinoculants, which is an important bacterial interaction in organic inoculated fertilizers for agronomic purposes.

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