Journal of Applied Biology & Biotechnology Vol. 14(6), pp. 127-134, November-December, 2026
Available online at http://www.jabonline.in
DOI: 10.7324/jabb.2026.317926

Effect of biofertilizers combined with varying levels of NPK fertilizers on growth, yield, and quality of beetroot (*Beta vulgaris* L.) under subtropical conditions

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ARTICLE INFO

Article history:
Received on: 19/04/2026
Accepted on: 26/06/2026
Available Online: 25/09/2026

Key words:
Biofertilizers, beetroot, integrated nutrient management, azospirillum, *Pseudomonas fluorescens*, yield, NPK, subtropical

ABSTRACT

A field experiment was conducted during the Rabi season (November 2024–March 2025) at the Research Farm, RSM PG College, Dhampur, Uttar Pradesh, India (latitude 29.3°N), under subtropical agro-climatic conditions. The study evaluated the effect of biofertilizer inoculation combined with the recommended dose of NPK fertilizers (100:60:40 kg N: P_2O_5:K_2O ha^{-1}) and its reduced levels (75% and 50%) on the growth, yield, and quality of beetroot (*Beta vulgaris* L.). Farmyard manure (FYM @ 10 t ha^{-1}) was applied uniformly to all plots as a baseline organic input. The experiment followed a Randomized Block Design with 18 treatment combinations and three replications. The combination of 100% NPK with vermicompost and mycorrhiza (T18) produced the highest plant height (12.37 cm at 90 DAS), superior leaf dimensions, and the highest total soluble solids (10.9 °Brix), representing improvements of approximately 54.6% and 49.3% over the FYM-baseline treatment (T1), respectively. The highest root yield in this experiment (24.95 t ha^{-1}) was recorded in T16 (75% NPK + *Azospirillum* + *Pseudomonas fluorescens*), which was 23.8% higher than T1, indicating enhanced nutrient-use efficiency at reduced inorganic fertilizer levels. The study objectives were: (I) to evaluate the growth, yield, and quality response of beetroot to biofertilizer inoculation; (II) to assess whether biofertilizers can sustain productivity under reduced inorganic fertilizer levels; and (III) to identify the most effective treatment combination for sustainable beetroot cultivation under subtropical conditions. Further validation through factorial designs and multi-location trials is recommended.

1. INTRODUCTION

Beetroot (*Beta vulgaris* L. subsp. *vulgaris*) is an important root vegetable valued for its nutritional composition, including dietary nitrates, betalain pigments, and antioxidant compounds with potential cardiovascular and anti-inflammatory benefits [1,2]. It is cultivated widely in the subtropical plains of northern India as a key Rabi vegetable. Beetroot requires an adequate and balanced supply of nitrogen (N), phosphorus (P), and potassium (K) for optimum root development and quality. N promotes vegetative growth and chlorophyll synthesis, P supports root proliferation, and K regulates osmotic balance and assimilate partitioning [3].

Despite productivity gains from chemical fertilizers, their excessive use leads to soil structural deterioration, decline in microbial biodiversity, and environmental concerns related to nutrient runoff [4]. Integrated nutrient management, which combines biofertilizers, organic amendments, and reduced inorganic fertilizer levels, has emerged as a viable sustainability strategy [5].

Biofertilizers encompass plant growth-promoting microorganisms that enhance nutrient availability through biological nitrogen fixation, phosphate solubilization, potassium mobilization, and phytohormone synthesis [4]. *Azospirillum* is an associative nitrogen fixer that promotes root hair proliferation and enhances water and mineral uptake [6]. *Azotobacter* is a free-living nitrogen fixer that also synthesizes growth-promoting vitamins [7]. *Pseudomonas fluorescens* solubilizes inorganic phosphates and plays a role in biocontrol of soilborne pathogens [8]. *Bacillus subtilis* is known for phosphate-solubilizing and plant growth-promoting activities [9]. *Frateuria aurantia* is a potassium-solubilizing bacterium [10], and arbuscular mycorrhizal fungi (AMF) enhance phosphorus uptake through hyphal networks, improve water absorption, and promote antioxidant accumulation [11].

Organic amendments such as vermicompost can contribute to improved soil fertility by supplying nutrients and enhancing soil physical and biological properties [12]. Their integration with inorganic fertilizers has also been associated with improved growth, yield, and quality of beetroot [13]. Such integrated nutrient-management approaches may therefore help maintain crop productivity while reducing exclusive dependence on mineral fertilizers and supporting more sustainable soil-fertility management. [12,13].

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Despite increasing evidence supporting biofertilizer effectiveness in vegetable and field crops, including wheat and lettuce [14,15], their combined effects with reduced inorganic fertilizer levels specifically in beetroot (*Beta vulgaris* L.) under subtropical conditions remain insufficiently explored. Therefore, the present study was undertaken with the following objectives: (1) to evaluate the effect of different biofertilizer combinations on growth, yield, and quality of beetroot; (2) to assess whether biofertilizers can sustain productivity under reduced inorganic fertilizer levels (50% and 75% NPK); and (3) to identify the most effective integrated treatment for sustainable beetroot cultivation under subtropical conditions.

2. MATERIALS AND METHODS

2.1. Experimental Site and Agro-climatic Conditions

The field experiment was conducted during the Rabi season (November 2024–March 2025) at the Research Farm of RSM PG College, Dhampur, Bijnor District, Uttar Pradesh, India (latitude 29.3°N, longitude 78.5°E, altitude 208 m above mean sea level), within the subtropical agro-climatic zone (Zone IV, Indo-Gangetic Plains; mean temperature 10°C–22°C during the crop growth period). The soil was sandy loam in texture with pH 7.2, electrical conductivity 0.38 dS m^{-1}, organic carbon 0.48%, and available N, P, and K of 182, 14.3, and 164 kg ha^{-1}, respectively, determined by standard methods [16–18].

Table 1. Treatment combinations used in the experiment.

Treatment code	Treatment description
T1	FYM baseline only (10 t ha^{-1}); no mineral NPK or biofertilizer
T2	100% recommended dose of fertilizer (RDF: 100:60:40 kg N:P_2O_5:K_2O ha^{-1})
T3	Azospirillum (seed treatment @ 25 g kg^{-1} seed)
T4	Azotobacter (soil application @ 5 kg ha^{-1})
T5	Azospirillum + Azotobacter
T6	*Bacillus subtilis* (seed treatment @ 25 g kg^{-1} seed)
T7	*P. fluorescens* (soil application @ 5 kg ha^{-1})
T8	*Azospirillum* + *Bacillus subtilis* (seed treatment @ 25 g kg^{-1} seed)
T9	*Frateuria aurantia* (soil application @ 5 kg ha^{-1})
T10	Azospirillum + *Frateuria aurantia*
T11	Mycorrhiza (soil application @ 5 kg ha^{-1})
T12	Mycorrhiza (soil application @ 5 kg ha^{-1}) + Bacillus subtilis (soil application @ 5 kg ha^{-1})
T13	Mycorrhiza + Azospirillum
T14	Azospirillum + *P. fluorescens* + *Frateuria aurantia*
T15	Azospirillum (seed treatment @ 25 g kg^{-1} seed) + *B. subtilis* (soil application @ 5 kg ha^{-1}) + *F. aurantia* + Mycorrhiza
T16	75% NPK + *Azospirillum brasilense* + *P. fluorescens*
T17	50% NPK + Mycorrhiza (*Glomus mosseae*) + *B. subtilis* (soil application @ 5 kg ha^{-1})
T18	100% NPK + Vermicompost (5 t ha^{-1}) + Mycorrhiza (*Glomus mosseae*)

DAS = days after sowing; FYM = farmyard manure; NPK = nitrogen, phosphorus, potassium; RDF = recommended dose of fertilizer.

2.2. Experimental Design and Treatments

The experiment was laid out in a randomized block design (RBD) with 18 treatment combinations, each replicated 3 times (54 experimental units; plot size 1.80 m × 3.00 m = 5.40 m^2). To maintain comparable soil organic matter across all plots, FYM at 10 t ha^{-1} was applied uniformly to every plot before sowing [13]. T1, therefore, represents a FYM baseline only (10 t ha^{-1}; no mineral NPK or biofertilizer) treatment with a uniform FYM baseline, and should not be regarded as an absolute control in the strict sense. Treatment details are presented in Table 1.

2.3. Biofertilizer Preparation and Application

All microbial inoculants were procured from a government-approved biofertilizer production unit and verified for viability (minimum 10^8 CFU g^{-1}). Seed-treatment organisms—*Azospirillum* (used throughout, alone or in combination) and *Bacillus subtilis* when used alone (T6) or combined only with *Azospirillum* (T8)—were applied at 25 g kg^{-1} seed using 10% jaggery solution as a sticker, shade-dried for 30 minutes, and sown immediately [5]. Mycorrhiza and soil-applied organisms—Azotobacter, *P. fluorescens*, *F. aurantia*, and *B. subtilis* when combined with Mycorrhiza and/or other soil-applied organisms (T12, T15, T17)—were incorporated into the root zone at 5 kg ha^{-1} mixed with 50-kg decomposed compost before sowing.

2.4. Fertilizer and Organic Amendment Application

The recommended dose of fertilizers (RDF) was 100:60:40 kg N:P_2O_5:K_2O ha^{-1} [19], applied as urea (46% N), single superphosphate (16% P_2O_5), and muriate of potash (60% K_2O). Half the N and full P and K were applied basally; the remaining N was top-dressed at 30 DAS. For T16 (75% NPK) and T17 (50% NPK), respective proportions followed the same schedule. Vermicompost (C: N ratio 15:1, @ 5 t ha^{-1}) was incorporated 15 days before sowing in T18 in addition to 100% NPK [13].

2.5. Crop Management

Beetroot cultivar "Detroit Dark Red" was sown at 30 cm × 10 cm spacing (~3.33 lakh plants ha^{-1}; 180 plants per plot). Standard practices–irrigation (6–7 irrigations), weeding (twice at 25 and 50 DAS), and preventive disease management (mancozeb @ 2.5 g L^{-1} at 45 DAS)–were uniformly followed.

Table 2. Effect of different biofertilizer and nutrient management treatments on growth parameters of beetroot (*Beta vulgaris* L.).

Treatment	Plant height 60 DAS (cm)	Plant height 75 DAS (cm)	Plant height 90 DAS (cm)	Leaves plant^{-1} 60 DAS	Leaves plant^{-1} 75 DAS	Leaves plant^{-1} 90 DAS	Leaf length 90 DAS (cm)	Leaf width 90 DAS (cm)	Fresh Wt Plant (g)	Shoot dry Wt (g)
T1	3.40	7.77	8.00	4.43	7.73	7.67	17.10	4.63	159.48	15.97
T2	4.27	8.53	11.37	4.63	7.70	8.53	24.27	7.07	168.89	17.08
T3	4.27	8.47	10.47	5.53	8.10	7.73	21.60	6.47	224.32	20.28

Continued

Treatment	Plant height 60 DAS (cm)	Plant height 75 DAS (cm)	Plant height 90 DAS (cm)	Leaves plant^{-1} 60 DAS	Leaves plant^{-1} 75 DAS	Leaves plant^{-1} 90 DAS	Leaf length 90 DAS (cm)	Leaf width 90 DAS (cm)	Fresh Wt Plant (g)	Shoot dry Wt (g)
T4	4.53	7.77	10.87	5.13	7.83	7.67	20.77	6.17	224.08	21.48
T5	3.60	8.63	9.93	3.73	8.43	7.33	20.33	6.27	238.46	23.66
T6	4.13	9.13	10.07	4.30	7.03	6.73	19.97	6.17	246.38	25.09
T7	4.43	8.60	8.73	4.87	7.67	7.00	18.13	5.17	239.85	24.44
T8	4.37	8.50	9.07	4.50	7.73	7.00	19.47	5.63	262.60	27.72
T9	4.00	8.57	9.53	5.00	7.37	7.20	20.00	6.00	223.04	22.21
T10	4.20	8.33	9.00	4.90	7.70	7.27	19.22	5.49	233.89	24.25
T11	4.37	7.77	10.53	5.60	8.00	8.07	20.80	6.50	244.62	25.66
T12	4.47	8.37	8.00	4.60	7.47	7.53	19.60	5.90	254.42	27.28
T13	4.10	7.97	8.67	4.93	7.60	7.53	19.27	5.67	265.60	28.60
T14	3.83	8.07	8.27	4.53	6.90	7.73	19.80	6.00	272.22	29.83
T15	4.10	9.33	9.40	5.30	7.87	7.07	20.93	5.20	282.22	31.36
T16	5.50	9.57	11.60	4.87	8.33	9.67	27.13	8.57	294.16	33.05
T17	4.53	9.67	11.87	5.67	7.73	9.20	28.40	9.33	289.25	31.68
T18	5.20	10.20	12.37	5.80	8.57	8.73	28.73	9.20	296.80	33.97
Mean	4.29	8.62	9.88	4.91	7.76	7.76	21.42	6.41	245.57	25.76
CD (5%)	1.02	1.16	2.03	1.49	0.63	1.44	3.42	1.38	6.49	0.95
SEm±	0.35	0.40	0.70	0.52	0.22	0.50	1.19	0.48	2.25	0.33
CV (%)	14.19	8.09	12.36	18.31	4.85	11.12	9.58	12.93	1.59	2.20

CD = critical difference at 5% level; CV = coefficient of variation; DAS = days after sowing.

2.6. Observations Recorded

Growth parameters (plant height, number of leaves per plant^{-1}, leaf length, leaf width) were recorded at 60, 75, and 90 DAS on five tagged plants per plot. Leaf area was not measured; leaf dimensions (length and width) were recorded as proxies. Shoot fresh weight and shoot dry weight (oven-dried at 65°C to constant weight) were recorded at 90 DAS. Yield parameters–root diameter, root length, root weight plant^{-1}, root fresh mass, and root dry mass–were recorded at harvest (95 DAS) from five randomly selected plants. Root weight plant^{-1} denotes the fresh weight of the trimmed, marketable storage root (crown and fine/fibrous rootlets removed) recorded immediately after washing, whereas root fresh mass denotes the fresh weight of the entire, untrimmed root system (storage root together with attached fibrous and lateral roots) from which root dry mass was subsequently obtained after oven-drying; the two parameters are, therefore, not directly comparable. Root yield was calculated on a plot basis and converted to t ha^{-1}. The root-to-shoot dry weight ratio was computed as: root dry mass (g) / shoot dry mass (g). Total soluble solids (TSS) were measured using a hand refractometer (Erma, Japan) and expressed in °Brix [20].

2.7. Statistical Analysis

Data were subjected to ANOVA for RBD following Gomez and Gomez [21]. Treatment means were compared using the critical difference (CD) at 5% level of significance. Statistical analyses were performed using OPSTAT software (CCSNIAU, Hisar, India).

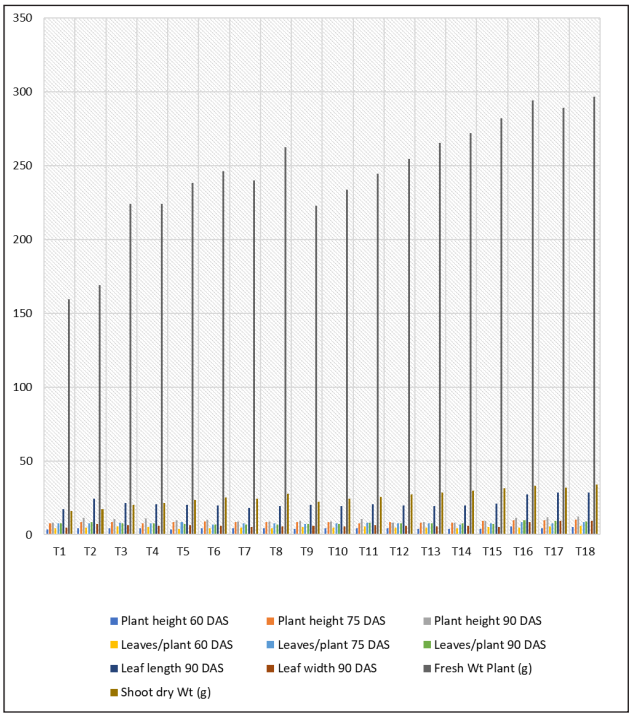

Figure 1. Effect of different biofertilizers and nutrient management treatments on growth parameters of beetroot *(Beta vulgaris L.)*.

3. RESULTS AND DISCUSSION

3.1. Growth Parameters

Significant variation among treatments was recorded for all growth parameters at 60, 75, and 90 DAS (Table 2; Fig. 1). T16 recorded the highest plant height at 60 DAS (5.50 cm), whereas T18 recorded the highest plant height at 75 and 90 DAS (10.20 and 12.37 cm, respectively), along with the highest leaf length (28.73 cm) at 90 DAS–an improvement of approximately 54.6% in plant height over T1 (8.00 cm at 90 DAS); T17 recorded the numerically highest leaf width (9.33 cm), followed by T18 (9.20 cm), though this difference

Table 3. Effect of biofertilizer and nutrient management treatments on yield attributes of beetroot (*Beta vulgaris* L.).

Treatment	Root diameter (cm)	Root length (cm)	Root Wt plant^{-1} (g)	Root yield (t ha^{-1})	Root fresh mass (g plant^{-1})	Root dry mass (g plant^{-1})	Root: shoot dry Wt ratio
T1	3.70	15.93	56.67	20.15	125.80	17.37	1.09
T2	3.69	15.47	56.37	20.62	129.40	18.17	1.06
T3	3.79	16.47	65.27	20.76	140.50	19.30	0.95
T4	3.76	15.00	67.40	21.41	144.80	20.27	0.94
T5	4.56	14.80	56.27	21.36	150.53	21.53	0.91
T6	3.74	13.93	57.03	21.99	155.50	22.70	0.90
T7	3.31	13.93	50.19	22.14	160.87	23.37	0.96
T8	3.58	14.00	57.37	23.82	165.73	24.63	0.89
T9	3.80	14.33	61.47	22.50	170.13	26.07	1.17
T10	4.38	16.87	61.67	22.92	175.60	27.27	1.12
T11	3.95	16.27	57.20	23.30	179.40	28.47	1.11
T12	4.18	14.53	70.33	23.53	183.30	29.60	1.09
T13	3.92	15.67	62.17	23.77	188.67	30.97	1.08
T14	4.03	15.33	59.80	23.95	192.07	32.30	1.08
T15	3.83	17.27	61.17	24.72	198.70	33.90	1.08
T16	4.66	17.33	75.00	24.95	202.60	35.00	1.06
T17	4.64	16.33	96.17	24.66	207.27	36.40	1.15
T18	4.29	16.13	76.67	24.92	211.47	37.57	1.11
Mean	3.99	15.53	63.79	22.86	171.24	26.94	1.04
CD (5%)	0.89	2.88	20.74	0.29	1.90	0.34	0.12
SEm±	0.31	1.02	7.19	0.10	0.66	0.12	0.04
CV (%)	13.38	11.36	19.51	0.77	0.67	0.77	6.73

Root: Shoot ratio = root dry mass/shoot dry mass (g/g). CD = critical difference at 5% level. Root Wt plant^{-1} = fresh weight of the trimmed, marketable storage root; Root Fresh Mass = fresh weight of the entire, untrimmed root system from which Root Dry Mass was obtained; the two are not directly comparable (see Section 2.6). The authors have re-verified the underlying raw field data, units, and replicate-level calculations for root Wt plant^{-1}, root fresh mass, and root dry mass against the original datasheets and confirm no transposition, transformation, or transcription error. The lower CV for root fresh mass/root dry mass relative to root Wt plant^{-1} (see CV row above) is consistent with this measurement distinction: root Wt plant^{-1} was recorded on the trimmed, marketable root only and is therefore more sensitive to plant-to-plant variability in trimming, whereas root fresh mass/root dry mass were recorded on the entire, untrimmed root system and represent a more stable, composite measure. Raw replicate data are available from the corresponding author on request (see Section 12).

should be interpreted against CD = 1.38 cm. The greatest number of leaves at 90 DAS was recorded in T16 (9.67 plant^{-1}), followed by T17 (9.20 plant^{-1}) and T18 (8.73 plant^{-1}), indicating that leaf-number response was maximized under partially reduced NPK combined with biofertilizer inoculation, whereas T18 remained the superior treatment for plant height and leaf dimensions. Treatments T16 and T17 performed significantly better than the FYM-baseline treatment (T1) for most vegetative parameters; however, their superiority over sole NPK (T2) was parameter-dependent and must be assessed against respective CD values (e.g., CD = 2.03 cm for plant height at 90 DAS).

The superior vegetative growth under T18 is attributable to the synergistic interaction among inorganic macronutrients, humic substances from vermicompost, and enhanced phosphorus uptake by mycorrhizal hyphae. Vermicompost and other composted organic amendments improve soil aggregation, water-holding capacity, and microbial activity [12,13,22], while AMF extend functional root surface area through extraradical hyphae, improving uptake of phosphorus and secondary nutrients [11]. These findings are consistent with Maloisane and Kayombo [23] reported improved beetroot growth and yield under vermicompost treatments compared with mineral fertilizer and untreated soil, and Youssef et al. [24], who observed markedly improved plant height under combined AMF and mineral fertilizer in root vegetables.

3.2. Yield and Yield Attributes

Yield parameters differed significantly among treatments (Table 3; Fig. 2). The highest root yield in this experiment (24.95 t ha^{-1}) was recorded in T16 (75% NPK + *Azospirillum* + *P. fluorescens*), followed by T18 (24.92 t ha^{-1}) and T17 (24.66 t ha^{-1}); these three treatments were statistically equivalent in root yield (CD = 0.29 t ha^{-1}). This conclusion was verified using unrounded replicate means and the unrounded CD/error term from the ANOVA output, confirming that the equivalence is not an artifact of rounding to two decimal places. Root yield under T16 was 23.8% higher than T1 (20.15 t ha^{-1}) and 21.0% higher than T2 (20.62 t ha^{-1}).

Regarding individual root weight, T17 recorded the highest value (96.17 g plant^{-1}), followed by T18 (76.67 g plant^{-1}) and then T16 (75.00 g plant^{-1}). The apparent discrepancy–T17 had larger individual roots yet lower total yield than T16–arises because hectare yield was derived from total plot yield, and the number of uniformly marketable-sized roots harvested per plot was higher in T16. The root-to-shoot dry weight ratio was numerically highest in T9 (1.17), followed by T17 (1.15); both values reflect strong assimilate partitioning towards root storage, although CD = 0.12 should be considered before inferring superiority between treatments.

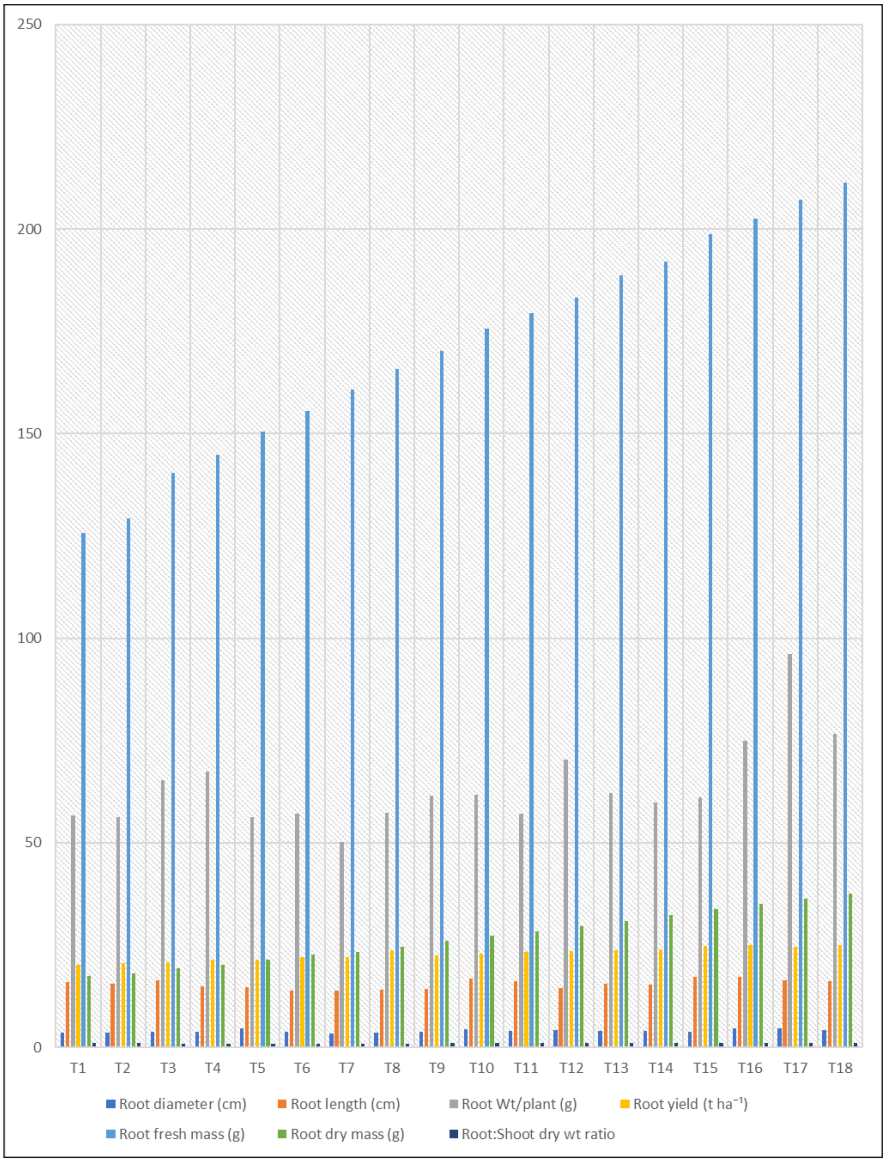

Figure 2. Effect of biofertilizers and nutrient management treatments on yield attributes of beetroot *(Beta vulgaris L.)*.

Table 4. Effect of biofertilizer and nutrient management treatments on quality (TSS) of beetroot (*Beta vulgaris* L.).

Treatment	Treatment details	TSS (°Brix)
T1	No mineral NPK or biofertilizer (FYM baseline only, 10 t ha^{-1})	7.3
T2	100% NPK (RDF only)	7.7
T3	Azospirillum	7.9
T4	Azotobacter	8.3
T5	Azospirillum + Azotobacter	8.6
T6	*B. subtilis*	8.9
T7	Pseudomonas fluorescens	9.2
T8	Azospirillum + *B. subtilis*	9.6
T9	Frateuria aurantia	9.0
T10	Azospirillum + Frateuria aurantia	8.7
T11	Mycorrhiza	8.3
T12	Mycorrhiza + *B. subtilis*	8.1
T13	Mycorrhiza + Azospirillum	8.5
T14	Azospirillum + *P. fluorescens* + *Frateuria aurantia*	8.9
T15	Azospirillum + *Bacillus subtilis* + *Frateuria aurantia* + Mycorrhiza	9.9
T16	75% NPK + Azospirillum + *P. fluorescens*	10.2
T17	50% NPK + Mycorrhiza + *B. subtilis*	10.5
T18	100% NPK + Vermicompost + Mycorrhiza	10.9
Mean	–	8.92
CD (5%)	–	0.13
SEm±	–	0.044
CV (%)	–	0.85

All pairwise differences among T16 (10.2 °Brix), T17 (10.5 °Brix), and T18 (10.9 °Brix) exceed CD = 0.13 °Brix and are statistically significant.

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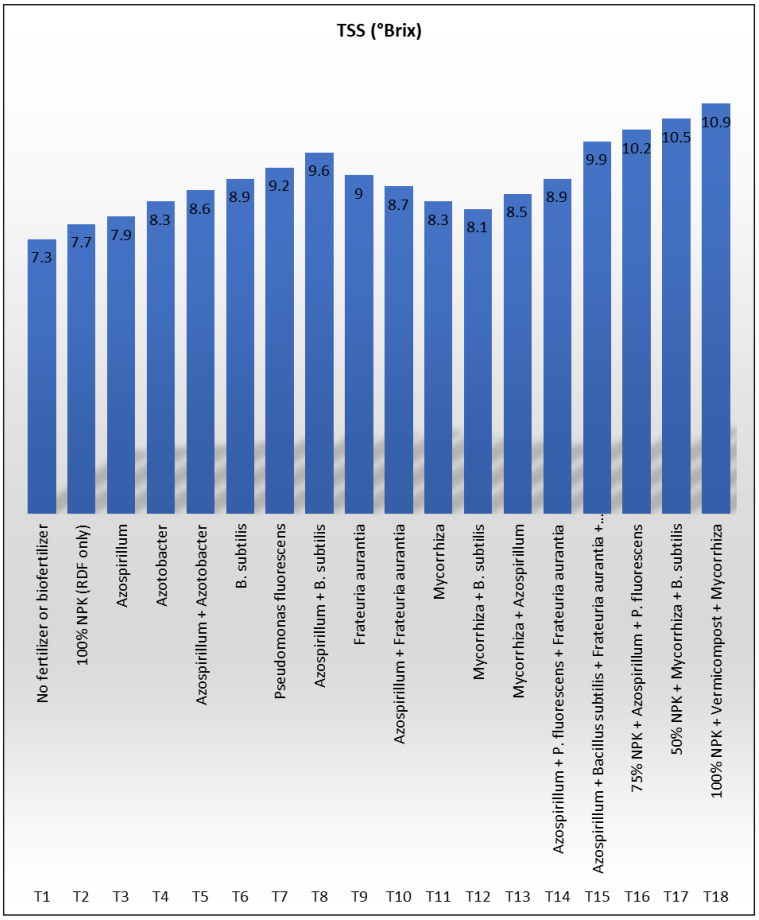

Figure 3. Effect of biofertilizers and nutrient management treatments on quality (TSS) of beetroot *(Beta vulgaris L.)*.

The superior yield of T16 despite receiving only 75% of the recommended NPK dose reflects the dual contribution of *Azospirillum* (biological N fixation and IAA-mediated root stimulation) and *P. fluorescens* (phosphate solubilization via organic acid production) in improving nutrient-use efficiency [6,8], consistent with Rajput and Singh [25], who documented enhanced root yield with *P. fluorescens* at reduced fertilizer doses in carrot. The contrasting pattern–T18 excelling in vegetative growth and quality while T16 maximized yield–suggests differential assimilate partitioning driven by the hormonal environment of each treatment.

3.3. Quality Parameters

TSS showed significant variation among treatments (CD = 0.13 °Brix; Table 4; Fig. 3). All three integrated treatments were significantly different from each other: T18 (10.9 °Brix) > T17 (10.5 °Brix) > T16 (10.2 °Brix), with pairwise differences of 0.4, 0.3, and 0.7 °Brix, respectively, all exceeding the CD. T18 recorded the highest TSS, representing a 49.3% improvement over T1 (7.3 °Brix) and 41.6% over T2 (7.7 °Brix).

The improvement in TSS under T18 is mechanistically linked to balanced macro- and micronutrient availability, promoting higher rates of carbohydrate synthesis and sugar accumulation. Vermicompost supplies humic substances and readily available nutrients that may contribute to improved quality and soluble solids accumulation in beetroot [13], and AMF enhance carbon allocation to storage organs [11]. These findings corroborate Kondal et al. [13] and Youssef et al. [24], who reported improved TSS and sugar content in beetroot and root vegetables with vermicompost and mycorrhizal inoculation, respectively.

4. CONCLUSION

The present investigation demonstrates that biofertilizer inoculation combined with varying NPK levels significantly enhances the growth, yield, and quality of beetroot under subtropical conditions. The conclusions drawn in relation to the study objectives are: (1) Responses to biofertilizer and nutrient-management treatments were parameter-dependent, with the integrated treatments T16–T18 generally producing the strongest responses for key growth, yield, and TSS outcomes (2) The combination of 75% NPK with *Azospirillum brasilense* and *Pseudomonas fluorescens* (T16) produced the highest root yield in this experiment (24.95 t ha^{-1}; 23.8% over T1 and 21.0% over T2), indicating that partial replacement of inorganic NPK with biofertilizer inoculation can sustain root yield comparable to full NPK fertilisation under the tested combinations (see Section 5, regarding the absence of an NPK-only comparator). Similarly, 50% NPK + Mycorrhiza + *Bacillus subtilis* (T17) achieved 24.66 t ha^{-1} (22.4% over T1); And (3) The combination of 100% NPK + vermicompost + mycorrhiza (T18) was the most effective for vegetative growth and TSS quality (10.9 °Brix; 49.3% above T1). T18 is recommended where quality is the primary objective; T16 is recommended where yield maximization with reduced mineral-fertilizer input is the priority. Future studies should

employ factorial designs, include NPK-only reduced treatments, measure soil biological indicators, and conduct multi-location trials.

5. LIMITATIONS OF THE STUDY

The non-factorial design limits the separation of individual and interactive treatment effects. No reduced-NPK-only treatment was included, limiting evaluation of the independent biofertilizer contribution. Results are specific to this location and season. Quality evaluation was restricted to TSS. Soil biological properties and nutrient uptake data were not analysed.

6. USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors used Claude (Anthropic, San Francisco, CA; claude.ai) solely for English language editing, grammar correction, and structural improvement of the manuscript text. Claude was not used to generate, fabricate, or alter research data, statistical analyses, experimental design, or scientific conclusions. All data were collected from the field experiment, and all interpretations and conclusions represent the intellectual work of the authors. The authors confirm that no AI-generated scientific content, data, or fabricated references are present in this manuscript. This disclosure is provided in full transparency in accordance with the journal's policy on the use of AI tools.

7. ACKNOWLEDGEMENTS

The authors sincerely acknowledge the facilities provided by the Department of Horticulture, RSM PG College, Dhampur, affiliated with M.J.P. Rohilkhand University, Bareilly, Uttar Pradesh, India.

8. AUTHORS' CONTRIBUTIONS

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agree to be accountable for all aspects of the work. All the authors are eligible to be authors as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines.

9. FUNDING

This research received no specific financial support from public, commercial, or non-profit funding agencies.

10. CONFLICT OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

11. ETHICAL APPROVAL

This study did not involve human or animal subjects; therefore, ethical approval was not required.

12. DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

13. PUBLISHER'S NOTE

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How to cite this article:
Saini H, Pal SL, Kumar T, Saini D, Singh M, Saini S, Amit. Effect of biofertilizers combined with varying levels of NPK fertilizers on growth, yield, and quality of beetroot (*Beta vulgaris* L.) under subtropical conditions. J Appl Biol Biotech 2026;14(6):127-134. DOI: 10.7324/jabb.2026.317926