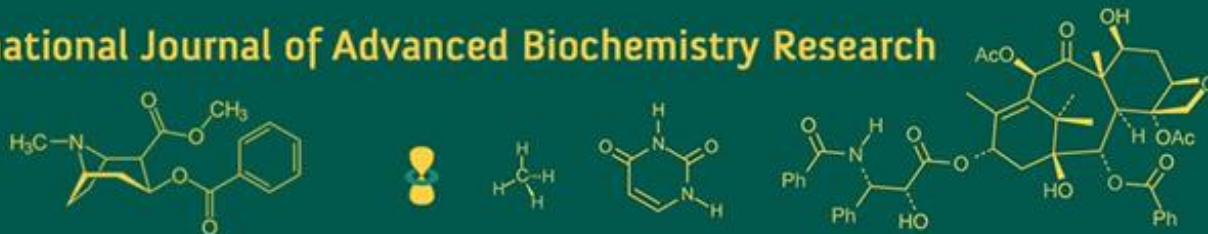


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
 ISSN Online: 2617-4707
 NAAS Rating (2026): 5.29
 IJABR 2026; SP-10(8): 707-720
www.biochemjournal.com
 Received: 10-05-2026
 Accepted: 20-06-2026

Ashalata
 Ph.D. (Horticulture),
 Department of Vegetable
 Science, Indira Gandhi Krishi
 Vishwavidyalaya, Raipur,
 Chhattisgarh, India

Dr. Annu Verma
 Professor, Department of
 Vegetable Science, Indira
 Gandhi Krishi
 Vishwavidyalaya, Raipur,
 Chhattisgarh, India

Dr. Anil Kotasthane
 Professor, Department of
 Plant Pathology, Indira
 Gandhi Krishi
 Vishwavidyalaya, Raipur,
 Chhattisgarh, India

Shatavisa Nayak
 Ph.D. (Agriculture),
 Department of Agronomy,
 Indira Gandhi Krishi
 Vishwavidyalaya, Raipur,
 Chhattisgarh, India

Pooja Sahu
 Ph.D. (Horticulture),
 Department of Vegetable
 Science, Indira Gandhi Krishi
 Vishwavidyalaya, Raipur,
 Chhattisgarh, India

Corresponding Author:
Ashalata
 Ph.D. (Horticulture),
 Department of Vegetable
 Science, Indira Gandhi Krishi
 Vishwavidyalaya, Raipur,
 Chhattisgarh, India

Physiological and root responses of PGPRs seed treated tomato (*Solanum lycopersicum* L.) plant to moisture stress tolerance

Ashalata, Annu Verma, Anil Kotasthane, Shatavisa Nayak and Pooja Sahu

DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i8Si.9517>

Abstract

A field experiment was conducted during Rabi season 2024-25 at Instructional cum Research Farm, Indira Gandhi Krishi Vishwavidyalaya, Raipur, (C.G.) to study the effect of Plant Growth Promoting Rhizobacteria treatment on Physiology and root responses of tomato. The tomato was grown and treatments were replicated three times in completely randomized block design. The experiment consists of 11 combinations of 5 PGPRs culture and control with 100% RDF (120:80:80)/ha. The result revealed that physiological parameters viz seed germination (%), Root length (cm), Root volume (cm³) higher in T9 100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + Azotobacter 5 ml/kg Seed, Membrane stability index (%), Relative water content (%) higher in T3 100% RDF + Azotobacter 5 ml/kg Seed T4 100% RDF + Azospirillum 5 ml/kg Seed, Leaf rolling, Tip drying higher in T11 100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + PSB 5 ml/kg Seed and Plant survival percentage higher in was recorded in T8 100% RDF + 9704 *Pseudomonas fluorescens* 5gm/kg Seed + PSB 5 ml/kg Seed and lowest growth parameters were recorded under without treated with PGPRs culture 100% RDF (120:80:80)/ha (control).

Keywords: Bio-control agent, pgprs, morphology, psb and rdf

Introduction

Tomato (*Solanum lycopersicum* L.) a member of the solanaceae family, is one of the most important horticultural crop cultivated globally. It holds significant economic and nutritional value, being rich in energy 18–20 kcal, water 94.5 g, carbohydrates 3.9 g, protein 0.9 g, and fat 0.2 g, making it a low-calorie and hydrating food. It is an excellent source of vitamins and minerals, containing about 13–15 mg of vitamin C, 42 µg of vitamin A (as β-carotene), 0.54 mg vitamin E, 7.9 µg vitamin K, 237 mg potassium, 24 mg phosphorus, 11 mg magnesium, and small amounts of calcium, iron, zinc, copper, and manganese. In addition, tomatoes are rich in health-promoting phytochemicals such as lycopene (2.5–3.0 mg/100 g) and β-carotene (0.449 mg/100 g), which act as potent antioxidants. However, tomato production is highly sensitive to environmental stresses, particularly moisture stress which has become increasingly prevalent due to erratic climate patterns and water scarcity. Moisture stress adversely affects seed germination, fruit set and overall yield in tomato crops. (Rai *et al.*, 2024) [1]. Plant growth promoting Rhizobacteria (PGPR) are the group of micro-organisms which soil inhabitant in nature, promoting the growth parameters of the plants by colonizing the roots. Several mechanisms are involved directly and indirectly in the plant growth promotion like production of siderophores that chelates the iron from the soil and make it available to the roots of the plants, atmospheric nitrogen fixation, phosphorus solubilization, uptake of nutrients viz., nitrogen, potassium and phosphorus and production of different phytohormones like synthesis of gibberellic acid and IAA (indole acetic acid) (Varma *et al.*, 2017) [2], (Khan A.G. 2005) [3] and (Altomare *et al.*, 1999 and Hermosa *et al.*, 2012) [4, 5]. Different types of secondary metabolites produced by *Trichoderma* spp. evaluated for their growth promoting effects (Vinale *et al.*, 2008, Liu *et al.*, 2021) [6]

Materials and methods

A field experiment was conducted during Rabi season 2024-25 at the Horticulture cum Research Farm, under Indira Gandhi Krishi Vishwavidyalaya, Raipur (C.G.). The tomato was grown and

treatments were replicated three times in completely randomized block design. One isolates of *Trichoderma* (BARC mutant G2) and four isolates of Bacteria (*Pseudomonas fluorescens* (9074), *Azotobacter*, *Azospirillum* and PSB) obtain from department of plant pathology, Indira Gandhi Krishi Vishwavidyalaya, Raipur. The bio-control agent treated seeds directly sown in the portrays than transplant in field and Observation was recorded on the five randomly selected plants were used for calculating the mean. Observation was Seed germination (%), Root length (cm), Root volume (cm³), Membrane stability index (%), Relative water content (%) Leaf rolling, Tip drying and Plant survival (%).

Germination percentage per treatments

The germination percentage of tomato seeds was determined according to the guidelines of the International Seed Testing Association (ISTA, 1985) [7]. For each treatment, 100 seeds were randomly selected and placed on moistened germination paper in sterile Petri plates. Adequate moisture was maintained throughout the germination period by adding distilled water whenever required. Germinated seeds were counted after 3 days, and the germination percentage was calculated using the following formula:

$$\text{Germination}(\%) = \frac{\text{No. of seeds germinated}}{\text{Total no. of seeds taken for germination}} \times 100$$

Root length per plant (cm)

Root length was recorded at 30 days after transplanting (DAT). Five tomato plants were randomly selected from each treatment and carefully uprooted to preserve the entire root system. The roots were gently washed under running tap water to remove adhering soil particles without damaging the fine roots. The cleaned root samples were scanned using a root scanner, and the captured images were analyzed using root analysis software to determine the total root length, following the procedure described by Bouma *et al.* (2000) [8]. Root length was expressed in centimeters (cm) per plant, and the average value of the five sampled plants from each treatment was used for statistical analysis.

Root volume per plant (cm³)

Root volume was assessed at 30 days after transplanting (DAT) using five randomly selected tomato plants from each treatment. The plants were carefully removed from the soil, and the root systems were gently washed under running water to remove adhering soil particles. Root volume was determined by the water displacement method, in which the cleaned roots were immersed in a graduated measuring cylinder containing a known volume of water, following the procedure described by Bohm (1979) [9]. The increase in water level after immersion was recorded as the root volume and expressed in cubic centimeters (cm³) per plant. The mean root volume of the five sampled plants from each treatment was used for statistical analysis.

Membrane Stability Index (MSI)

The membrane stability index (MSI) was determined following the method described by Sairam (1994) [10] with slight modifications. Fresh leaf or root samples (0.1 g) were cut into small, uniform pieces and transferred into test tubes containing 10 mL of distilled water in two separate sets. The first set was incubated at 40 °C for 30 minutes, after which the electrical conductivity (C₁) of the solution was recorded using an EC meter. The second set was then heated at 100 °C for 15 minutes to completely disrupt the cellular membranes, and the final electrical conductivity (C₂) was measured after cooling. The

membrane stability index was calculated using the following formula:

$$\text{MSI}(\%) = 1 - \frac{C_1}{C_2} \times 100$$

Relative Water Content (RWC)

Relative water content (RWC) was determined following the method of Barrs and Weatherley (1962) [11]. Fresh leaf samples were collected and their fresh weight (FW) was recorded immediately after harvesting. The leaves were then immersed in distilled water for 48 hours at room temperature to attain full turgidity, after which the turgid weight (TW) was measured. Subsequently, the samples were oven-dried at 70 °C until a constant weight was obtained, and the dry weight (DW) was recorded. The relative water content was calculated using the following formula:

$$\text{RWC}(\%) = \frac{(FW - DW)}{(TW - DW)} \times 100$$

Leaf rolling

Leaf rolling was assessed at 60 Days After Transplanting (DAT) by randomly selecting five plants from each treatment. The degree of leaf rolling was visually evaluated using the Standard Evaluation System (SES) for Drought Tolerance developed by IRRI (1996) [12]. Each selected plant was assigned a score based on the severity of leaf rolling, and the mean score of the five plants was calculated to represent the treatment for statistical analysis.

Table 1: Standard evaluation system (SES-IRRI, 1996) in vegetative stage of tomato plant leaf rolling for Drought tolerance

Scale	Symptoms
0	Leaves healthy (no rolling)
1	Leaves start to fold (shallow rolling)
3	Leaves folded in a deep V-shape
5	Leaves fully cupped (U-shape)
7	Leaf margins touching (O-shape)
9	Leaves tightly rolled

Tip Drying

Tip drying was recorded at 60 Days After Transplanting (DAT) by observing five randomly selected plants from each treatment. The severity of tip drying was visually assessed following the Standard Evaluation System (SES) for Drought Tolerance prescribed by IRRI (1996) [12]. The scores obtained for the five plants were averaged, and the mean value was considered for statistical analysis.

Table 2: Standard evaluation system (SES-IRRI, 1996) [12] in vegetative stage of tomato plant tip drying for Drought tolerance
Plant Survival (%)

Scale	Symptoms
0	No symptoms
1	Slight tip drying
3	Tip drying extended up to 1/4 of the leaf
5	One-fourth to one-half of the leaf dried
7	More than two-thirds of the leaf fully dried
9	All plants apparently dead. Length in most leaves fully dried

Plant survival was determined by counting the number of seedlings that remained alive after transplanting and expressing it as a percentage of the total number of seedlings initially transplanted. The observations were recorded for each treatment, and the survival percentage was calculated using the following formula (Gomez & Gomez, 1984) [13]:

$$\text{Plant Survival (\%)} = \frac{\text{No. of Plant Survived}}{\text{No. of plants transplanted}} \times 100$$

Results and Discussion

Seed germination percentage (%)

The results revealed that moisture stress adversely affected seed germination in tomato, with the untreated control (T12) showing the lowest germination percentage under stress conditions. In contrast, seeds treated with different PGPR strains exhibited significantly higher germination compared to the untreated stressed control, indicating the beneficial role of PGPR in improving seed establishment under limited moisture availability. Although slight differences were observed among the PGPR treatments, their effects on seed germination were statistically at par, suggesting that all the tested strains were equally effective in enhancing germination and promoting early seedling establishment under moisture stress.

Significantly the highest germination percent of tomato seed was found under higher in T9 100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + *Azotobacter* 5 ml/kg Seed (92.32%) which was statistically superior over rest of the treatment. However, it was statistically at par with T6 100% RDF + 9704 *Pseudomonas fluorescens* 5gm/kg Seed + *Azotobacter* 5 ml/kg Seed and T11 100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + PSB 5 ml/kg Seed (91.52%) and (87.56%). The lowest germination percent of tomato seeds (79.62%) was found under without treated with PGPRs culture 100% RDF (120:80:80)/ha (control) (Table 1).

Seed treatment with PGPR significantly improves tomato growth and tolerance to moisture stress by enhancing seed germination, root development, water uptake, osmotic adjustment, and antioxidant defense systems. Under drought conditions, PGPR produce phytohormones (e.g., IAA), ACC deaminase, exopolysaccharides, and osmo-protectants, which help maintain plant water status and reduce oxidative damage. Similar findings have been reported by [Mayak et al. \(2004\)](#) [14], who demonstrated that PGPR improved drought tolerance and plant biomass under water-deficit conditions. [Yang et al. \(2009\)](#) [15] reported that PGPR regulate plant hormonal balance and improve stress adaptation. [Vurukonda et al. \(2016\)](#) [16].

Concluded that PGPR enhance root growth, relative water content, antioxidant enzyme activity, and overall drought tolerance. Likewise, [Backer et al. \(2018\)](#) [17] reviewed that seed inoculation with PGPR enhances nutrient acquisition, stress resilience, and crop productivity under abiotic stress. More recently, [Ahmad et al. \(2022\)](#) [18] reported that PGPR-mediated

seed treatment effectively improves tomato performance under drought by enhancing physiological and biochemical responses. Similarly, [Al-Turki et al. \(2023\)](#) [19] highlighted that PGPR improve drought resilience through enhanced root development, reduced stress ethylene production, and improved water-use efficiency. [Kumar et al. \(2024\)](#) [20] further reviewed that drought-responsive PGPR activate multiple physiological and molecular mechanisms that enhance seed germination and plant establishment under water-deficit conditions. In tomato, [Krishna et al. \(2024\)](#) [21] also demonstrated that plant growth-promoting microbial consortia improve physiological performance, biochemical attributes, and drought tolerance, leading to better crop establishment under moisture stress. Therefore, the higher seed germination percentage recorded in the present investigation confirms that PGPR seed treatment is an effective and eco-friendly strategy for improving tomato establishment under limited soil moisture

Table 3: Effect of plant growth promoting rhizobacteria on tomato seed germination %

S. No.	Treatments	Seed germination (%)
		2024-26
1.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed	86.09
2.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed	89.42
3.	100% RDF + <i>Azotobacter</i> 5 ml/kg Seed	86.84
4.	100% RDF + <i>Azospirillum</i> 5 ml/kg Seed	87.82
5.	100% RDF + PSB 5 ml/kg Seed	84.16
6.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + <i>Azotobacter</i> 5 ml/kg Seed	92.20
7.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + <i>Azospirillum</i> 5 ml/kg Seed	94.07
8.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + PSB 5 ml/kg Seed	89.73
9.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + <i>Azotobacter</i> 5 ml/kg Seed	93.05
10.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + <i>Azospirillum</i> 5 ml/kg Seed	85.22
11.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + PSB 5 ml/kg Seed	90.57
12.	100% RDF (120:80:80)/ha	79.62
	CD (5%)	6.58
	CV	4.42
	SE(m)	2.25

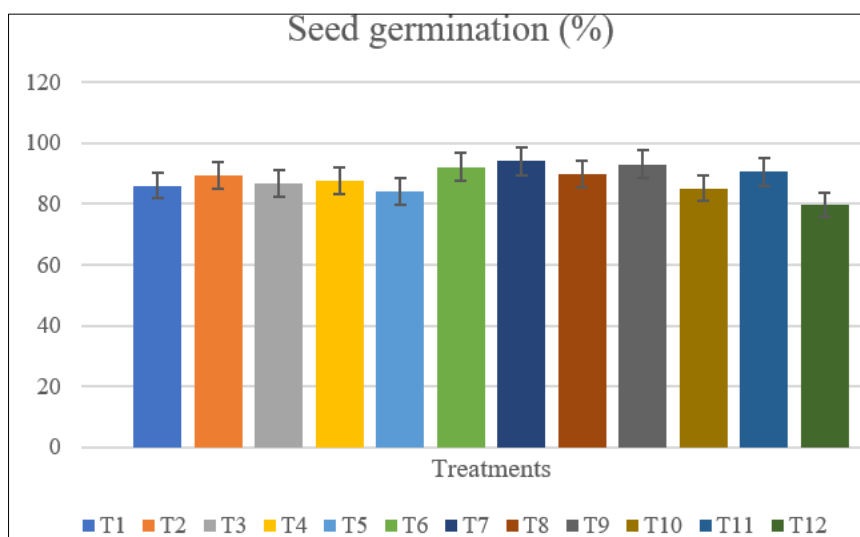


Fig 4: Effect of plant growth promoting rhizobacteria on tomato seed germination %

Root Length (cm)

The results indicated that moisture stress significantly reduced the root length of tomato plants, with the untreated control (T12) recording the shortest roots under stress conditions. In contrast, seed treatment with different PGPR strains significantly increased root length compared with the untreated stressed control, demonstrating the beneficial effect of PGPR on root growth under limited moisture availability. Although slight variations were observed among the PGPR treatments, their effects were statistically at par, indicating that all the tested strains were similarly effective in promoting root elongation and improving drought tolerance.

The findings of the study revealed that the moisture stress condition had a significant impact on the root length of Tomato. The maximum root (25.13 cm) was recorded under T9 100%

RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + *Azotobacter* 5 ml/kg Seed which was statistically superior over rest of the treatment. However, it was statistically at par with T8 100% RDF + 9704 *Pseudomonas fluorescens* 5gm/kg Seed + PSB 5 ml/kg Seed (23.76 cm) and in T10 100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + *Azospirillum* 5 ml/kg Seed (21.22 cm) during 2024-25 analysis respectively. The minimum root length of Tomato was recorded under T12 (100% RDF (120:80:80)/ha) which was (9.67 cm) during 2024-25 analysis respectively (Table 2, Figure 3 and 4).

The findings of the present study are in agreement with Vessey (2003) [22], reported that plant growth-promoting rhizobacteria stimulate root growth through improved nutrient availability and phytohormone production.

Table 4: Effect plant growth promoting rhizobacteria on tomato plant root length (cm)

S. No.	Treatments	Root length (cm)
		2024-26
1.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed	19.39
2.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed	20.67
3.	100% RDF + <i>Azotobacter</i> 5 ml/kg Seed	20.33
4.	100% RDF + <i>Azospirillum</i> 5 ml/kg Seed	19.75
5.	100% RDF + PSB 5 ml/kg Seed	18.59
6.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + <i>Azotobacter</i> 5 ml/kg Seed	16.33
7.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + <i>Azospirillum</i> 5 ml/kg Seed	13.09
8.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + PSB 5 ml/kg Seed	23.76
9.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + <i>Azotobacter</i> 5 ml/kg Seed	25.13
10.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + <i>Azospirillum</i> 5 ml/kg Seed	21.29
11.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + PSB 5 ml/kg Seed	18.97
12.	100% RDF (120:80:80)/ha	9.67
	CD (5%)	5.34
	CV	16.74
	SE(m)	1.83

Demonstrated that endophytic PGPR isolated from tomato roots significantly enhanced root development and plant vigor after inoculation. Lucas *et al.* (2023) [23] also observed that PGPR inoculation under moderate water stress improved tomato root growth, physiological performance, and drought adaptation. Furthermore, Pathania *et al.* (2023) [24] reported that efficient PGPR isolates effectively colonized the tomato rhizosphere and significantly promoted root development and overall plant growth under greenhouse conditions. These findings support the results of the present investigation, indicating that PGPR seed treatment is an effective strategy for improving root length and drought tolerance in tomato plants.

Lugtenberg and Kamilova (2009) [25] also explained that PGPR

enhance root architecture and plant growth by producing growth-promoting metabolites and facilitating nutrient uptake. Similarly, Bhattacharyya and Jha (2012) [26] concluded that PGPR improve root development and water acquisition through multiple direct and indirect mechanisms, leading to better plant performance under abiotic stress. Furthermore, Backer *et al.* (2018) [17] emphasized that PGPR-mediated improvement in root system architecture is a major factor contributing to enhanced drought tolerance and crop productivity. Therefore, the increased root length observed in the present investigation confirms the beneficial role of PGPR seed treatment in improving root development and drought adaptation in tomato plants.

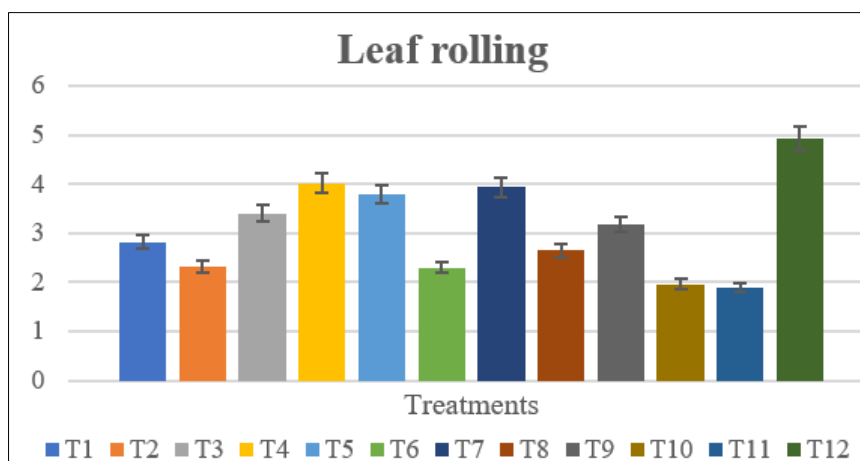


Fig 2: Effect plant growth promoting rhizobacteria on tomato plant root length (cm)



Fig 3: Effect plant growth promoting rhizobacteria on tomato plant root length and morphology under pot in moisture stress condition (T1) 100% RDF + 9704 *Pseudomonas fluorescens* 5gm/kg Seed, (T2) 100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed, (T3) 100% RDF + Azotobacter 5 ml/kg Seed, (T4) 100% RDF + Azospirillum 5 ml/kg Seed (T5) 100% RDF + PSB 5 ml/kg Seed, (T6) 100% RDF + 9704 *Pseudomonas fluorescens* 5gm/kg Seed + Azotobacter 5 ml/kg Seed



Fig 4: Effect plant growth promoting rhizobacteria on tomato plant root length and morphology under pot in moisture stress condition, (T7) 100% RDF + 9704 *Pseudomonas fluorescens* 5gm/kg Seed + Azospirillum 5 ml/kg Seed, (T8) 100% RDF + 9704 *Pseudomonas fluorescens* 5gm/kg Seed + PSB 5 ml/kg Seed (T9) 100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + Azotobacter 5 ml/kg Seed, (T10) 100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + Azospirillum 5 ml/kg Seed, (T11) 100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + PSB 5 ml/kg Seed, (T12) 100% RDF (120:80:80)/ha

Root Volume (cm³)

The results showed that moisture stress markedly reduced the root volume of tomato plants, with the untreated control (T12) recording the lowest root volume under stress conditions. However, seed treatment with different PGPR strains significantly improved root volume compared with the untreated stressed control, indicating the ability of PGPR to stimulate root proliferation under limited water availability. The differences among the PGPR treatments were statistically at par, suggesting that all the tested strains were equally effective in enhancing root development and improving plant adaptation to moisture stress.

The findings of the study revealed that the moisture stress condition had a significant impact on the root volume of Tomato. The maximum root volume (4.43 cm³) was recorded under T9 100% RDF + BARC G2 *Trichoderma virens* 5gm/kg

Seed + Azotobacter 5 ml/kg Seed during 2024-25, 2025-26 and in pooled analysis respectively, which was statistically superior over rest of the treatment. However, it was statistically at par T8 100% RDF + 9704 *Pseudomonas fluorescens* 5gm/kg Seed + PSB 5 ml/kg Seed (4.33 cm³) and in T10 100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + Azospirillum 5 ml/kg Seed (4.16 cm³) during 2024-25 analysis respectively. The minimum root volume of Tomato was recorded under T12 (100% RDF (120:80:80)/ha) which was (1.23 cm³) during 2024-25, 2025-26 and in pooled analysis respectively (Table 3). Plant growth-promoting rhizobacteria (PGPR) significantly increased root volume in tomato plants under moisture stress by stimulating root cell division, lateral root initiation, and root hair development through the production of phytohormones, particularly indole-3-acetic acid (IAA), along with improved nutrient solubilization and ACC deaminase activity. A larger root system enables plants to explore a greater soil volume for water and nutrient uptake, thereby improving drought tolerance and maintaining plant growth under limited moisture availability. Glick (2012) [27] reported that ACC deaminase-producing PGPR reduce stress-induced ethylene levels, resulting in enhanced root growth and better adaptation to water deficit conditions. Similarly, Lugtenberg and Kamilova (2009) [25] explained that effective rhizosphere colonization by PGPR promotes root system architecture and enhances plant performance under abiotic stress. More recently, Pathania *et al.* (2023) [24] demonstrated that efficient PGPR isolates significantly improved root development and overall growth of tomato through successful rhizosphere colonization. The results of the present investigation are in close agreement with these findings, as PGPR-treated tomato plants exhibited greater root volume than untreated plants under moisture stress.

Table 5: Effect plant growth promoting rhizobacteria on tomato plant root volume (cm³)

S. No.	Treatments	Root Volume (cm ³)
		2024-26
1.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed	19.39
2.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed	20.67
3.	100% RDF + Azotobacter 5 ml/kg Seed	20.33
4.	100% RDF + Azospirillum 5 ml/kg Seed	19.75
5.	100% RDF + PSB 5 ml/kg Seed	18.59
6.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + Azotobacter 5 ml/kg Seed	16.33
7.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + Azospirillum 5 ml/kg Seed	13.09
8.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + PSB 5 ml/kg Seed	23.76
9.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + Azotobacter 5 ml/kg Seed	25.13
10.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + Azospirillum 5 ml/kg Seed	21.29
11.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + PSB 5 ml/kg Seed	18.97
12.	100% RDF (120:80:80)/ha	9.67
	CD (5%)	5.34
	CV	16.74
	SE(m)	1.83

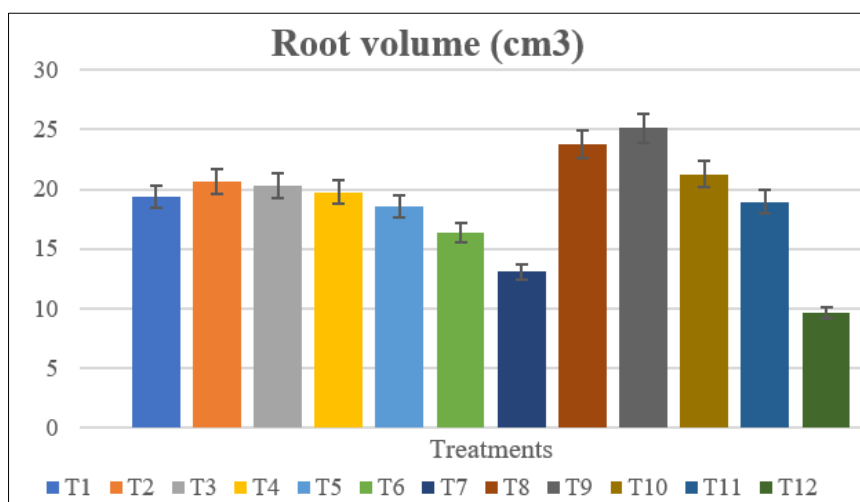


Fig 5: Effect plant growth promoting rhizobacteria on tomato plant root volume (cm³)

Membrane Stability Index (%)

The membrane stability index of tomato plants decreased under moisture stress, with the untreated control (T12) showing the lowest membrane stability. Seed treatment with PGPR significantly improved MSI compared with the untreated stressed control, suggesting that PGPR protected cellular membranes from drought-induced damage. Although slight differences were observed among the PGPR treatments, their effects were statistically at par, indicating similar effectiveness in preserving membrane integrity under moisture stress.

The findings of the study revealed that the moisture stress condition had a significant impact on the membrane stability index of Tomato. The highest membrane stability index (22.54%) was recorded under T3 100% RDF + *Azotobacter* 5 ml/kg Seed 2024-25, analysis respectively, which was

statistically superior over rest of the treatment. However, it was statistically at par with T11 100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + PSB 5 ml/kg Seed (20.29%) and in T5 (100% RDF + PSB 5 ml/kg Seed) (19.57 %) during 2024-25 analysis respectively. The lowest membrane stability index of Tomato was recorded under T12 (100% RDF (120:80:80)/ha) which was (14.61 %) during 2024-25 analysis respectively (Table 4).

The membrane stability index (MSI) was significantly higher in PGPR-treated tomato plants under moisture stress than in untreated plants, indicating better maintenance of cellular membrane integrity during drought conditions. PGPR enhance membrane stability by reducing oxidative damage through the activation of antioxidant defense enzymes, improving osmotic adjustment, and decreasing lipid peroxidation.

Table 6: Effect of plant growth promoting rhizobacteria in tomato Membrane stability index

S. No.	Treatments	Membrane stability index (%)
		2024-26
1.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed	18.07
2.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed	17.75
3.	100% RDF + <i>Azotobacter</i> 5 ml/kg Seed	22.54
4.	100% RDF + <i>Azospirillum</i> 5 ml/kg Seed	18.21
5.	100% RDF + PSB 5 ml/kg Seed	19.57
6.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + <i>Azotobacter</i> 5 ml/kg Seed	18.53
7.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + <i>Azospirillum</i> 5 ml/kg Seed	17.56
8.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + PSB 5 ml/kg Seed	19.17
9.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + <i>Azotobacter</i> 5 ml/kg Seed	18.40
10.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + <i>Azospirillum</i> 5 ml/kg Seed	17.32
11.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + PSB 5 ml/kg Seed	20.29
12.	100% RDF (120:80:80)/ha	14.61
	CD (5%)	1.99
	CV	6.37
	SE(m)	0.68

These responses help preserve membrane permeability and minimize electrolyte leakage, thereby improving cellular function under water-deficit stress. Yang *et al.* (2009) [15] reported that PGPR enhance plant tolerance to abiotic stress by regulating physiological and biochemical processes, including the protection of cellular membranes from oxidative injury. Similarly, Glick (2014) [28] explained that PGPR producing ACC deaminase lower stress-induced ethylene accumulation, thereby reducing membrane damage and improving stress tolerance. In tomato, Lucas *et al.* (2023) [23] demonstrated that

PGPR inoculation enhanced physiological performance under water stress by maintaining membrane integrity and improving antioxidant activity. Likewise, Pathania *et al.* (2023) [24] observed that efficient PGPR isolates promoted plant vigor and stress tolerance through successful rhizosphere colonization and improved physiological characteristics. These reports support the findings of the present investigation, where PGPR-treated tomato plants maintained a higher membrane stability index than untreated plants under moisture stress, reflecting improved tolerance to drought-induced cellular damage.

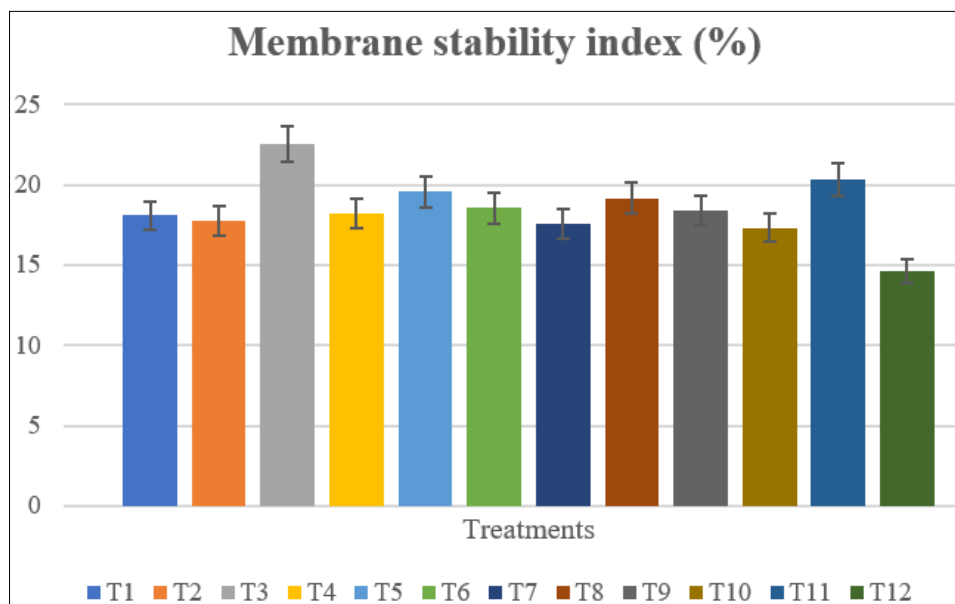


Fig 6: Effect of plant growth promoting rhizobacteria in tomato Membrane stability index

Relative Water Content (%)

Moisture stress caused a significant decline in the relative water content of tomato leaves, with the untreated control (T12) exhibiting the lowest RWC. In contrast, PGPR-treated plants maintained significantly higher relative water content than the

untreated stressed plants, reflecting improved water retention and plant water status under moisture deficit. The effects of the different PGPR strains were statistically at par, indicating their comparable efficiency in maintaining leaf hydration under stress conditions.

Table 7: Effect of plant growth promoting rhizobacteria in tomato Relative water content

S. No.	Treatments	Relative water content (%)
		2024-26
1.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed	63.35
2.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed	61.06
3.	100% RDF + <i>Azotobacter</i> 5 ml/kg Seed	70.19
4.	100% RDF + <i>Azospirillum</i> 5 ml/kg Seed	63.62
5.	100% RDF + PSB 5 ml/kg Seed	67.46
6.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + <i>Azotobacter</i> 5 ml/kg Seed	65.70
7.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + <i>Azospirillum</i> 5 ml/kg Seed	60.89
8.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kgSeed + PSB 5 ml/kg Seed	67.01
9.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kgSeed + <i>Azotobacter</i> 5 ml/kg Seed	65.35
10.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kgSeed + <i>Azospirillum</i> 5 ml/kg Seed	59.22
11.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kgSeed + PSB 5 ml/kg Seed	68.89
12.	100% RDF (120:80:80)/ha	52.51
	CD (5%)	7.76
	CV	7.22
	SE(m)	2.66

The findings of the study revealed that the moisture stress condition had a significant impact on the relative water content of Tomato. The highest relative water content (70.19%) was recorded under T3 100% RDF + *Azotobacter* 5 ml/kg Seed during 2024-25 in analysis respectively, which was statistically superior over rest of the treatment. However, it was statistically at par with T11 100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + PSB 5 ml/kg Seed (68.89%) and in T5 100% RDF + PSB 5 ml/kg Seed (67.46 %) during 2024-25, 2025-26 and in pooled analysis respectively. The lowest relative water content of Tomato was recorded under T12 (100% RDF

(120:80:80)/ha) which was (52.51 %) during 2024-25 in analysis respectively (Table 5).

The relative water content (RWC) of tomato leaves was significantly higher in PGPRtreated plants than in untreated plants under moisture stress, indicating improved plant water status and enhanced drought tolerance. PGPR help maintain leaf water content by stimulating root growth, increasing water uptake, promoting osmolyte accumulation, and regulating phytohormones such as abscisic acid and indole-3-acetic acid. These responses improve osmotic adjustment, reduce excessive water loss, and preserve cellular turgor under drought conditions

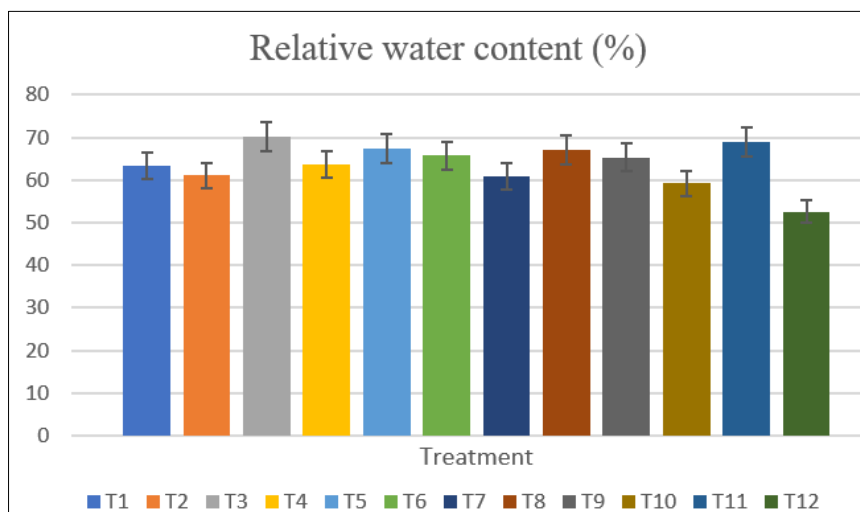


Fig 7: Effect of plant growth promoting rhizobacteria in tomato Relative water content

Vurukonda *et al.* (2016) ^[16] reported that PGPR improve plant water relations by enhancing root architecture, osmotic regulation, and water absorption under moisture-deficit conditions. Similarly, Backer *et al.* (2018) ^[17] explained that PGPR-mediated modifications in root growth and physiological processes enable plants to maintain higher tissue water content during abiotic stress. In tomato, Lucas *et al.* (2023) ^[23] demonstrated that PGPR inoculation significantly improved plant water status and physiological performance under moderate water stress, resulting in better drought tolerance. Likewise, Pathania *et al.* (2023) ^[24] observed that efficient PGPR isolates enhanced root development and plant vigor in tomato, thereby improving the plant's ability to withstand moisture stress. These findings are consistent with the results of the present investigation, where PGPR-treated tomato plants maintained significantly higher relative water content than untreated plants under moisture stress, indicating improved water retention capacity and enhanced tolerance to drought.

Leaf Rolling at 30 DAT

Moisture stress induced severe leaf rolling in tomato plants, with the untreated control (T12) exhibiting the highest degree of leaf rolling. However, PGPR-treated plants showed significantly lower leaf rolling than the untreated stressed plants, indicating improved plant water status and stress tolerance. The response of the different PGPR treatments was statistically at par, suggesting that all the tested strains were equally effective in reducing leaf rolling under moisture stress. The findings of the study revealed that the moisture stress condition had a significant impact on the leaf rolling of Tomato. The minimum leaf rolling (1.89 %) was recorded under T11 (100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + PSB 5 ml/kg Seed) during 2024-25 in pooled analysis respectively, which was statistically superior over rest of the treatment. However, it was statistically at par with T10 (100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + *Azospirillum* 5 ml/kg Seed) (1.96 %) and in T2 (100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed) (2.31 %) during 2024-25, 2025-26 and in pooled analysis respectively. The maximum leaf rolling of Tomato was recorded under T12 (100% RDF (120:80:80)/ha) which was (4.93%) during 2024-25 in analysis respectively (Table 6).

Leaf rolling is a common adaptive response of tomato plants to moisture stress and develops due to reduced leaf water potential, loss of cell turgor, and impaired water balance. In the present study, PGPR-treated tomato plants exhibited significantly less leaf rolling than untreated plants under moisture stress, indicating improved tolerance to drought. PGPR reduce leaf rolling by enhancing root growth, increasing water uptake, improving osmotic adjustment, and regulating stress-responsive phytohormones, thereby maintaining leaf hydration and turgor pressure. Yang *et al.* (2009) ^[15] reported that PGPR improve plant adaptation to abiotic stresses by regulating physiological processes involved in water conservation and stress tolerance.

Table 8: Effect of plant growth promoting rhizobacteria on leaf rolling (%) of tomato

S. No.	Treatments	Leaf rolling
		2024-26
1.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed	2.82
2.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed	2.31
3.	100% RDF + <i>Azotobacter</i> 5 ml/kg Seed	3.40
4.	100% RDF + <i>Azospirillum</i> 5 ml/kg Seed	4.01
5.	100% RDF + PSB 5 ml/kg Seed	3.78
6.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + <i>Azotobacter</i> 5 ml/kg Seed	2.30
7.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + <i>Azospirillum</i> 5 ml/kg Seed	3.93
8.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + PSB 5 ml/kg Seed	2.64
9.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + <i>Azotobacter</i> 5 ml/kg Seed	3.17
10.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + <i>Azospirillum</i> 5 ml/kg Seed	1.96
11.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + PSB 5 ml/kg Seed	1.89
12.	100% RDF (120:80:80)/ha	4.93
	CD (5%)	0.70
	CV	13.35
	SE(m)	0.24

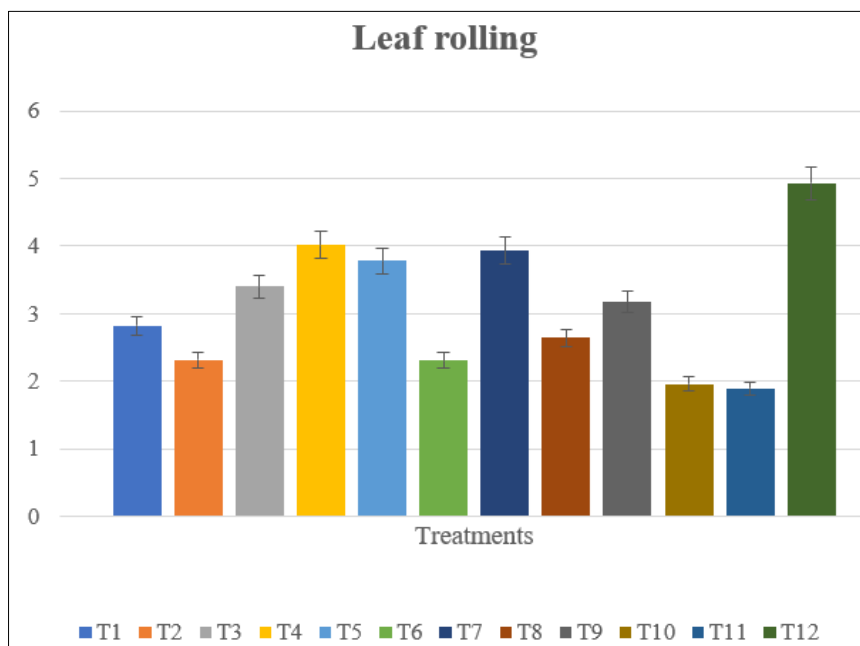


Fig 8: Effect of plant growth promoting rhizobacteria on leaf rolling (%) of tomato



Fig 9: Effect plant growth promoting rhizobacteria on tomato plant physiological traits under moisture stress condition (T1) 100% RDF + 9704 *Pseudomonas fluorescens* 5gm/kg Seed, (T2) 100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed, (T3) 100% RDF + *Azotobacter* 5 ml/kg Seed, (T4) 100% RDF + *Azospirillum* 5 ml/kg Seed



Fig 10: Effect plant growth promoting rhizobacteria on tomato plant physiological traits under moisture stress condition conditions (T5) 100% RDF + PSB 5 ml/kg Seed, (T6) 100% RDF + 9704 *Pseudomonas fluorescens* 5gm/kg Seed + *Azotobacter* 5 ml/kg Seed, (T7) 100% RDF + 9704 *Pseudomonas fluorescens* 5gm/kg Seed + *Azospirillum* 5 ml/kg Seed, (T8) 100% RDF + 9704 *Pseudomonas fluorescens* 5gm/kg Seed + PSB 5 ml/kg Seed

Glick (2014) [28] further explained that ACC deaminase-producing PGPR reduce stress-induced ethylene production, which minimizes drought injury and helps maintain normal plant growth under water-deficit conditions. Nadeem *et al.* (2014) [29] observed that PGPR inoculation improves plant water status, osmotic balance, and physiological stability under drought, thereby reducing visible stress symptoms such as leaf

rolling and wilting. More recently, Pathania *et al.* (2023) [24] demonstrated that efficient PGPR isolates enhanced tomato growth and stress tolerance through effective rhizosphere colonization and improved root development. These findings support the results of the present investigation, where PGPR-treated tomato plants showed reduced leaf rolling under moisture stress compared with untreated plants.

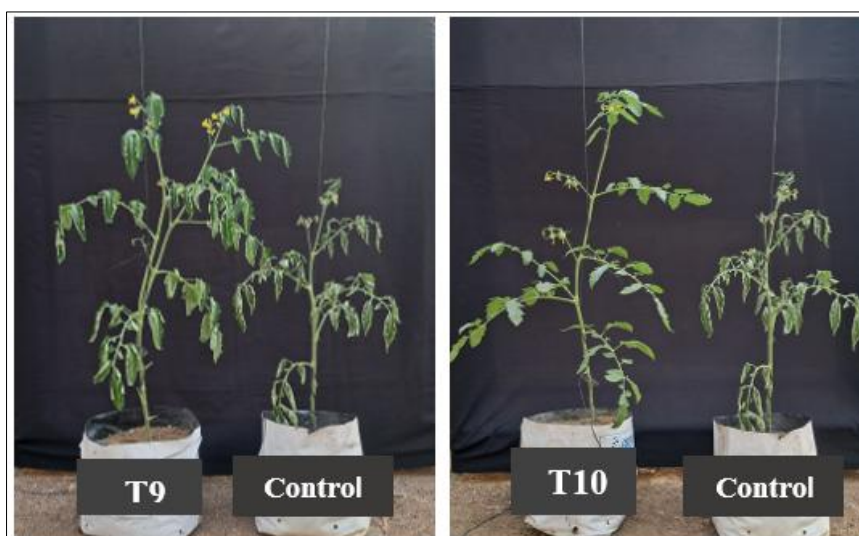




Fig 11: Effect plant growth promoting rhizobacteria on tomato plant physiological traits under moisture stress condition conditions (T9) 100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + Azotobacter 5 ml/kg Seed, (T10) 100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + Azospirillum 5 ml/kg Seed, (T11) 100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + PSB 5 ml/kg Seed

Tip drying 30 DAT

The severity of tip drying increased under moisture stress, with the untreated control (T12) showing the maximum tip drying symptoms. Seed treatment with different PGPR strains significantly reduced tip drying compared with the untreated stressed control, reflecting the protective role of PGPR in minimizing drought-induced leaf damage. The differences among the PGPR treatments were statistically at par, indicating that all the tested strains were similarly effective in alleviating tip drying under moisture stress.

The findings of the study revealed that the moisture stress condition had a significant impact on the tip drying of tomato.

Table 9: Effect of plant growth promoting rhizobacteria on Tip drying (%) of tomato

S. No.	Treatments	Tip drying
		2024-26
1.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed	5.10
2.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed	4.53
3.	100% RDF + Azotobacter 5 ml/kg Seed	5.47
4.	100% RDF + Azospirillum 5 ml/kg Seed	5.98
5.	100% RDF + PSB 5 ml/kg Seed	5.64
6.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + Azotobacter 5 ml/kg Seed	4.66
7.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + Azospirillum 5 ml/kg Seed	5.87
8.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + PSB 5 ml/kg Seed	4.80
9.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + Azotobacter 5 ml/kg Seed	5.31
10.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + Azospirillum 5 ml/kg Seed	4.31
11.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + PSB 5 ml/kg Seed	4.03
12.	100% RDF (120:80:80)/ha	6.63
	CD (5%)	1.34
	CV	15.30
	SE(m)	0.46

The minimum tip drying (4.03 %) was recorded under T11 (100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + PSB 5 ml/kg Seed) during 2024-25 in pooled analysis respectively, which was statistically superior over rest of the treatment. However, it was statistically at par with T10 (100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + Azospirillum 5 ml/kg Seed) (4.31 %) and in T2 (100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed) (4.53 %) during 2024-25 in analysis respectively. The maximum tip drying of Tomato was recorded under T12 (100% RDF (120:80:80)/ha) which was (6.63%) during 2024- 25in analysis respectively (Table 7).

The incidence of tip drying was markedly reduced in PGPR-treated tomato plants under moisture stress compared with untreated plants. Tip drying is a typical symptom of drought-induced cellular dehydration and oxidative damage, which adversely affects leaf function and plant growth. PGPR reduce these adverse effects by enhancing root water uptake, improving nutrient acquisition, regulating phytohormones, and activating antioxidant defense systems that protect cellular membranes from oxidative injury. Nadeem *et al.* (2014) ^[29] reported that PGPR improve plant water relations and osmotic adjustment under drought, thereby minimizing tissue dehydration and maintaining plant growth. Ngumbi and Kloepper (2016) ^[30] further explained that PGPR enhance drought tolerance through improved physiological and biochemical responses, including efficient water use and ROS detoxification. More recently, Chandrasekaran *et al.* (2022) ^[31] reported that drought-tolerant PGPR significantly enhanced plant water status, antioxidant activity, and stress tolerance, thereby reducing visible drought injury in crop plants. Likewise, Ojuederie *et al.* (2019) ^[32] demonstrated that PGPR improve plant resilience under water deficit by promoting antioxidant metabolism and maintaining cellular homeostasis. These findings are in close agreement with the present investigation, where PGPR-treated tomato plants exhibited significantly lower tip drying than untreated plants under moisture stress

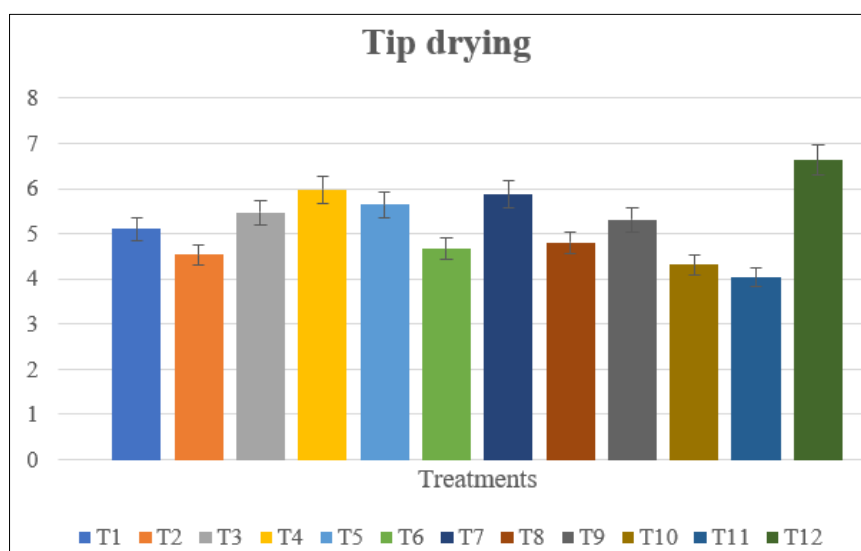


Fig 12: Effect of plant growth promoting rhizobacteria on Tip drying (%) of tomato Plant Survival (%) at 30 DAT

Moisture stress adversely affected the plant survival percentage of tomato plants, with the untreated control (T12) recording the lowest survival. In contrast, PGPR-treated plants exhibited significantly higher plant survival percentages, demonstrating the beneficial role of PGPR in improving plant establishment and tolerance to moisture stress. The survival rates among the PGPR treatments were statistically at par, indicating that all the tested strains were similarly effective in enhancing plant survival under moisture-deficit conditions.

The findings of the study revealed that the moisture stress condition had a significant impact on the plant survival of Tomato. The maximum plant survival (92.32 %) was recorded under T8 (100% RDF + 9704 *Pseudomonas fluorescens* 5gm/kg Seed + PSB 5 ml/kg Seed) during 2024-25 in analysis respectively, which was statistically superior over rest of the treatment. However, it was statistically at par with T6 (100% RDF + 9704 *Pseudomonas fluorescens* 5gm/kg Seed + *Azotobacter* 5 ml/kg Seed) (91.52%) and in T11 (100% RDF + BARC G2 *Trichoderma virens* 5gm/kg Seed + PSB 5 ml/kg Seed) (87.56 %) during 2024-25 in analysis respectively. The minimum plant survival of Tomato was recorded under T12 (100% RDF (120:80:80)/ha) which was (77.86%) during 2024-25 in analysis respectively. (Table 8).

The survival percentage of tomato plants was significantly higher in PGPR-treated plants than in untreated plants under moisture stress. Improved plant survival can be attributed to the ability of PGPR to enhance root development, improve water and nutrient uptake, maintain cellular water status, and activate antioxidant defense mechanisms that protect plants from drought-induced oxidative damage. In addition, PGPR regulate phytohormones and stimulate osmolyte accumulation, enabling plants to sustain physiological activities under limited soil moisture. Nadeem *et al.* (2014) [29] reported that PGPR improve drought tolerance by enhancing root growth, nutrient acquisition, osmotic adjustment, and stress-responsive physiological processes, thereby increasing plant survival under water-deficit conditions. Similarly, Ngumbi and Kloepper (2016) [30] demonstrated that beneficial rhizobacteria improve plant adaptation to drought through enhanced water-use efficiency, antioxidant activity, and regulation of stress-related metabolites. Ahluwalia *et al.* (2021) [33] further explained that PGPR alleviate drought stress by improving root architecture, maintaining plant water balance, and reducing oxidative damage, resulting in better crop establishment and survival. Likewise, Zia *et al.* (2021) [34] reported that PGPR-mediated production of exopolysaccharides, osmoprotectants, and

phytohormones improves rhizosphere moisture retention and cellular homeostasis, thereby enhancing plant survival under drought conditions.

Table 10: Effect plant growth promoting rhizobacteria on tomato Plant survival (%)

S. No.	Treatments	Plant survival (%)
		2024-26
1.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed	82.43
2.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed	82.98
3.	100% RDF + <i>Azotobacter</i> 5 ml/kg Seed	81.50
4.	100% RDF + <i>Azospirillum</i> 5 ml/kg Seed	80.82
5.	100% RDF + PSB 5 ml/kg Seed	80.78
6.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + <i>Azotobacter</i> 5 ml/kg Seed	91.52
7.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + <i>Azospirillum</i> 5 ml/kg Seed	83.56
8.	100% RDF + 9704 <i>Pseudomonas fluorescens</i> 5gm/kg Seed + PSB 5 ml/kg Seed	92.32
9.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + <i>Azotobacter</i> 5 ml/kg Seed	84.07
10.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + <i>Azospirillum</i> 5 ml/kg Seed	86.56
11.	100% RDF + BARC G2 <i>Trichoderma virens</i> 5gm/kg Seed + PSB 5 ml/kg Seed	87.56
12.	100% RDF (120:80:80)/ha	77.86
	CD (5%)	6.99
	CV	4.92
	SE(m)	2.39

More recently, Ahmad *et al.* (2022) [18] observed that PGPR increase drought tolerance by regulating phytohormones, ACC deaminase activity, antioxidant enzymes, and osmolyte accumulation, leading to improved plant growth and survival. Furthermore, Zhao *et al.* (2023) [35], through a meta-analysis, concluded that PGPR inoculation significantly enhances plant physiological performance, antioxidant defense, and water-use efficiency, ultimately increasing plant survival under drought stress. These findings are in close agreement with the present investigation, where PGPR-treated tomato plants recorded a significantly higher survival percentage than untreated plants under moisture stress, confirming the effectiveness of PGPR in improving drought tolerance.

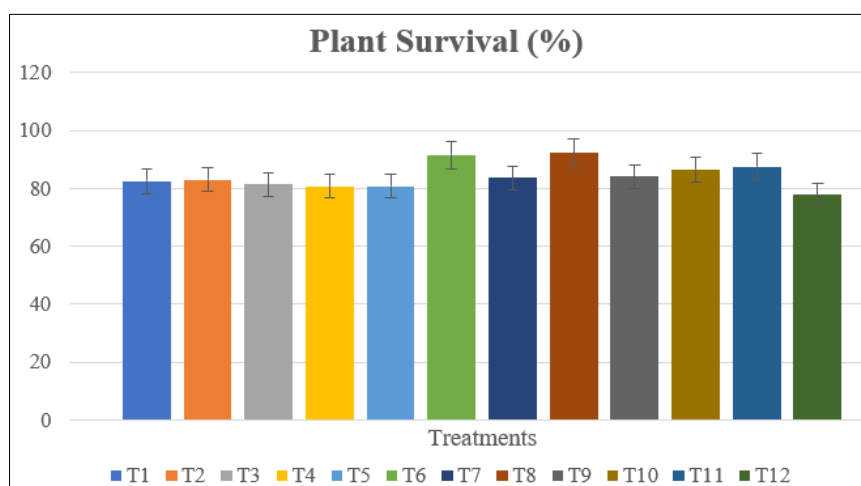


Fig 13: Effect plant growth promoting rhizobacteria on tomato Plant survival (%)

References

- Rai GK, Magotra I, Khanday DM, Choudhary SM, Bhatt A, Gupta V, *et al.* Boosting drought tolerance in tomatoes through stimulatory action of salicylic acid imparted antioxidant defense mechanisms. *Agronomy*. 2024;14(6):1227.
- Varma A, Tuteja N, Choudhary DK. PGPR-mediated amelioration of crops under salt stress. In *Plant-microbe interaction: an approach to sustainable agriculture*. Singapore: Springer Singapore; 2017:205-226.
- Khan AG. Role of soil microbes in the rhizospheres of plants growing on trace metal contaminated soils in phytoremediation. *Journal of trace Elements in Medicine and Biology*. 2005;18(4):355-364.
- Altomare C, Norvell WA, Björkman T, Harman GE. Solubilization of phosphates and micronutrients by the plant-growth-promoting and biocontrol fungus *Trichoderma harzianum* Rifai 1295-22. *Applied and Environmental Microbiology*. 1999;65(7):2926-2933.
- Hermosa R, Viterbo A, Chet I, Monte E. Plant-beneficial effects of *Trichoderma* and of its genes. *Microbiology*. 2012;158(1):17-25.
- Liu X, Zhang W, Feng W. Impact of PGPR on Tomato Drought Tolerance: Insights into Plant Stress Mechanisms. *Frontiers in Plant Science*. 2021;12:717-732.
- International Seed Testing Association. International rules for seed testing. *Seed Science and Technology*. 1985;13(2):299-355.
- Bouma TJ, Nielsen KL, Koutstaal B, Lynch JP. Sample preparation and scanning protocol for computerized analysis of root length and diameter. *Plant and Soil*. 2000;218(1-2):185-196.
- Bohm W. *Methods of studying root systems*. Springer-Verlag; 1979.
- Sairam RK. Effects of moisture stress on physiological activities of two contrasting wheat genotypes. *Indian Journal of Experimental Biology*. 1994;32:584-593.
- Barrs HD, Weatherley PE. A re-examination of the relative turgidity technique for estimating water deficits in leaves. *Australian Journal of Biological Sciences*. 1962;15(3):413-428.
- International Rice Research Institute. *Standard evaluation system for rice* (4th ed.). International Rice Research Institute; 1996.
- Gomez KA, Gomez AA. *Statistical procedures for agricultural research* (2nd ed.). John Wiley & Sons; 1984.
- Mayak S, Tirosh T, Glick BR. Plant growth-promoting bacteria confer resistance in tomato plants to salt and water stress. *Plant Science*. 2004;166(2):525-530.
- Yang J, Kloepper JW, Ryu CM. Rhizosphere bacteria help plants tolerate abiotic stress. *Trends in Plant Science*. 2009;14(1):1-4.
- Vurukonda SSKP, Vardharajula S, Shrivastava M, SkZ A. Enhancement of drought stress tolerance in crops by plant growth-promoting rhizobacteria. *Microbiological Research*. 2016;184:13-24.
- Backer R, Rokem JS, Ilangumaran G, Lamont J, Praslickova D, Ricci E, *et al.* Plant growth-promoting rhizobacteria: Context, mechanisms of action, and roadmap to commercialization of bio-stimulants for sustainable agriculture. *Frontiers in Plant Science*. 2018;9:1473.
- Ahmad HM, Fiaz S, Hafeez S, Zahra S, Shah AN, Gul B, Aziz O, Mahmood-Ur-Rahman, Fakhar A, Rafique M, Chen Y, Yang SH, Wang X. Plant growth-promoting rhizobacteria eliminate the effect of drought stress in plants: A review. *Frontiers in Plant Science*. 2022;13:875774.
- Al-Turki A, Murali M, Omar AF, Rehan M, Sayyed R. Recent advances in PGPR-mediated resilience toward interactive effects of drought and salt stress in plants. *Frontiers in Microbiology*. 2023;14.<https://doi.org/10.3389/fmicb.2023.1214845>
- Kumar P, Vashistha H, Kumar S. PGPR attributes and molecular identification of non-rhizobial Endophytes for growth enhancement of *Sesbania sesban* (L) Merr.. *The Journal of the Indian Botanical Society*. 2024;104(03).<https://doi.org/10.61289/jibs2024.05.15.123>
- Krishna R, Ansari WA, Altaf M, Jaiswal DK, Pandey S, Singh AK, *et al.* Impact of plant growth-promoting microorganism (PGPM) consortium on biochemical properties and yields of tomato under drought stress. *Life*. 2024;14(10):1333.
- Vessey JK. Plant growth promoting rhizobacteria as biofertilizers. *Plant and Soil*. 2003;255(2):571-586.
- Lucas JA, Garcia-Villaraco A, Montero-Palmero MB, Montalban B, Ramos-Solano B, Gutierrez-Mañero FJ. Physiological and genetic modifications induced by plant-growth-promoting rhizobacteria (PGPR) in tomato plants under moderate water stress. *Biology*. 2023;12(7):901.
- Pathania P, Gulati D, Setia H, Bhatia R. Characterization and performance evaluation of plant growth promoting bacteria in tomato rhizosphere. *South African Journal of Botany*. 2023;161:388-394.

25. Lugtenberg B, Kamilova F. Plant-growth-promoting rhizobacteria. Annual Review of Microbiology. 2009;63:541–556.
26. Bhattacharyya PN, Jha DK. Plant growth-promoting rhizobacteria (PGPR): Emergence in agriculture. World Journal of Microbiology and Biotechnology. 2012;28(4):1327–1350.
27. Glick BR. Plant growth-promoting bacteria: Mechanisms and applications. Scientifica. 2012;2012:963401.
28. Glick BR. Bacteria with ACC deaminase can promote plant growth and help to feed the world. Microbiological Research. 2014;169(1):30–39.
29. Nadeem SM, Ahmad M, Zahir ZA, Javaid A, Ashraf M. The role of mycorrhizae and plant growth-promoting rhizobacteria (PGPR) in improving crop productivity under stressful environments. Biotechnology Advances. 2014;32(2):429–448.
30. Ngumbi E, Kloepper JW. Bacterial-mediated drought tolerance: Current and future prospects. Applied Soil Ecology. 2016;105:109–125.
31. Chandrasekaran M, Chanratana M, Kim K, Seshadri S, Sa T. Plant growthpromoting rhizobacteria improve drought stress tolerance in crop plants: Mechanisms and applications. Frontiers in Plant Science. 2022;13:1031278.
32. Ojuederie OB, Olanrewaju OS, Babalola OO. Plant growth-promoting rhizobacterial mitigation of drought stress in plants: Implications for sustainable agriculture. Agronomy. 2019;9(11):712.
33. Ahluwalia O, Singh PC, Bhatia R. A review on drought stress in plants: Implications, mitigation and the role of plant growth-promoting rhizobacteria. Resources, Environment and Sustainability. 2021;5:100032.
34. Zia R, Nawaz MS, Siddique MJ, Hakim S, Imran A. Plant survival under drought stress: Implications, adaptive responses, and integrated rhizosphere management strategy for stress mitigation. Microbiological Research. 2021;242:126626.
35. Zhao X, Yuan X, Xing Y, *et al.* A meta-analysis on morphological, physiological and biochemical responses of plants with PGPR inoculation under drought stress. Plant, Cell & Environment. 2023;46(1):199–214.
36. Ahmad HM, Fiaz S, Hafeez S, *et al.* Plant growth-promoting rhizobacteria eliminate the effect of drought stress in plants: A review. Frontiers in Plant Science. 2022;13:875774.
37. Cortleven A, Leuendorf JE, Frank M, Pezzetta D, Bolt S, Schmülling T. The cytokinin-producing plant beneficial bacterium *Pseudomonas fluorescens* G20-18 primes tomato (*Solanum lycopersicum*) for enhanced drought stress responses. Journal of Plant Physiology. 2022;270:153629.
38. Krishna R, Ansari WA, Soumia PS, Yadav A, Jaiswal DK, Kumar S, *et al.* Biotechnological interventions in tomato (*Solanum lycopersicum*) for drought stress tolerance: Achievements and future prospects. BioTech. 2022;11(4):48.