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(RESEARCH ARTICLE)

EFFECTS OF RHIZOSPHERIC *BACILLUS* SP. INOCULATION ON THE GROWTH OF COMMON BEAN (*PHASEOLUS VULGARIS* L.)

Patrice Hermann RALAIARISON [1,*], Sergio TONISSA [1], Nazirah MOHAMED [1], Tsianis ZARALAHY [2], Manarivo Ulrich Anito JAO [2] and Taratra Andrée FENORADOSOA [2]

[1] Doctoral Research Team.« Chemistry of Natural Substances – Endemic Plants and Beneficiary Communities, Doctoral School Nature, Structure of Matter and Nuclear Metrology», University of Antsiranana, Madagascar.
[2] Natural and Environmental Sciences » Program, Faculty of Sciences, University of Antsiranana, Madagascar.
* Corresponding Author; Email: patrice.ralaiarison@gmail.com

ORCID Details
Patrice Hermann RALAIARISON: https://orcid.org/0009-0008-1149-2203

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ABSTRACT

This study evaluated the effect of inoculation with a *Bacillus* sp. strain on the growth of common bean (*Phaseolus vulgaris* L.). Fifteen bacterial isolates were obtained from different rhizospheres in the Antsiranana region of Madagascar and characterized based on their morphological characteristics and Gram staining. The strain *Bacillus* sp. FM 02/1, isolated from the maize rhizosphere, was selected for inoculation assays at 20, 40, 60, and 80% inoculation rates, with a non-inoculated control. Inoculation significantly affected plant growth ($F(4,105) = 7.5874$; $p = 0.00002$). The 60% inoculation rate produced the best performance, with a mean plant height of 30.5 cm and a root length of approximately 15 cm, compared with 22 cm and 4 cm, respectively, in the control. Early appearance of flower buds and pods was also observed at the 40 and 60% inoculation rates. These results indicate that *Bacillus* sp. FM 02/1 has plant growth-promoting potential in common bean, with the best response observed at the 60% inoculation rate.

Keywords: Bacillus sp; PGPR; Inoculation; *Phaseolus vulgaris* L; Plant growth; Rhizosphere

1 INTRODUCTION

Agricultural soil degradation is a major concern because of its effects on soil fertility, crop productivity, and the sustainability of agricultural systems. It is characterized by a loss of organic matter, depletion of nutrients, and changes in the physical, chemical, and biological properties of soils [1]. Soil fertility also depends on biological activity, particularly on interactions between plant roots and microorganisms inhabiting the rhizosphere [2]. The rhizosphere is a dynamic environment in which plant roots interact with the surrounding soil and a wide diversity of microorganisms. Root exudates and mineral nutrient uptake modify the physicochemical conditions of this zone and influence the microbial communities associated with plant roots [2,3]. Among these microorganisms, certain rhizospheric bacteria, known as plant growth-promoting rhizobacteria (PGPR), can enhance plant growth and development through various mechanisms, including improved nutrient acquisition, production of growth-promoting

substances, and protection against certain phytopathogens [4]. The genus *Bacillus* represents one of the most extensively studied bacterial groups because of its plant growth-promoting properties and its potential use as a biofertilizer [5,6]. These bacteria can contribute to improved plant development and represent a promising biological alternative in the context of reducing the excessive use of chemical fertilizers. Common bean (*Phaseolus vulgaris* L.) is an important crop whose growth depends, among other factors, on nutrient availability and the biological conditions of the soil. In this context, the use of rhizospheric bacteria with PGPR potential could promote plant development and improve certain growth parameters. However, the effectiveness of this approach depends on the characteristics of the bacterial strain used and its interaction with the host plant. There fore, the present study aimed to evaluate the effect of inoculation with a *Bacillus* sp. strain on the growth of common bean (*Phaseolus vulgaris* L.). More specifically, the study aimed to determine the influence of inoculation on the main plant growth parameters and to assess the potential of the selected strain as a plant growth-promoting bacterium.

2 MATERIALS AND METHODS

2.1 Rhizospheric Sample Collection

Rhizospheric soil samples were collected from healthy plants in the localities of Sakaramy and Joffre Ville, located approximately 20 km south of Antsiranana, in northern Madagascar. Six rhizospheric samples associated with different host plants were collected. Samples were taken in the immediate vicinity of the roots, placed in sterile containers, and transported to the laboratory for microbiological analysis. The geographical locations of the sampling sites are presented in Figure 1.

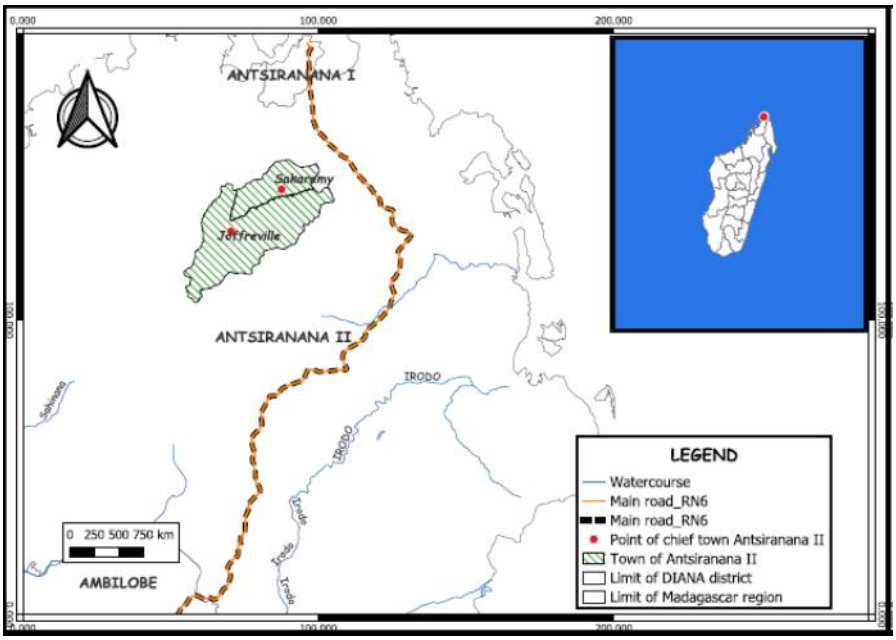


Figure 1: Geographical location of the rhizospheric soil sampling sites

2.2 Isolation and Purification of Rhizospheric Bacteria

Bacteria present in the rhizospheric samples were isolated on nutrient agar. Suspensions prepared from the soil samples were inoculated onto the culture medium and incubated at

37 °C for 48 h. Colonies displaying distinct morphological characteristics were successively subcultured on the same medium to obtain pure cultures.

2.3 Characterization and Selection of the Bacterial Strain

The preliminary characterization of the isolates was based on colony observation and microscopic examination following Gram staining. The macroscopic characteristics considered included colony morphology, size, color, and appearance. Microscopic examination was used to determine the Gram-staining reaction, cell shape, and cellular arrangement.

2.4 Plant Material and Seed Preparation

The *Phaseolus vulgaris* seeds used in the experiment were obtained from a local supplier. Only healthy seeds with a uniform appearance and free from visible damage were selected for the experiment. Before sowing, the seeds were surface-disinfected by immersion in a bleach solution for 5 min and then rinsed twice with sterile distilled water for 2 min each. After drying under aseptic conditions, the seeds were pre-germinated in sterile Petri dishes containing cotton wool moistened with sterile distilled water.

2.5 Preparation and Standardization of the Bacterial Inoculum

The *Bacillus* sp. strain was cultured on nutrient agar until a young, pure culture was obtained. Bacterial colonies were then aseptically collected and suspended in sterile 0.85% NaCl physiological saline solution. The bacterial suspension was homogenized and adjusted by measuring its optical density at 620 nm. The suspension used for inoculation had an optical density of 0.125, corresponding to an estimated concentration in the range of 10^7-10^8 CFU/mL according to the McFarland scale.

2.6 Establishment of the Inoculation Experiment

The experiment was conducted using young *Phaseolus vulgaris* plants grown in a substrate consisting of 90 g of non-sterile soil supplemented with 10 g of Guanomad fertilizer per pot. Four bacterial inoculum rates (20, 40, 60, and 80%) were compared with a non-inoculated control treatment. Each pot was sown with three pre-germinated seeds. The bacterial inoculum was applied directly to the substrate near the root zone of the young plants. The pots were then maintained under controlled growing conditions throughout the experimental period. A photoperiod of 16 h of light and 8 h of darkness was applied. Watering was carried out regularly to maintain appropriate substrate moisture without causing waterlogging.

2.7 Evaluation of *Phaseolus vulgaris* Growth

The effect of *Bacillus* sp. inoculation on common bean growth was evaluated using several morphological and agronomic parameters.

2.7.1 Emergence Rate

The number of seeds that produced emerged seedlings was determined three weeks after sowing. The emergence rate was calculated using the following formula :

Emergence rate (%) = (Number of emerged plants / Total number of seeds sown) × 100

2.7.2 Survival Rate

The survival rate was determined at the end of the observation period. It was calculated using the following formula:

Survival rate (%) = (Number of surviving plants / Number of emerged plants) × 100

2.7.3 Plant Height

Plant height was measured using a graduated ruler, from the collar to the apical tip of the main stem. Measurements were taken regularly throughout the experiment to monitor the progression of aboveground growth.

2.7.4 Root System Length

At the end of the experiment, the plants were carefully removed from the substrate, and the roots were washed with water to remove soil particles. The length of the main root was then measured using a graduated ruler, from the collar to the distal end of the root.

2.7.5 Flower Bud Number

The number of flower buds was determined at the flowering stage by directly counting the buds present on each plant.

2.7.6 Pod Number

The number of pods produced per plant was determined during the reproductive phase. The pods present on each plant were counted to assess the effect of inoculation on the reproductive performance of common bean.

2.8 Statistical Analysis

The data obtained for the different growth parameters were subjected to analysis of variance (ANOVA) to evaluate the effects of the inoculation treatments on the parameters studied. When the ANOVA indicated a significant difference among treatments, multiple comparisons of means were performed using Tukey's HSD test. Statistical analyses were performed using Statistica software. The results were expressed as means ± standard deviation. The statistical significance threshold was set at $p < 0.05$.

3 RESULTS

3.1 Evaluation of the Macroscopic Characteristics of the Selected Bacterial Strains

Inoculation of the rhizospheric samples onto nutrient agar followed by incubation at 37 °C for 48 h yielded 15 bacterial isolates exhibiting distinct macroscopic characteristics (Figure 2).



Figure 2: Macroscopic appearance of bacterial colonies isolated and cultured on nutrient agar, observed by the naked eye after incubation

All isolates produced irregularly shaped colonies, although variations were observed in colony surface, color, opacity, and consistency. Most isolates exhibited smooth and shiny colony surfaces. The colonies were predominantly white, transparent, or yellowish-white. Their opacity ranged from translucent to opaque. The consistency was mainly creamy, while some colonies exhibited a mucoid or dry consistency. This diversity in macroscopic characteristics provided an initial basis for differentiating the isolates obtained from the different rhizospheres. It allowed colonies displaying distinct morphologies to be selected for further characterization by microscopic examination and Gram staining.

3.2 Microscopic Characteristics and Gram Staining

Microscopic examination following Gram staining complemented the phenotypic characterization of the 15 isolates. The results showed a predominance of rod-shaped bacteria. Fourteen isolates were described as bacilli, whereas R3S1, isolated from the rhizosphere of vanilla at Sakaramy, was described as a coliform rod (Table 1).

Table 1: Microscopic characteristics of bacterial species isolated from rhizospheres

Code	Form	Gram	Arrangement
R1S1	Bacilli	Negative	In chains
R1S2	Bacilli	Positive	In chains
R1S3	Bacilli	Positive	In chains
R2S1	Bacilli	Positive	In chains
R2S2	Bacilli	Positive	Single
R2S3	Bacilli	Positive	In chains
R3S1	Coliform	Negative	In chains
R4S1	Bacilli	Positive	In chains
R4S2	Bacilli	Positive	In chains

R4S3	Bacilli	Positive	In chains
R5S1	Bacilli	Negative	In chains
R5S2	Bacilli	Négatif	In chains
R6S1	Bacilli	Positif	In chains
R6S2	Bacilli	Positif	In chains
R6S3	Bacilli	Positif	In chains

R1 : Rice plant rhizosphere ; R2 : Lemon plant rhizosphere ; R3 : Vanilla plant rhizosphere from Sakaramy; R4 : Maize plant rhizosphere ; R5 : Fern plant rhizosphere; R6 : vanilla plant rhizosphere from Joffre Ville ; S : Strain.

Gram staining revealed that 11 isolates were Gram-positive and 4 were Gram-negative (Table 1). The Gram-negative isolates were R1S1, R3S1, R5S1, and R5S2, whereas the remaining isolates were Gram-positive. Fourteen isolates exhibited a bacillary morphology, while R3S1 was recorded as a coliform isolate. Most isolates showed a chain-like cellular arrangement, whereas R2S2 was observed as single cells. These microscopic characteristics provided preliminary information for differentiating the isolates and guiding the selection of a strain for subsequent inoculation assays.

3.3 Selection of the Bacterial Strain for the Inoculation Assay

Based on the observed macroscopic and microscopic characteristics, a strain exhibiting morphological characteristics associated with the genus *Bacillus* was selected for the inoculation assay on common bean. The selected strain was *Bacillus* sp. FM 02/1, isolated from the maize rhizosphere. This strain was selected for further evaluation of its plant growth-promoting potential in *Phaseolus vulgaris*. Inoculation assays were conducted at different inoculation rates to evaluate the plant response according to the amount of inoculum applied.

3.4 Effect of Inoculation on the Growth of *Phaseolus vulgaris*

3.4.1 Effect of Inoculation on Stem Height

The height of *Phaseolus vulgaris* plants varied according to the inoculation rate applied (Figure3).

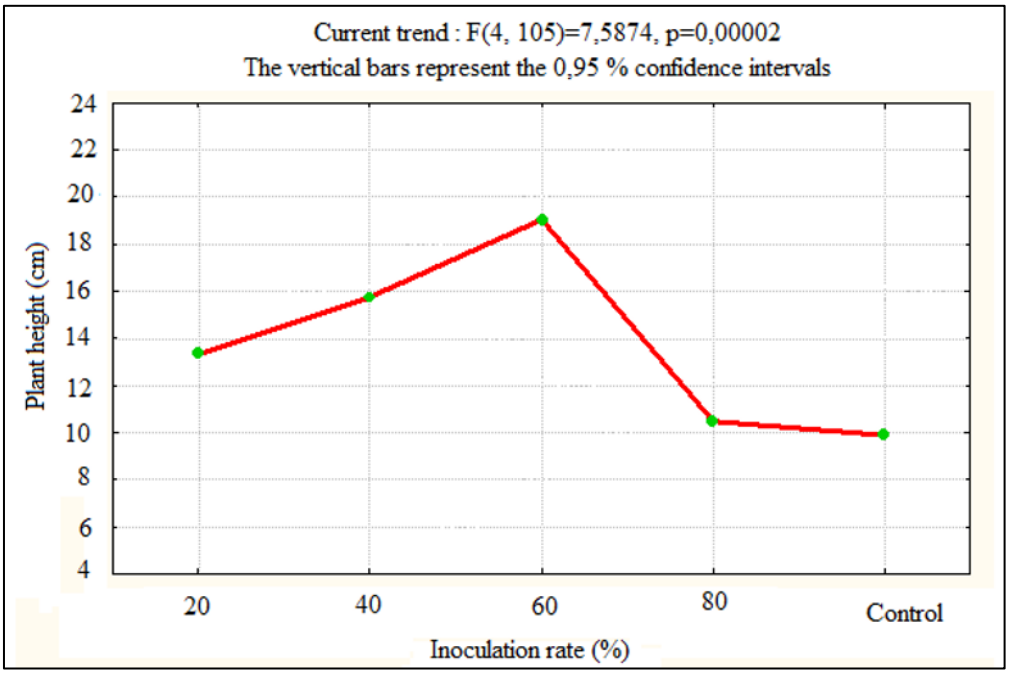


Figure 3: Effect of different inoculation rates on the stem height of *Phaseolus vulgaris* after three weeks of growth. Vertical bars represent 95% confidence intervals

The analysis of variance revealed a highly significant effect of the treatment on plant height ($F(4,105) = 7.5874$; $p = 0.00002$). The 60% inoculation treatment resulted in the highest mean plant height, reaching 30.5 cm after three weeks of growth, compared with approximately 22 cm for the non-inoculated control. The 20% and 40% treatments also

resulted in greater plant growth than the control. In contrast, the 80% treatment did not show a comparable improvement to that observed at the intermediate inoculation rates.

3.4.2 Effect of Inoculation on Root Development

Inoculation with *Bacillus* sp. FM 02/1 also influenced the development of the root system of *Phaseolus vulgaris* (Figure 4).

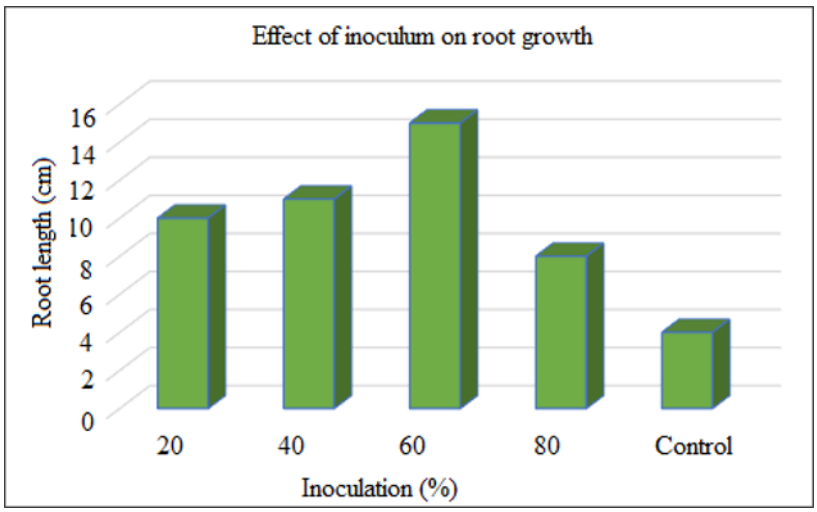


Figure 4: Effect of different inoculation rates on root length of *Phaseolus vulgaris* after three weeks of growth

The 60% inoculation treatment resulted in the greatest root length, reaching approximately 15 cm, whereas the non-inoculated control showed a root length of approximately 4 cm. The 20% and 40% treatments also resulted in greater root development than the control.

In contrast, the 80% treatment showed a limited response, comparable to that of the control. These results indicate that the effect of inoculation on root development varied according to the inoculation rate, with the best response observed at the 60% inoculation rate. Observation of the root systems further confirmed this trend (Figure 5).

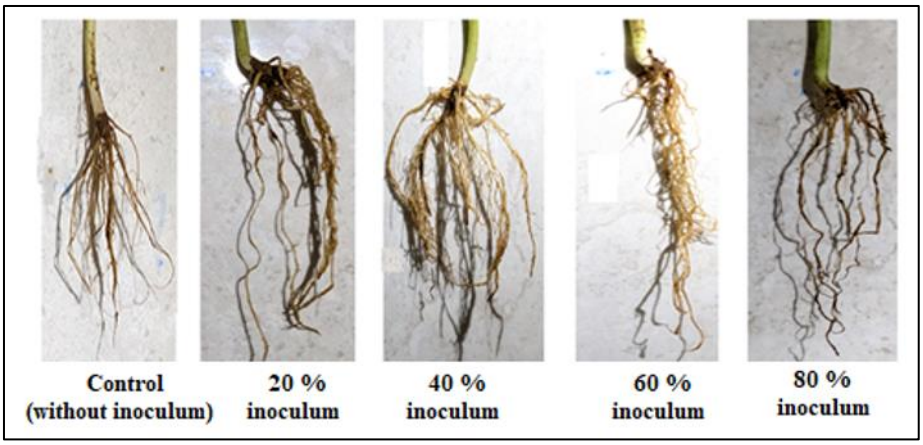


Figure 5: Morphology of the root systems of *Phaseolus vulgaris* after three weeks of inoculation at different inoculation rates

Plants inoculated at 60% exhibited a more developed root system, whereas the non-inoculated control plants and those subjected to the 80% treatment showed shorter roots.

3.4.3 Effect of Inoculation on the Appearance of Flower Buds and Pods

Inoculation was also associated with changes in the reproductive development of *P. vulgaris*. Flower buds were observed as early as 22 days after sowing in plants subjected to the 40% and 60% inoculation treatments, whereas flowering generally occurred later under the conditions studied. Figure 6 presents the numbers of flower buds and pods observed under the different treatments.

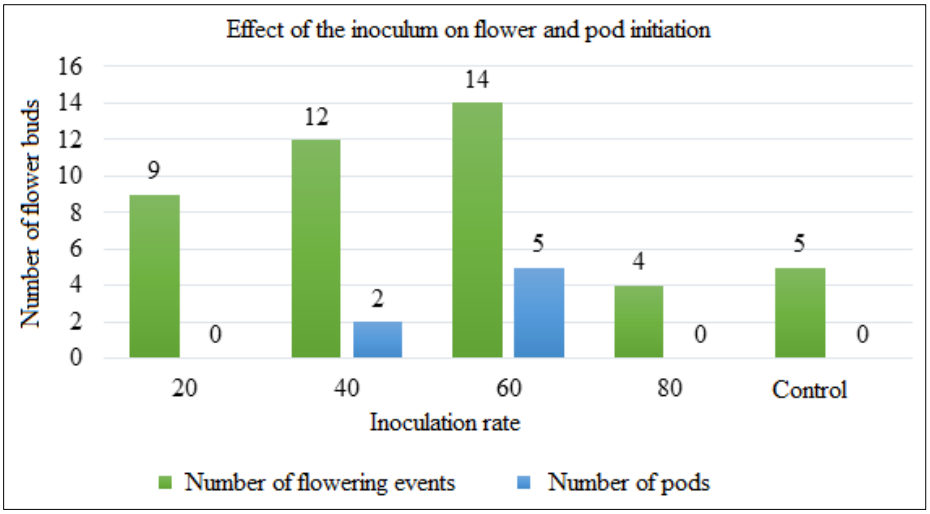


Figure 6: Number of flower buds and pods of *Phaseolus vulgaris* observed 22 days after sowing under the different inoculation rates

The observations showed a more pronounced response in plants inoculated at the intermediate rates, particularly at 40% and 60%. The earlier appearance of reproductive organs in inoculated plants was associated with the greater vegetative and root development observed under these treatments.

4 DISCUSSION

4.1 Macroscopic Morphological Characteristics of the Bacterial Isolates

Macroscopic observations revealed phenotypic diversity among the 15 bacterial isolates obtained from the different rhizospheres investigated. The observed variations mainly concerned colony surface, color, opacity, and consistency, whereas all isolates exhibited an irregular shape. Such morphological variability may reflect differences in the characteristics of the bacterial isolates recovered from the rhizosphere. Previous studies have shown that rhizosphere bacterial communities can vary according to the host plant and the characteristics of the root environment, including root exudates and plant–microorganism interactions [2,7,8]. However, these factors were not directly investigated in the present study and cannot be considered the demonstrated causes of the morphological differences observed. Most isolates produced smooth and shiny colonies, whereas R2S1 and R2S2 exhibited rough and dry surfaces. These differences may be related to strain-specific characteristics and growth conditions on the culture medium. Colony color ranged from transparent to white and yellowish-white, while opacity varied from translucent to opaque. These characteristics provided useful preliminary criteria for differentiating the isolates before further characterization. Nevertheless, colony morphology alone is insufficient for reliable taxonomic identification because different bacterial taxa may exhibit similar macroscopic characteristics under the same culture conditions. The colonies predominantly exhibited a creamy consistency, although some showed a mucoid appearance. Mucoid colony morphology may be associated with the production of extracellular polymeric substances, which can contribute to bacterial adhesion and biofilm formation [9]. However, extracellular polymer production and biofilm formation were not directly investigated in this study, and this interpretation therefore remains a hypothesis. Overall, the macroscopic characteristics provided an initial basis for differentiating the isolates and supported subsequent microscopic examination and Gram staining. Further biochemical or molecular analyses would be required to establish their taxonomic identities more precisely.

4.2 Microscopic Characteristics and Gram Staining of the Bacterial Isolates

Microscopic examination revealed a predominance of rod-shaped cells among the 15 bacterial isolates studied. Fourteen isolates exhibited a rod-shaped morphology, whereas R3S1 was described as having a coccobacillary morphology. Gram staining further classified 10 isolates as Gram-positive and five as Gram-negative. These observations demonstrate morphological and staining variability among the bacteria recovered from the different rhizospheres. However, cellular morphology and Gram reaction are preliminary identification criteria and are insufficient to establish the taxonomic identity of an isolate at the genus or species level. Rod-shaped bacteria, including members of the genus *Bacillus*, have been widely investigated for their potential applications in agriculture because certain strains can promote plant growth through different direct and indirect mechanisms [10]. Nevertheless, rod-shaped morphology and a Gram-positive reaction are not exclusive to the genus *Bacillus*. Therefore, the identification of strain FM 02/1 as *Bacillus* sp. should be considered provisional unless supported by additional biochemical or molecular analyses. Most isolates also exhibited a chain-like cellular arrangement, whereas R2S2 was observed as isolated cells. These characteristics provided additional information for distinguishing the isolates. Rhizosphere

bacterial communities may vary according to host plant characteristics and the physicochemical conditions of the root environment [8,11]. The isolates obtained from rice, lemon, vanilla, maize, and fern rhizospheres displayed phenotypic differences consistent with the diversity of bacteria recovered from these environments. Nevertheless, the present observations do not establish a direct relationship between the host plant and the differences observed. Based on the preliminary characterization, *Bacillus* sp. FM 02/1, isolated from the maize rhizosphere, was selected for the bean inoculation experiments to evaluate its potential effects on the growth and development of *Phaseolus vulgaris*.

4.3 Effect of Inoculation on the Growth of *Phaseolus vulgaris*

Inoculation with *Bacillus* sp. FM 02/1 was associated with significant differences in the growth of *Phaseolus vulgaris* among the treatments evaluated. Analysis of variance revealed a statistically significant effect of the inoculation rate on plant height ($F(4,105) = 7.5874$; $p = 0.00002$). The greatest mean plant height was recorded in the 60% treatment, reaching 30.5 cm compared with approximately 22 cm in the non-inoculated control. These findings indicate that plant height varied significantly among the inoculation treatments under the experimental conditions. The observed response is consistent with previous studies reporting beneficial effects of certain plant growth-promoting rhizobacteria (PGPR) on plant development [12,13]. PGPR may influence plant growth through several mechanisms, including improved nutrient availability, the production of growth-regulating compounds, and interactions with other microorganisms in the rhizosphere [12,13]. However, these mechanisms were not directly investigated in the present study. Consequently, the increase in plant height observed following inoculation cannot be attributed to a specific biochemical or physiological mechanism. Further analyses would be necessary to determine whether particular plant growth-promoting properties of strain FM 02/1 contributed to the observed response. The response also varied according to the inoculation rate. Although the 60% treatment produced the greatest mean plant height, the 80% treatment did not show a comparable improvement. This finding indicates that increasing the inoculation rate did not result in a proportional increase in plant growth. The effectiveness of bacterial inoculation may depend on interactions among the bacterial strain, the host plant, the inoculum level, and environmental conditions [14,15]. However, the mechanism responsible for the weaker response at 80% remains unclear. Under the conditions tested, the 60% treatment produced the most favorable plant-height response among the treatments evaluated. Further experiments involving additional inoculation rates and independent trials would be required to determine the most effective application level more precisely.

4.4 Effect of Inoculation on Root Development

Root development is an important parameter for evaluating plant responses to bacterial inoculation because the root system contributes to substrate exploration and the acquisition of water and mineral nutrients. In the present study, the greatest root length was observed in the 60% treatment, reaching approximately 15 cm compared with approximately 4 cm in the non-inoculated control. The 20% and 40% treatments also showed improved root development, whereas the 80% treatment exhibited a weaker response. These observations indicate that root growth varied according to the inoculation rate under the experimental conditions. Previous studies have reported that certain PGPR can influence root development through different mechanisms, including the production of growth-regulating compounds and improvements in plant nutrient acquisition [14–16]. Nevertheless, the bacterial functions potentially involved in these processes were not directly measured in the present study. Therefore, the increased root length observed in the inoculated plants cannot be attributed to a specific mechanism. The results instead demonstrate differences in root development among the treatments and support further investigation of the plant growth-promoting potential of strain FM 02/1. The greater root length observed in the 60% treatment coincided with the highest mean plant height. A more developed root system could potentially improve substrate exploration and access to water and mineral nutrients, thereby contributing to shoot development. However, water uptake, nutrient acquisition, and the physiological relationship between root and shoot growth were not directly measured. It is therefore not possible to establish a causal relationship between increased root length and greater plant height. Overall, the 60% treatment produced the most favorable root-growth response among the treatments evaluated, highlighting the importance of assessing inoculation rates when investigating bacterial inoculants for agricultural applications.

4.5 Effect of Inoculation on Reproductive Development

In addition to differences in vegetative growth, observations made during the experiment indicated differences in reproductive development among the treatments. Flower buds were observed as early as 22 days after sowing in plants subjected to the 40% and 60% treatments. Pods were also recorded during this period. These observations suggest that reproductive structures appeared earlier in these treatments according to the observation schedule used. However, the date of the first recorded observation does not necessarily correspond to the exact time when the organs initially developed. The earlier observation of reproductive structures may be associated with the greater vegetative and root development recorded in the inoculated plants. Improved plant growth could potentially contribute to the acquisition and allocation of resources required for reproductive development. Previous studies have reported that certain plant growth-promoting bacteria can influence plant development through interactions affecting root growth, nutrient availability, and plant physiological processes [17–19]. Nevertheless, these general mechanisms cannot be assumed to

explain the response observed in the present experiment because the relevant physiological processes were not directly measured. In particular, it would be premature to attribute the earlier appearance of flower buds and pods to the production of a specific phytohormone by *Bacillus* sp. FM 02/1. The experiment did not directly assess phytohormone production or other biochemical mechanisms potentially associated with reproductive development. Furthermore, if reproductive parameters were recorded only through visual observations, the results should be interpreted as preliminary observations rather than definitive evidence of improved reproductive performance. Further experiments should quantify the number of flower buds and pods, determine the time to flowering, and assess final yield to clarify the effects of inoculation on reproductive development. Overall, the earlier observation of reproductive structures in the 40% and 60% treatments, together with the greater plant height and root length recorded in the inoculated plants, suggests that *Bacillus* sp. FM 02/1 has potential to promote the growth and development of *P. vulgaris* under the experimental conditions tested. However, additional experiments are required to confirm the reproducibility of these effects, determine the most effective inoculation rate, and investigate the mechanisms potentially involved.

5 CONCLUSION

This study enabled the isolation and preliminary characterization of 15 bacterial isolates from different rhizospheres in the Antsiranana region of northern Madagascar, revealing morphological and microscopic diversity. Among these isolates, *Bacillus* sp. FM 02/1, obtained from the maize rhizosphere, was selected to evaluate its potential to promote the growth of common bean (*Phaseolus vulgaris* L.). The inoculation experiments showed that the effects on plant growth varied according to the inoculation rate. The 60% treatment produced the greatest mean plant height and root length among the treatments evaluated, with values of 30.5 cm and approximately 15 cm, respectively, compared with approximately 22 cm and 4 cm in the non-inoculated control. Statistical analysis confirmed a significant effect of the inoculation treatment on plant height. Flower buds and pods were also observed at an earlier stage in the 40% and 60% treatments, although further quantitative assessment is needed to confirm the effect on reproductive development. These findings suggest that *Bacillus* sp. FM 02/1 has potential as a plant growth-promoting rhizobacterium for common bean under the experimental conditions investigated. Nevertheless, further research is required to confirm the taxonomic identity of the strain through molecular analyses, investigate the mechanisms potentially involved in plant growth promotion, determine the most effective inoculation rate, and evaluate its performance under different agroecological conditions. Such investigations will be essential to assess its suitability for future applications in sustainable agricultural production and biofertilization in northern Madagascar.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The author declares no conflicts of interest regarding this manuscript.

REFERENCES

[1] Adjanohoun A, Baba-Moussa LS, Dagbénonbakin G, Saïdou A, Toukourou F. Use of soil microorganisms to increase agricultural productivity: learner's manual. Cotonou: CNS-Maize/INRAB/SNRA; 2017. 76 p.

[2] Lynch JM, Whipps JM. Substrate flow in the rhizosphere. *Plant Soil*. 1990 ;129(1) :1-10.

[3] Hinsinger P, Bengough AG, Vetterlein D, Young IM. Rhizosphere : biophysics, biogeochemistry and ecological relevance. *Plant Soil*. 2009 ;321(1-2) :117-152.

[4] Felici C, Vettori L, Giraldi E, Forino LMC, Toffanin A, Tagliasacchi AM. Single and co-inoculation of *Bacillus subtilis* and *Azospirillum brasilense* on *Lycopersicon esculentum:* effects on plant growth and rhizosphere microbial community. *Appl Soil Ecol*. 2008 ;40(2) :260-270.

[5] Berg G. Plant-microbe interactions promoting plant growth and health : perspectives for controlled use of microorganisms in agriculture. *Appl Microbiol Biotechnol*. 2009 ;84(1) :11-18.

[6] Figueiredo MVB, Seldin L, de Araujo FF, Mariano RLR. Plant growth promoting rhizobacteria : fundamentals and applications. In : Maheshwari DK, editor. Plant growth and health promoting bacteria. *Berlin : Springer* ; 2010. p.21-43.

[7] Hartmann A, Schmid M, van Tuinen D, Berg G. Plant-driven selection of microbes. *Plant Soil*. 2008 ;321(1-2) :235-257.

[8] Smalla K, Wieland G, Buchner A, Zock A, Parzy J, Kaiser S. Bulk and rhizosphere soil bacterial communities studied by denaturing gradient gel electrophoresis of PCR-amplified 16S rRNA gene fragments. *Appl Environ Microbiol*. 2001 ;67(10) :4742-4751.

[9] Rivas R, Martens M, de Lajudie P, Willems A. Multilocus sequence analysis of the genus *Bradyrhizobium*. *Syst Appl Microbiol*. 2009 ;32(2) :101-110.

[10] Pérez-García A, Romero D, Zeriouh H, de Vicente A. Biological control of phytopathogenic fungi by aerobic endospore-formers. In : Logan NA, De Vos P, editors. Endospore-forming soil bacteria. *Berlin : Springer* ; 2011. p.157-180.

[11] Philippot L, Raaijmakers JM, Lemanceau P, van der Putten WH. Going back to the roots : the microbial ecology of the rhizosphere. *Nat Rev Microbiol*. 2013 ;11(11) :789-799.

[12] Vessey JK. Plant growth promoting rhizobacteria as biofertilizers. *Plant Soil*. 2003 ;255(2) :571-586.

[13] Lucy M, Reed E, Glick BR. Applications of free living plant growth-promoting rhizobacteria. Antonie Van Leeuwenhoek. 2004 ;86(1) :1-25.

[14] Compant S, Clément C, Sessitsch A. Plant growth-promoting bacteria in the rhizo- and endosphere of plants: their role, colonization, mechanisms involved and prospects for utilization. *Soil Biol Biochem*. 2010;42(5):669-678.

[15] Lifshitz R, Kloepper JW, Kozlowski M, Simonson C, Carlson J, Tipping EM, et al. Growth promotion of canola (rapeseed) seedlings by a strain of *Pseudomonas putida* under gnotobiotic conditions. *Can J Microbiol*. 1987 ;33(5) :390-395.

[16] Dobbelaere S, Croonenborghs A, Thys A, Vande Broek A, Vanderleyden J. Phytostimulatory effect of *Azospirillum brasilense* wild type and mutant strains altered in IAA production on wheat. *Plant Soil*. 1999;212(2):153-162.

[17] Creus CM, Graziano M, Casanovas EM, Pereyra MA, Simontacchi M, Puntarulo S, et al. Nitric oxide is involved in the *Azospirillum brasilense*-induced lateral root formation in tomato. *Planta*. 2005 ; 221(2) :297-303.

[18] Molina-Favero C, Creus CM, Simontacchi M, Puntarulo S, Lamattina L. Aerobic nitric oxide production by *Azospirillum brasilense* Sp245 and its influence on root architecture in tomato. *Mol Plant Microbe* Interact. 2008 ;21(7) :1001-1009.

[19] Stemmer M, Gerzabek MH, Kandeler E. Invertase and xylanase activity of bulk soil and particle-size fractions during maize straw decomposition. *Soil Biol Biochem*. 1999 ;31 :9-18.