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EVALUATION OF COMMERCIAL AND NON-COMMERCIAL PLANT GROWTH-PROMOTING RHIZOBACTERIA (PGPR) FOR IMPROVING TOMATO GROWTH AND FRUIT QUALITY

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Abstract

Plant growth-promoting rhizobacteria (PGPR) have emerged as sustainable alternatives to synthetic fertilizers for improving crop productivity and fruit quality; however, comparative field evaluations of commercial and locally developed multi-strain formulations remain limited. Therefore, this study evaluated the comparative effects of two commercial (TB1 and TB2) and four non-commercial (BS1, BS2, BS3 and BS4) PGPR combinations, together with a mineral fertilizer treatment (G) and an untreated control (O), on the yield, vegetative growth, and fruit quality of 'Gülpembe' tomato (*Solanum lycopersicum* L.). The trial was established under field conditions in a randomized complete block design (RCBD) with three replications and fifteen plants per replicate. The bacterial combinations contained strains of *Bacillus megaterium, Bacillus licheniformis*, *Bacillus subtilis*, *Pseudomonas fluorescens* and *Pantoea agglomerans*, selected on the basis of complementary plant growth-promoting traits, including phosphate solubilization, indole-3-acetic acid (IAA) production, siderophore production, biological nitrogen fixation and induction of systemic resistance. The parameters evaluated included total fruit yield, plant height, stem (collar) diameter, average fruit weight, fruit chroma and hue angle, fruit firmness, titratable acidity, total soluble solids (°Brix), lycopene content, total phenolic content and antioxidant capacity. Combined application of PGPR significantly improved vegetative growth, yield, and quality as compared with the control. Notably, the performance of non-commercial four-strain combinations BS3 and BS4 was equal or better than the commercially available PGPR and conventional mineral fertilizers for all traits like lycopene content, total phenolic content (TPC), antioxidant capacity and total soluble solids (TSS). These results suggest that locally characterized multi-strain PGPR combinations are effective biofertilizers for sustainable tomato production. Moreover, these biofertilizers were cost-effective and environment friendly alternatives to conventional chemical fertilizers.

Key words: Bacillus; Biofertilizer; Fruit quality; Pseudomonas; Plant growth-promoting rhizobacteria; Sustainable agriculture; Tomato yield

Introduction

Tomato (*Solanum lycopersicum* L.) is famous for its nutritional and economical value, cultivated across the globe with total annual production, approximately 186 million tons in 2022 (Anon., 2023). Beyond its widespread culinary use, tomato is recognized as a major dietary source of health-promoting bioactive compounds, including lycopene, carotenoids, phenolic compounds, flavonoids and ascorbic acid (Issifu *et al.,* 2023; Tatar et al., 2025; Wei et al., 2025). Globally, continuous increase in tomato demand, combined with growing concern over the environmental sustainability of intensive vegetable production, has triggered massive research into production strategies that reduce reliance on synthetic chemical inputs while maintaining or improving yield and fruit quality and moreover, it necessitates to develop cost effective and environment friendly strategy (Adedayo *et al.,* 2022; Sun *et al.,* 2024).

The long-term dependence of conventional agriculture on chemical fertilizers has been associated with serious environmental drawbacks, including degradation of soil structure, contamination of water resources and disruption of soil microbial communities (Biswas *et al.,* 2024; Igiehon *et al.,* 2024; Sajid et al., 2025). These concerns have directed scientific attention toward environmentally compatible alternatives, among which the application of plant growth-promoting rhizobacteria (PGPR) is considered one of the most promising strategies (Khan *et al.,* 2023a; Khan *et al.,* 2023b; Hasan *et al.,* 2024). PGPR colonize the plant rhizosphere and stimulate plant growth and stress tolerance through a combination of direct and indirect mechanisms.

PGPR promote plant growth through mechanisms such as biological nitrogen fixation, phosphate solubilization, production of phytohormones (including indole-3-acetic acid and cytokinins), siderophore biosynthesis and induction of systemic resistance against pathogens (Hernández-Amador *et al.,* 2024; Igiehon *et al.,* 2024; Hammoud et al., 2025). Bacterial genera most frequently associated with plant growth promotion include *Bacillus*, *Pseudomonas*, *Azospirillum*, *Azotobacter* and *Pantoea*. Due to their dual role, these microorganisms are extensively being used as these are not only helpful to improve soil fertility but also improve the quality of fruit (Biswas et al., 2024; Hasan et al., 2024).

Gashash *et al.,* (2022) reported that inoculation with *Bacillus subtilis* and *Bacillus amyloliquefaciens* significantly increased plant biomass, total soluble solids and ascorbic acid content. Issifu *et al*., (2023) demonstrated that *Pseudomonas fluorescens* and related strains markedly improved lycopene, carotenoid and tannin content together with antioxidant activity in tomato fruit. Similarly, Pérez Rodriguez *et al.,* (2020) showed that co-

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inoculation with *Pseudomonas fluorescens* and *Azospirillum brasilense* enhanced both yield and fruit quality under field conditions. More recently, Khomampai *et al.,* (2024) reported that inoculation with endophytic actinomycetes improved vitamin C, lycopene and antioxidant capacity in tomato fruit, while Torres-Solórzano *et al.,* (2025) showed that selected *Pseudomonas* spp. isolates increased tomato yield by 54–73% and substantially raised fruit lycopene concentration under a fertilization program reduced by up to 50% in nitrogen, phosphorus and calcium. In a related approach, Altimira *et al.,* (2024) demonstrated that a two-strain *Bacillus safensis–Bacillus siamensis* formulation maintained full tomato productivity under a fertilization program reduced by 33%, underscoring the practical potential of PGPR-based fertilizer-replacement strategies. Tahiri *et al.,* (2022) further confirmed that PGPR, whether applied alone or combined with arbuscular mycorrhizal fungi and compost, improved tomato growth, yield, fruit quality and water-stress tolerance. At the field scale, Kurt (2025) showed that a locally adapted, five-strain PGPR consortium significantly improved nutrient dynamics and yield of a major field crop grown under semi-arid conditions in Türkiye, supporting the agronomic relevance of regionally isolated, multi-strain bacterial combinations for Turkish production systems.

Although numerous studies have demonstrated the beneficial effects of individual PGPR strains on tomato growth and fruit quality, comparatively few investigations have directly evaluated the field performance of commercial and locally developed multi-strain formulations under identical experimental conditions (Adedayo *et al.,* 2022; Altimira *et al.,* 2024; Moussa et al., 2026). Furthermore, limited information is available regarding whether locally isolated bacterial consortia can provide agronomic and fruit-quality benefits comparable to commercially available products. Because the effectiveness of multi-strain PGPR formulations depends on complex interactions among bacterial strains, host genotype, and environmental conditions, comparative field evaluations are essential for identifying cost-effective and regionally adapted biofertilizer strategies (Hernández-Amador *et al.,* 2024; Sun *et al.,* 2024).

'Gülpembe' tomato is a locally adapted, commercially significant cultivar valued for its distinctive organoleptic characteristics. However, the effects of PGPR application on the yield and quality traits of this particular cultivar have not been systematically investigated. Therefore, the present study aimed to evaluate, under field conditions, the comparative effects of two commercial and four non-commercial PGPR combinations, a mineral fertilizer application and an untreated control, on several agronomic and quality parameters of 'Gülpembe' tomato.

Materials and Methods

Plant material and experimental site: The study was conducted in Eskişehir, Türkiye, over four consecutive growing seasons between 2020 and 2024. Tomato seedlings were initially raised under controlled greenhouse conditions to ensure uniform seedling establishment and were transplanted to the experimental field at the 4–5 true-leaf stage. The field experiment was subsequently conducted under open-field conditions using standard horticultural cultivation practices recommended for the region, thereby enabling the evaluation of PGPR performance under practical production conditions (Adedayo *et al.,* 2022; Ullah et al., 2026).

The field experiment was conducted at the experimental research facilities of Eskişehir Osmangazi University, Eskişehir, Türkiye. The region is characterized by a continental climate, with hot, dry summers and cold winters, conditions that are representative of major tomato-growing areas in central Türkiye. Standard agronomic management practices, including irrigation, weed control, and pest management, were uniformly applied to all experimental plots throughout the study to minimize the influence of non-treatment factors on plant growth and fruit development.

Experimental design and treatments: The trial was arranged in a randomized complete block design (RCBD) with three replications, each replicate comprising fifteen plants per treatment. Eight treatments were applied in total: two commercial bacterial combinations (TB1 and TB2), four non-commercial bacterial combinations (BS1, BS2, BS3 and BS4), a mineral fertilizer treatment (G) based on soil test results, and an untreated control (O). The different treatment combinations for bacterial application are presented in Table 1.

Preparation of bacterial combinations were made in such a way that different bacterial strains were applied with different plant growth promoting traits to improve biological nitrogen fixation, phosphate solubilization, indole-3-acetic acid (IAA) production, siderophore production, biocontrol activity, and induced systemic resistance (ISR). This multi-trait approach was exploited to capitalize the potential collaborative interactions among bacterial strains and to assess whether functionally diverse associations provide superior agronomic performance compared with simpler formulations under field conditions.

Bacterial inoculation procedure: Before transplanting bacterial strains were cultured and formulated. Concentration of bacterial suspensions of approximately 10^8 colony forming units (CFU) mL^{-1} were prepared, with standard inoculum densities for field-scale PGPR trials as reported by Kurt, (2025) and Tahiri *et al.* (2022). While, manufacturer guidelines were used for commercial combinations (TB1 and TB2), however, for direct comparison non-commercial combinations (BS1–BS4) were applied at the same inoculum density. Bacterial inoculation was done at transplanting through root-dip, furthermore two times soil-drench with prepared concentrations was applied at 30-days interval after transplanting. Selection of application schedule was made to ensure the early root colonization, maintain an adequate bacterial population during entire growing period, and exploit the persistence and functional activity of PGPR strains under field conditions as performed in recent studies (Kurt, 2025; Tahiri *et al*., 2022).

Measurements and observations: During the growing season and at harvest, the following parameters were recorded: Vegetative growth parameters were recorded at physiological maturity immediately before harvest, whereas fruit quality analyses were performed using fully ripened fruits collected at commercial harvest maturity. Unless otherwise stated, measurements were conducted using representative samples collected from each experimental plot following standard horticultural evaluation procedures.

Agronomic parameters: total fruit yield (kg plant^{-1} and t ha^{-1}), plant height (cm), stem (collar) diameter (mm), average fruit weight (g) and yield per plant (kg).

Colorimetric parameters: Fruit colour was measured on the equatorial region of three representative fruits per plot using a colorimeter. Chroma (C*) and hue angle (h°) were calculated from the CIE L*, a*, b* coordinates using the standard formulae $C^* = (a^{*2} + b^{*2})^{1/2}$ and $h° = \arctan(b^*/a^*)$, a colorimetric approach widely used in tomato fruit-quality assessment (Ordookhani *et al.,* 2010; Issifu *et al.,* 2023).

Physical quality parameters: Fruit firmness was measured on the equatorial region of five fruits per replicate using a penetrometer (mm 10 s^{-1}), consistent with firmness-assessment protocols used in previous PGPR–tomato studies (Hernández-Amador *et al.,* 2024).

Chemical quality parameters: Titratable acidity (TA) was expressed as % citric acid equivalent. Total soluble solids (TSS) were determined with a digital refractometer and expressed as °Brix. Lycopene content (mg 100 g^{-1} fresh weight) was determined spectrophotometrically following the method of Fish *et al.,* (2002). Total phenolic content (TPC) was determined by the Folin-Ciocalteu method and expressed as mg gallic acid equivalent (GAE) per 100 g fresh weight, while antioxidant capacity was assessed using the DPPH free-radical-scavenging assay and expressed as % inhibition; both protocols are widely adopted in PGPR fruit-quality research (Gashash *et al.,* 2022; Khomampai *et al.,* 2024).

Statistical analysis

Data presented in this study represent the mean values obtained from four consecutive growing seasons (2020–2024). Statistical analyses were performed using IBM SPSS Statistics for Windows (Version 26.0; IBM Corp., Armonk, NY, USA). The experimental unit for all statistical analyses was the individual experimental plot (replication), and the mean values of the three replicates were used for data presentation. Treatment effects were evaluated by one-way analysis of variance (ANOVA), and mean comparisons were performed using Duncan's Multiple Range Test (DMRT) at a significance level of $p \leq 0.05$. Results are presented as mean ± standard error (SE).

To further explore the relationships among the measured agronomic and fruit-quality variables, Pearson correlation analysis and principal component analysis (PCA) were performed using treatment means (eight treatments × twelve variables). Prior to PCA, all variables were standardized by z-score transformation to eliminate differences in measurement scale. Principal components were retained according to their eigenvalues and cumulative explained variance. Because Pearson correlation analysis and PCA were performed using treatment means rather than individual replicate observations, these multivariate analyses should be interpreted as exploratory and descriptive tools for visualizing treatment relationships rather than as inferential statistical analyses. This analytical approach is consistent with previous PGPR studies on tomato (Yagmur & Gunes, 2021).

Table 1. Bacterial combinations and their constituent strains are used in the trial.

Combination	Type	Bacterial strains	Main functional traits
TB1	Commercial	*Bacillus megaterium* RC07 *Pantoea agglomerans* RC58 *Pseudomonas fluorescens* RC77	P solubilization, IAA production, siderophore production, nitrogen fixation, antibiotic production
TB2	Commercial	*Bacillus megaterium* RC3D *Bacillus licheniformis* RC521 *Pseudomonas fluorescens* RC512	P solubilization, IAA production, enzyme production, induced systemic resistance (ISR), antibiotic and siderophore production
BS1	Non-commercial	*Bacillus megaterium* RC16Y *Bacillus subtilis* RC210 *Pseudomonas fluorescens* RC512	Siderophore, antibiotic, IAA, enzyme production, antifungal activity, P solubilization
BS2	Non-commercial	*Bacillus megaterium* RC16Y *Bacillus subtilis* RC210 *Pseudomonas fluorescens* RC512 *Bacillus licheniformis* RC601	Siderophore, antibiotic, enzyme production, IAA, antifungal activity, P solubilization
BS3	Non-commercial	*Bacillus subtilis* RC17Y *Bacillus megaterium* RC32Y *Pantoea agglomerans* RC58 *Pseudomonas fluorescens* RC82Y	P solubilization, IAA, antifungal activity, siderophore, antibiotic production, nitrogen fixation
BS4	Non-commercial	*Bacillus megaterium* RC32Y *Bacillus subtilis* RC210 *Pseudomonas fluorescens* biotype A RC481 *Bacillus licheniformis* RC502	P solubilization, IAA, antifungal activity, enzyme production, biocontrol, induced systemic resistance (ISR)
G	Mineral fertilizer	—	N, P, K and micronutrient fertilization based on soil analysis results
O	Control	—	No application

TB: Commercial bacteria; BS: Non-commercial bacterial strains; G: Chemical fertilizer; O: Control

Table 2. Effects of bacterial and mineral fertilizer treatments on plant height, stem diameter and fruit colour parameters (L*, chroma, hue angle) of 'Gülpembe' tomato.

Treatment	Plant height (cm)	Stem diameter (mm)	L* (Lightness)	Chroma (colour saturation)	Hue (colour tone)
TB1	41.67 ± 5.22 ab	14.25 ± 1.21 a	41.17 ± 2.23 ab	44.01 ± 2.42 b	1.02 ± 0.14 a
TB2	41.89 ± 4.46 ab	13.88 ± 1.67 a	41.10 ± 1.79 ab	40.54 ± 2.58 ab	1.01 ± 0.15 a
BS1	40.56 ± 1.81 ab	14.49 ± 1.45 a	42.66 ± 1.44 b	43.59 ± 3.06 ab	1.01 ± 0.10 a
BS2	45.00 ± 3.43 bc	15.15 ± 1.57 a	41.85 ± 1.09 ab	42.11 ± 3.72 ab	1.04 ± 0.10 a
BS3	50.22 ± 2.99 d	15.80 ± 1.02 a	40.30 ± 0.58 a	39.86 ± 2.17 a	1.16 ± 0.07 b
BS4	40.11 ± 2.20 a	14.57 ± 1.73 a	42.42 ± 1.28 ab	43.23 ± 1.67 ab	1.00 ± 0.12 a
G	43.44 ± 2.07 a-c	14.90 ± 1.32 a	40.92 ± 0.66 ab	43.11 ± 2.02 ab	1.13 ± 0.06 ab
O (Control)	46.33 ± 3.54 c	15.29 ± 1.43 a	40.62 ± 2.26 ab	40.49 ± 3.72 ab	1.02 ± 0.09 a
F value	9.029	1.647	2.716	3.067	2.843
p value	0.000	0.13848	0.0157	0.00755	0.01216
Significance	**	NS	*	**	*
CV (%)	10.44	10.05	4.03	7.20	11.37

TB: Commercial bacteria, BS: Non-commercial bacterial strains, G: Chemical fertilizer, O: Control. *$p \leq 0.05$, **$p \leq 0.01$
NS: Not significant. Means with different letters within the same column are significantly different (Duncan's Multiple Range Test, α=0.05)

Table 3. Effects of bacterial and mineral fertilizer treatments on average fruit weight, firmness, total soluble solids and titratable acidity of 'Gülpembe' tomato fruit.

Treatment	Fruit weight (g)	Firmness (kg/cm²)	Total soluble solids (°Brix)	Titratable acidity (%)
TB1	162.05 ± 3.65 a	2.10 ± 0.30 a-c	4.10 ± 0.30 a	8.02 ± 1.14 f
TB2	183.29 ± 14.44 b	2.43 ± 0.34 c	5.00 ± 0.14 b	3.82 ± 0.21 a
BS1	197.14 ± 12.28 c	2.01 ± 0.31 ab	4.91 ± 0.20 b	5.18 ± 0.24 bc
BS2	224.30 ± 6.22 e	2.36 ± 0.18 bc	5.10 ± 0.20 b	7.06 ± 1.83 ef
BS3	190.41 ± 6.91 bc	1.97 ± 0.28 ab	4.90 ± 0.10 b	6.01 ± 0.39 c-e
BS4	226.20 ± 8.29 e	1.88 ± 0.25 a	4.01 ± 0.11 a	6.73 ± 2.34 d-f
G	207.25 ± 10.15 d	1.86 ± 0.11 a	4.03 ± 0.14 a	5.51 ± 0.55 cd
O	197.00 ± 5.38 c	2.09 ± 0.44 a-c	4.10 ± 0.31 a	4.11 ± 0.58 ab
F value	48.95	4.038	50.054	13.636
p value	0.000	0.00115	0.000	0.000
Significance	**	**	**	**
CV (%)	10.95	16.30	11.15	30.30

TB: Commercial bacteria, BS: Non-commercial bacterial strains, G: Chemical fertilizer, O: Control. *$p \leq 0.05$, **$p \leq 0.01$
Means with different letters within the same column are significantly different (Duncan's Multiple Range Test, α=0.05)

Results and Discussion

Vegetative growth parameters: Significant differences among treatments were observed for plant height, while differences in stem (collar) diameter were not statistically significant (Table 2). PGPR-treated plants generally exhibited greater height compared with the untreated control (O), consistent with previous reports showing that PGPR strains promote vegetative growth via IAA production, phosphate solubilization and biological nitrogen fixation (Hernández-Amador *et al.,* 2024; Biswas *et al.,* 2024; Igiehon *et al.,* 2024).

Greater plant height was recorded in the plants treated with *Bacillus megaterium* strains (TB1, BS1, BS2, BS3 and BS4), which may be due to phosphate solubilizing ability and produce plant growth-regulating substances. The performance of BS3 was superior which is associated with complementary functional traits of its four constituent bacterial strains, which collectively offer multiple plant growth-promoting mechanisms, including solubilization of phosphate, biological N-fixation, production of indole-3-acetic acid (IAA), siderophore production, and suppression of soil-borne pathogens. These combined functions improve the nutrient uptake and growth of root which leads to improved overall vegetative growth as compared to simpler bacterial formulations. The findings of current study were aligned with the findings of recent studies (Yagmur & Gunes, 2021; Gashash *et al.,* 2022; Hasan *et al.,* 2024 and Sun *et al.,* 2024), who confirmed that functionally diverse bacterial combinations normally perform better than single-strain inoculants under field conditions owing to their complementary modes of action within the rhizosphere.

Yield parameters: Significant positive effect was recorded with the application of PGPR, on average fruit weight (Table 3). The mineral fertilizer treatment (G) produced high fruit-weight; however, several bacterial combinations also produced similar results, and the four-strain BS4 and three-strain BS2 combinations gained heaviest individual fruits weight among all treatments. Among the bacterial treatments, the four-strain BS3 combination (*B. megaterium* RC32Y, *B. subtilis* RC17Y, *P. fluorescens* RC82Y, *P. agglomerans* RC58) was linked with highest overall fruit yield among PGPR-treated plants, suggesting that the synergistic action of four complementary strains maximized yield potential.

The findings of current study revealed that several PGPR treatments significantly improved fruit yield and which was very close to mineral fertilizer treatment. Particularly, BS3 and BS4 combinations performed excellent which was comparable with mineral fertilizers, suggesting that application of bacterial strains can replace conventional fertilizers without compromising yield. Improvement in yield is associated with enhanced nutrient uptake, root development, and photosynthetic activity which ultimately leads to improved tomato fruit yield on sustainable basis (Biswas *et al.,* 2024). Similar results were authenticated by Sheikhalipour *et al.,* (2019), Torres-Solórzano *et al.,* (2025), and Altimira *et al.,* (2024), similar findings aligned with previous results is agreement that multi-strain PGPR formulations can maintain or improve tomato productivity while minimizing dependence on synthetic chemical fertilizers. Furthermore, the locally locally developed PGPR combinations have potential to serve as alternative to chemically synthesised fertilizers for commercial tomato production.

The significant difference was recorded for fruit weight, among the treatments, bacterial combinations containing *P. fluorescens* strains produced heavier individual fruits as compared to control. These findings support the results of Hernández-Amador *et al*., (2024), who observed notable increases in total biomass and root traits in PGPR-inoculated tomato plants.

Fruit colour characteristics: Bacterial treatments also significantly affected the fruit colour parameters (chroma and hue angle) (Table 2). PGPR-treated plants showed higher chroma values, which indicating more intensive colour as compared to control, while variations in hue angle reflected subtle shifts within the red-yellow spectrum of fruit colour. Enhanced lycopene biosynthesis and carotenoid accumulation was associated with changes in fruit colour induced by specific PGPR strains.

Association between application of PGPR and improved fruit colour has been previously reported by Ordookhani *et al.,* (2010) who found that Pseudomonas application improved lycopene content in tomato fruit, directly affecting the visual colour traits of tomato fruit. Darker red colour fruit is associated with higher lycopene concentrations and consequently distinct chroma and hue values, which are important for both consumer acceptance and nutritional value. İn another recent study similar results were confirmed that microbial inoculation was helpful lycopene biosynthesis (Khomampai *et al*., 2024).

Fruit firmness: Fruit firmness is an important quality trait affecting both postharvest shelf life and the consumer acceptability of fresh tomatoes. In current study, PGPR treatments exhibited a significant effect on fruit firmness (Table 3), although the application of PGPR with different combinations have significant effect on fruit firmness as compared to control. These finding were in accordance with the findings of Issifu et al., (2023) and Pérez Rodriguez et al., (2020), who reported that effect PGPR on fruit firmness parameters depending on the strains and combinations used.

Change in fruit firmness with the application of PGPR may be associated with activation of cell-wall synthesis genes and change in ethylene biosynthesis. İt was observed that application of *Pseudomonas fluorescens* has been linked with variation in fruit firmness through modulation of pectin methylesterase (PME) and polygalacturonase (PG) enzyme activities that regulate integrity of cell-wall (Hernández-Amador *et al.,* 2024; Li et al., 2025; Sun et al., 2025). Significant firmness responses following the application of *Pseudomonas* spp. were also reported by Torres-Solórzano *et al.,* (2025), strengthening the consistency of this physiological pathway across independent tomato production systems.

Titratable acidity and total soluble solids: Tomato flavour and processing quality can be assessed through titratable acidity (TA) and total soluble solids (TSS, °Brix) as these are key traits. Results revealed that there was statistically significant difference among the treatments (Table 3) as TSS values were highest in the plants treated with TB2, BS1, BS2 and BS3, suggesting that combinations integrating Bacillus and Pseudomonas species can improve sugar accumulation in tomato, through improved photosynthetic rate and carbohydrate segmentation.

The findings of current study were align with Sheikhalipour *et al.,* (2019), who reported that PGPR application improved TSS values, titratable acidity and vitamin C content in tomato fruit. Similarly, application of *P. fluorescens* and *Azospirillum brasilense* was found helpful to improve fruit quality, including TSS and titratable acidity, as compared to chemical fertilization (Pérez Rodriguez *et al.,* 2020). The increments in TSS recorded in current study for several non-commercial combinations suggest that the locally isolated strains used in BS1–BS4 may be well adapted to local soil and climatic conditions, a pattern also reported by Altimira *et al.,* (2024) for locally isolated *Bacillus* strains evaluated against standard commercial fertilization regimes.

Concludingly, the improvements observed in fruit colour, TSS, TA, and lycopene accumulation suggest that application of PGPR influenced multiple physiological and biochemical pathways linked with fruit ripening rather than affecting individual quality traits independently. The coordinated improvements of these attributes indicates improved carbon assimilation, nutrient uptake, and biosynthesis of secondary metabolite, authenticating hypothesis that multi-strain PGPR combinations contribute to overall fruit quality traits through integrated metabolic regulation rather than through isolated physiological responses.

Lycopene content: The major carotenoid in tomato fruit is lycopene, is well known for its potent antioxidant activity and associated health benefits. Bacterial inoculation significantly affected lycopene content (Table 4), with most PGPR treatments producing significantly higher concentrations than the untreated control, although the mineral fertilizer treatment (G) recorded the highest overall value. Treatments containing *P. fluorescens* strains, particularly the four-strain combinations BS3 and BS4, showed the highest lycopene accumulation among the bacterial treatments, consistent with the well-established role of this species in upregulating the carotenoid biosynthesis pathway.

Issifu *et al.,* (2023) reported exceptionally high lycopene content in *Pseudomonas*-inoculated tomato fruit, among the highest values reported in the PGPR literature. Loganathan *et al.,* (2014) also confirmed that both *B. subtilis* and *B. amyloliquefaciens* increased lycopene content. In the present study, the four-strain combinations integrating *Bacillus* and *Pseudomonas* species (BS2, BS3, BS4) showed lycopene values that significantly exceeded the control and approached the mineral fertilizer treatment, suggesting that PGPR-mediated enhancement of lycopene biosynthesis is both strain-specific and combination-dependent. This is consistent with the substantial lycopene increases (exceeding 130 mg kg^{-1} fresh fruit) reported by Torres-Solórzano *et al.,* (2025) following inoculation with selected *Pseudomonas* isolates, further supporting the central role of this genus in carotenoid-biosynthesis enhancement.

Although the mineral fertilizer treatment produced the highest lycopene concentration, the non-commercial PGPR formulations (particularly BS3 and BS4) achieved comparable improvements while simultaneously enhancing several additional quality attributes, including total phenolic content, antioxidant capacity, and total soluble solids. This finding suggests that mineral fertilization may preferentially promote specific biochemical responses, whereas multi-strain PGPR consortia provide a more balanced improvement across multiple fruit-quality characteristics. Consequently, evaluating overall fruit quality rather than individual biochemical parameters offers a more comprehensive assessment of treatment performance.

Total phenolic content and antioxidant capacity: Total phenolic content (TPC) and antioxidant capacity (% DPPH inhibition) were significantly increased by PGPR application (Table 4). Four-strain bacterial combinations (TB2, BS3) produced the highest TPC values, suggesting that increasing strain diversity within a combination can enhance phenolic metabolism in tomato fruit. PGPR strains are known to increase phenolic-compound accumulation by upregulating phenylalanine ammonia-lyase (PAL) expression, a key enzyme of phenylpropanoid biosynthesis (Khan *et al.,* 2023b).

Antioxidant capacity showed a strong positive relationship with lycopene and TPC values across treatments, with the highest antioxidant values recorded in the BS4 and TB2 treatments. This is consistent with Gashash *et al.,* (2022) and Biswas *et al.,* (2024), who reported marked increases in antioxidant capacity following rhizobacterial inoculation. These results are further supported by Khomampai *et al.,* (2024) and Tahiri *et al.,* (2022), both of whom documented coordinated improvements in antioxidant-related biochemical parameters following microbial inoculation of tomato. Collectively, these findings demonstrate that multi-strain PGPR combinations have the potential not only to enhance yield but also to substantially improve the nutritional quality of tomato fruit.

Both commercial (TB1 and TB2) and non-commercial (BS1–BS4) PGPR formulations consistently outperformed the untreated control for most agronomic and fruit-quality parameters. More importantly, the locally developed non-commercial formulations, particularly BS3 and BS4, frequently produced responses comparable to those of the commercial products and, in several cases, approached the performance of mineral fertilization. This finding has important practical implications because it demonstrates that locally isolated and functionally selected bacterial consortia can provide an effective alternative to commercially available biofertilizers while reducing dependence on synthetic fertilizers. From economic point of view, the development of local PGRP formulations have lower cost of production, wider adoptability to local envionmental conditions and easily available for growers for sustainable agricultural practices. Adedayo et al. (2022) also reported similar findings, as he focused on locally adopted PGPR strains, found superior performance in field conditions. Morover, Sun et al., (2024), reported his findings which were aline with current study.

Table 4. Effect of different bacterial formulations and mineral fertilizer on total phenolic content, antioxidant capacity, and lycopene content of tomato ('Gülpembe') fruits.

Treatment	Total phenolic content (mg GAE/g)	Antioxidant capacity (mg/g)	Lycopene (mg/kg)
TB1	0.095 ± 0.004 ab	0.116 ± 0.012 bc	65.65 ± 2.17 b
TB2	0.098 ± 0.011 b	0.126 ± 0.012 cd	67.26 ± 3.53 b
BS1	0.096 ± 0.006 ab	0.106 ± 0.008 ab	69.72 ± 2.15 c
BS2	0.090 ± 0.010 ab	0.091 ± 0.009 a	66.52 ± 3.81 b
BS3	0.098 ± 0.007 b	0.125 ± 0.019 cd	74.78 ± 2.87 d
BS4	0.095 ± 0.006 ab	0.134 ± 0.012 d	80.04 ± 1.78 e
G	0.086 ± 0.004 a	0.090 ± 0.023 a	87.38 ± 1.19 f
O (Control)	0.094 ± 0.011 ab	0.095 ± 0.010 a	62.72 ± 1.69 a
F value	2.497	13.793	97.429
p value	0.02475	0.000	0.000
Significance	*	**	**
CV (%)	8.85	18.97	11.52

TB: Commercial bacteria, BS: Non-commercial bacterial strains, G: Chemical fertilizer, O: Control. *$p \leq 0.05$, **$p \leq 0.01$
Means with different letters within the same column are significantly different (Duncan's Multiple Range Test, α=0.05)

Table 5. Pearson correlation coefficients among the measured yield and quality parameters of 'Gülpembe' tomato (calculated on treatment means, n = 8).

	PH	SD	L*	Chr	Hue	FW	Frm	TSS	TA	TPC	AOX	Lyc
PH	1											
SD	**0.87**	1										
L*	**-0.75**	-0.44	1									
Chr	**-0.75**	-0.47	**0.66**	1								
Hue	**0.72**	**0.67**	-0.62	-0.33	1							
FW	-0.04	0.32	0.45	0.05	0.00	1						
Frm	0.00	-0.32	-0.05	-0.35	-0.39	-0.17	1					
TSS	0.24	0.05	0.11	-0.40	0.06	0.02	0.63	1				
TA	-0.11	0.06	0.24	0.58	0.05	0.03	-0.20	-0.19	1			
TPC	0.04	-0.18	-0.01	-0.37	-0.27	-0.46	0.21	0.34	-0.19	1		
AOX	-0.18	-0.31	0.09	-0.11	-0.16	-0.22	-0.06	0.04	0.10	**0.77**	1	
Lyc	-0.09	0.13	0.05	0.27	0.54	0.41	**-0.69**	-0.36	0.11	-0.46	0.07	1

PH: Plant height; SD: Stem diameter; L*: Lightness; Chr: Chroma; Hue: Hue angle; FW: Fruit weight; Frm: Firmness; TSS: Total soluble solids; TA: Titratable acidity; TPC: Total phenolic content; AOX: Antioxidant capacity; Lyc: Lycopene. Coefficients were calculated from treatment means and are presented for descriptive purposes

Taken together, the results indicate that no single treatment was superior for every measured parameter. Instead, each treatment exhibited distinct strengths depending on the agronomic or fruit-quality attribute considered. Nevertheless, the non-commercial multi-strain formulations, particularly BS3 and BS4, consistently ranked among the best-performing treatments across a broad range of vegetative, yield, and biochemical characteristics. This consistency across multiple independent variables is of greater agronomic significance than superiority in any single parameter, as commercial tomato production requires the simultaneous optimization of yield, fruit quality, and sustainability. Therefore, the overall performance profile of BS3 and BS4 provides stronger evidence of their practical value than comparisons based on individual measurements alone.

Correlation analysis: Pearson correlation analysis among the measured parameters (Table 5; Fig. 1) revealed several biologically meaningful associations. Plant height and stem diameter were strongly and positively correlated ($r = +0.87$, $p<0.01$), confirming that treatments stimulating vertical growth also promoted radial stem development, as expected for a coordinated vegetative-growth response to PGPR inoculation. Total phenolic content and antioxidant capacity were likewise strongly and positively correlated ($r = +0.77$, $p<0.05$), in agreement with the well-established role of phenolic compounds as primary contributors to the DPPH radical-scavenging activity of tomato fruit; this relationship is consistent with the coordinated phenolic–antioxidant responses to rhizobacterial inoculation reported by Gashash *et al.,* (2022) and Khomampai *et al*., (2024).

Fruit firmness was negatively correlated with lycopene content ($r = -0.69$), reflecting the expected physiological trade-off whereby advancing ripening and carotenoid accumulation coincide with softening of the fruit tissue. A moderate positive association between hue angle and lycopene ($r = +0.54$) further linked the colour shift toward deeper red tones with carotenoid accumulation, supporting the interpretation advanced by Ordookhani *et al*., (2010) and Suo *et al*., (2026) that PGPR-mediated enhancement of lycopene biosynthesis is directly reflected in the visual colour attributes of the fruit. The positive correlation between firmness and total soluble solids ($r = +0.63$) indicated that treatments preserving fruit firmness also tended to maintain higher soluble-solids concentrations, a combination favourable for both fresh-market quality and postharvest performance.

Overall, the correlation analysis provides important biological support for the individual treatment responses discussed above. The strong positive associations among vegetative growth, fruit yield, soluble solids, antioxidant activity, total phenolic content, and lycopene indicate that these traits responded in a coordinated manner to PGPR inoculation rather than as isolated physiological events. These relationships suggest that enhanced nutrient acquisition, improved root function, and increased metabolic activity collectively contributed to the observed improvements in plant productivity and fruit quality. Consequently, the correlation analysis reinforces the hypothesis that multi-strain PGPR consortia exert integrated effects on tomato growth through multiple complementary mechanisms rather than through a single dominant pathway.

Principal component analysis: Principal component analysis (PCA) was applied to assess overall pattern of treatment responses across all measured traits (Fig. 2). The first two principal components together explained 56.9% of the total variance (PC1 = 30.5%, PC2 = 26.5%), while the first five components explained 90.6% of total variation. Mainly vegetative growth and colour traits were defined by PC1 as It showed strong positive contributions for plant height, stem diameter, and hue angle, while strong negative contributions from L* and chroma was defined. This grouped treatments based on differences in plant growth and colour traits. PC2 was mainly defined fruit quality and biochemical traits. It had strong positive contributions for lycopene content and fruit weight, however TSS, firmness and total phenolic content showed strong negative contributions. This grouped treatments according to differences in fruit quality and biochemical traits.

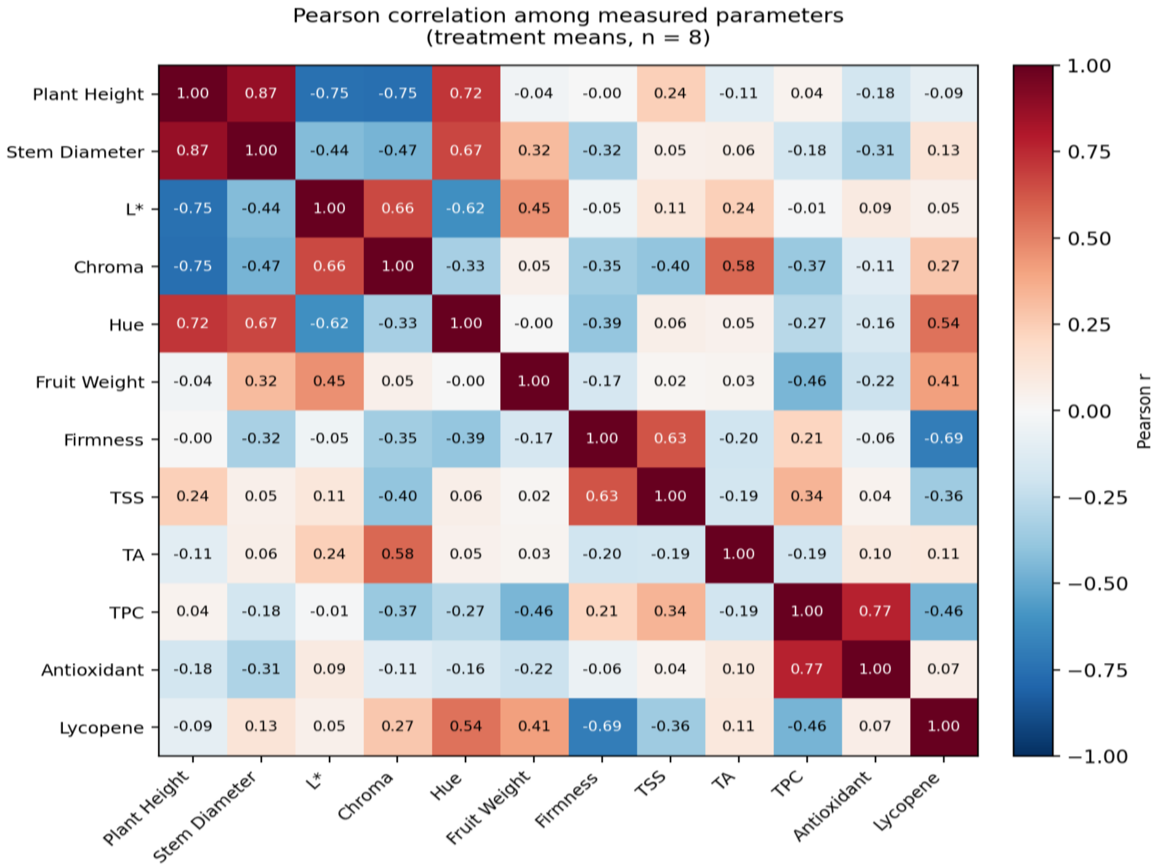

Fig. 1. Heat map of Pearson correlation coefficients among the measured yield and quality parameters of 'Gülpembe' tomato (treatment means, n = 8). Red and blue shades indicate positive and negative correlations, respectively.

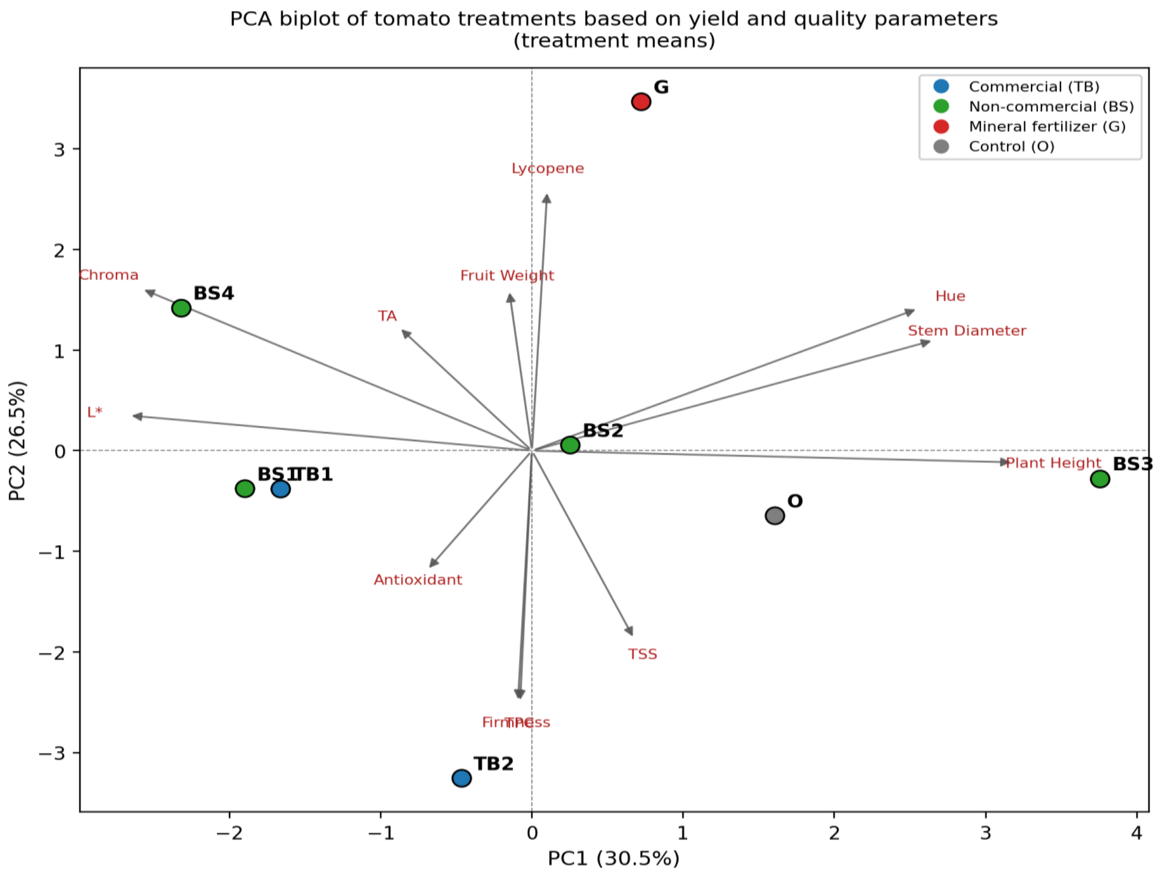

Fig. 2. Principal component analysis (PCA) biplot of the eight treatments based on the measured yield and quality parameters of 'Gülpembe' tomato. Points represent treatments (TB: Commercial; BS: Non-commercial; G: Mineral fertilizer; O: Control) and vectors represent parameter loadings. PC1 and PC2 explain 30.5% and 26.5% of the total variance, respectively.

In the PCA biplot, the treatments were clearly differentiated according to their multivariate profiles. The non-commercial combination BS3 was positioned at the positive extreme of PC1, reflecting its association with the greatest plant height and stem diameter, whereas BS4 was distinguished along the chroma and antioxidant vectors, consistent with its high antioxidant capacity and lycopene content. The mineral fertilizer treatment (G) was separated along the lycopene vector, in line with its high lycopene value, while the untreated control (O) occupied a distinct position reflecting its generally lower quality attributes. Importantly, the non-commercial combinations (BS) were distributed across the same regions of the ordination space as the commercial combinations (TB) and the mineral fertilizer treatment, rather than clustering separately. This overlap provides multivariate support for the central finding of the study that locally isolated, non-commercial PGPR combinations can achieve response profiles comparable to those of commercial formulations and mineral fertilization. A comparable use of PCA to discriminate PGPR treatments in tomato was reported by Yagmur & Gunes (2021), who likewise identified soluble solids, titratable acidity and yield as principal discriminating variables.

The PCA results offer autonomous multivariate validation of the conclusions gained from the individual trait analyses. Whereas the univariate analyses identified statistically significant differences for individual agronomic and fruit-quality traits, the PCA concurrently unified all measured variables and established that BS3 and BS4 consistently positioned the region linked with better plant growth, yield, and fruit-quality traits. This promise between univariate and multivariate analyses significantly rise confidence in the robustness of the findings and validates that the better performance of these treatments was not determined by isolated variables but reflected an overall improvement across multiple complementary traits

Conclusion

Current study focused on evaluation of both commercial and locally developed multi-strain plant growth-promoting rhizobacteria (PGPR) formulations. Results clearly dipected a significant improvement in tomato growth, yield, and fruit quality as compared with control. Performance of non-commercial formulations BS3 and BS4 consistently was found superior across all agronomic, biochemical, and quality traits and results were almost very close to conventional mineral fertilization. Multivariate and univariate analyses confirmed that application of multi-strain PGPR formulations significantly improved plant growth, yield and quality, these findings confirmed that locally isolated PGPR formulations are effective for sustainable tomato production in field conditions.

Through application of locally developed PGPR formulations can minimize the usage of mineral fertilizers with lower production cost. Further studies under different soil types and climatic conditions needed to confirm long term usage for tomato production on sustainable basis

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