

AMFAND PGPR SYNERGY: BOOSTING TOMATO YIELD AND QUALITY IN VERTISOL WITH LESS FERTILIZER

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ABSTRACT

Increasing demand for high crop productivity with reduced dependence on mineral fertilizers has stimulated interest in microbial inoculants capable of improving nutrient acquisition and crop quality. A two-year field experiment was conducted during the Rabi seasons of 2023–24 and 2024–25 at the Research Farm of the Vegetable Research Centre, Vasantao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India, to evaluate the effects of arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR) on tomato productivity and fruit quality under Vertisol conditions. Twelve nutrient and microbial inoculation treatments were evaluated in a randomized block design with three replications. Pooled analysis revealed significant improvements in tomato productivity, plant nutrient concentration and fruit biochemical quality following combined microbial inoculation. Soil application of 75% RDF + AMF + PGPR (*Pseudomonas fluorescens*, *Bacillus megaterium* and *Trichoderma asperellum*) recorded the highest plant N (1.97%), P (0.30%) and K (1.99%) concentrations. The treatment also produced the highest fruit yield (376.74 q ha⁻¹), representing increases of 117.54% and 27.27% over the absolute control and 100% RDF, respectively. The same treatment produced the highest dry matter yield (46.34 q ha⁻¹), with increases of 66.03% and 38.49% over the absolute control and 100% RDF, respectively. Fruit quality was substantially improved, with 2.49% reducing sugar, 5.26% non-reducing sugar, 5.85 °Brix TSS, 9.12 mg 100 g⁻¹ lycopene and 26.42 mg 100 g⁻¹ ascorbic acid. Combined microbial inoculation through soil application consistently outperformed the corresponding seedling application. Among individual microbial inoculation treatments, soil application of AMF with 75% RDF performed best. The results demonstrate that AMF–PGPR integration with 75% RDF can simultaneously enhance tomato yield, plant nutrient concentration and fruit quality while reducing mineral fertilizer input by 25% under Vertisol conditions.

KEYWORDS: (AMF, PGPR, Tomato yield and fruit quality).

INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is an economically important vegetable crop widely cultivated for fresh consumption and processing and has gained recognition as a functional food owing to its rich composition of essential nutrients and biologically active phytochemicals (Giovannetti *et al.*, 2012; Maurya *et al.* 2025). Tomato fruits contain several nutritionally important compounds, including soluble sugars, vitamin C and carotenoids, which contribute to their dietary and functional value (Bona *et al.*, 2016; Paskovic *et al.*, 2021). Among these constituents, lycopene is the major carotenoid responsible for the characteristic red colour of ripe tomato fruits has attracted considerable scientific interest because epidemiological studies have associated tomato and lycopene consumption with a reduced risk of certain cancers and cardiovascular diseases (Giovannetti *et al.*, 2012; Nasir *et al.* 2015). In addition to lycopene, fruit quality is influenced by soluble solids, sugars and ascorbic acid, which are important determinants of fruit flavour, maturity, nutritional quality and consumer acceptability (Bona *et al.*, 2016; Paskovic *et al.*, 2021). Therefore, improving both tomato productivity and the accumulation of nutritionally important fruit constituents is an important objective of sustainable tomato production. Maintaining high tomato productivity while improving fruit quality requires efficient management of mineral nutrients and biological resources (Li *et al.* 2025). Conventional tomato production is highly dependent on mineral fertilizers, but increasing fertilizer inputs do not necessarily result in proportional increases in crop productivity or nutrient-use efficiency (Adesemoye *et al.*, 2009). The use of beneficial microorganisms with reduced fertilizer inputs has gained increasing attention as a sustainable nutrient management strategy, as microbial inoculants can partially compensate for lower mineral fertilizer application while maintaining crop growth, nutrient acquisition and yield (Adesemoye *et al.*, 2009; Ye *et al.*, 2020).

Arbuscular mycorrhizal fungi (AMF) form mutualistic associations with plant roots and develop extraradical hyphal networks that enhance the uptake of relatively immobile nutrients, particularly phosphorus, thereby improving plant growth and nutritional status (Smith and Read, 2008). In tomato, AMF inoculation has been reported to improve fruit yield and quality, including nutrient composition, antioxidant capacity and carotenoid accumulation (Copetta *et al.*, 2011; Bona *et al.*, 2016). Field studies further indicate that AMF can enhance tomato productivity and fruit quality under different fertilization regimes, supporting its potential role in efficient nutrient management (Paskovic *et al.*, 2021).

Plant growth-promoting rhizobacteria (PGPR) constitute another important group of beneficial microorganisms that can influence plant development through multiple direct and indirect mechanisms (Backer *et al.*, 2018). PGPR can enhance nutrient availability, stimulate root development, produce or modulate phytohormones, and improve plant growth through interactions occurring in the rhizosphere (Yang *et al.* 2024). Members of the genera *Pseudomonas* and *Bacillus* have been widely investigated for their ability to promote plant growth and improve nutrient acquisition under different production environments (Lugtenberg and Kamilova 2009; Backer *et al.* 2018). Beneficial *Trichoderma* spp. can additionally contribute to root development, nutrient mobilization and improved plant performance through their interactions with plants and the rhizosphere (Ye *et al.*, 2020).

The simultaneous use of AMF and PGPR is particularly promising because these microbial groups can perform complementary functions in the plant–soil system (Bona *et al.*, 2017). AMF primarily expands the effective root-soil interface and facilitates nutrient acquisition, whereas PGPR can modify the rhizosphere environment and stimulate root activity and nutrient mobilization (Adesemoye *et al.*, 2009; Bona *et al.*, 2017). Consequently, combined bacterial and mycorrhizal inoculation may provide broader benefits than individual microbial inoculation (Bona *et al.*, 2017).

However, limited information is available on the performance of AMF in combination with *Pseudomonas fluorescens*, *Bacillus megaterium* and *Trichoderma asperellum* in tomato under reduced fertilizer input, particularly in Vertisol. Therefore, the present study evaluated the effects of individual and combined AMF–PGPR application with 75% recommended dose of fertilizer (RDF) on tomato plant nutrient concentration, dry matter and fruit yield, and fruit quality attributes including reducing sugar, non-reducing sugar, total soluble solids (TSS), ascorbic acid and lycopene. The study also compared seedling and soil application methods to assess the potential of microbial inoculation to improve tomato productivity and fruit quality while reducing mineral fertilizer use by 25%.

2. MATERIALS AND METHODS

2.1 Experimental site and soil characteristics

A two-year field experiment was conducted during the Rabi seasons of 2023–24 and 2024–25 at the Research Farm of the Vegetable Research Centre, Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra, India. The experimental soil was a Vertisol with clayey texture and moderately alkaline reaction. Before initiation of the experiment, composite surface soil samples (0–15 cm) were collected for characterization. The initial soil had pH 8.06, electrical conductivity 0.385 dS m⁻¹, organic carbon 6.0 g kg⁻¹, CaCO₃ 70.63 g kg⁻¹, available N 149.80 kg ha⁻¹, available P 15.43 kg ha⁻¹ and available K 625.72 kg ha⁻¹.

2.2 Experimental design and treatments

Tomato cv. PBNT-5 was used as the test crop. The experiment was laid out in a randomized block design with 12 treatments and three replications, giving a total of 36 experimental plots. Each plot measured 4.8 × 4.0 m, with a spacing of 60 × 50 cm between rows and plants, respectively. The crop was established by transplanting. The recommended dose of fertilizer (RDF) was 100:50:50 kg N: P₂O₅: K₂O ha⁻¹, supplied through urea, single superphosphate and muriate of potash.

The treatments were:

Treatments No.	Treatments
T ₁	Absolute control
T ₂	100 % RDF
T ₃	75% RDF + AMF (Seedling treatment)
T ₄	75% RDF + <i>Pseudomonas fluorescens</i> (Seedling treatment)
T ₅	75% RDF + <i>Bacillus megaterium</i> (Seedling treatment)
T ₆	75% RDF + <i>Trichoderma asperellum</i> (Seedling treatment)
T ₇	75% RDF + AMF + <i>Pseudomonas fluorescens</i> + <i>Bacillus megaterium</i> + <i>Trichoderma asperellum</i> (Seedling treatment)
T ₈	75% RDF + AMF (Soil application)
T ₉	75% RDF + <i>Pseudomonas fluorescens</i> (Soil application)
T ₁₀	75% RDF + <i>Bacillus megaterium</i> (Soil application)
T ₁₁	75% RDF + <i>Trichoderma asperellum</i> (Soil application)
T ₁₂	75% RDF + AMF + <i>Pseudomonas fluorescens</i> + <i>Bacillus megaterium</i> + <i>Trichoderma asperellum</i> (Soil application)

2.3 Microbial inoculant application

For seedling treatment, AMF (*Glomus sp.*) inoculum was suspended at 100 g in 10 L water and tomato seedlings were dipped in the suspension immediately before transplanting. PGPR inoculation was performed using 100 mL liquid culture in 10 L water, in which seedlings were dipped before transplanting. For soil application, AMF was applied at 5 kg acre⁻¹ (12.35 kg ha⁻¹) and PGPR at 2 L acre⁻¹ (4.94 L ha⁻¹) through root-zone soil drenching at 30 days after transplanting.

2.4 Plant nutrient analysis

At harvest, representative plant samples were collected, washed, oven-dried and ground for nutrient analysis. For phosphorus and potassium estimation, 1 g of finely ground sample was digested using a HNO₃ and HClO₄ in the ratio of 9:4. Nitrogen was determined by the micro-Kjeldahl method following AOAC (1990). Phosphorus was estimated spectrophotometrically by the vanadomolybdate yellow colour method described by Jackson (1973), while potassium was determined using a flame photometer following Piper (1966). Nutrient concentrations were expressed on a dry-weight basis as percentage.

2.5 Fruit yield and dry matter yield

Five representative plants were tagged in each plot for recording observations. Mature fruits harvested from each net plot at successive pickings were weighed and the cumulative yield was converted to $q\ ha^{-1}$. Dry matter yield was determined from the harvested plant biomass and expressed as $q\ ha^{-1}$.

2.6 Fruit biochemical quality

Fully ripe tomato fruits representative of each treatment were used for biochemical quality analysis. Total soluble solids (TSS) were determined using an Erma hand refractometer and expressed as °Brix. Ascorbic acid content was estimated by titration with 2,6-dichlorophenol indophenol reagent following the AOAC method (AOAC, 1975) and expressed as $mg\ 100\ g^{-1}$ fresh fruit. Reducing sugar was determined by Benedict's quantitative method, whereas non-reducing sugar was estimated after acid hydrolysis using Benedict's method. Lycopene was extracted from ripe tomato fruits using a hexane-based solvent system and quantified spectrophotometrically at 503 nm. The lycopene concentration was expressed as $mg\ 100\ g^{-1}$ fresh fruit (Anthon and Barrett, 2007).

2.7 Statistical analysis

The data obtained from the experiment were subjected to statistical analysis following the procedures outlined by Panse and Sukhatme (1985). Treatment effects were tested through analysis of variance (ANOVA) appropriate for a randomized block design (RBD). The standard error of the mean (S.E.) and critical difference (C.D.) at the 5% probability level were calculated to assess the significance of differences among treatment mean

3. RESULTS AND DISCUSSION

3.1 Plant nutrient concentration

The application of AMF and PGPR under reduced fertilizer input significantly influenced plant N, P and K concentration at harvest in both seasons. The pooled data consistently showed the superiority of the combined soil-applied consortium treatment (T_{12}) over individual inoculants, 100% RDF and the absolute control. The highest nitrogen (1.97%), phosphorous (0.30%) and potassium (1.99%) concentrations were recorded with T_{12} (75% RDF + AMF + *Pseudomonas fluorescens*, *Bacillus megaterium* and *Trichoderma asperellum* through soil application), followed by T_7 - 75% RDF + AMF + *Pseudomonas fluorescens* + *Bacillus megaterium* + *Trichoderma asperellum* through seedling treatment (1.80, 0.28 and 1.83%, respectively) and T_8 - 75% RDF + AMF through soil application (1.63, 0.25 and 1.67%, respectively). The lowest N, P and K concentrations were observed under the absolute control (T_1), with values of 1.24, 0.16 and 1.36%, respectively. Compared with 100% RDF (T_2), T_{12} increased N, P and K concentration by 34.93, 50.00 and 30.07%, respectively.

The concurrent enhancement of N, P and K concentrations indicates improved nutrient acquisition under combined microbial inoculation. AMF-mediated root exploration, together with PGPR-induced nutrient mobilization and root development, may have contributed to improved plant nutritional status. The stronger response to soil application suggests more effective root-zone establishment and sustained activity of the microbial inoculants. The enhanced N concentration under combined AMF-PGPR inoculation corroborates previous evidence of improved N acquisition through specific microbial associations, including AMF + *Trichoderma harzianum* in tomato (Nzanza *et al.*, 2011) and *Glomus intraradices* + helper bacteria in mango (Sant Ram, 2011), as well as AMF-based co-inoculation in cowpea (Jadhav, 2009). Likewise, the enhanced P concentration is consistent with reports of improved P acquisition under *Paenibacillus polymyxa* + *Burkholderia arboris* + AMF in soybean (Singh, 2018) and *Glomus mosseae* + *Bacillus subtilis* in rose-scented geranium (Alam *et al.*, 2011). The increased K concentration also agrees with findings obtained with AMF + PGPR5 in rice (Chen *et al.*, 2023) and AMF + PGPR in sunflower under saline irrigation (Pereira *et al.*, 2016). These improvements may be attributed to enhanced nutrient solubilization and mobilization, greater root exploration and improved nutrient uptake efficiency associated with AMF-PGPR associations.

3.2 Tomato fruit and dry matter yield

Microbial inoculation significantly enhanced fruit and dry matter yield of tomato. The highest pooled fruit yield ($376.74\ q\ ha^{-1}$) and dry matter yield ($46.34\ q\ ha^{-1}$) were recorded with T_{12} - 75% RDF + AMF + *Pseudomonas fluorescens* + *Bacillus megaterium* + *Trichoderma asperellum* through soil application, followed by T_7 - 75% RDF + AMF + *Pseudomonas fluorescens* + *Bacillus megaterium* + *Trichoderma asperellum* through seedling treatment (349.31 and $41.53\ q\ ha^{-1}$) and T_8 - 75% RDF + AMF through soil application (322.14 and $36.59\ q\ ha^{-1}$), respectively. The lowest fruit yield ($173.18\ q\ ha^{-1}$) and dry matter yield ($27.91\ q\ ha^{-1}$) were recorded under the absolute control. T_{12} increased fruit yield by 27.27% and dry matter yield by 38.49% over 100% RDF.

Table 3.1. Effect of arbuscular mycorrhizal fungi and plant growth promoting rhizobacteria on plant nutrient concentration and yield of tomato (Mean)

Treatment	N (%)	P (%)	K (%)	Fruit yield (q ha^{-1})	Dry matter yield (q ha^{-1})
T₁: Absolute control	1.24 e	0.16 h	1.36 h	173.18 e	27.91 e
T₂: 100 % RDF	1.46 d	0.20 gh	1.53 gh	296.01 d	33.46 d
T₃: 75% RDF + AMF (ST)	1.53 cd	0.22 ef	1.59 ef	311.55 cd	34.90 d
T₄: 75% RDF + <i>P.f.</i>	1.50 cd	0.22 f	1.58 f	308.16 cd	34.59 d
T₅: 75% RDF + <i>B.m.</i> (ST)	1.49 cd	0.21 g	1.56 g	303.65 cd	34.17 d
T₆: 75% RDF + <i>T.a.</i> (ST)	1.47 d	0.20 gh	1.55 gh	302.60 cd	33.90
T₇: 75% RDF + AMF + <i>P.f.</i> + <i>B.m.</i> + <i>T.a.</i> (ST)	1.80 b	0.28 b	1.83 b	349.31 b	41.53 b
T₈: 75% RDF + AMF (SA)	1.63 c	0.25 c	1.67 c	322.14 c	36.59 c

T₉: 75% RDF + <i>P.f.</i> (SA)	1.60 cd	0.23 cd	1.65 cd	318.14 cd	36.33 c
T₁₀: 75% RDF + <i>B.m.</i> (SA)	1.58 cd	0.23 de	1.62 de	314.67 cd	35.89 cd
T₁₁: 75% RDF + <i>T.a.</i> (SA)	1.55 cd	0.22 e	1.61 e	311.89 cd	35.47 cd
T₁₂: 75% RDF + AMF + <i>P.f.</i> + <i>B.m</i> + <i>T.a</i> (SA)	1.97 a	0.30 a	1.99 a	376.74 a	46.34 a
S.Em.±	0.05	0.01	0.05	6.97	1.67
C.D. at 5 %	0.16	0.03	0.15	20.46	4.90

Note: *P.f.* = *Pseudomonas fluorescens*; *B.m.* = *Bacillus megaterium*; *T.a.* = *Trichoderma asperellum*; *ST* = Seedling treatment; *SA* = Soil application. Seedling treatment: AMF @ 100 g in 10 L of water and PGPR @ 100 mL in 10 L of water. Soil application: AMF @ 5 kg acre⁻¹ (12.35 kg ha⁻¹) and PGPR @ 2 L acre⁻¹ (4.94 L ha⁻¹)

The enhanced fruit and dry matter yields under combined AMF–PGPR inoculation may be attributed to improved N, P and K acquisition, greater root exploration and enhanced assimilate production and partitioning. The superior performance of the soil-applied consortium may further reflect better establishment and activity of the inoculants in the rhizosphere. These findings corroborate earlier reports of improved productivity under microbial co-inoculation, including combined *Azotobacter chroococcum* + *Bacillus* sp. + *Glomus fasciculatum* in wheat (Khan and Zaidi, 2007), *Rhizophagus intraradices* + *R. fasciculatus* + *Acinetobacter junii* in tomato (Padmavathi et al., 2015), and *Azotobacter chroococcum* + AMF in field crops (Kumar, 2015). Bharti (2017) further demonstrated that AMF + PGPR co-inoculation produced biological yield comparable with 100% RDF, supporting the potential of microbial consortia to sustain productivity under reduced fertilizer input.

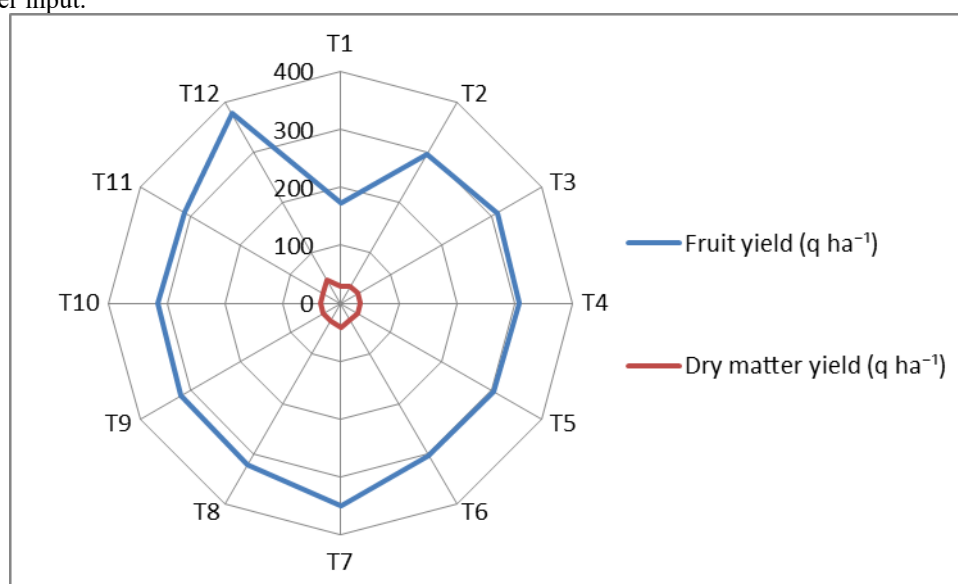


Fig 3.1. Effect of arbuscular mycorrhizal fungi and plant growth promoting rhizobacteria on pooled yield of tomato.

3.3 Reducing and non-reducing sugars

The application of AMF and PGPR significantly influenced the sugar composition of tomato fruits. The highest pooled reducing sugar (2.49%) and non-reducing sugar (5.26%) contents were recorded with 75% RDF + AMF + *Pseudomonas fluorescens* + *Bacillus megaterium* + *Trichoderma asperellum* through soil application (T₁₂), followed by 75% RDF + AMF + *Pseudomonas fluorescens* + *Bacillus megaterium* + *Trichoderma asperellum* through seedling treatment (T₇) with 2.16 and 4.86%, respectively, and 75% RDF + AMF (soil application) (T₈) with 1.85 and 4.48%, respectively. The lowest reducing and non-reducing sugar contents were recorded under absolute control (T₁) (1.41 and 3.70%, respectively), compared with 1.55 and 4.13% under 100% RDF (T₂). Compared with 100% RDF, T₁₂ increased reducing and non-reducing sugars by 60.65 and 27.36%, respectively.

The enhanced accumulation of reducing and non-reducing sugars under combined AMF–PGPR inoculation may be attributed to improved nutrient acquisition and physiological activity, facilitating photosynthate production and translocation to developing fruits. The complementary effects of AMF, *P. fluorescens*, *B. megaterium* and *T. viride* may have favoured carbohydrate metabolism and sugar accumulation. The present findings corroborate Bona *et al.* (2017), who reported improved sugar composition in tomato following AMF–*Pseudomonas* co-inoculation under reduced fertilization, and Gupta *et al.* (2021), who observed enhanced sugar accumulation with *Rhizophagus intraradices* inoculation. The comparatively greater response to soil application may be associated with better establishment and activity of the microbial consortium in the rhizosphere.

3.4 Total soluble solids

Total soluble solids of tomato fruits were significantly affected by the treatments. The highest pooled TSS (5.85 °Brix) was recorded with 75% RDF + AMF + *Pseudomonas fluorescens* + *Bacillus megaterium* + *Trichoderma asperellum* (soil application) (T₁₂), followed by 75% RDF + AMF + *Pseudomonas fluorescens* + *Bacillus megaterium* + *Trichoderma asperellum* (seedling treatment) (T₇) (5.33 °Brix). The lowest TSS was observed under absolute control (T₁) (3.72 °Brix),

while 100% RDF (T₂) recorded 4.37 °Brix. T₁₂ increased TSS by 33.87% over 100% RDF and 57.26% over the absolute control. T₁₂ was significantly superior to all other treatments.

The enhanced TSS under combined AMF–PGPR inoculation may be associated with greater accumulation of soluble carbohydrates, as reflected by the corresponding increase in reducing and non-reducing sugars. Improved nutrient acquisition and assimilate translocation under microbial inoculation may have promoted the accumulation of soluble solids in developing fruits. The present findings corroborate the documented improvement in TSS following integrated application of *Azotobacter*, PSB and VAM with recommended fertilization (Nagar, 2019), as well as the enhancement of tomato TSS under AMF inoculation (Rajat, 2016). The superior response of the soil-applied consortium (T₁₂) over the corresponding seedling treatment (T₇) may be attributed to better establishment and sustained activity of the inoculants in the rhizosphere, thereby facilitating nutrient acquisition and fruit biochemical development.

3.5 Ascorbic acid

Fruit ascorbic acid concentration responded significantly to the different microbial treatments. The combined soil application of 75% RDF + AMF + *Pseudomonas fluorescens* + *Bacillus megaterium* + *Trichoderma asperellum* (T₁₂) resulted in the maximum ascorbic acid content (26.42 mg 100 g⁻¹), 75% RDF + AMF + *Pseudomonas fluorescens* + *Bacillus megaterium* + *Trichoderma asperellum* through seedling treatment (T₇) recorded 24.37 mg 100 g⁻¹. Among the individual microbial treatments, 75% RDF + AMF through soil application (T₈) was the most effective, recording 22.24 mg 100 g⁻¹, compared with 20.08 mg 100 g⁻¹ under 100% RDF (T₂) and 18.15 mg 100 g⁻¹ under the absolute control (T₁). The combined soil-applied consortium increased ascorbic acid content by 31.57% over 100% RDF and 45.56% over the absolute control.

Table 3.2. Effect of arbuscular mycorrhizal fungi and plant growth promoting rhizobacteria on biochemical quality parameters of tomato.

Treatment	Reducing sugar	Non reducing sugar	Total soluble solid (°B)	Ascorbic Acid (mg/100g)	Lycopene (mg/100g)
T ₁ : Absolute control	1.41 e	3.70 e	3.72 f	18.15 e	5.62e
T ₂ : 100 % RDF	1.55d	4.13 d	4.37e	20.08d	7.19 d
T ₃ : 75% RDF + AMF (ST)	1.72 d	4.33 cd	4.61 cd	21.63 cd	7.42 d
T ₄ : 75% RDF + <i>P.f.</i>	1.68 d	4.29 cd	4.54 de	21.18 cd	7.32d
T ₅ : 75% RDF + <i>B.m.</i> (ST)	1.65 d	4.26 cd	4.45 de	21.01 cd	7.30 d
T ₆ : 75% RDF + <i>T.a.</i> (ST)	1.60 d	4.23cd	4.41de	20.78 d	7.22 d
T ₇ : 75% RDF + AMF + <i>P.f.</i> + <i>B.m.</i> + <i>T.a.</i> (ST)	2.16 b	4.86 b	5.33 b	24.37 b	8.43 b
T ₈ : 75% RDF + AMF (SA)	1.85 c	4.48 c	4.83 c	22.24 c	7.87 c
T ₉ : 75% RDF + <i>P.f.</i> (SA)	1.79 cd	4.42 cd	4.79 c	22.14 c	7.71 cd
T ₁₀ : 75% RDF + <i>B.m.</i> (SA)	1.77 cd	4.38 cd	4.71 cd	22.05 c	7.65 cd
T ₁₁ : 75% RDF + <i>T.a.</i> (SA)	1.72 d	4.36 cd	4.64 cd	21.84 cd	7.50 d
T ₁₂ : 75% RDF + AMF + <i>P.f.</i> + <i>B.m.</i> + <i>T.a.</i> (SA)	2.49 a	5.26 a	5.85 a	26.42 a	9.12 a
S.Em.±	0.09	0.13	0.16	0.75	0.24
C.D. at 5 %	0.33	0.40	0.52	2.19	0.70

Note: *P.f.* = *Pseudomonas fluorescens*; *B.m.* = *Bacillus megaterium*; *T.a.* = *Trichoderma asperellum*; ST = Seedling treatment; SA = Soil application. Seedling treatment: AMF @ 100 g in 10 L of water and PGPR @ 100 mL in 10 L of water. Soil application: AMF @ 5 kg acre⁻¹ (12.35 kg ha⁻¹) and PGPR @ 2 L acre⁻¹ (4.94 L ha⁻¹)

The enhanced ascorbic acid concentration under microbial inoculation may be associated with improved nutrient acquisition and physiological activity, particularly AMF-mediated P uptake and enhanced antioxidant metabolism. The superior performance of T₈ (75% RDF + AMF, soil application) among individual inoculation treatments highlights the contribution of AMF to fruit nutritional quality. The comparable response of T₁₂ and T₇ indicates effective enhancement through both soil and seedling application. These findings are consistent with the enhancement of ascorbic acid under AMF + *Azotobacter* + phosphate-solubilizing bacteria (PSB) inoculation in chilli (Pujari, 2016) and with AMF + PGPR, particularly *Pseudomonas* spp., in strawberry (Todeschini *et al.*, 2018), supporting the role of beneficial microbial interactions in improving fruit nutritional quality.

3.6 Lycopene

Lycopene accumulation in tomato fruits was significantly affected by the microbial treatments. 75% RDF + AMF + *Pseudomonas fluorescens* + *Bacillus megaterium* + *Trichoderma asperellum* through soil application (T₁₂) produced the highest lycopene concentration (9.12 mg 100 g⁻¹), while the corresponding seedling treatment of AMF + *Pseudomonas fluorescens* + *Bacillus megaterium* + *Trichoderma asperellum* along with 75% RDF (T₇) recorded 8.43 mg 100 g⁻¹. Among the individual inoculation treatments, 75% RDF + AMF through soil application (T₈) was the most effective (7.87 mg 100 g⁻¹), exceeding the value under 100% RDF (T₂) (7.19 mg 100 g⁻¹). In contrast, the absolute control (T₁) recorded the lowest lycopene concentration (5.62 mg 100 g⁻¹). Relative to 100% RDF, T₁₂ enhanced lycopene content by 26.84%, while the increase over the absolute control was 62.28%.

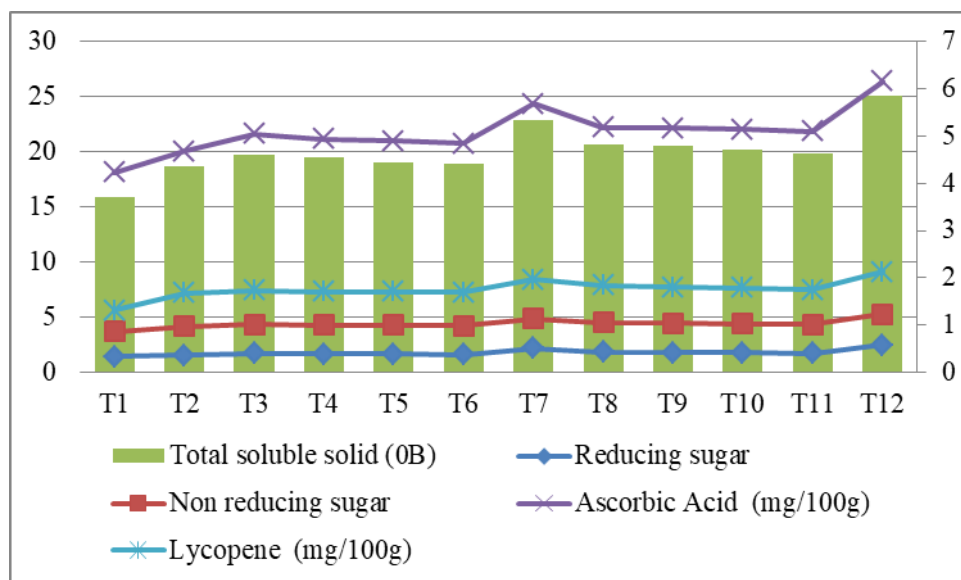


Fig 3.2. Effect of arbuscular mycorrhizal fungi and plant growth promoting rhizobacteria on pooled quality of tomato.

The enhanced lycopene concentration under combined AMF–PGPR inoculation may reflect improved nutrient acquisition, photosynthetic efficiency and metabolic activity, thereby favouring carotenoid biosynthesis during fruit development. The superior response of T₁₂ (75% RDF + AMF + *P. fluorescens* + *B. megaterium* + *T. viride*, soil application) and its consistent advantage over the corresponding seedling treatment further indicate the importance of effective root-zone establishment and sustained plant–microbe interactions. These findings are consistent with Ordoorkhani *et al.* (2010), who demonstrated enhanced lycopene accumulation in tomato following co-inoculation with AMF and PGPR, particularly combinations involving *Pseudomonas*, *Azotobacter* and *Azospirillum*. The reported improvement was associated with enhanced nutrient uptake, including K, and improved physiological efficiency, supporting the role of AMF–PGPR interactions in promoting nutritionally important fruit quality attributes.

4. CONCLUSION:

The pooled results across the two experimental years demonstrated that integration of AMF and PGPR with reduced mineral fertilizer input can simultaneously improve plant nutrient status, biomass production, tomato fruit yield and biochemical quality under Vertisol conditions. Among the treatments evaluated, soil application of 75% RDF + AMF + *Pseudomonas fluorescens* + *Bacillus megaterium* + *Trichoderma asperellum* was the most effective treatment. The consortium treatment produced the highest plant N, P and K concentration, dry matter yield (46.34 q ha⁻¹) and fruit yield (376.74 q ha⁻¹), while also recording superior reducing sugar (2.49%), non-reducing sugar (5.26%), TSS (5.85 °Brix), ascorbic acid and lycopene (9.12 mg 100 g⁻¹). Importantly, these improvements were achieved with 75% RDF, indicating that microbial inoculation enabled a 25% reduction in mineral fertilizer input without compromising productivity.

The close association between improved plant nutrient concentration, biomass accumulation, fruit yield and biochemical quality suggests that enhanced nutrient acquisition was an important component of the beneficial response to AMF–PGPR integration. Soil application was more effective than seedling application, highlighting the importance of microbial placement for successful field establishment. Thus, the combined use of AMF and PGPR with 75% RDF represents a promising integrated nutrient management strategy for sustainable tomato production in Vertisol.

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