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EVALUATION OF PLANT GROWTH-PROMOTING RHIZOBACTERIA ON CHILLI (*Capsicum annuum* L.) AND BRINJAL (*Solanum melongena* L.) GROWTH

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ABSTRACT

This study investigates the potential of Plant Growth-Promoting Rhizobacteria (PGPR) strains, isolated from the rhizosphere of *Oroxylum indicum*, to enhance the growth of chilli (*Capsicum annuum* L.) and brinjal (*Solanum melongena* L.). With the increasing global demand for sustainable agricultural practices, PGPR offers an eco-friendly alternative to chemical fertilizers and pesticides. The research involved screening ten PGPR strains and their consortia for compatibility, followed by evaluating their effects on plant growth parameters, including plant height, shoot biomass, and root biomass, under controlled conditions. Statistical analysis indicated that both individual and consortia PGPR treatments significantly improved growth performance compared to untreated controls. Results demonstrated that three individual strains (*Btr*-7, *Bcer*-24, and *Bcer*-25) significantly enhanced plant height and biomass in chilli plants. For brinjal plants, the strains *Erog*-1 and *Bcer*-21 showed significant growth improvements when applied individually. Additionally, the use of PGPR consortia, specifically *Btro*-7+*Bcer*-13, *Ptai*-40+*Sarl*-43, *Bthu*-4+*Bcer*-24, and *Bcer*-24+*Bcer*-25, led to substantial increases in plant height and biomass for both chilli and brinjal plants. These findings highlight the potential of PGPR, both as individual strains and in consortia, to promote sustainable crop production, reducing the reliance on chemical fertilizers. Future research should focus on field trials to validate these results under diverse agro-climatic conditions and explore the commercialization potential of effective PGPR strains.

Keywords: Plant Growth-Promoting Rhizobacteria (PGPR), Sustainable Agriculture, Biofertilizers, Chilli and Brinjal Growth, Rhizosphere Microbiology, Integrated Plant Nutrient Management (INM).

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INTRODUCTION

The global population surpassed 8 billion in 2022, with continuous growth projected in the coming years, leading to an increased demand for food and other agricultural products. Enhancing agricultural productivity is essential to address the risks of malnutrition and poverty associated with this population surge. Traditionally, to meet the rising demand for food, modern agriculture has heavily relied on chemical fertilizers and pesticides, which have resulted in significant environmental and health concerns. The Green Revolution and its aftermath, despite boosting food production, also highlighted the adverse effects of overusing chemical inputs on soil health and the environment.

Excessive cultivation on the same land coupled with the inappropriate use of agrochemicals has degraded soil quality, reducing its fertility over time. To mitigate these detrimental impacts, the adoption of sustainable agricultural practices is necessary. Recent trends emphasize biological approaches such as Integrated Plant Nutrient Management (INM) and Integrated Pest Management (IPM), which promote the use of bio-resources like biopesticides and biofertilizers to establish environmentally friendly agriculture (Bargaz et al., 2018; Barzman et al., 2015). One promising approach to sustainable agriculture is the use of Plant Growth-Promoting Rhizobacteria (PGPR), which offer an eco-friendly alternative to chemical fertilizers and pesticides (Lugtenberg et al., 2002).

PGPR are beneficial microorganisms that enhance plant growth by various mechanisms, including nutrient solubilization and biological processes that improve plant development (Vessey, 2003). These bacteria colonize the rhizosphere, the soil zone immediately surrounding plant roots, where they play a critical role in nutrient cycling and improving soil fertility (Glick, 2012). Through their interactions with plant roots, PGPR can significantly impact plant health and productivity, making them a valuable component of sustainable crop production.

Microorganisms in the rhizosphere influence plant growth either directly by providing essential nutrients or indirectly by suppressing soil-borne pathogens. PGPR can be classified into different functional groups: biofertilizers that enhance nutrient availability, phytostimulators that promote plant growth via phytohormone production, rhizoremediators that degrade organic pollutants, and biopesticides that control diseases through antibiotic and antifungal activity (Somer et al., 2004). These interactions between plants and PGPR are typically symbiotic, with both partners deriving mutual benefits (Kundan et al., 2015).

The compatibility of host plant root exudates with PGPR is crucial, as it affects the microbial community composition in the rhizosphere. This host-specific interaction highlights the importance of selecting effective PGPR strains tailored to particular crops to maximize their potential in agricultural applications. Isolating and screening rhizospheric microbes for plant growth-promoting activity is thus fundamental to identifying suitable PGPR strains.

Although microbial inoculants have gained acceptance as an alternative to chemical fertilizers, their field application and commercialization require consistent efficacy and reliable performance across different conditions. This study focuses on evaluating the effects of PGPR strains, isolated from the rhizospheric soil of *Oroxylum indicum*, on two economically important crops: chilli (*Capsicum annuum* L.) and brinjal (*Solanum melongena* L.).

O. indicum (L.) Benth. ex Kurz (Family: Bignoniaceae) is a medicinal plant widely used in traditional and modern medicine for treating various ailments (Nath et al., 2016). It thrives well in its natural habitat and is rarely reported to suffer from diseases. However, the overexploitation and habitat loss of *O. indicum* have led to its inclusion in the list of endangered plants in India (Ravikumar & Ved, 2000; Saraf et al., 2013). Exploring the rhizospheric microbiota of such resilient plants could provide valuable insights into the selection of effective PGPR strains that

enhance crop productivity. PGPR could offer a sustainable solution to enhance the productivity of crops, contributing to eco-friendly and economically viable farming practices (Shaikh et al., 2020). The present study aims to assess the potential of PGPR strains from the rhizosphere of *O. indicum* in promoting the growth of chilli and brinjal.

MATERIALS AND METHODS

PGPR strains and seed material

Pure cultures of ten Plant Growth-Promoting Rhizobacteria strains, pre-isolated from the rhizospheric soils of *O. indicum*, were obtained from the Microbiology and Systematic Laboratory, Department of Botany, Gauhati University (Table 1). The bacterial strains were namely, *Enterobacter roggenkampii* PGPR_1, *Bacillus thuringiensis* PGPR_4, *Bacillus tropicus* PGPR_7, *Bacillus cereus* PGPR_13, *B. cereus* PGPR_21, *B. cereus* PGPR_24, *B. cereus* PGPR_25, *B. thuringiensis* PGPR_38, *Pseudomonas taiwanensis* PGPR_40, and *Staphylococcus arlettae* PGPR_43 and were abbreviated as *Erog*-1, *Bthu*-4, *Btro*-7, *Bcer*-13, *Bcer*-21, *Bcer*-24, *Bcer*-25, *Bthu*-38, *Ptai*-40 and *Sarl*-43, respectively. Chilli and brinjal seeds were procured from National Seeds Corporation Ltd., Guwahati, Assam. The cultivars used in the experiments were Pusa Jwala (PJ) for chilli and PUSA Purple Long (PPL) for brinjal.

Consortia formulation

Biocompatibility among the PGPR strains was assessed by streaking them as intersecting straight lines on nutrient agar plates and incubating at 30 ℃ for 48 hours. The presence of a bacteriostatic zone indicated antagonism, while its absence confirmed biocompatibility between the strains (Gou et al., 2020).

Soil collection and preparation

Soil for seed bed and pot experiments was collected from the open paddy field in the Rani area near Gauhati University. The collected field soil was autoclaved (Optics Technology, India) at 15 psi and 121^{o}C for 15 minutes, prior to use in the seed beds and pot to eliminate native microorganisms.

Table 1. List of PGPR strains considered for treatment to brinjal and chilli plants. A - ammonia producing; HCN - hydrogen cyanide; H - HCN producing; IAA - indole acetic acid; I - IAA producing; P - phosphate solubilising; PGP - plant growth promoting

PGPR Strain code	Species	GenBank Accession	PGP Characteristics
Erog-1	*Enterobacter roggenkampii* PGPR_1	PQ223386	AIP
Bthu-4	*Bacillus thuringiensis* PGPR_4	PQ223388	AH
Btro-7	*Bacillus tropicus* PGPR_7	PQ223391	AIP
Bcer-13	*Bacillus cereus* PGPR_13	PQ223395	AI
Bcer-21	*Bacillus cereus* PGPR_21	PQ223402	AP
Bcer-24	*Bacillus cereus* PGPR_24	PQ223404	AH
Bcer-25	*Bacillus cereus* PGPR_25	PQ223405	A
Bthu-38	*Bacillus thuringiensis* PGPR_38	PQ223414	AHP
Ptai-40	*Pseudomonas taiwanensis* PGPR_40	PQ223415	AHP
Sarl-43	*Staphylococcus arlettae* PGPR_43	PQ223417	AP

Soil analysis

The pH of the autoclaved soil sample was measured using a digital pH meter (MK-VI, Systronics) with a soil-to-water ratio of 1:1. Macronutrient analysis was performed using the HiMedia Soil Testing Kit (K054). The analyzed soil parameters included organic

carbon content, available phosphate (P_2O_5), potassium (K_2O), nitrate nitrogen (NO_3-N), and ammoniacal nitrogen (NH_3-N).

Seed germination and sapling preparation

Chilli and brinjal seeds were sown separately in seed beds within plastic pots to facilitate germination. After 20 days, saplings of about 10 cm in height were carefully uprooted and selected for PGPR treatment using the root dip method.

PGPR preparation and treatment

Active cultures of PGPR strains were grown in a nutrient broth medium and incubated at 30 □± □2 □°C for 24 hours. The cell density was adjusted to approximately 1 × 10^5 cells/mL in a 4% jaggery solution and applied to the roots of uprooted saplings for 30 minutes (Verma et al., 2022). Subsequently, the treated and control saplings were transferred to plastic pots each containing 1.5 kg of autoclaved soil. Each treatment, including the negative control, was replicated three times.

Experimental design

Four sets of experiments (two for chilli and two for brinjal) were conducted over two years during the months of October and November, with temperatures ranging between 17 °C and 30 °C. The pot experiments were carried out inside a net-house under natural light and temperature conditions. In the first year, uprooted brinjal and chilli plants were treated with 10 PGPR strains individually using the root-dipping method. Each set of brinjal and chilli treatments with individual PGPR strains included a total of 33 plants (i.e., 3 control plants + 3 plants for each of the 10 PGPR treatments). In the second year, nine PGPR consortia, each made of two compatible strains, were used to treat the roots of uprooted brinjal and chilli plants in a similar manner as the individual strain treatments. Each set of brinjal and chilli treatments with PGPR consortia consisted of a total of 30 plants (i.e., 3 control plants + 3 plants for each of the 9 PGPR consortia). Treated plants were irrigated regularly with sterile water. Growth performance parameters—plant height, dry root biomass, and shoot biomass—were monitored and recorded after 30 days of growth in open sunlight. Dry biomass was obtained by drying the plant materials in a hot-air oven at 60 ℃ for approximately 48 hours until a constant weight was achieved.

Statistical analysis

Data were statistically analyzed using Analysis of Variance (ANOVA) at a 5% significance level. Post hoc analysis was performed using the Least Significant Difference (LSD) test at $p < 0.05$ to determine the significance of PGPR strain treatments (individually and in consortia) on the growth performance of chilli and brinjal plants.

RESULTS

Compatibility and consortia formation of PGPR strains

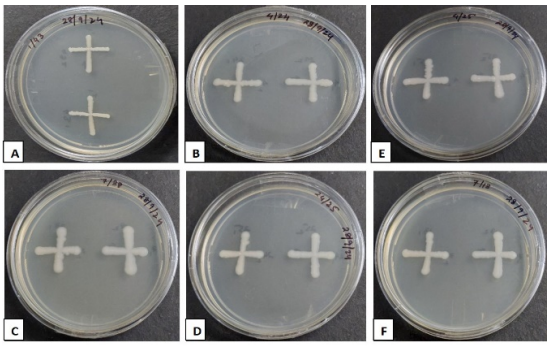

Figure 1. Representative photographs of compatible PGPR strains in nutrient agar plates of dual culture assay. Two strains were cross-inoculated to each other and incubated at 30 °C for 24 to 48 hr. A - (*Erog*-1/*Sarl*-43); B - (*Bthu*-4/*Bcer*-24); C - (*Btro*-7/*Bthu*-38); D - (*Bcer*-24/*Bcer*-25); E - (*Bthu*-4/*Bcer*-25); F - (*Btro*-7/*Bcer*-13)

The compatibility test of ten PGPR strains, forming 45 pair-wise combinations, revealed that a significant number of strains were compatible with each other in dual culture plates. Nine consortia, each comprising two different strains from different species, were selected based on their plant growth-promoting (PGP) activities and compatibility in dual

culture plates (Fig. 1) for further pot experiments on the candidate plants.

The nutritional analysis results of the soil samples used for growing PGPR-treated and non-treated (control) plants are presented in Table 2. The levels of organic carbon and available phosphate were adequate, while the levels of potassium and nitrate nitrogen were medium. The level of ammoniacal nitrogen was recorded as low. The soil pH was 5.91.

Table 2. Macronutrients in the paddy field soil that was considered for pot experiments. Analysis was done by using the HiMedia Soil Testing Kit (K054). Remarks are as per HiMedia

Macronutrients	Quantity	Remark
Organic carbon	0.75%–1%	Medium High
Available phosphate (P_2O_5)	56–73 kg/hectare	Medium High
Available Potassium (K_2O)	112–280 kg/hectare	Medium
Ammoniacal-Nitrogen (NH_3-N)	About 15 kg/hectare	Low
Nitrate-Nitrogen (NO_3-N)	About 20 kg/hectare	Medium

Overall ANOVA results

One-way ANOVA at a 5% significance level led to the rejection of the null hypothesis across all four experimental sets. Despite variability in mean values among treatments with different strains (individual and consortia), PGPR-treated plants consistently exhibited better growth performance compared to non-treated negative control plants.

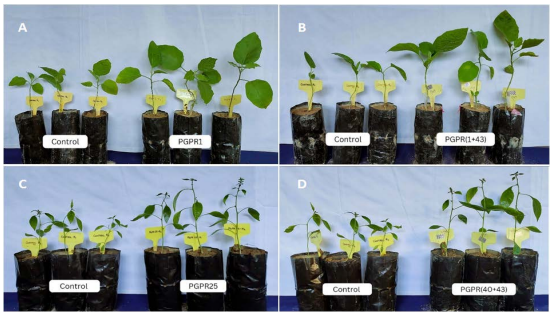

Figure 2. Representative photographs of brinjal and chilli plants treated with PGPR or without PGPR (Control) after 30 days of growing in pot conditions. A, B - brinjal plants treated with strain *Erog*-1 and *Erog*-1+*Sarl*-43, respectively along with control plants; C, D - chilli plants treated with strain *Bcer*-25 and *Ptai-40*+*Sarl*-43, respectively along with control plants

Growth performance of brinjal plants treated with individual PGPR strains

Brinjal plants treated with the individual PGPR strains showed varied growth responses. The maximum mean height was observed in plants treated with *Bcer*-21, followed by those treated with *Erog*-1. All PGPR-treated plants exhibited increased mean height compared to the negative control, except those treated with *Sarl*-43, which showed a slight decrease. Fisher's LSD analysis indicated a significant increase in height for plants treated with six strains: *Erog*-1, *Bthu*-4, *Btro*-7, *Bcer*-13, *Bcer*-21, and *Bcer*-25 (Table 3).

The mean shoot biomass was higher in plants treated with six strains: *Erog*-1, *Bthu*-4, *Btro*-7, *Bcer*-13, *Bcer*-21, and *Ptai*-40, compared to the negative control. However, significant increases in shoot biomass were observed only in the case of treatments with *Erog*-1 and *Bcer*-21 on the basis of Fisher's LSD analysis. Treated brinjal plants showed higher mean root biomass with seven strains: *Erog*-1, *Bthu*-4, *Btro*-7, *Bcer*-13, *Bcer*-21, *Bcer*-25, and *Ptai*-40 (Table 3, Fig. 3). Similar to shoot biomass, significant root biomass increases were noted only in plants treated with *Erog*-1 and *Bcer*-21. The highest overall growth rate change was recorded in brinjal plants treated with *Bcer*-21, followed by *Erog*-1.

Table 3. Growth performance of brinjal plants after one month of treatment with individual PGPR strain in pot experiments. Mean values are the average of triplicates in each treatment. Values in bold indicates the significance of PGPR treatment in Fisher's LSD analysis

PGPR Treatment	Mean height (cm) ± SD (Difference between treatment mean and control mean at $LSD_{0.05}$ = 2.43)	Mean shoot biomass (mg) ± SD (Difference between treatment mean and control mean at $LSD_{0.05}$ = 217.25)	Mean root biomass (mg) ± SD (Difference between treatment mean and control mean at $LSD_{0.05}$ = 54.28)
Negative Control	12.67 ± 0.58 (NA)	231.33 ± 68.14 (NA)	28.33±9.87 (NA)
Erog-1	17.67 ± 2.52 (**5**)	490 ± 84 (**258.67**)	130 ± 34.7 (**101.67**)
Bthu-4	15.33 ± 2.52 (**2.66**)	405.67 ± 36.47 (174.34)	76.33 ± 42.15 (48)
Btro-7	16.33 ± 1.16 (**3.66**)	316 ± 319.24 (84.67)	64.67 ± 70.55 (36.34)
Bcer-13	16.17 ± 1.04 (**3.5**)	264 ± 47.03 (32.67)	40±9.64 (11.67)
Bcer-21	18 ± 1.73 (**5.33**)	731.67 ± 183.19 (**500.34**)	157.33 ± 44.47 (**129**)
Bcer-24	13.33 ± 1.16 (0.66)	184 ± 9.85 (-47.33)	28 ± 4.58 (-0.33)
Bcer-25	15.33 ± 0.58 (**2.66**)	161.33 ± 83.39 (-70)	29 ± 8.54 (0.67)
Bthu-38	14 ± 1 (1.33)	118 ± 15.13 (-113.33)	19.33 ± 3.79 (-9)
Ptai-40	14.33 ± 1.16 (1.66)	278 ± 148.74 (46.67)	62.33 ± 31.88 (34)
Sarl-43	12.33 ± 0.58 (-0.34)	148 ± 30.35 (-83.33)	20 ± 7.21 (-8.33)

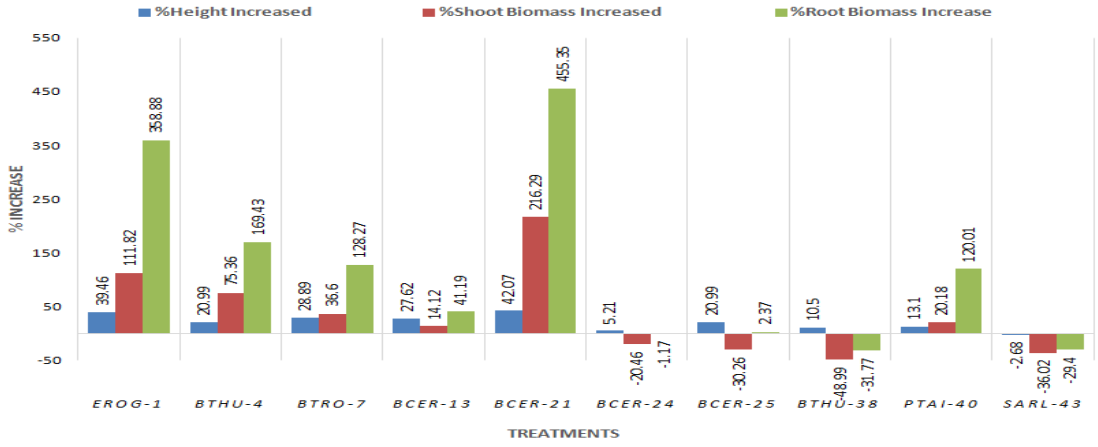

Figure 3. Relative change in mean height, shoot biomass and root biomass of brinjal plants in response to individual PGPR strain treated over untreated control plants after one month of growth in a pot experiment. Soils were sterilized before use in the pot experiments. All the plants were hydrated with sterile distilled water at a regular basis

Growth performance of brinjal plants treated with PGPR consortia

All brinjal plants treated with different PGPR consortia showed higher mean height, shoot biomass, and root biomass compared to the negative controls (Table 4). The highest percentage increase in mean height was observed in plants treated with the *Erog*-1+*Sarl*-43 consortium, while the maximum increase in mean shoot biomass and mean root biomass occurred in plants treated with the *Bcer*-24+*Bcer*-25 consortium (Fig. 4).

Table 4. Growth performance of brinjal plants after one month of treatment with consortia of two strains in pot experiments. Mean values are the average of triplicates in each treatment. Values in bold indicates the significance of PGPR treatment in Fisher's LSD analysis

PGPR Treatment	Mean height (cm) ± SD (Difference between treatment mean and control mean at $LSD_{0.05}$ = 1.96)	Mean shoot biomass (mg) ± SD (Difference between treatment mean and control mean at $LSD_{0.05}$ = 145.21)	Mean root biomass (mg) ± SD (Difference between treatment mean and control mean at $LSD_{0.05}$ = 27.41)
Negative Control	12 ± 1 (NA)	127.33 ± 38.55 (NA)	23.67 ± 3.79 (NA)
Erog-1 + *Bcer*-24	15.67 ± 0.58 (**3.67**)	163 ± 21.28 (35.67)	35 ± 8 (11.33)
Bthu-4 + *Bcer*-25	17.33 ± 1.15 (**5.33**)	251.67 ± 189.09 (124.34)	47 ± 33.87 (23.33)
Btro-7 + *Bthu*-38	15.67 ± 1.15 (**3.67**)	263.33 ± 26.10 (136)	39 ± 4.58 (15.33)
Btro-7 + *Bcer*-13	16 ± 1 (**4**)	351.33 ± 92.72 (**224**)	55.67 ± 11.15 (**32**)
Erog-1 + *Btro*-7	16.33 ± 1.53 (**4.33**)	221 ± 87.20 (93.67)	37.67 ± 8.51 (14)
Bcer-24 + *Bcer*-25	17.5 ± 1.5 (**5.5**)	395.33 ± 93.52 (**268**)	90± 17.69 (**66.33**)
Bthu-4 + *Bcer*-24	17.67 ± 1.53 (**5.67**)	192 ± 46.36 (64.67)	24.33 ± 8.50 (0.66)
Erog-1 + *Sarl*-43	18 ± 1 (**6**)	364.67 ± 54.63 (**237.34**)	42.33 ± 17.62 (18.66)
Ptai-40 + *Sarl*-43	16.33 ± 0.58 (**4.33**)	355 ± 65.05 (**227.67**)	76.67 ± 21.22 (**53**)

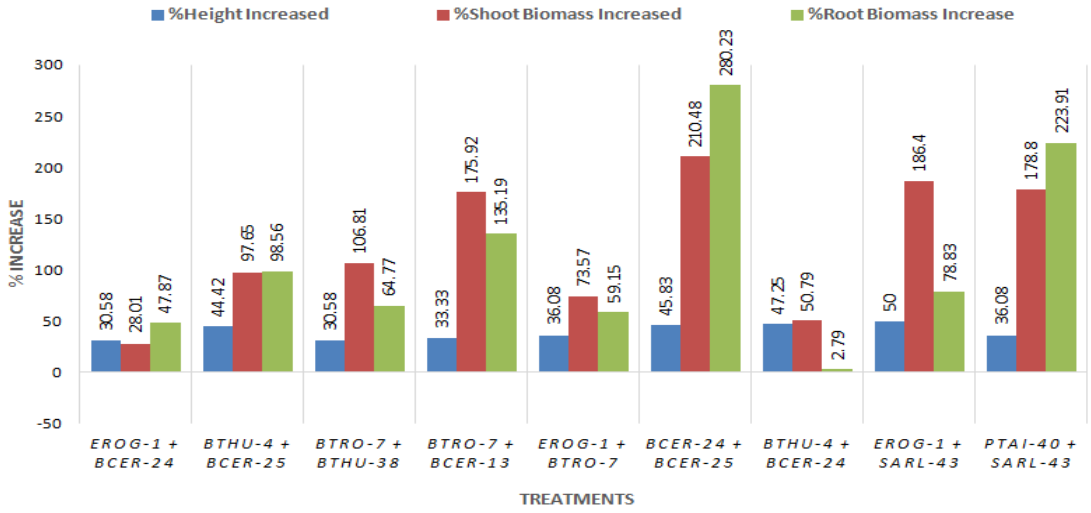

Figure 4. Relative change in mean height, shoot biomass and root biomass of brinjal plants in response to PGPR consortia treated over untreated control plants after one month of growth in a pot experiment. Soils were sterilized before use in the pot experiments. All the plants were hydrated with sterile distilled water at a regular basis

Fisher's LSD analysis revealed significant increases in height for all PGPR consortia treatments. However, a significant increase in shoot biomass was supported by Fisher's LSD only for four consortia: *Btro*-7+*Bcer*-13, *Bcer*-24+*Bcer*-25, *Erog*-1+*Sarl*-43, and *Ptai*-40+*Sarl*-43. Similarly, a significant increase in root biomass was supported by Fisher's LSD only for three consortia: *Btro*-7+*Bcer*-13, *Bcer*-24+*Bcer*-

25, and *Ptai*-40+*Sarl*-43 (Table 4). The highest overall growth rate change was observed in the plants treated with *Bcer*-24+*Bcer*-25.

Table 5. Growth performance of chilli plants after one month of treatment with individual PGPR strain in pot experiments. Mean values are the average of triplicates in each treatment. Values in bold indicates the significance of PGPR treatment in Fisher's LSD analysis

PGPR Treatment	Mean height (cm) ± SD (Difference between treatment mean and control mean at $LSD_{0.05}$ = 3.34)	Mean shoot biomass (mg) ± SD (Difference between treatment mean and control mean at $LSD_{0.05}$ = 195.41)	Mean root biomass (mg) ± SD (Difference between treatment mean and control mean at $LSD_{0.05}$ = 10.52)
Negative Control	13.33 ± 1.53 (NA)	94.67 ± 16.50 (NA)	20.67 ± 8.02 (NA)
Erog-1	13.67 ± 2.08 (0.34)	104.67 ± 10.02 (10)	22.33 ± 2.31 (1.66)
Bthu-4	15 ± 2 (1.67)	132.33 ± 23.71 (37.66)	17 ± 2.65 (-3.67)
Btro-7	17.67 ± 2.08 (**4.34**)	586 ± 100.50 (**491.33**)	37.67 ± 11.02 (**17**)
Bcer-13	15.67 ± 1.53 (2.34)	110.67 ± 6.03 (16)	17.33 ± 6.81 (-3.34)
Bcer-21	16 ± 2.65 (2.67)	353.33 ± 53.27 (**258.66**)	29.33 ± 6.03 (8.66)
Bcer-24	19.67 ± 1.53 (**6.34**)	382 ± 202.24 (**287.33**)	39 ± 2 (**18.33**)
Bcer-25	18.67 ± 0.58 (**5.34**)	341.67 ± 19.60 (**247**)	31.67 ± 7.23 (**11**)
Bthu-38	20 ± 1.73 (**6.67**)	306.67 ± 54.85 (**212**)	28.33 ± 3.06 (7.66)
Ptai-40	21.33 ± 2.52 (**8**)	476.67 ± 255.82 (**382**)	26 ± 4.58 (5.33)
Sarl-43	21.33 ± 2.52 (**8**)	388 ± 151.16 (**293.33**)	30.33 ± 7.51 (9.66)

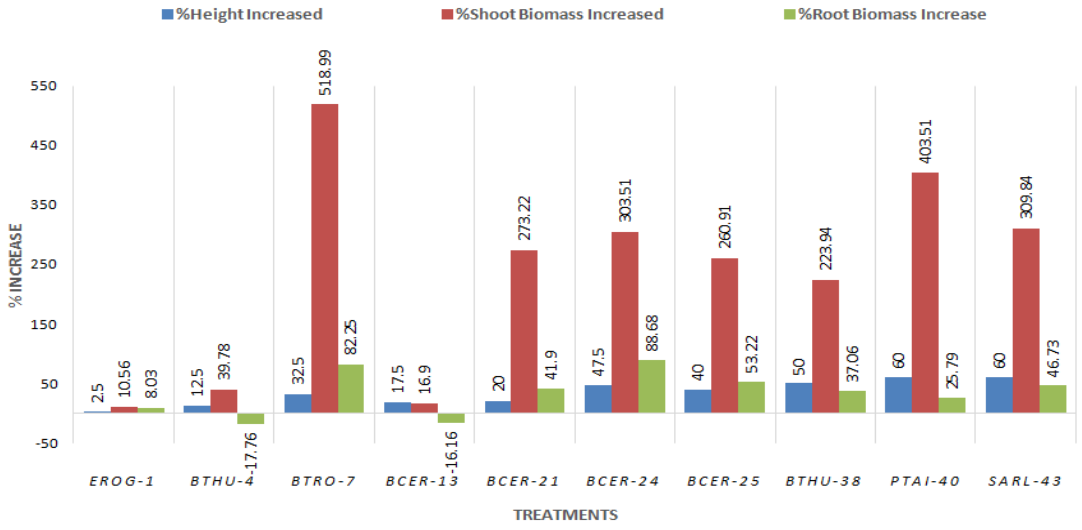

Figure 5. Relative change in mean height, shoot biomass and root biomass of chilli plants in response to individual PGPR strain treated over untreated control plants after one month of growth in a pot experiment. Soils were sterilized before use in the pot experiments. All the plants were hydrated with sterile distilled water at a regular basis

Growth performance of chilli plants treated with individual PGPR strains

Chilli plants treated with individual PGPR strains exhibited a slightly different pattern of growth. Both plant height and shoot biomass were higher in all PGPR-treated chilli plants compared to the negative controls (Table 5, Fig. 5). Root biomass increased in all treated plants except those treated with the strains *Bthu*-4 and *Bcer*-13.

The highest percentage increase in plant height was recorded in chilli plants treated with *Ptai*-40 and *Sarl*-43. In contrast, the highest percentage increases in shoot biomass and root biomass were recorded in plants treated with *Btro*-7 and *Bcer*-24, respectively (Fig. 5).

Fisher's LSD analysis indicated significant improvements in height in plants treated with *Btro*-7, *Bcer*-24, *Bcer*-25, *Bthu*-38, *Ptai*-40, and *Sarl*-43 (Table 5). Significant shoot biomass increases were observed in plants treated with *Btro*-7, *Bcer*-21, *Bcer*-24, *Bcer*-25, *Bthu*-38, *Ptai*-40, and *Sarl*-43. A significant increase in root biomass was supported only in plants treated with *Btro*-7, *Bcer*-24, and *Bcer*-25.

Growth performance of chilli plants treated with PGPR consortia

Chilli plants treated with PGPR consortia showed enhanced plant height, shoot biomass, and root biomass compared to their respective negative control plants (Table 6). The maximum increases in height, shoot biomass, and root biomass were observed in plants treated with *Bthu*-4+*Bcer*-24, *Btro*-7+*Bcer*-13, and *Btro*-7+*Bthu*-38, respectively (Fig. 6). Fisher's LSD analysis revealed significant height improvements in all consortia-treated chilli plants. However, the significance of shoot biomass increases was supported by Fisher's LSD only for plants treated with the following PGPR consortia: *Bthu*-4+*Bcer*-25, *Btro*-7+*Bcer*-13, *Bcer-24*+*Bcer*-25, *Bthu*-4+*Bcer*-24, *Erog*-1+*Sarl*-43, and *Ptai*-40+*Sarl*-43. Root biomass increases were significant in plants treated with the consortia: *Erog*-1+*Bcer*-24, *Btro*-7+*Bthu*-38, *Btro*-7+*Bcer*-13, *Bthu*-4+*Bcer*-24, and *Ptai*-40+*Sarl*-43 (Table 6).

Table 6. Growth performance of chilli plants after one month of treatment with consortia of two PGPR strains in pot experiments. Mean values are the average of triplicates in each treatment. Values in bold indicates the significance of PGPR treatment in Fisher's LSD analysis

PGPR Treatment	Mean height (cm) ± SD (Difference between treatment mean and control mean at $LSD_{0.05}$ = 3.96)	Mean shoot biomass (mg) ± SD (Difference between treatment mean and control mean at $LSD_{0.05}$ = 120.34)	Mean root biomass (mg) ± SD (Difference between treatment mean and control mean at $LSD_{0.05}$ = 11.37)
Negative Control	13 ± 1 (NA)	84 ± 36.59 (NA)	14.67 ± 3.22 (NA)
Erog-1 + *Bcer*-24	19 ± 3 (**6**)	159.33 ± 74.31 (75.33)	30 ± 9.85 (**15.33**)
Bthu-4 + *Bcer*-25	18.67 ± 3.51 (**5.67**)	216.67 ± 83.38 (**132.67**)	21.67 ± 8.51 (7)
Btro-7 + *Bthu*-38	19 ± 2.65 (**6**)	145.33 ± 41.86 (61.33)	35.33 ± 6.11 (**20.66**)
Btro-7 + *Bcer*-13	20.33 ± 2.31 (**7.33**)	312.67 ± 77.98 (**228.67**)	28.33 ± 5.86 (**13.66**)
Erog-1 + *Btro*-7	19.33 ± 2.08 (**6.33**)	169 ± 62.19 (85)	21 ± 5.20 (6.33)
Bcer-24 + *Bcer*-25	20 ± 2.65 (**7**)	247.33 ± 94.69 (**163.33**)	21 ± 2.65 (6.33)
Bthu-4 + *Bcer*-24	21 ± 1.73 (**8**)	246 ± 68.61 (**162**)	26.33 ± 8.51 (**11.66**)
Erog-1 + *Sarl*-43	19 ± 1 (**6**)	236.33 ± 65.21 (**152.33**)	19.67 ± 7.37 (5)
Ptai-40 + *Sarl*-43	20 ± 2 (**7**)	286 ± 80.55 (**202**)	29.67 ± 5.86 (**15**)

DISCUSSION

The present study evaluated the compatibility and synergistic effects of various PGPR strains on the growth performance of brinjal and chilli plants. The compatibility tests revealed that a significant number of the ten PGPR strains were compatible, allowing the formation of nine effective consortia. This compatibility is crucial for the successful establishment of multi-strain inoculants in the rhizosphere, enhancing their collective plant growth-promoting (PGP) activities (Nunes et al., 2024).

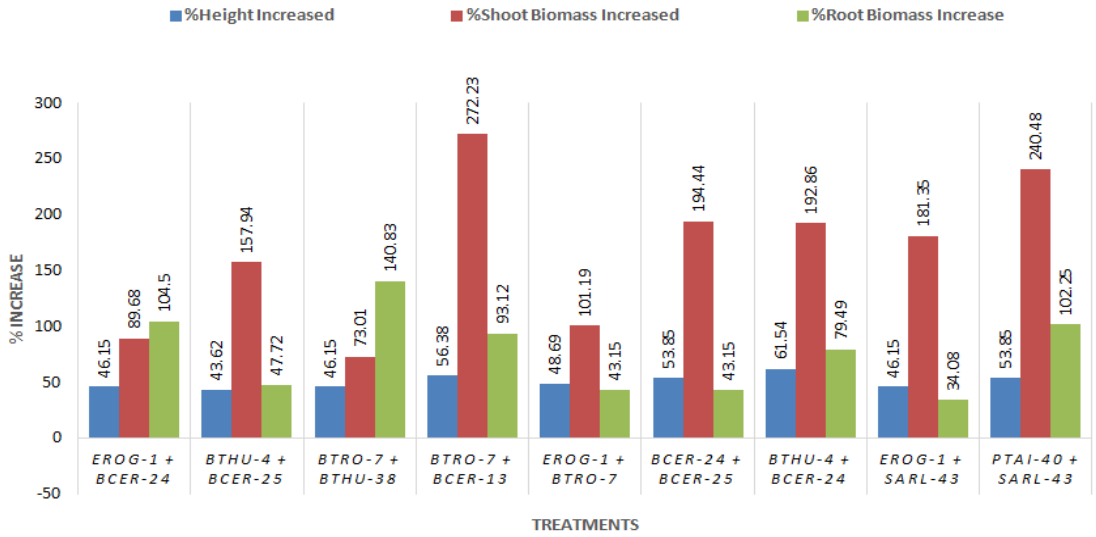

Figure 6. Relative change in mean height, shoot biomass and root biomass of chilli plants in response to PGPR consortia treated over untreated control plants after one month of growth in a pot experiment. Soils were sterilized before use in the pot experiments. All the plants were hydrated with sterile distilled water at a regular basis

Nutrient availability, temperature, water, and pH are significant contributing factors that determine the vigor of microbes (Msimbira & Smith, 2020). One of the key factors contributing to variability in strain performance is differential sensitivity to pH changes. Deviations from the optimal pH range for a specific strain can negatively impact essential microbial processes, such as nutrient uptake, ultimately reducing their efficiency in promoting plant growth. Additionally, PGPR and microbial communities residing in the rhizospheric region share a complex and dynamic ecosystem. The competitiveness of PGPR is influenced by various environmental factors, including soil type, organic matter content, and the presence of other microorganisms, which can hinder their performance (Vejan et al., 2016; Santoyo et al., 2021).

Sterilization through autoclaving can significantly alter the physical and chemical properties of soil. However, sterilized soil provides a controlled environment for studying specific plant-microbe interactions, which is essential to validate and confirm the PGP activities of test microorganisms on target host plants. Natural soil, on the other hand, serves as a repository of diverse microorganisms. The external augmentation of microorganisms to natural soil may result in either positive or negative interactions with the native microbial community. The successful application of PGPR in natural field conditions depends on the compatibility and viability of the PGPR within the soil ecosystem. Therefore, field

trials should follow tests of PGP activities conducted in sterile soil conditions to confirm the potential of candidate microbial strains for use as PGPR in crop improvement under natural field conditions.

In this study, the soil used in the experiment was acidic in nature (pH 5.91) with adequate levels of organic carbon and available phosphate, medium potassium and nitrate nitrogen, and low ammoniacal nitrogen (Table 2). Acidic soils often pose challenges to nutrient availability and microbial activity; however, the presence of medium to high organic carbon may facilitate microbial metabolism and nutrient cycling, potentially mitigating some adverse effects of low pH (Nookongbut et al., 2019). The ANOVA results unequivocally demonstrated that all PGPR treatments significantly improved plant growth parameters compared to the non-treated controls. This aligns with extensive literature documenting the beneficial impacts of PGPR on plant growth and maintaining soil fertility by recycling the soil nutrients (Glick, 2003; Bhattacharyya & Jha, 2012; Zaidi et al., 2015; Basu et al., 2021).

Our results demonstrated that individual application of PGPR strains like *B. tropicus* (*Btro*-7) and *B. cereus* (*Bcer*-24 and *Bcer*-25) significantly improved plant height, shoot biomass, and root biomass in chilli plants (Table 5). This corroborates the findings of Gowtham et al. (2018), who demonstrated that *Bacillus* spp. significantly enhanced plant height and biomass across various crops. Similarly, Gou et al. (2020) reported that a biofertilizer consortium involving *Bacillus* strains significantly increased plant growth parameters in chilli. Contrary to Syaziana et al. (2024), our study found that *E. roggenkampii* (*Erog*-1) did not significantly promote chilli plant growth, indicating variability in strain efficacy under different conditions.

Interestingly, though some *Bacillus* strains improved brinjal growth corroborating the previous studies by Kloepper et al. (2004), some strains did not significantly improve brinjal growth in our study suggesting that the effectiveness of PGPR strains can be context-dependent, influenced by factors such as soil type, plant species, and environmental conditions. *P. taiwanensis* (*Btai*-40) showed improvement in brinjal growth (but without significant difference in Fisher's LSD analysis) corroborating the earlier reports of growth improvement in brinjal by other *Pseudomonas* strains (Fu et al., 2010; Singh et al., 2017).

Previous studies have highlighted the importance of using PGPR consortia over individual strains for optimal plant growth (Kanchana et al., 2014). In our investigation, consortia treatments consistently outperformed individual treatments in both chilli and brinjal plants, reinforcing the concept that the combined effects of different PGPR strains can lead to more robust plant growth. The most significant growth enhancements in chilli plants were observed with the consortia treatment of *B. thuringiensis* (*Bthu*-4) + *B. cereus* (*Bcer*-24), resulting in a 61.54% increase in plant height. This is in line with the study by Datta et al. (2011), which reported similar growth enhancements in chilli when treated with a combined PGPR treatment. Consortia treatments also proved effective in brinjal plants, where combinations like *B. tropicus* (*Btro*-7) + *B. cereus* (*Bcer*-13) significantly improved all growth parameters, emphasizing the synergistic effect of multiple PGPR strains.

Plant growth-promoting rhizobacteria are capable of enhancing plant growth and development through various mechanisms, including the production of plant growth-promoting metabolites, nitrogen fixation, increasing the bioavailability of phosphate and micronutrients, and biological control (Ahemad & Kibret, 2013). The observed improvements in growth parameters in this study can also be linked to such PGP mechanisms. PGPR strains may also induce systemic resistance, protecting plants from pathogens and abiotic stresses, thereby contributing to overall plant health and vigor (Sabnis et al., 2015; Lugtenberg & Kamilova, 2009). This supports the broader role of PGPR in enhancing plant growth by directly affecting root and shoot development, nutrient uptake, and overall plant vigor.

CONCLUSION

The study demonstrated that PGPR inoculation, both as individual strains and consortia, significantly improved plant growth parameters in chilli and brinjal. Notably, *B. tropicus* (*Btro*-7) showed the best results for chilli, while *B. cereus* (*Bcer*-21) was the most effective for brinjal. Among the consortia, the combination of *P. taiwanensis* (*Ptai*-40) and *S. arlettae* (*Sarl*-43) induced the most substantial growth benefits for both crops, significantly increasing height, shoot biomass, and root biomass by up to 53.85%, 240.48%, and 102.25%, respectively, in chilli; and 36.08%, 178.80%, and 223.91%, respectively, in brinjal. The LSD analysis supported the findings that specific PGPR strain consortia, particularly *Btro*-7 + *Bcer*-13 and *Bcer*-24 + *Bcer*-25, might serve as promising biofertilizers, potentially reducing the need for chemical fertilizers and promoting sustainable agricultural practices. However, field trials without soil sterilization are necessary for successful application in natural crop fields. The use of PGPR consortia offers a strategic approach to enhancing crop productivity while maintaining ecological balance in agro-ecosystems.

Agro-climatic conditions vary significantly across regions, influencing factors such as soil properties, water availability, pest and disease prevalence, and soil microbial diversity. As a result, the effectiveness of PGPR application in agriculture may vary depending on specific agro-climatic conditions. Field trials conducted in diverse environments can help identify location-specific adaptations and management strategies, enhancing the large-scale efficiency of PGPR use while minimizing environmental impacts. This approach contributes to a more versatile and sustainable application of PGPR in agricultural systems worldwide.

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