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Evaluation of efficient plant growth promoting rhizobacteria isolates on growth and biomass of chilli (*Capsicum annuum* L.) under greenhouse conditions

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Abstract
Plant growth-promoting rhizobacteria are beneficial soil microorganisms that enhance plant growth through nutrient mobilization, phytohormone production and other plant–microbe interactions. The present study evaluated the efficacy of selected PGPR isolates for improving the growth, biomass production and quality attributes of chilli under greenhouse conditions. Forty bacterial isolates obtained from chilli rhizosphere soils collected from Raichur and Bidar districts of Karnataka. Further, forty isolates were coded, characterized based on morphological and biochemical tests and were screened for different plant growth promoting traits. Based on their superior activities SMP4, SMP36 as *Bacillus sp* and SMP15 as *Pseudomonas sp*. tentatively identified and were selected for evaluation under greenhouse condition. The experiment was conducted in a completely randomized design with three replications, eight treatments using chilli variety Byadagi. Observations on plant height, number of branches, number of fruits, chlorophyll content, root length, root biomass, shoot biomass, total microbial population and ascorbic acid content were recorded at different growth stages. The combined application of SMP4 + SMP15 + SMP36 with 75% RDF exhibited superior growth and biomass attributes compared with 75% RDF alone. The findings indicate that a consortium of efficient PGPR isolates can improve chilli growth and productivity while offering potential for reducing dependence on higher fertilizer inputs.

Keywords: Plant growth-promoting rhizobacteria, biomass, chilli, sustainable agriculture

Introduction

Chilli (*Capsicum annuum* L.) is an economically important crop cultivated extensively used as a vegetable, spice, condiment and processed food ingredient. In Karnataka, chilli is cultivated extensively in Raichur, Ballari, Dharwad, Chitradurga, Koppal and Vijayanagara districts. Among these, Raichur is one of the major chilli-producing regions owing to its favourable agro-climatic conditions and assured irrigation facilities. Green chilli productivity in Raichur district reaches nearly 60 t ha^{-1}, whereas dry chilli productivity is around 10 t ha^{-1}. Within the district, Devadurga taluk accounts for the largest area under chilli cultivation, followed by Manvi, Raichur and Lingasugur taluks. Chilli cultivation plays a significant role in improving the socio-economic status of farmers in this region. Sustaining high productivity under increasing production constraints requires efficient management of soil nutrients and plant health. Conventional chilli production relies considerably on chemical fertilizers and other external inputs. Although these inputs support crop productivity, their excessive use may adversely influence soil quality and environmental sustainability (Backer *et al.*, 2018; Aloo *et al.*, 2021) [2, 4]. Therefore, biological approaches that complement fertilizer application have gained importance in sustainable crop production.

Plant growth-promoting rhizobacteria are naturally occurring beneficial microorganisms that colonize the rhizosphere and promote plant development through several direct and indirect mechanisms *viz.*, phosphate solubilization, phytohormone production, nitrogen fixation, rhizosphere colonization and stimulation of beneficial microbial activity (Khan *et al.*, 2022) [10]. Consequently, identification of efficient isolates and evaluation of their performance under crop-growing conditions are essential.In the present study, bacterial isolates obtained from the rhizosphere of chilli were screened for multiple plant growth-promoting traits. Three efficient isolates, namely SMP4, SMP15 and SMP36, were subsequently evaluated in combination under greenhouse conditions. The study aimed to determine their influence on the growth, biomass production, fruiting, chlorophyll content, rhizosphere microbial population and ascorbic acid content of chilli. Particular emphasis was placed on evaluating whether the selected PGPR consortium could maintain or improve crop performance with 75% RDF.

Materials and Methods

Experimental site and design

The greenhouse experiment was conducted at the Department of Microbiology, College of Agriculture, University of Agricultural Sciences, Raichur, Karnataka, India. The experiment consisted of eight treatments with three replications and was laid out in a completely randomized design and chilli cv. Byadagi was used for the experiment. The treatment combinations consisted of 100% RDF, 75% RDF with three efficient isolates (Table 1).

Table 1: Treatment details of the pot culture of chilli under greenhouse condition.

S No.	Particulars	Details
1	Treatments	T_1- 100% RDF
		T_2- 75% RDF
		T_3- 75%RDF + Efficient PGPR Isolate 1
		T_4- 75% RDF + Efficient PGPR Isolate 2
		T_5- 75% RDF + Efficient PGPR Isolate 3
		T_6 - 75% RDF+ Efficient PGPR Isolate 1+2
		T_7- 75% RDF + Efficient PGPR Isolate 2+3
		T_8- 75% RDF + Efficient PGPR Isolate 1+2+3

Selection of efficient PGPR isolates

Forty bacterial isolates obtained from chilli rhizosphere soil samples collected from Raichur and Bidar districts were screened for plant growth-promoting traits. Based on their performance for indole-3-acetic acid production, nitrogen fixation, ammonia production and phosphate solubilisation. Out of all isolates SMP4, SMP15 and SMP36 exhibited highest multiple traits were selected for greenhouse evaluation.

Preparation and application of inoculants

Nutrient broth was prepared in conical flasks and sterilized at 121 °C for 30 min. After cooling, each flask was inoculated with 1 mL of the respective bacterial inoculum and incubated on a rotary shaker for seven days. The resulting culture was mixed with lignite carrier material at a ratio of 1:2.5 and allowed to cure. Approximately 200 g of the carrier-based formulation was packed for application. Chilli seedlings were treated by the seedling-dip method for 30 min before transplanting.

Observations recorded

Plant height, number of branches per plant, number of fruits per plant, chlorophyll content, root length, root biomass, shoot biomass, total microbial population and ascorbic acid content were recorded at 30, 60 and 90 days after transplanting (DAT) and at harvest. Plant height and root length were expressed in centimetres. Root and shoot biomass were determined after drying the plant material to constant weight at 60 °C and expressed as g plant^{-1}. Chlorophyll content was recorded using a SPAD meter. Total microbial population was determined from chilli rhizosphere soil. Ascorbic acid content at harvest was estimated using the 2,6-dichlorophenol indophenol titrimetric method.

Statistical analysis

The treatment means were compared using Duncan's Multiple Range Test (DMRT). Means followed by different letters were considered significantly different at $P < 0.01$, as indicated in the experimenntal data.

Results and Discussion

Plant height

Plant height showed significant variation among treatments at all growth stages. T8 (75% RDF + SMP-4 + SMP-15 + SMP-36) recorded the highest plant height of 18.40, 36.20, 41.20 and 44.20 cm at 30, 60, 90 DAT and harvest, respectively. Where as, T2 (75% RDF) recorded the lowest plant height of 13.00, 25.50, 29.40 and 32.00 cm, respectively (Table 2).

Table 2: Plant height of chilli at different stages as influenced by efficient PGPR isolates

Treatments	Plant height (cm)			
	30 DAT	60 DAT	90 DAT	At harvest
T_1- 100% RDF	14.20 ^{ef}	27.80 ^{e}	31.80 ^{e}	34.50 ^{e}
T_2- 75% RDF	13.00 ^{g}	25.50 ^{g}	29.40 ^{g}	32.00 ^{g}
T_3- 75%RDF + SMP 4	15.20 ^{f}	30.20 ^{f}	34.80 ^{f}	37.50 ^{f}
T_4- 75% RDF + SMP 15	15.90 ^{cd}	31.80 ^{cd}	36.80 ^{cd}	39.80 ^{cd}
T_5- 75% RDF + SMP 36	16.50 ^{de}	33.00 ^{d}	37.30 ^{de}	40.20 ^{de}
T_6 - 75% RDF+ SMP-4 + SMP-15	17.20 ^{bc}	34.20 ^{bc}	39.00 ^{bc}	42.00 ^{bc}
T_7- 75% RDF +SMP-15 +SMP-36	17.80 ^{ab}	35.00 ^{ab}	40.00 ^{ab}	43.00 ^{ab}
T_8- 75% RDF + SMP-4+ SMP-15 + SMP-36	18.40 ^{a}	36.20 ^{a}	41.20 ^{a}	44.20 ^{a}
SE(m) ±	0.33	0.42	0.37	0.38
CD (P<0.01)	0.99	1.28	1.14	1.45

The results are in line with findings of Bucao and Leon (2014) [5], who reported that enhanced plant height under T8 may be attributed to the combined PGPR activities of SMP-4, SMP-15 and SMP-36, particularly IAA production and improved nutrient availability, which promote cell division, elongation and root development.

Number of branches per plant

Number of branches per plant showed significant variation among treatments at all growth stages. T8 (75% RDF + SMP-4 + SMP-15 + SMP-36) recorded the highest number of branches per plant with 6.67, 7.33, 14.67 and 16.67 at 30, 60, 90 DAT and harvest, respectively. Whereas, T2 (75% RDF) recorded the lowest number of branches per plant with 2.67, 4.33, 5.67 and 7.00 at 30, 60, 90 DAT and harvest, respectively (Table 3).

The results are in line with the findings of Kammar *et al.* (2019), who reported that Bacillus isolates ESK-26 and ESK-32 significantly increased the number of branches per plant in chilli. The enhanced branching under T8 may be attributed to the combined PGPR activities of SMP-4, SMP-15 and SMP-36, particularly the production of plant growth-

promoting substances such as IAA, gibberellins and cytokinins, along with improved nutrient availability and root development, which stimulate cell division and lateral bud development. Similarly, Tariq *et al.* (2014) [17] reported that inoculation of chilli with a PGPR consortium consisting of *Klebsiella* sp., *Burkholderia* sp., *Paenibacillus* sp. and *Bacillus* sp. significantly increased the number of branches per plant compared to the control.

Number, of fruits per, plant

The number of fruits per plant showed significant variation among treatments at different growth stages. T8 (75% RDF + SMP-4 + SMP-15 + SMP-36) recorded the highest number of fruits per plant with 16.30, 24.00 and 29.00 at 60, 90 DAT and harvest, respectively. Whereas, T2 (75% RDF) recorded the lowest number of fruits per plant with 9.70, 15.00 and 20.00 at 60, 90 DAT and harvest, respectively. T7 (75% RDF + SMP-15 + SMP-36) recorded the second highest number of fruits per plant with 15.30, 22.70 and 28.00 at 60, 90 DAT and harvest, respectively (Table 3).

The results are in accordance with the findings of Kulia *et al.* (2020), who reported that combined inoculation of *Acaulospora* (AM fungi), *Azotobacter* and phosphate-solubilizing *Pseudomonas* significantly enhanced the number of fruits in chilli under phosphorus- and nitrogen-deficient lateritic soil conditions. The increased number of fruits under T8 may be attributed to the combined PGPR activities of SMP-4, SMP-15 and SMP-36, particularly their ability to improve nutrient availability through nitrogen fixation and phosphate solubilization, along with the production of plant growth-promoting substances. These activities enhance root development, nutrient uptake and vegetative growth, resulting in greater photosynthetic activity and availability of photosynthates for flower and fruit deve; opment and reduce flower and fruit drop, ultimately increasing the number of fruits per plant. Similarly, Kanchana *et al.* (2014) [9] reported that combined inoculation of *Azospirillum* (Azs-2), *Pseudomonas* (Ps-2) and *Bacillus* (BS-2) significantly increased the number of fruits and fruit yield of chilli compared with individual inoculation and the uninoculated control. The increase in fruit number was attributed to the synergistic effects of the PGPR consortium in producing phytohormones, improving nutrient availability and enhancing root development.

Table 3: Number of branches and fruits of chilli at different stages as influenced by efficient PGPR isolates.

Treatments	No. of branches per plant				No. of fruits per plant		
	30 DAT	60 DAT	90 DAT	At Harvest	60 DAT	90 DAT	At harvest
T_1- 100% RDF	4.33 ^{cd}	5.30 ^{cd}	9.32 ^{e}	11.00 ^{de}	12.00 ^{d}	17.00 ^{ef}	22.60 ^{de}
T_2- 75% RDF	2.67 ^{e}	4.33 ^{e}	5.67 ^{f}	7.00 ^{f}	9.70 ^{f}	15.00 ^{g}	20.00 ^{f}
T_3- 75%RDF + SMP 4	4.67 ^{d}	5.67 ^{d}	9.67 ^{e}	12.33 ^{e}	12.10 ^{e}	18.70 ^{fg}	23.00 ^{e}
T_4- 75% RDF + SMP 15	5.00 ^{cd}	6.00 ^{bcd}	10.67 ^{d}	11.67 ^{de}	12.30 ^{d}	20.00 ^{cd}	23.70 ^{cd}
T_5- 75% RDF + SMP 36	5.10 ^{cd}	6.20 ^{bcd}	11.00 ^{c}	12.67 ^{bc}	12.70 ^{d}	21.00 ^{de}	24.70 ^{d}
T_6 - 75% RDF+ SMP-4 + SMP-15	5.33 ^{bc}	6.33 ^{bc}	12.33 ^{cd}	13.67 ^{cd}	14.30 ^{c}	22.00 ^{bc}	26.70 ^{bc}
T_7- 75% RDF +SMP-15 +SMP-36	6.00 ^{ab}	6.67 ^{ab}	13.33 ^{b}	15.33 ^{ab}	15.30 ^{b}	22.70 ^{ab}	28.00 ^{ab}
T_8- 75% RDF + SMP-4+ SMP-15 + SMP-36	6.67 ^{a}	7.33 ^{a}	14.67 ^{a}	16.67 ^{a}	16.30 ^{a}	24.00 ^{a}	29.00 ^{a}
SE(m) ±	0.26	0.28	0.31	0.50	0.10	0.21	0.43
CD (P<0.01)	0.79	0.87	0.94	1.51	0.30	0.72	1.30

Chlorophyll content

Chlorophyll content showed significant variation among treatments at all growth stages. T8 (75% RDF + SMP-4 + SMP-15 + SMP-36) recorded the highest chlorophyll content with 46.85, 57.00, 60.72 and 56.24 SPAD units at 30, 60, 90 DAT and harvest, respectively. Whereas, T2 (75% RDF) recorded the lowest chlorophyll content with 34.58, 41.23, 43.86 and 40.15 SPAD units at 30, 60, 90 DAT and harvest, respectively (Table 4).

Table 4: Chlorophyll content and root length of chilli at different stages as influenced by efficient PGPR isolates.

Treatments	Chlorophyll content (SPAD units)				Root length (cm)			
	30 DAT	60 DAT	90 DAT	At harvest	30 DAT	60 DAT	90 DAT	At harvest
T_1-100% RDF	38.24 ^{e}	45.67 ^{e}	48.35 ^{f}	44.82 ^{d}	5.40 ^{de}	8.20 ^{de}	10.40 ^{ef}	12.00 ^{de}
T_2-75% RDF	34.58 ^{f}	41.23 ^{f}	43.86 ^{g}	40.15 ^{e}	4.80 ^{f}	7.20 ^{f}	9.20 ^{g}	10.80 ^{f}
T_3-75%RDF+SMP 4	40.36 ^{d}	48.42 ^{d}	51.27 ^{e}	47.86 ^{c}	5.80 ^{ef}	8.80 ^{e}	10.90 ^{fg}	12.60 ^{e}
T_4- 75% RDF + SMP 15	40.84 ^{c}	50.16 ^{c}	51.04 ^{d}	47.63 ^{c}	6.10 ^{cd}	9.30 ^{c}	11.70 ^{cd}	13.60 ^{c}
T_5- 75% RDF + SMP 36	41.92 ^{cd}	51.35 ^{cd}	52.18 ^{d}	49.54 ^{c}	6.40 ^{de}	9.80 ^{cd}	12.20 ^{de}	14.10 ^{cd}
T_6 - 75% RDF+ SMP-4 + SMP-15	43.68 ^{b}	53.42 ^{b}	56.33 ^{c}	52.17 ^{b}	6.90 ^{bc}	10.60 ^{b}	13.20 ^{bc}	15.20 ^{b}
T_7- 75% RDF +SMP-15 +SMP-36	44.52 ^{b}	54.76 ^{b}	57.48 ^{b}	53.46 ^{b}	7.30 ^{ab}	11.00 ^{ab}	13.80 ^{ab}	15.90 ^{ab}
T_8- 75% RDF + SMP-4+ SMP-15 + SMP-36	46.85 ^{a}	57.00 ^{a}	60.72 ^{a}	56.24 ^{a}	7.80 ^{a}	11.70 ^{a}	14.60 ^{a}	16.80 ^{a}
SE(m) ±	0.34	0.49	0.60	0.50	0.23	0.26	0.37	0.42
CD (P<0.01)	1.04	1.49	1.82	1.53	0.70	0.79	1.13	2.00

The results are in agreement with the findings of Praveen *et al.* (2012) [14], who reported that inoculation with fluorescent *Pseudomonas* strains P10 and P13 in combination with arbuscular mycorrhizal fungi significantly increased the chlorophyll content of chilli compared to the uninoculated control. The enhanced chlorophyll content under T8 may be attributed to the combined plant growth-promoting activities of SMP-4, SMP-15 and SMP-36, including phosphate solubilization, siderophore production, improved nutrient availability, and production of phytohormones such as IAA

and gibberellic acid (GA_3), which collectively promote chlorophyll synthesis and photosynthetic efficiency. Similarly, Shahzad *et al.* (2021) [15] reported that inoculation with *Pseudomonas fluorescens*, *Bacillus subtilis* and *Azospirillum brasilense* significantly increased chlorophyll content in chilli through improved nutrient acquisition, particularly nitrogen and phosphorus, along with phytohormone production.

Root length

Root length showed significant variation among treatments at all growth stages. T8 (75% RDF + SMP-4 + SMP-15 + SMP-36) recorded the highest root length with 7.80, 11.70, 14.60 and 16.80 cm at 30, 60, 90 DAT and harvest, respectively. Whereas, T2 (75% RDF) recorded the lowest root length with 4.80, 7.20, 9.20 and 10.80 cm at 30, 60, 90 DAT and harvest, respectively (Table 4).

The results agree with the findings of Zawad *et al.* (2025) [18], who reported that inoculation with PGPR isolates, particularly *Acinetobacter oleivorans* PGPR-14 and a PGPR consortium, significantly enhanced root length and biomass in chilli under both pot and field conditions. The enhanced root growth under T8 may be attributed to the combined PGPR activities of SMP-4, SMP-15 and SMP-36, particularly the production of phytohormones such as indole-3-acetic acid (IAA), improved nutrient availability and stimulation of root development, which collectively promoted root elongation and improved root architecture. Similarly, Ashrafuzzaman *et al.* (2009) [3] reported that inoculation of chilli seedlings with efficient PGPR isolates PGB4, PGG2 and PGT3 significantly increased root length compared to the uninoculated control. The enhanced root growth was attributed to IAA production, improved phosphate solubilization and increased nutrient uptake, which stimulated root elongation and development of a more extensive root system.

Root biomass

Root biomass showed significant variation among treatments at all growth stages. T8 (75% RDF + SMP-4 + SMP-15 + SMP-36) recorded the highest root biomass with 0.09, 0.20, 0.33 and 0.47 g plant^{-1} at 30, 60, 90 DAT and harvest, respectively. Whereas, T2 (75% RDF) recorded the lowest root biomass with 0.03, 0.10, 0.17 and 0.25 g plant^{-1} at 30, 60, 90 DAT and harvest, respectively (Table 5).

The results are in line with the findings of Shankar *et al.* (2013) [16], who reported that *Pseudomonas* sp. (PSB4) significantly enhanced root biomass in chilli under pot conditions. The enhanced root biomass under T8 may be attributed to the combined PGPR activities of SMP-4, SMP-15 and SMP-36, particularly phosphate solubilization, IAA production and siderophore production, which improved nutrient availability, stimulated root elongation, lateral root formation and root hair development, thereby promoting healthier and more extensive root growth. Similarly, Kanchana *et al.* (2014) [9] reported that combined inoculation of *Azospirillum* (Azs-2), *Pseudomonas* (Ps-2) and *Bacillus* (BS-2) significantly increased root biomass in chilli plants. The enhanced root biomass was attributed to the synergistic production of phytohormones, particularly indole-3-acetic acid (IAA), along with improved nutrient acquisition and root development.

Table 5: Root biomass and shoot biomass of chilli at different stages as influenced by efficient PGPR isolates.

Treatments	Root Biomass (g/plant)				Shoot Biomass (g/plant)			
	30 DAT	60 DAT	90 DAT	At harvest	30 DAT	60 DAT	90 DAT	At harvest
T_1-100% RDF	0.03 ^{a}	0.12 ^{bc}	0.20 ^{def}	0.28 ^{de}	0.17 ^{bc}	0.44 ^{e}	0.79 ^{f}	1.02 ^{d}
T_2- 75% RDF	0.03 ^{a}	0.10 ^{c}	0.17 ^{f}	0.25 ^{f}	0.15 ^{c}	0.39 ^{f}	0.68 ^{h}	0.90 ^{e}
T_3- 75%RDF + SMP 4	0.04 ^{a}	0.14c	0.23 ^{ef}	0.32 ^{ef}	0.19 ^{bc}	0.53 ^{f}	0.92 ^{g}	1.18 ^{e}
T_4- 75% RDF + SMP 15	0.04 ^{a}	0.15 ^{abc}	0.24 ^{bcd}	0.35 ^{cd}	0.21 ^{ab}	0.65 ^{cd}	1.08 ^{d}	1.36 ^{c}
T_5- 75% RDF + SMP 36	0.05 ^{a}	0.16 ^{abc}	0.26 ^{cde}	0.37 ^{d}	0.22 ^{abc}	0.70 ^{d}	1.16 ^{e}	1.45 ^{c}
T_6 - 75% RDF+ SMP-4 + SMP-15	0.05 ^{a}	0.18 ^{ab}	0.29 ^{abc}	0.41 ^{bc}	0.23 ^{a}	0.76 ^{bc}	1.28 ^{c}	1.58 ^{b}
T_7- 75% RDF +SMP-15 +SMP-36	0.07 ^{a}	0.19 ^{ab}	0.31 ^{ab}	0.44 ^{ab}	0.24 ^{a}	0.80 ^{ab}	1.36 ^{b}	1.66 ^{ab}
T_8- 75% RDF + SMP-4+ SMP-15 + SMP-36	0.09 ^{a}	0.20 ^{a}	0.33 ^{a}	0.47 ^{a}	0.25 ^{a}	0.84 ^{a}	1.45 ^{a}	1.76 ^{a}
SE(m) ±	0.01	0.01	0.01	0.02	0.01	0.03	0.04	0.07
CD (P<0.01)	0.04	0.03	0.04	0.06	0.03	0.07	0.09	0.21

Shoot biomass

Shoot biomass showed significant variation among treatments at all growth stages. T8 (75% RDF + SMP-4 + SMP-15 + SMP-36) recorded the highest shoot biomass with 0.25, 0.84, 1.45 and 1.76 g plant^{-1} at 30, 60, 90 DAT and harvest, respectively. Whereas, T2 (75% RDF) recorded the lowest shoot biomass with 0.15, 0.39, 0.68 and 0.90 g plant^{-1} at 30, 60, 90 DAT and harvest, respectively (Table 5).

The results are in accordance with the findings of Noumavo *et al.* (2013) [13], who reported that a combination of *Pseudomonas fluorescens* and *Pseudomonas putida* produced the highest shoot biomass in chilli, increasing aerial dry matter by 59.11 per cent over the control. The enhanced shoot biomass under T8 may be attributed to the combined PGPR activities of SMP-4, SMP-15 and SMP-36, particularly improved nutrient availability and uptake, phytohormone production and enhanced root development, which collectively promoted vegetative growth and dry matter accumulation. Similarly, Tariq *et al.* (2014) [17] reported that inoculation of chilli with a PGPR consortium comprising *Klebsiella* sp., *Burkholderia* sp., *Paenibacillus* sp. and *Bacillus* sp. significantly increased shoot biomass compared to the uninoculated control.

Total, microbial count

Total microbial count showed significant variation among treatments at all growth stages. T8 (75% RDF + SMP-4 + SMP-15 + SMP-36) recorded the highest total microbial count with 43.00 × 10^6, 49.40 × 10^6, 55.20 × 10^6 and 52.40 × 10^6 CFU g^{-1} soil at 30, 60, 90 DAT and harvest, respectively. Whereas, T2 (75% RDF) recorded the lowest

total microbial count with 23.10 × 10^6, 25.20 × 10^6, 26.80 × 10^6 and 25.60 × 10^6 CFU g^{-1} soil at 30, 60, 90 DAT and harvest, respectively (Table 6).

The results are in accordance with the findings of Chinakwe *et al.* (2019) [6], who reported that PGPR isolates such as *Micrococcus*, *Bacillus*, *Corynebacterium* and *Enterococcus* sp. increased the microbial population in the chilli rhizosphere. The higher microbial count under T8 may be attributed to the combined effects of SMP-4, SMP-15 and SMP-36, particularly efficient rhizosphere colonization, enhanced root exudation and improved nutrient availability, which created a favourable environment for the multiplication and establishment of beneficial soil microorganisms. Similarly, Compant *et al.* (2005) [7] reported that PGPR inoculation increased the abundance of beneficial microorganisms in the rhizosphere through efficient root colonization and improved nutrient cycling. These interactions enhanced microbial activity and contributed to higher microbial populations in the root zone of chilli.

Ascorbic acid content

Ascorbic acid content showed significant variation among treatments at harvest. T8 (75% RDF + SMP-4 + SMP-15 + SMP-36) recorded the highest ascorbic acid content with 129.60 mg 100 g^{-1}, followed by T7 (75% RDF + SMP-15 + SMP-36) with 120.80 mg 100 g^{-1}, whereas T2 (75% RDF) recorded the lowest ascorbic acid content with 76.40 mg 100 g^{-1}, as presented in Table 15 and Fig. 12. The variation in ascorbic acid content among treatments may be attributed to the application of efficient PGPR isolates during transplanting. Among the eight treatments, T8 (75% RDF + SMP-4 + SMP-15 + SMP-36) recorded the highest ascorbic acid content (Table 6).

The results agree with the findings of Kloepper *et al.* (2004) [11], who reported that *Bacillus* species enhanced ascorbic acid content, which was attributed to improved plant metabolism and enhanced nutrient uptake, favouring the biosynthesis and accumulation of vitamin C in chilli. Similarly, Ahemad and Kibret (2014) [1] reported that PGPR, particularly *Bacillus* and *Pseudomonas* species, enhanced ascorbic acid content through phytohormone production and induction of systemic resistance. The increased ascorbic acid content may be attributed to improved plant metabolism and nutrient acquisition mediated by PGPR, which favoured the biosynthesis and accumulation of vitamin C in plant tissues.

Table 6: Total microbial count and ascorbic acid of chilli at different stages as influenced by efficient PGPR isolates.

Treatments	TMC (×10^6 CFU g^{-1} soil)				Ascorbic Acid (mg 100 g^{-1})
	30 DAT	60 DAT	90 DAT	At harvest	At harvest
T_1- 100% RDF	25.20 ^{f}	28.00 ^{f}	30.20 ^{f}	29.00 ^{f}	84.20 ^{g}
T_2- 75% RDF	23.10 ^{g}	25.20 ^{g}	26.80 ^{g}	25.60 ^{g}	76.40 ^{h}
T_3- 75%RDF + SMP 4	30.60 ^{e}	35.20 ^{e}	38.00 ^{e}	35.80 ^{e}	93.60 ^{f}
T_4- 75% RDF + SMP 15	30.00 ^{d}	34.40 ^{d}	37.20 ^{d}	35.00 ^{d}	96.80 ^{d}
T_5- 75% RDF + SMP 36	33.00 ^{e}	37.64 ^{e}	41.20 ^{e}	39.00 ^{e}	101.40 ^{e}
T_6 - 75% RDF+ SMP-4 + SMP-15	37.20 ^{c}	43.00 ^{c}	47.00 ^{c}	44.60 ^{c}	112.20 ^{c}
T_7- 75% RDF +SMP-15 +SMP-36	39.60 ^{b}	45.80 ^{b}	50.60 ^{b}	48.00 ^{b}	120.80 ^{b}
T_8- 75% RDF + SMP-4+ SMP-15 + SMP-36	43.00 ^{a}	49.40 ^{a}	55.20 ^{a}	52.40 ^{a}	129.60 ^{a}
SE(m) ±	0.40	0.47	0.41	0.46	0.448
CD (P<0.01)	1.23	1.42	1.24	1.39	1.13

Note: Mean values followed by the different letter are significantly different (P<0.01) from each other as evaluated from Duncan's Multiple Range Test (DMRT).

Conclusion

The greenhouse evaluation demonstrated that application of efficient PGPR isolates substantially improved the growth and biomass related attributes of chilli compared with 75% RDF alone. Among the treatments, T8 comprising 75% RDF + SMP4 + SMP15 + SMP36 consistently produced the highest values for plant height, branching, fruit production, chlorophyll content, root length, root biomass, shoot biomass, rhizosphere microbial population and ascorbic acid content. The performance of the consortium was also superior to that of individual PGPR applications for most of the recorded parameters. These results indicate that the selected PGPR consortium has considerable potential as a biological input for improving chilli performance under reduced fertilizer application. Further identification of PGPR molecular work has to be done and validation under field conditions is necessary to determine its consistency, economic feasibility and suitability for wider adoption.

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