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Effect of integrated nutrient management on growth, yield, nutritional value, and nutraceutical quality of onion bulbs (*Allium cepa* L.)

Raju Lal Bhardwaj[1*], Anita Sharma[2], Premlata Meena[3], K Choudhary[2], S R Kumawat[1] & Aabha Parashar[3]

[1]*College of Agriculture, Baytu-Barmer, 304 034, Agriculture University, Jodhpur*

[2]*College of Agriculture, Sumerpur-Pali 306 902, Agriculture University, Jodhpur*

[3]*Agricultural Research Sub Station, Sumerpur-Pali 306 902, Agriculture University, Jodhpur*

Email: premlata@aujodhpur.ac.in

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Abstract

The use of mineral fertilizers for onion cultivation can degrade soil physical properties and microbial diversity, thereby adversely affecting crop productivity and nutritional quality of onion bulbs. To address this concern, a long-term field experiment was conducted with six treatments to evaluate the effects of varying proportions of mineral fertilizers and organic manures, combined with the plant growth-promoting microorganisms (PGPMs), on bulb yield attributes, nutritional quality, sensory characteristics, spicing superiority, and nutraceutical contents of onion bulbs. The results demonstrated that applying 100 per cent of the recommended dose of fertilizers (RDF) through organic manures, in combination with PGPMs inoculation, significantly improved plant growth parameters (ranging from 2.39% to 21.95%), bulb yield attributes (3.28% to 16.53%), physicochemical properties (7.30% to 53.08%), economic returns (7.64% to 18.69%), total mineral content (0.68% to 39.88%), and nutraceutical concentrations (21.47% to 75.32%). Moreover, this integrated approach enhanced crop resistance mechanisms against major diseases and insect infestations compared to the exclusive use of 100% RDF via mineral fertilizers. Overall, the study suggests that integrating organic manure-based RDF with PGPMs inoculation enhances onion productivity and nutritional quality. In conclusion, the combined use of organic manure and PGPMs significantly improved the nutritional density, organoleptic properties, and flavour qualities of onion bulbs, while also contributing to reduction of pathogen and insect pest infestations during cultivation.

Keywords: Disease resistance, *in-vitro* digestibility, nutritional value, productivity, sensory quality, soil fertility

Introduction

Onion (*Allium cepa* L.) ranks as the fourth most economically important vegetable and spice crop globally (Torquato-Tavares *et al*., 2017). India is the leading producer, harvesting over 31 million metric tons in 2022 from a cultivated area of 1.94 million hectares (FAO, 2024). Onions play a vital role in culinary practices due to their distinctive flavour and appetite-stimulating properties, serving both as a staple in national cuisine and a major contributor to foreign exchange earnings among fresh fruits and vegetables. Nutritionally, onion bulbs contain approximately 86.8% moisture, 11.0 grams of carbohydrates, 1.2 grams of protein, 0.6 grams of fiber, and provide about 38 calories per 100 grams. They are also rich in vitamins such as ascorbic acid (11 mg), thiamine (0.08 mg), riboflavin (0.01 mg), and niacin (0.2 mg), as well as minerals including phosphorus (39 mg), calcium (27 mg), sodium (1.0 mg), iron (0.7 mg), and potassium (157 mg) of per 100 grams bulbs (Singh & Verma, 2001). Despite its high production, India's onion productivity remains below the global average, with an average yield of 16.32 tons ha^{-1}, compared to the global average of 18.53 tons ha^{-1}. A key limiting factor is the indiscriminate use of mineral fertilizers, which not only undermines long-term agricultural sustainability but also contributes to environmental pollution (Jaiswal *et al*., 2022). While the widespread adoption of chemical fertilizers has improved yield and accelerated crop growth (Bhardwaj and Parashar, 2023), this intensive approach often compromises the flavour and spicing quality of the bulbs (Bhardwaj *et al*., 2024). Excessive reliance on synthetic fertilizers can disrupt the natural nutrient balance in the soil, adversely affecting the uptake of essential secondary metabolites and sulfur-containing compounds, responsible for the characteristic pungency, spicing flavour, and distinctive taste of onions. Moreover, mineral fertilizers may suppress beneficial soil microorganisms that play a crucial role in nutrient cycling and enhancing the biosynthesis of flavour-related compounds (Bhardwaj *et al*., 2025a). Currently, onion production is heavily dependent on chemical fertilizers, which often results in bulbs with a milder taste, diminished aroma intensity, and lower concentrations of nutritionally valuable phytochemicals. This decline in flavour quality negatively impacts consumer satisfaction, as well as the culinary and food processing industries that depend on onions with strong and consistent taste profiles. Chemical-based farming systems disrupt plant nutrient homeostasis, and excessive nitrogen levels increase tissue succulence, making plants more susceptible to diseases and insect infestations. Additionally, the declining nutritional quality of crops poses a serious concern for human dietary nutrient intake (Marles, 2017). For instance, essential vegetables such as tomatoes, onions, and potatoes have experienced a decline in nutritional density by approximately 25–50% over the past eighty years, with significant reductions in sodium (52%), iron (50%), copper (49%), and magnesium (10%) (Mayer *et al*., 2022; Bhardwaj *et al.,* 2024). The continuous and excessive use of chemical fertilizers has had a detrimental impact on soil health (Huang *et al.,* 2023), disrupting the intricate interactions between plants and beneficial soil microorganisms (Huang *et al.,* 2019). The decline in soil organic matter and alteration in soil physicochemical and biological properties have led to significant nutrient depletion in agricultural produce, thereby reducing the nutritional, sensory, and flavour qualities of onion bulbs (Han *et al.,* 2024).

Conventional chemical fertilizers directly enhance crop yields by supplying nutrients that plants can assimilate either directly or indirectly (Erana *et al*., 2019). However, their prolonged use can negatively impact agricultural ecosystems, contributing to the degradation of soil fine structure (Bhardwaj *et al*., 2024), reduced microbial diversity, groundwater contamination, and atmospheric pollution (Erana *et al*., 2019). Continuous application of inorganic fertilizers often leads to micronutrient deficiencies, imbalances in soil physicochemical properties, and unsustainable onion production (Jayathilake *et al*., 2006). In contrast, organic manures contribute to the buildup of soil organic carbon through biological oxidative transformation, producing a stable and slow-release source of nutrients (Deepesh *et al*., 2016). Organic manures are rich in humus-like organic matter, which improves soil structure, enhances soil moisture retention, buffers soil pH, increases cation exchange capacity, facilitates nutrient availability, particularly nitrogen, phosphorus, and potassium, and promotes microbial growth and activity (Lee *et al*., 2018; Erana *et al*., 2019; Showler, 2022; Bhardwaj *et al*., 2025a). Organically cultivated vegetables generally contain higher levels of protein, phosphorus, potassium, iron, magnesium, calcium, and beneficial secondary metabolites such as polyphenols and other nutraceutical compounds (Popa *et al*., 2019). These bioactive components contribute to enhanced organoleptic properties, including improved taste, aroma, and texture, due to the presence of diverse phytochemicals (Bhardwaj *et al*., 2024). Healthy plants typically exhibit higher vigour and improved resistance to pathogens, highlighting the pivotal role of mineral nutrients in disease resilience (Ojha & Jha, 2021). Balanced nutrition vital for promoting plant health and imparting resistance against biotic stresses (Gupta *et al*., 2017). Organic sources of plant nutrition, when combined with soil microbial inoculation, offer a holistic solution to address soil nutrient imbalances, promoting soil health and optimizing crop yields by improving nutrient availability (Qiu *et al*., 2023; Yang *et al*., 2024). The application of plant growth-promoting rhizobacteria (PGPR), endophytic fungi, or vesicular-arbuscular mycorrhizae, in combination with mineral fertilizers, has been shown to enhance plant growth and crop yield by facilitating phytohormone secretion, nutrient mobilization, and pathogen suppression (Zhang *et al*., 2021; Yu *et al*., 2024). In particular, phosphorus-solubilizing bacteria (PSB) play a critical role in converting fixed or insoluble phosphorus into forms that are readily available to plant uptake (Bhardwaj *et al*., 2024; Wang *et al*., 2024; Xu *et al*., 2024). These practices contribute to creating multilayered defense systems, enabling plants to resist and tolerate pathogen invasion and infection (Sun *et al*., 2020). This study aims to identify effective nutrient management strategies that mitigate the adverse effects of excessive mineral fertilizer use in onion cultivation by incorporating organic manure in combination with plant growth-promoting microorganisms. This integrated approach is expected to enhance plant growth, bulb productivity, physicochemical attributes, economic returns, and crop resistance mechanisms, ultimately resulting in improved nutraceutical quality. The use of organic manures such as farmyard manure, vermicompost, and poultry manure, together with PGPM inoculation, represents an eco-friendly and cost-effective alternative to synthetic fertilizers. This strategy not only meets the nutritional requirements of onion crops but also contributes to sustainable agricultural practices. Therefore, a field experiment was conducted to find out the optimal fertilization ratio and the role of plant growth-promoting microorganisms (PGPMs) in enhancing the nutritional, nutraceutical, and spicing-flavour qualities of onion bulbs, while simultaneously improving productivity and plant resistance to insects and diseases.

Materials and methods

Experimental site

The field experiment was conducted at the College of Agriculture in Sumerpur-Pali, Rajasthan, to evaluate the impact of various nutrient sources combined with soil microbial inoculation on plant growth, bulb productivity, nutritional and sensory qualities of onion bulbs. This study spanned two consecutive seasons: November 2022 to April 2023 and November 2023 to April 2024. The research station is situated at 73°05′ East longitude and 25°09′ North latitude, with an elevation of 272 meters above mean sea level. The experimental site experiences a subtropical climate characteristic of arid regions, receiving an average annual rainfall of 356.8 mm and a relative humidity of 62.25%. During the cultivation periods, maximum air temperatures ranged from 25.4°C to 32.8°C, while minimum temperatures varied between 10.7°C and 17.2°C. The soil analysis showed that the experimental site had a pH of 8.2, EC 0.30 ds/m with 0.25 per cent organic carbon. It has 28 kg P_2O_5 ha^{-1}, 139 kg K_2O ha^{-1}, 0.16 ppm Zn, 1.26 ppm Fe, 0.20 ppm Cu, and 0.82 ppm Mn. The soil was sandy-loamy with an aggregation of 8% clay, 30% silt, and 62% sand.

Treatments detail

Both years experiments were conducted using a randomized block design (RBD) during the rabi seasons, with six treatments and four replications. The details of various treatments applied to the onion crop with the symbols used are as follows:

T_1 = 100% RDF supplied by mineral fertilizers

T_2 = 75% RDF by mineral fertilizers + 25% RDF by organic manures

T_3 = 50% RDF by mineral fertilizers + 50% RDF by organic manures

T_4 = 25% RDF by mineral fertilizers + 75% RDF by organic manures

T_5 = 100% RDF by organic manures

T_6 = 100% RDF by organic manures + microbes (PGPMs) inoculation

During land preparation, well-decomposed organic manures such as farmyard manure (FYM), vermicompost, and poultry manure were applied in equal proportions (1:1:1). Additionally, the full recommended doses of phosphorus, potassium, sulfur, and one-third of the nitrogen were incorporated into the field soil up to 5 cm. The fertilizers used included urea (46% N) for nitrogen, diammonium phosphate (48% P_2O_5 and 18% N) for phosphorus, muriate of potash (60% K_2O) for potassium, and Sulfex Gold (80% sulfur) for sulfur. The remaining two-thirds of the nitrogen was applied in two equal top-dressings at 30 and 60 days after transplanting. The required quantity of FYM was procured from the college's dairy unit, vermicompost from the vermicompost unit, and poultry manure from the poultry unit. The vermicompost was prepared by using cow dung, while poultry manure consists of a mixture of poultry droppings and litter. The nutritional composition of the FYM (0.68% N, 0.47% P, 0.79% K and 0.32% S), vermicompost (1.85% N, 1.15% P, 1.35% K, 0.75% S), and poultry manure (2.95% N, 2.50% P, 1.50% K and 0.85% S) was analyzed before application. For the experimental zone, the recommended nutrient dose for onion cultivation is 140 N: 80 P: 80 K: 40 S kg ha^{-1} which is effective in achieving maximum bulb yield (Bhardwaj and Parashar, 2023). Bio-inoculants (PGPMs) were obtained from the Plant Microbiology Laboratory, Department of Microbiology, IARI, New Delhi. Liquid cultures of the bacterial strains were prepared in the nutrient broth at 28°C, maintaining a cell concentration of 10^9 cfu/ml. The cultures were mixed with the recommended dose of vermicompost and applied before transplanting of onion seedlings.

The field was prepared by ploughing with a disc plough, followed by tilling with a cultivator. Raised beds, measuring 90 cm in width and 10 meters in length, were constructed after the soil was pulverized using a raised bed maker. Forty-five-day-old seedlings of the Agri-found Dark Red (AFLR) cultivar were transplanted at a spacing of 12.5 cm between rows and 10 cm between plants during the third week of November in both years. Weeding was performed manually at 30 and 45 days after transplanting, and other intercultural operations were conducted timely manner, following the standard package of practices for Rajasthan Agro-climatic Zone IIB. In each plot, ten intermediate plants were labeled and measured for growth parameters. Onion bulbs were harvested in the first week of April, once 50 percent of the crop exhibited top fall. After five days of field curing with foliage intact, the bulbs were trimmed, leaving a 2.5 cm neck.

Plant growth and physicochemical observations

Fifteen days before harvest, observations were recorded on ten randomly selected, competitive plants per treatment and replication. Plant height was determined by measuring from ground level to the tip of the longest leaf. The count of fully grown, green, and photosynthetically active leaves was noted. The neck diameter, located just below the junction of the leaf lamina, was measured using a digital vernier caliper. Bulb polar and equatorial diameters were assessed with a vernier caliper and expressed in millimeters. Root length was measured using a standard measuring scale and recorded in centimeters. The number of roots per bulb was counted manually from ten randomly selected bulbs and averaged. The duration from seedling transplanting to harvest readiness was documented as the days to maturity. Chlorophyll content in mature leaves was evaluated using a SPAD meter on ten leaves, with the values averaged. All bulbs harvested from each plot were individually weighed after detaching the tops to determine bulb weight. Metrics such as total bulb yield, split bulb yield, unmarketable bulb yield, biological yield, and marketable yield per hectare were calculated accordingly. The harvest index was computed by dividing the economic (bulb) yield per hectare by the total biological yield per hectare on a fresh weight basis, expressed as a percentage. Bolting in onions refers to the premature flowering of the plant before full bulb development. The bolting percentage was calculated using the formula:

$$\text{Bolting percentage} = (\text{Number of bolted plants}/\text{Total number of plants}) \times 100)$$

The Total Soluble Solids (TSS) content was determined using an ATAGO TC-1E hand refractometer, which has a measurement range of 0 to 32 °Brix with a resolution of 0.2 °Brix. To perform the measurement, 1 to 2 drops of clear onion juice were placed on the refractometer prism. Before each use, the prism was washed with distilled water and dried with tissue paper to ensure accuracy. The refractometer was calibrated against distilled water, corresponding to 0% TSS. Sensory quality parameters of the onion bulbs, including taste, pungency, spicing qualities, consumer preference, and bulb colour, were evaluated by a panel of semi-trained judges. These assessments were conducted using the 10-point hedonic scale, a widely used method in sensory evaluation that ranges from dislike extremely (1.0 point) to like extremely

(10.0 point) (Amerine *et al*., 1965). The dry matter recovery percentage of an onion bulb is calculated using the formula of dry matter recovery percentage = [Fresh weight of the bulb (g)/Dry weight of the bulb (g)] x 100]. The gross return was determined by multiplying the onion yield by the average market price during the investigation period. Net return was calculated by subtracting the total cost of cultivation for each treatment from the corresponding gross return. The benefit-cost ratio (BCR) was then computed by dividing the net return by the total cost of cultivation. The total cost of cultivation encompassed expenses related to land preparation, seedling transplanting, intercultural operations, fertilizers, crop protection measures, irrigation, harvesting, and associated labour charges. These calculations align with standard methodologies for evaluating agricultural profitability. Disease and insect infestations in onion crop were assessed using standardized visual scoring methods. Disease symptoms were identified by observing discoloured spots, lesions, or mould growth on leaves and bulbs. Insect infestations were detected by noting silvery blotches, distorted leaves, or the presence of insect populations. Percentages of leaves that had been injured by onion thrips were determined by examining all the green leaves on five onion plants per plot for feeding scars. Numbers of onion thrips (nymphs and adults) were counted using a hand lens on eight fully expanded leaves from each plot.

Proximate composition and nutraceutical observations

The evaluation of the proximate composition and nutraceutical qualities of the edible part of the onion bulbs was analyzed by using standardized scientific methods, as detailed in Table 1.

The data were collected during both years of experimentation (2022-23 and 2023-24), and the pooled results were used for interpretation and presented in tabular form. Analysis of variance (ANOVA) was performed for each attribute, and mean comparisons were conducted using mathematical calculations in the form of "percent change." A post hoc analysis with the least significant difference (LSD) test was carried out to compare means following ANOVA, with statistically significant differences determined at a significance level of $\alpha = 0.05$ ($p < 0.05$). Statistical analysis was performed using JMP software (version 8, SAS Institute Inc., Cary, NC, USA).

Results and discussion

Effects on vegetative growth parameters

The vegetative growth parameters of the onion bulb crop were significantly influenced by different nutrient supply sources and PGPMs inoculation (Table 2). A significant and consistent decline in growth parameters was observed when mineral fertilizers were entirely replaced with organic manure. However, positive results were reported when a microbial consortium (PGPMs) was incorporated along with organic manures such as FYM, vermicompost, and poultry manure. Notably, the mineral fertilizer treatment (T_1) resulted in significantly greater plant height and number of leaves compared to all other treatments. The highest plant height (57.50 cm) was recorded in the T_1 treatment, followed closely by the T_6 treatment (56.50 cm), whereas the T_4 treatment recorded the shortest plants (48.17 cm). The number of leaves per plant ranged from 10.90 in the T_4 treatment to 15.17 in the T_1 treatment, with the T_6 treatment also showing relatively higher values (13.95). Root length significantly increased with the addition of organic manure for crop nutrition. Compared to T_1 treatment (6.15 cm), root length was 7.32% higher in T_2 treatment (6.60 cm), 12.52% in T_3 treatment

Table 1. Methods for evaluating the proximate composition and nutraceutical qualities of onion bulbs.

S.N.	Compound/ nutrient	Methods/ and processes	Reference
1	Moisture (%)	The calculation was performed using the oven-dry method, in which the weight loss of the sample was divided by its initial fresh weight.	AOAC (2016)
2	Crude protein (%)	Nitrogen content was determined using Duma's combustion method, subsequently converted to crude protein by applying the conversion factor N × 6.25.	AOAC (2016)
3	Crude fat (%)	Crude fat was estimated by using the Automatic SOCS Plus Solvent Extraction Apparatus.	AOAC (2000)
4	Ash (%)	Ash content was estimated based on the weight loss after complete oxidation of organic materials at a high temperature of 500–600°C.	AOAC (2000)
5	Crude fiber (%)	Estimated by the application of the Total Dietary Fibre assay kit	Prosky *et al*. (1992)
6	Total carbohydrates (g/100g DM)	By the applying the formula; Total carbohydrates (%) =100– [moisture (%) + crude protein (%) + crude fat (%) + crude fibre (%) + total ash (%)].	-
6	Total sugars (%)	Total sugars in plant extracts were estimated using the Anthrone reagent method.	Yemm & Willis (1954)
7	Reducing sugar (%)	The Somogyi-Nelson method was employed, which is based on measuring the absorbance at 520 nm of a colored complex formed between a copper-oxidized sugar and arsenic-molybdate.	Somogyi (1945)
8	Non-reducing sugar (%)	Non-reducing sugars were calculated as the difference between total sugars and reducing sugars.	-
9	Starch (%)	The application of the anthrone reagent enables the colorimetric estimation of starch.	Clegg (1956)
10	Total nitrogen (g)	Total nitrogen content was determined by the micro-Kjeldahl method	AOAC (2016)
11	Phosphorus (mg)	Using a vanadate-molybdate reagent, absorbance was measured at 420 nm	Jackson (1967)
12	Potassium (mg)	Potassium was determined by using a flame photometer	AOAC (2016)
13	Iron, zinc, calcium, and magnesium (mg)	The acid-digested samples were analyzed for elemental composition using an Atomic Absorption Spectrophotometer	Lindsey & Norwell (1969)
14	*In-vitro* starch digestibility	*In-vitro* starch digestibility was estimated by the application of the method described by Englyst *et al*. (1992), with slight modification.	Englyst *et al*. (1992)

15	*In-vitro* protein digestibility	-	Akeson & Stahoman (1964) and Singh & Jambunathan (1981)
16	Total flavonoids (mg QE/g)	Samples were analyzed using 1% 2-aminoethyl diphenylborate, and absorbance was measured at 404 nm.	Zhishen *et al*. (1999)
17	Total phenolic content (mg GAE/g)	The analysis was conducted using the Folin-Ciocalteu method, and absorbance was measured at 760 nm.	Singleton & Rossi (1965)
18	Radicals scavenging activity (DPPH, μmol Trolox/g)	The assay was performed by mixing 20 **μl** of the sample with 200 **μl** of DPPH solution, and the absorbance was measured at 520 nm.	Brand-Williams *et al*. (1995)
19	*FRAP (μmol Trolox/g) assay	The method was employed to assess the total antioxidant capacity of the methanolic extracts	Benzie & Strain, 1996
20	**ABTS (μmol Trolox/g) assay	A total of 230 **μl** of ABTS solution was mixed with 20 **μl** of the sample, and the absorbance was measured at 734 nm using a SpectraMax Microplate Reader.	Re *et al*. (1999)

(6.92 cm), 13.98% in T_4 treatment (7.01 cm), 16.26% in T_5 treatment (7.15 cm), and was the longest in T_6 treatment (7.50 cm), an increase of 21.95%. However, the number of roots per plant, neck thickness, days to maturity, bulb polar diameter, bulb equatorial diameter, and chlorophyll content decreased in the T_2 treatment by 4.39%, 7.70%, 2.31%, 2.61%, 0.31%, and 4.86%, respectively, compared to the T_1 treatment. In contrast, all these parameters increased significantly in the T_6 treatment by 5.95%, 5.58%, 2.39%, 5.70%, 7.72%, and 5.30%, respectively. Similarly, the highest number of roots per plant (142.5) was observed in the T_6 treatment, while the T_4 treatment recorded the lowest (122.5). Neck thickness followed the same trend, with T_1 treatment recording the highest (13.25 mm) and T_4 treatment the lowest (10.17 mm). Days to maturity varied among treatments, with the longest duration required in T_6 treatment (128.5 days) and the shortest in T_5 treatment (115.5 days). The polar diameter of onion bulbs ranged from 41.78 mm (T_5 treatment) to 48.97 mm (T_6 treatment), while the equatorial diameter varied between 52.84 mm (T_5 treatment) and 59.87 mm (T_6 treatment). Chlorophyll content (SPAD value) was highest in T_6 treatment (61.15) and lowest in T_5 treatment (50.77).

The improvements in plant growth parameters with the application of FYM, vermicompost, and poultry manure, along with PGPM inoculation, were statistically significant compared to all other partial organic treatments and were comparable to the 100% RDF from mineral fertilization. This may be attributed to the faster decomposition and nutrient release from mineral fertilizers compared to organic manures, which support the rapid growth of plants. In the presence of a microbial consortium, organic manures likely released nitrogen and other nutrients gradually and consistently throughout the growing period, contributing to enhanced vegetative growth over both integrated and solely chemical

Table 2. Effects of nutrient sources on plant growth, yield, the physicochemical qualities, and crop resistance against insects and diseases of the onion variety AFLR (data pooled from both years of experimentation, 2022-23 to 2023-24)

Quality parameter	Nutrition supply sources for the onion bulb								
	T_1	T_2	T_3	T_4	T_5	T_6	S. Em±	C.D. (p=0.05)	% change
Plant growth parameter									
Plant height (cm)	57.50	53.22	51.75	48.17	49.68	56.50	0.469	**	-1.74
No. of leaves plant^{-1}	15.17	14.50	11.25	10.90	11.01	13.95	0.460	**	-8.04
Root length (cm)	6.15	6.60	6.92	7.01	7.15	7.50	0.052	**	21.95
No. of roots plant^{-1}	134.5	128.6	125.4	122.5	126.9	142.5	1.684	**	5.95
Neck thickness (mm)	13.25	12.23	11.43	10.17	10.83	12.51	0.402	**	5.58
Days taken for maturity	125.5	122.6	120.4	117.8	115.5	128.5	2.035	**	2.39
Polar diameter (mm)	46.33	45.12	42.70	42.75	41.78	48.97	0.810	**	5.70
Equatorial diameter (mm)	57.72	57.54	55.88	54.80	52.84	59.87	0.880	**	3.72
Chlorophyll content (SPAD value)	58.07	55.25	52.13	52.13	50.77	61.15	0.961	**	5.30
Bulb yield attributes									
Bulb weight^{-1} (g)	70.01	75.47	70.45	62.40	56.23	81.58	1.206	**	16.53
Bulb yield (t ha^{-1})	38.79	39.80	37.90	34.56	30.17	42.15	1.166	**	8.66
Biological yield (t ha^{-1})	74.06	76.88	73.24	70.14	68.27	81.27	1.574	**	9.74
Harvest index	47.83	47.54	46.63	44.55	38.83	49.40	1.410	**	3.28
Economic parameters									
Marketable yield (t ha^{-1})	35.42	36.55	34.15	31.25	26.51	39.15	0.671	**	10.53
Unmarketable (t ha^{-1})	3.37	3.25	3.75	3.31	3.66	4.00	0.055	**	18.69
Gross returns (₹ in lakhs)	5.31	5.48	5.12	4.68	3.97	6.02	0.078	**	13.37
Net returns (₹ in lakhs)	4.06	4.16	3.74	3.26	2.52	4.37	0.090	**	7.64
B: C ratio	3.25	3.15	2.71	2.30	1.74	2.65	0.021	**	18.46
Physico-chemical attributes									
Bolting per cent	6.75	7.24	8.15	8.27	8.10	6.15	0.886	**	-8.89
Split bulb (t ha^{-1})	3.15	2.85	2.45	1.89	1.70	2.92	0.063	**	-7.30

Bulb TSS (º Brix)	10.02	10.50	11.01	11.20	11.50	12.00	0.267	**	19.76
Taste score (10 marks)	6.25	6.40	7.41	7.82	8.37	9.12	0.186	**	37.92
Pungency (10 levels)	7.37	7.49	7.68	7.94	8.00	8.10	0.145	**	9.91
Spicing qualities	7.38	7.45	7.52	7.73	8.12	8.42	0.124	**	14.09
Consumer preference	6.01	6.49	7.20	7.49	8.75	9.20	0.193	**	53.08
Bulb colour score	8.05	8.15	8.55	8.90	9.15	9.70	0.216	**	20.50
Dry matter recovery (%)	12.15	12.37	12.82	12.97	13.45	13.56	0.263	**	11.60
Status of diseases and insect resistance									
Purple blotch	XXX	XXX	XX	XX	X	X	-	-	-
Bulb rot	XX	XX	XX	XX	XX	N	-	-	-
Downy mildew	X	X	X	XX	XX	N	-	-	-
Thrips / Jassids	XXX	XXX	XX	XX	XX	X	-	-	-
Onion leaf miner	XX	XX	X	X	N	N	-	-	-

When <5 of plants infested (X), 5 to 25% of plants infested (XX), >25% of plants infested (xxx), no infestation N

fertilizer treatments. Organic manures also supply micronutrients in addition to major nutrients and help improve soil conditions (Bhardwaj *et al*., 2025a). Vermicompost has been shown to contain several plant growth promoters, enzymes, beneficial bacteria, and mycorrhizae (Bhardwaj *et al*., 2024). Therefore, the availability of higher nutrient concentrations, improved soil physical properties, and increased microbial activity may have promoted greater plant height, leaf number, and other growth parameters. The beneficial effects of PGPMs may be due to enhanced root activity in the rhizosphere, stimulation of hormonal responses, and improved nutrient uptake (Bhardwaj *et al*., 2025a). Additionally, PSPMs and PSBs may influence the production and availability of key plant hormones such as auxins, cytokinins, and gibberellins (Kenneth *et al*., 2019; Raza *et al*., 2019), which regulate vital growth processes like cell elongation, leaf expansion, and shoot development. By modulating these hormone levels, PSBs may indirectly enhance plant height, leaf area, and overall biomass accumulation (Malik *et al*., 2019). Similar effects were also observed by Mangaraj *et al*. (2022) also noted that improved nutrient availability leads to enhanced carbohydrate-to-protein conversion, boosting meristematic activity—including cell division and elongation- which results in increased plant growth, dry matter accumulation, and ultimately, higher crop yields. These findings are consistent with those of Song *et al*. (2023) and Zhai *et al*. (2024), who reported that integrating a 10% to 20% reduction in chemical fertilizer with the use of bio-organic and mixed fertilizers can enhance plant growth and development. Furthermore, the application of 100% RDF along with *S. indica* or PSB has been shown to significantly enhance plant growth, nutrient uptake, and onion yield (Arunachalam *et al*., 2024). Similar improvements in plant height with the application of organic manures were also reported by Rai *et al*. (2016) in onion and by Bhardwaj *et al*. (2025a) in tomato, okra, and brinjal.

Effect on yield and economic parameters

The yield attributes of onion bulbs showed a significant increase when the crop was nourished with organic nutrient sources in the presence of PGPMs (T_6 treatment). This was closely followed by the treatment with 75% recommended dose of fertilizers (RDF) from mineral fertilizer, with 25% RDF from organic manure (T_2 treatment). In contrast, the lowest yield performance was observed under 100% RDF from organic manure alone (T_5 treatment). The improvements in the T_6 treatment were particularly notable, with increases in bulb weight (16.53%), bulb yield (8.66%), biological yield (9.74%), and harvest index (3.28%) compared to the T_1 treatment (Table 2). Bulb weight was highest in the T_6 treatment (81.58 g), followed by T_2 (75.47 g), while the T_5 treatment recorded the lowest (56.23 g). The maximum bulb yield (42.15 t ha^{-1}) was also observed in the T_6 treatment, whereas T_5 yielded the least (30.17 t ha^{-1}). Biological yield followed a similar trend, with T_6 producing 81.27 t ha^{-1} and T_5 only 68.27 t ha^{-1}. The harvest index ranged from 38.83 in the T_5 treatment to 49.40 in the T_6 treatment. Moreover, the T_6 treatment, which combined PGPM inoculation with 100% RDF from organic manure, resulted in the highest marketable yield (39.15 t ha^{-1}), unmarketable yield (4.0 t ha^{-1}), gross return (₹ 6.02 lakhs), and net return (₹ 4.37 lakhs). This was followed by the T_2 treatment with a marketable yield of 36.55 t ha^{-1}, an unmarketable yield of 3.25 t ha^{-1}, a gross return of ₹ 5.48 lakhs, and a net return of ₹ 4.16 lakhs. In contrast, the T_5 treatment recorded the lowest values for marketable yield (26.51 t ha^{-1}), unmarketable yield (3.66 t ha^{-1}), gross return (₹ 3.97 lakhs), and net return (₹ 2.52 lakhs). The benefit-cost (B: C) ratio also varied significantly, with the highest value (3.25) observed in the T_1 treatment, followed by the T_2 treatment (3.15), and the lowest in the T_5 treatment (1.74). The reduced B: C ratio in T_5 was likely due to the higher cost of cultivation associated with organic nutrient sources for onion production. Higher bulb weight observed in treatments through FYM, vermicompost, poultry manure, and PGPMs can be attributed to improved bulb size and weight. This may result from reduced soil bulk density, increased porosity, and improved physical soil conditions conducive to better bulb development. The increased yield from using vermicompost and poultry manure with PGPMs might also be due to higher nutrient concentrations and bioactive growth-promoting compounds, which enhance the soil's physical environment. The beneficial effects of organic manures on yield can be linked to both the direct supply of nutrients and the overall improvement in the soils physicochemical and biological properties (Bhardwaj *et al*., 2025a). Additionally, upon decomposition and mineralization, the manures not only provide readily available nutrients to plants but also aid in solubilizing fixed forms of nutrients. Integrating 100% RDF with phosphate-solubilizing bacteria (PSB) has also been shown to improve onion productivity and nutrient use efficiency (Arunachalam *et al*., 2024). The findings of this study are consistent with those reported by Gashaw (2021), Upadhyay *et al*. (2023), Kumar *et al*. (2024) in onions, and Bhardwaj *et al*. (2025a) in other vegetables.

Effects on physico-chemical attributes of onion bulbs

Among the tested nutrient sources, the T_6 treatment consistently demonstrated superior performance in enhancing the physicochemical attributes of onion bulbs. Notable improvements were recorded in consumer preference (53.08%), taste score (37.92%), and total soluble solids (19.76%), underscoring the significant impact of nutrient sources and microbial inoculation on the qualitative characteristics of onion bulbs (Table 2). The lowest bolting percentage (6.15%) was observed in the T_6 treatment, followed closely by the T_1 treatment (6.75%), while the highest bolting rate occurred in the T_4 treatment (8.27%). The T_6 treatment, which involved organic manure combined with microbial inoculation, also resulted in a 7.30% reduction in split bulb incidence compared to the T_1 treatment. The occurrence of split bulbs per hectare varied across treatments, with the T_1 treatment showing the highest (3.15 t ha^{-1}) and the T_5 treatment the lowest (1.70 t ha^{-1}). As the proportion of organic nutrient sources increased, there was a corresponding upward trend in sensory-based physicochemical attribute scores, which were significantly higher than those observed under mineral-fertilizer-based nutrition (Table 2). The sensory evaluation scores for bulbs from the T_6 treatment were the highest, attributed to maximum levels of total soluble solids (12.0 ºBrix), taste score (9.12), pungency level (8.10), spicing quality (8.42), consumer preference (9.20), and bulb colour (9.70). In contrast, the T_1 treatment recorded the lowest values across these parameters (10.02 ºBrix, 6.25, 7.37, 7.38, 6.01, and 8.05, respectively). These figures represent respective increases in the T_6 treatment over the T_1 treatment of 19.76%, 37.92%, 9.91%, 14.09%, 53.08%, and 20.50%, respectively (Table 2). Dry matter recovery ranged from 12.15% in T_1 to 13.56% in T_6, indicating a significant enhancement. The quality analysis of onion bulbs also revealed that the integrated application of chemical fertilizers and organic manure improved the contents of volatile compounds, minerals, and phenolics, all of which contribute to specific bulb characteristics such as taste, pungency, and spicing quality, while also reducing moisture content.

One plausible explanation for the improvement in physicochemical quality is that the microbial consortium (PGPM) facilitates the transformation of essential nutrients from unavailable to bioavailable forms through biological processes (Macik *et al*., 2020). Organic manures amended in soils also exhibit improved organic matter content, pH balance, and levels of exchangeable nutrients such as potassium, magnesium, calcium, sodium, iron, zinc, and copper (Erana *et al*., 2019), which directly support the improvement of crop quality. Several studies have reported that organically grown vegetables contain higher levels of protein, vitamin C, phosphorus, potassium, iron, magnesium, and calcium, along with superior secondary metabolites and nutraceutical compounds (Popa *et al*., 2019), including phenolic compounds, polyphenols, carotenoids, and antioxidants (Mie *et al*., 2017; Showler, 2022; Bhardwaj *et al*., 2025b).

Effects on plant resistance quality against disease and insects

Plants nourished by organic sources of nutrients in the presence of a soil microbial consortium exhibit the highest resistance to diseases and insect infestations. Conversely, plant susceptibility tends to increase with higher rates of mineral fertilization. Among the treatments, the T_6 treatment demonstrated the strongest resistance capabilities, showing no infestation by bulb rot, downy mildew, or onion leaf miner and exhibiting the lowest infestation levels for purple blotch and thrips (Table 2). In contrast, treatments T_1 and T_2 were the most susceptible, with severe infestations (>25%) of purple blotch and thrips and moderate infestations (5–25%) of bulb rot, downy mildew, and onion leaf miner. Treatments T_3, T_4, and T_5 showed moderate resistance, with varying levels of infestation depending on the specific disease or pest. The highest susceptibility to purple blotch (>25% of plants infested) was recorded in the T_1 and T_2. Moderate infestation (5–25%) occurred in the T_3 and T_4, while minimal infestation (<5%) was observed in the T_5 and T_6, indicating better resistance in these treatments. Bulb rot infestation was moderate (5–25%) in treatments T_1 to T_5, whereas the T_6 showed better resistance capacity and found no infestation. Lower downy mildew infestation (<5%) was recorded in T_1, T_2, and T_3, while moderate infestation (5–25%) occurred in T_4 and T_5. Similarly, severe jassid infestation (>25%) was observed in the T_1 and T_2, with moderate levels in the T_3 and T_4, whereas treatments T_5 and T_6 exhibited only minimal infestation (<5%). Onion leaf miners showed moderate infestation (5–25%) in the T_1 and T_2, low infestation (<5%) in the T_3 and T_4, and no infestation in the T_5 and T_6. Possible causes behind the lower infestation of insects and disease in organically nourished crops, that the healthy plants typically exhibit increased vigour and resistance to disease, resulting in lower disease incidence. Plants suffering from nutrient deficiencies are more susceptible to disease, whereas adequate and balanced nutrition enhances plant tolerance and resistance. Mineral nutrients influence primary defense mechanisms, including the formation of mechanical barriers such as thicker cell walls and the synthesis of natural defense compounds like antioxidants, phytoalexins, and flavonoids (Fernando *et al*., 2021). The inoculation of endophytic fungus *Serendipita indica* likely supports onion root extension, aiding in nutrient uptake, stress tolerance, and systemic resistance (Gill *et al*., 2016). In organic production systems, the increased availability of zinc, an essential component of enzymes involved in auxin synthesis, infectivity, and toxin production in pathogens, plays a critical role (Tripathi *et al*., 2022). Biofertilizers and organic amendments, derived from diverse organic waste, are vital sources of mineral nutrients and also have antagonistic effects against different pathogenic soil microbes. Balanced nutrition generally results in healthier plants with reduced susceptibility to infection (Tripathi *et al*., 2022). Therefore, the timely application of nutrients is critical for effective disease control. Soluble silicon (Si) promotes rapid deposition of phenolics and phytoalexins at infection sites and may form weak complexes with phenolics, enhancing their synthesis and mobility in the apoplast. Potassium deficiency increases plant vulnerability to both obligate and facultative parasites by reducing the synthesis of proteins, starch, and cellulose, leading to an accumulation of low-molecular-weight compounds that serve as nutrient sources for pathogens. Calcium (Ca) plays a crucial role in pathogen recognition at the plasma membrane and in maintaining membrane stability. Foliar application of phosphate can induce both local and systemic resistance against some airborne pathogens by triggering the release of elicitor-active compounds from plant cell walls. A positive correlation is often observed between nitrogen (N) application and pest infestations. In contrast, silicon deposited in epidermal cell walls forms a mechanical barrier against penetration by sucking and chewing insects. High potassium levels enhance the production of secondary metabolites, reduce carbohydrate accumulation, and help protect plants from insect damage. Secondary macronutrients and micronutrients such as calcium, zinc, and sulphur also contribute to reducing pest populations (Bala *et al*., 2018).

Effects on nutritional quality of onion bulbs

The proximate composition of onion bulbs, as presented in Table 3, showed that with an increasing proportion of organic manure, the moisture content decreased, ranging from 86.01% in T_1 to 85.20% in T_6, a variation that was not statistically significant. The highest crude protein content (1.71%) was observed in T_1, which was significantly higher ($p < 0.05$) than in other treatments. The lowest protein content (1.50%) was recorded in T_5, with a 1.75% reduction observed in T_6 (1.68%) compared to T_1 (1.71%). The crude fat content showed notable improvement across treatments, with the highest value recorded in T_6 (0.34%), representing a 30.77% increase. Similarly, ash content progressively increased, reaching 0.63% in T_6, an improvement of 28.57% compared to T_1 (0.49%). Crude fiber content ranged from 2.44% in T_1 to 2.94% in T_4, indicating a 10.66% increase. Total carbohydrate content marginally decreased with increasing levels of organic nutrient sources up to T_5 (89.76 g) but slightly increased in T_6 (90.12 g), marking a 0.28% increase over T_1 (89.87 g). The highest total sugars (7.25%), reducing sugars (5.37%), and non-reducing sugars (1.88%) were recorded in T_6. These values were significantly higher than those in T_1 by 16.75%, 3.07%, and 88.0%, respectively. Non-reducing sugar content exhibited the most notable rise, increasing from 1.00 g in T_1 to 1.88 g in T_6. Starch content also improved significantly, with the highest value (2.14 g) observed in T_3, representing a 15.84% increase. The average mineral content increased by 0.68% to 39.88% across treatments, in the order: $T_1 < T_2 < T_3 < T_4 < T_5 < T_6$. The application of a 100% recommended dose of fertilizer (RDF) from organic manure combined with PGPMs inoculation (T_6) significantly enhanced the mineral content of onion bulbs. Nitrogen content gradually declined from 0.273% in T_1 to 0.239% in T_5. Phosphorus increased from 36.26 mg (T_1) to 37.74 mg (T_6, a 4.08% rise. Potassium content remained relatively stable across treatments, ranging between 169.97 mg (T_2) and 171.13 mg (T_6). Calcium levels ranged from 20.26 mg (T_1) to 21.99 mg (T_6), indicating an 8.54% increase. Iron content reached its highest value in T_6 (2.35 mg), marking a 39.88% increase, while zinc content improved by 35.84%, from 0.293 mg (T_1) to 0.398 mg (T_6). Magnesium levels showed minimal variation (not significant), increasing slightly from 16.61 mg (T_1) to 17.11 mg (T_6), a 3.01% increase. *In-vitro* protein digestibility improved significantly, peaking at 92.15% in T_6, an increase of 9.91% in comparison to T_1 (83.84%). Similarly, *in-vitro* starch digestibility progressively improved, reaching 74.48% in T_6, representing a 7.77% increase over the T_1 (69.11%). The best results in improving proximate composition, carbohydrate availability, total mineral content, and sensory quality, along with enhanced protein and starch digestibility, were observed in treatments with microbial consortium (PGPM) inoculation. Similar outcomes have been reported by Colla *et al.* (2015), who noted improvements in sweetness, secondary metabolites, antioxidant properties, and mineral and chlorophyll content in vegetables. Additionally, Lal *et al*. (2015) reported increased zinc content in broccoli following treatments with *Azotobacter* and phosphate-solubilizing bacteria. Radhakrishnan & Lee (2016) observed increased concentrations of nitrogen, phosphorus, potassium, iron, magnesium, zinc, sodium and calcium in lettuce with biofertilizer applications. Sousa *et al*. (2020) reported enhanced shoot dry matter and nutrient uptake (N, P, Ca, Mg, Mn, and Na) in lettuce with *Pseudomonas fluorescens* inoculation. Enrichment of field soils with rhizospheric microbes (PGPMs) enhances the availability and absorption of micronutrients, facilitating the synthesis of phytochemicals. This symbiotic interaction between soil microbes and onion roots may have expanded root surface area, improving water and nutrient uptake, including micronutrients (Padash *et al*., 2016; Li *et al*., 2023). These improvements not only elevate organoleptic quality but also contribute to better vitamin, flavonoid, antioxidant, and mineral profiles (Singh & Trivedi, 2017).

Effects on nutraceutical quality and antioxidant content

The nutrient supply treatments significantly influenced the content of all phenolic acids, flavonoids, radical scavenging capacity, and antioxidant activities in onion bulbs (Table 3). The total flavonoid content increased markedly, reaching a maximum of 4.12 mg QE/g in T_6, representing a 75.32% improvement, while the lowest value (2.35 mg QE/g) was recorded in the T_1. A similar trend was observed in total phenolic content, which peaked at 9.92 mg GAE/g in T_6, indicating a 28.33% increase compared to the T_1 (7.73 mg GAE/g). The radical scavenging activity of onion bulbs, assessed via the DPPH assay, showed a significant enhancement. The highest value was recorded in T_6 (14.85 µmol trolox/g), reflecting a 45.45% increase over T_1 (10.21 µmol trolox/g). Similarly, the ferric-reducing antioxidant power (FRAP) improved from 8.12 µmol trolox/g in the T_1 treatment to 12.65 µmol trolox/g in T_6, a notable 55.78% increase. The ABTS assay followed the same pattern: with increasing organic input, antioxidant activity significantly improved. The highest value (36.88 µmol trolox/g) was recorded in T_6, followed by T_5 (33.66 µmol trolox/g), representing 21.47% and 16.24% increases, respectively, over T_1. The enhanced nutraceutical and antioxidant qualities under organic systems with PGPM inoculation can be attributed to a more diverse and active microbial community. These microbes act as biostimulants, improving soil physicochemical properties, increasing biodiversity, and enhancing soil enzyme activity (Qi *et al*., 2021). These effects lead to an extended root system, often supported by mycelium, which aids in nutrient release and uptake. Gill *et al*. (2016) reported that enhanced plant growth and biomass accumulation could be attributed to improved root development facilitated by fungal colonization, which promotes nutrient uptake from the root zone. This colonization not only enhances root growth but also improves nutrient absorption across several crops, including sunflower, rapeseed, and rice (Li *et al*., 2023). The enhanced nutrient profile supports the biosynthesis of key phytochemicals such as antioxidants, flavonoids, and phenolic compounds. Rembiałkowska (2016) found that phenolic compounds were 20% higher in organically grown products compared to conventional ones. Similarly, organic systems with mycorrhizal inoculation have been reported to increase antioxidants, vitamins, and levels of ascorbic acid and lycopene by 35–60% in various fruits and vegetables (Mukherjee *et al*., 2020; Bhardwaj *et al*., 2025b). Moreover, the use of organic inputs in combination with bio-organic and chemical fertilizers has been shown to enhance the nutraceutical quality of crops (Li *et al*., 2021). Similar positive effects have been observed in other crops such as *Allium cepa*, *Oryza sativa*, *Saccharum officinarum*, *Abrus precatorius*, *Zea mays*, *Phaseolus vulgaris*, and *Tridax procumbans* (Gill *et al*., 2016; Roylawar *et al*., 2023). Phosphate-solubilizing bacteria (PSB) also play a critical role by converting both organic and inorganic phosphorus into plant-available forms. They achieve this through the secretion of extracellular enzymes, substrate mineralization, and the production of mineral-dissolving compounds (Kalayu, 2019; Rawat *et al*., 2021; Silva *et al*., 2023). For instance, the

Table 3. Effect of nutrient sources on nutritional and nutraceutical quality and digestibility of onion bulbs (data pooled from both years of experimentation, 2022-23 to 2023-24).

Quality parameter	Onion bulb (100 g of dry bulb)								
	T_1	T_2	T_3	T_4	T_5	T_6	S. Em±	C.D. (p=0.05)	% change
Proximate composition									
Moisture (%) in fresh bulb	86.01	85.58	85.35	85.31	85.25	85.20	1.315	NS	3.75
Crude protein (%)	1.71	1.67	1.60	1.56	1.50	1.68	0.009	**	1.75
Crude fat (%)	0.26	0.27	0.30	0.31	0.33	0.34	0.011	**	30.77
Ash (%)	0.49	0.52	0.54	0.57	0.58	0.63	0.014	**	28.57
Crude fiber (%)	2.44	2.59	2.63	2.94	2.82	2.70	0.055	**	10.66
Total Carbohydrates (g)	89.87	89.84	89.79	89.38	89.76	90.12	1.688	NS	0.28
Available carbohydrates									
Total sugars	6.21	9.75	9.60	6.59	6.92	7.25	0.184	**	16.75
Reducing sugar	5.21	8.42	8.19	5.25	5.11	5.37	0.167	**	3.07
Non-reducing sugars	1.00	1.33	1.41	1.34	1.81	1.88	0.017	**	88.00
Starch	1.01	1.91	2.14	1.05	1.04	1.17	0.020	**	15.84
Total minerals									
Nitrogen (%)	0.273	0.268	0.256	0.250	0.239	0.242	0.004	**	11.36
Phosphorus (mg)	36.26	36.43	36.68	36.95	37.30	37.74	0.208	**	4.08
Potassium (mg)	169.98	169.97	170.22	170.69	170.86	171.13	3.270	NS	0.68
Zinc (mg)	0.293	0.300	0.333	0.339	0.363	0.398	0.009	**	35.84
Magnesium (mg)	16.61	16.64	16.81	16.91	16.97	17.11	0.416	NS	3.01
Calcium (mg)	20.26	20.58	20.69	21.65	21.87	21.99	0.429	**	8.54
Iron (mg)	1.68	1.71	1.97	2.12	2.27	2.35	0.020	**	39.88
Digestibility									
In-vitro protein Digestibility (%)	83.84	85.84	86.79	87.93	89.60	92.15	1.229	**	9.91
In-vitro starch Digestibility (%)	69.11	70.88	71.18	72.18	73.29	74.48	1.310	**	7.77
Nutraceutical quality and antioxidant content									
#Total flavonoids	2.35	2.48	2.92	3.35	3.85	4.12	0.086	**	75.32
##Total phenolic content	7.73	8.02	8.84	9.02	9.20	9.92	0.208	**	28.33
Radicals scavenging activity (DPPH, μmol Trolox/g)	10.21	10.22	11.49	12.52	14.41	14.85	0.217	**	45.45
*FRAP (Ferric reducing ability of plasma) assay	8.12	8.91	9.41	10.74	12.52	12.65	0.211	**	55.78
**ABTS (2,2′-azino-bis-3-ethylbenzothiazoline-6-sulfonic acid) assay	30.36	30.93	33.10	32.60	35.29	36.88	0.619	**	21.47

T_1=100% Mineral source of nutrients; T_2= 75% Mineral source + 25% Organic source; T_3= 50% Mineral source + 50% Organic source; T_4= 25% Mineral source + 75% Organic source; T_5= 100% Organic source; T_6= 100% Organic source + Microbes (PGPR) inoculation; *FRAP (μmol trolox/g); ** ABTS (μmol trolox/g); # Total flavonoids (mg QE/g); ## Total phenolic content (mg GAE/g).

nutritional content of purslane, including total flavonoids and phenolic compounds, increased significantly, while anti-nutritional factors such as nitrates and soluble oxalic acid were reduced (Yang *et al*., 2018), thereby improving digestibility.

Conclusion

The comprehensive findings of the experimental results demonstrated that organic sources of crop nourishment, when combined with PGPM inoculation, significantly enhanced onion plant growth parameters, bulb yield attributes, physico-chemical qualities, nutritional and nutraceutical superiority, as well as the sensory evaluation of onion bulbs, compared to other treatments or the absence of microbial inoculation. These results contribute to the development of spicing quality and distinct taste characteristics in onion bulbs. The findings are valuable for formulating effective fertilization strategies aimed at producing onions with specific taste profiles and enhanced spicing quality. Furthermore, they provide a solid research foundation for the synergistic application of chemical fertilizers, organic manure, and microbial consortia to optimize both the productivity and quality of onion bulbs. Overall, this study is relevant to researchers, policymakers, and agricultural practitioners seeking innovative solutions to improve vegetable quality while promoting sustainable farming practices.

References

Akeson WR & Stahmann MA 1964 A pepsin pancreatin digest index of protein quality evaluation. The Journal of Nutrition 83(3): 257-261.

Amerine MA, Pangborn RM, Roessler EB 1965 Principles of sensory evaluation of food. In: Food Science and Technology Monographs, Academic Press, New York, 338-339p.

AOAC 2000 Official Methods of Analysis. 17th Edition, The Association of Official Analytical Chemists, published by AOAC International Maryland, USA, 1250p.

AOAC 2016 Official Methods of Analysis. 20th Edition, The Association of Official Analytical Chemists, Washington, DC, USA.

Arunachalam T, Gade K, Mahadule PA, Soumia PS, Govindasamy V, Gawande SJ & Mahajan V 2024 Optimizing plant growth, nutrient uptake, and yield of onion through the application of phosphorus-solubilizing bacteria and endophytic fungi. Front. Microbiol. 15:1442912.

Bala K, Sood AK, Pathania VS & Thakur S 2018 Effect of plant nutrition in insect pest management: A review. J. Pharmacogn. Phytochem. 7(4): 2737-2742.

Benzie IF & Strain JJ 1996 The ferric reducing ability of plasma (FRAP) as a measure of "antioxidant power" the FRAP assay. Anal. Biochem. 239(1): 70-76.

Bhardwaj RL & Parashar A 2023 Maximizing productivity in onion bulb cultivation through crop geometry and NPKS nutrient management. J. Appl. Hortic. 25(3): 308-312.

Bhardwaj RL, Parashar A, Parewa HP & Vyas L 2024 An alarming decline in the nutritional quality of foods: The biggest challenge for future generations health. Foods 13: 877.

Bhardwaj RL, Vyas L, Verma MP, Meena SC, Chattopadhyay A, Meena NK, Jakhar DS, & Kumawat SR 2025a Increasing productivity and recovering nutritional, organoleptic, and nutraceutical qualities of major vegetable crops for better dietetics. Foods 14: 254.

Bhardwaj RL, Nandal U, Meena P & Choudhary K 2025b Recovery of the original nutritional and nutraceutical quality of different vegetables for human nutrition and health security. Academia Nutrition and Dietetics 2: 1-9.

Brand-Williams W, Cuvelier ME & Berset CLWT 1995 Use of a free radical method to evaluate antioxidant activity. LWT-Food Sci. Technol. 28(1): 25-30.

Clegg KM 1956 The application of the anthrone reagent to the estimation of starch in cereals. J. Sci. Food Agric. 7(1): 40-44.

Colla G, Rouphael Y, Di Mattia E, El-Nakhel C & Cardarelli M 2015 Co-inoculation of *Glomus intraradices* and *Trichoderma atroviride* acts as a bio-stimulant to promote growth, yield, and nutrient uptake of vegetable crops. J. Sci. Food Agric. 95: 1706–1715.

Deepesh V, Verma VK, Suma K, Ajay S, Gnanavelu A & Madhusudanan M 2016 Evaluation of an organic soil amendment generated from municipal solid waste seeded with activated sewage sludge. J. Mater Cycles Waste Manag. 18:273-286.

Englyst HN, Kingman SM & Cummings, JH 1992 Classification and measurement of nutritionally important starch fractions. European Journal of Clinical Nutrition 46(Suppl 2): S33-S50.

Erana FG, Tenkegna TA & Asfaw SL 2019 Effect of agro industrial wastes compost on soil health and onion yield improvements: study at field condition. Int. J. Org. Waste Agric. 8: S5161-5171.

FAO 2024 FAOSTAT Database. Available at: https://www.fao.org/faostat/en/#data/QCL (Accessed April 12, 2024)

Fernando MSW, De Silva SHSA & Kanchana S 2021 Influence of gypsum application in disease management of onion (*Allium cepa* L.). International Journal of Innovative Science and Research Technology 6(8): 900-905.

Gashaw B 2021 Evaluation of different rates of NPS on growth and yield performances of garlic (*Allium sativum* L.) in Cheha district, Gurage Zone, Ethiopia. Int. J. Agron. 1-5.

Gill SS, Gill R, Trivedi DK, Anjum NA, Sharma KK, Ansari MW 2016 *Piriformospora indica*: potential and significance in plant stress tolerance. Front. Microbiol. 7:332.

Gupta N, Debnath S, Sharma S, Sharma P & Purohit J 2017 In Agriculturally Important Microbes for Sustainable Agriculture, eds V. S. Meena, et al. (Singapore: Springer Nature Singapore Pvt Ltd), 217–251p.

Han Z, Leng Y, Sun Z, Li Z, Xu P, Wu S, Liu S, Li S, Wang J & Zou J 2024 Substitution of organic and bio-organic fertilizers for mineral fertilizers to suppress nitrous oxide emissions from intensive vegetable fields. J. Environ. Manage. 349: 119390.

Huang C, Zhang K, Guo W, Huang H, Gou Z, Yang L, Chen Y, Oh K, Fang C & Luo L. 2023 The effects of partial substitution of fertilizer using different organic materials on soil nutrient condition, aggregate stability, and enzyme activity in a tea plantation. Plants 12: 3791.

Huang R, Mcgrath SP, Hirsch PR, Clark IM, Storkey J & Wu L 2019 Plant-microbe networks in soil are weakened by the century-long use of inorganic fertilizers. Microb. Biotechnol. 12: 1464– 75.

Jackson ML 1967 Soil chemical analysis. New Delhi, India: Prentice Hall of Index Private Ltd.

Jaiswal DK, Gawande SJ, Soumia PS, Krishna R, Vaishnav A & Ade AB 2022 Biocontrol strategies: An eco-smart tool for integrated pest and diseases management. BMC Microbiol. 22: 324.

Jayathilake PKS, Reddy LP, Srihari D & Reddy KR 2006 Productivity and soil fertility status as influenced by integrated use of N-fixing biofertilizers, organic manures and inorganic fertilizers in onion. J. Agric. Sci. 2: 46–58.

Kalayu G 2019 Phosphate-solubilizing microorganisms: promising approach as biofertilizers. Agron. J. 1–7.

Kenneth OC, Nwadibe EC, Kalu AU & Unah UV 2019 Plant growth promoting rhizobacteria (PGPR): a novel agent for sustainable food production. Am. J. Agric. Biol. Sci. 14: 35–54.

Kumar V, Kumar S, Rajvanshi & Kumar D 2024 Study on effect of INM on growth, yield and quality of onion (*Allium cepa* L.). Environment and Ecology 42 (4B): 1906-1911.

Lal S, Singh SP, Yadav TV & Meena AK 2015 Effect of bio-fertilizers and zinc on growth, yield and quality of sprouting broccoli (*Brassica oleraceae* var. italica L.). Progress Hortic. 47: 90–96.

Lee J, Hwang S, Min B, Kim H, Kim J, Hong K, Lee S, Shim S & Boyhan GE 2018 Effect of compost and mixed oilseed cake application rates on soil chemical properties, plant growth, and yield of organic bulb onions. Hort. Sci. Technol. 36:666–680.

Li BB, Roley SS, Duncan DS, Guo J, Quensen JF & Yu HQ 2021 Long-term excess nitrogen fertilizer increases the sensitivity of soil microbial community to seasonal change revealed by ecological network and metagenome analyses. Soil Biol. Biochem. 160: 108349.

Li L, Feng Y, Qi F & Hao R 2023 Research progress of *Piriformospora indica* in improving plant growth and stress resistance to plant. J. Fungi 9: 965.

Lindsey WL & Norwell MA 1969 A new DPTA-TEA soil test for zinc and iron. In: Agronomy Abstract 61: 84.

Macik L, Gryta A & Frac M 2020 Biofertilizers in agriculture: An overview on concepts, strategies, and effects on soil microorganisms. Adv. Agron. 162: 31–87.

Malik Z, Shah Z & Tariq M 2019 Biochar improves viability of arbuscular mycorrhizal fungi (AMF) in soil and roots of wheat (*Triticum aestivum*) and maize (*Zea mays* L.) under various cropping systems. Sarhad J. Agric. 35: 834–846.

Mangaraj S, Paikaray RK, Maitra S, Pradhan SR, Garnayak LM & Satapathy M (2022). Integrated nutrient management improves the growth and yield of rice and green gram in a rice-green gram cropping system under the coastal plain agro-climatic condition. Plan. Theory 11:142.

Marles RJ 2017 Mineral nutrient composition of vegetables, fruits, and grains: the context of reports of apparent historical declines. J. Food Comp. Analys. 56: 93–103.

Mayer AMB, Trenchard L & Rayns F 2022 Historical changes in the mineral content of fruit and vegetables in the UK from 1940 to 2019: A concern for human nutrition and agriculture. Int. J. Food Sci. Nutr. 73: 315–326.

Mie A, Andersen HR, Gunnarsson S, Kahl J, Kesse-Guyot E, Rembialkowska E, Quaglio G & Grandjean P 2017 Human health implications of organic food and organic agriculture: A comprehensive review. Environ. Health 16: 111.

Mukherjee A, Omondi EC, Hepperly PR, Seidel R & Heller WP 2020 Impacts of organic and conventional management on the nutritional level of vegetables. Sustainability 12: 8965.

Ojha RK & Jha SK 2021 Role of mineral nutrition in management of plant diseases, In: Farmers' Prosperity through Improved Agricultural Technologies, eds H. K. Singh, S. S. Solankey, and M. K. Roy (New Delhi: Jaya Publishing House), pp 241–261.

Padash A, Shahabivand S, Behtash F & Aghaee A 2016 A practicable method for zinc enrichment in lettuce leaves by the endophyte fungus *Piriformospora indica* under increasing zinc supply. Sci. Hortic. 213: 367–372.

Popa ME, Mitelut AC, Popa EE, Stan A & Popa VI 2019 Organic foods contribution to nutritional quality and value. Trends Food Sci. Technol. 84: 15–18.

Pretty J, Benton TG, Bharucha ZP, Dicks LV, Flora CB, Godfray HCJ, Goulson D, Hartley S, Lampkin N & Morris C 2018 Global assessment of agricultural system redesign for sustainable intensification. Nat. Sustain. 1: 441–446.

Prosky L, Asp NG, Schweizer TF, Devries JW & Furda I 1992. Determination of insoluble and soluble dietary fiber in foods and food products: collaborative study. Journal of AOAC International 75(2): 360-367.

Qi Y, Jiang F, Zhou R, Wu Y, Hou X, Li J, Lin W & Wu Z 2021 Effects of reduced nitrogen with bio-organic fertilizer on soil properties, yield and quality of non-heading Chinese cabbage. Agronomy 11: 2196.

Qiu S, Yang H, Zhang S, Huang S, Zhao S & Xu X 2023 Carbon storage in an arable soil combining field measurements, aggregate turnover modeling, and climate scenarios. Catena 220:106708.

Radhakrishnan R & Lee IJ 2016 Gibberellins-producing *Bacillus methylotrophicus* KE2 supports plant growth and enhances nutritional metabolites and food values of lettuce. Plant Physiol. Biochem. 109:181–189.

Rai S, Rani P, Kumar M, Rai A & Shahi SK 2016 Effect of integrated nutrient management on nutrient uptake and productivity of onion. Nat. Environ. Pollut. Technol. 15(2): 573-577.

Rawat P, Das S, Shankhdhar D & Shankhdhar S 2021 Phosphate-solubilizing microorganisms: mechanism and their role in phosphate solubilization and uptake. J. Soil Sci. Plant Nutr. 21: 49–68.

Raza A, Razzaq A, Mehmood SS, Zou X, Zhang X & Lv Y 2019 Impact of climate change on crops adaptation and strategies to tackle its outcome: a review. Plan. Theory 8:34.

Re R, Pellegrini N, Proteggente A, Pannala A, Yang M & Rice-Evans C 1999 Antioxidant activity applying an improved ABTS radical cation decolorization assay. Free Radic. Biol. Med. 26(9-10): 1231-1237.

Rembialkowska E 2016 Organic food: Effect on nutrient composition. In: Encyclopedia of Food and Health 171-177p. https://doi.org/10.1016/B978-0-12-384947-2.00505-5.

Roylawar P, Khandagale K, Nanda S, Soumia PS, Jadhav S & Mahajan V (2023). Colonization of *Serendipita indica* promotes resistance against *Spodoptera exigua* in onion (*Allium cepa* L.). Front. Microbiol. 14:1190942.

Showler AT 2022 Effects of compost on onion quality, yield, and thrips infestation. Environ. Syst. Res. 11: 22.

Silva LI, Pereira MC, Carvalho AMX, Buttros VH, Pasqual M & Doria J 2023 Phosphorus-solubilizing microorganisms: a key to sustainable agriculture. Agriculture 13: 462.

Singh SP & Verma AB 2001 Response of onion (*Allium cepa* L.) to potassium application. Indian J. Agron. 46(1): 182- 185.

Singh U & Jambunathan R 1981 Studies on desi and Kabuli chickpea (*Cicer arietinum* L.) cultivars: levels of protease inhibitors, levels of polyphenolic compounds, and *in-vitro* protein digestibility. J. Food Sci. 46(5): 1364-1367

Singh B & Trivedi P 2017 Microbiome and the future for food and nutrient security. Microb. Biotechnol. 10: 50–53.

Singleton VL & Rossi AJ 1965 Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. Am. J. Enol. Vitic. 16:144-158.

Somogyi M 1945 A new reagent for the determination of sugars. J. Biol. Chem. 160(1): 61-68.

Song Z, Duan J, Liang Z, Jia M, Li Y & Cao D 2023 Effects of different nitrogen application rates on growth, photosynthetic characteristics, and yield of day lily (*Hemerocallis citrina* Baroni) at the bolting stage. North Hortic. 13: 8–14.

Sousa WDS, de Pontes JR & de Melo OFP 2020 Effect of biofertilizer on soil fertility and lettuce nutrition. Rev. Agrogeoambiental. 12: 26–39.

Sun H & Weaver CM 2020 Rise in potassium deficiency in the US population linked to agriculture practices and dietary potassium deficits. J. Agricul. Food Chem. 68:11121–11127.

Tadhani MB & Subhash R 2009 Stevioside and stevia leaf extract as a replacement of sucrose in common beverages: sensory evaluation. Beverage and Food World 36(1): 55-59.

Torquato-Tavares A, Pascual-Reyes ID, Barros-Milhomens KK, Alves-Ferreira T & Rodrigues-do-Nascimento I 2017 Planting dates of *Allium cepa* L. hybrids in Gurupi, Tocantins, Brazil. Revista Chapingo Serie Horticultura 23: 123–133.

Tripathi R, Tewari R, Singh KP, Keswani C, Minkina T, Srivastava AK, De Corato U & Sansinenea E 2022 Plant mineral nutrition and disease resistance: A significant linkage for sustainable crop protection. Front. Plant Sci. 13: 883970.

Upadhyay A, Singh RB, Singh P, Lai B & Singh S 2023 Effect of integrated nutrient management on yield attributing parameters of *kharif* onion (*Allium cepa* L.). International Journal of Environment and Climate Change 13 (10): 4187-4193.

Wang Z, Liu T, Yang G & Zhao S 2024 Preparation and research on cationic modified vermiculite with strong adsorption capacity for mineralizing bacteria. Mater. Lett. 363:136313.

Xu Q, Zhang T, Niu Y, Mukherjee S, Abou-Elwafa SF, Nguyen NSH 2024 A comprehensive review on agricultural waste utilization through sustainable conversion techniques, with a focus on the additives effect on the fate of phosphorus and toxic elements during the composting process. Sci. Total Environ. 942:173567.

Yang X, Zhang K, Chang T, Shaghaleh H, Qi Z & Zhang J 2024 Interactive effects of microbial fertilizer and soil salinity on the hydraulic properties of salt-affected soil. Plan Theory 13:473.

Yang X, Ying Z, Liu H, Ying X & Yang G 2018 A new homoisoflavone from *Portulaca oleracea* L. and its antioxidant activity. Nat. Prod. Res. 6419: 3500–3506.

Yemm EW & Willis A 1954 The estimation of carbohydrates in plant extracts by anthrone. Biochem. J. 57(3): 508-514.

Yu W, Hayat K, Ma J, Fan X, Yang Y & Zhang Q 2024 Effect of antibiotic perturbation on nitrous oxide emissions: An in-depth analysis. Crit. Rev. Environ. Sci. Technol. 1–21.

Zhai C, Cheng Y, Qiu L, Wang X & Ge L 2024 Effects of combined application of bio-organic fertilizer with reduced chemical fertilizer on growth, yield, and quality of *Brassica campestris* ssp. chinensis *var*. rosularis. Chin. Agric. Sci. Bull. 40: 35–43.

Zhang J, Cook J, Nearing JT, Zhang J, Raudonis R, Glick BR, Langille MGI & Cheng Z 2021. Harnessing the plant microbiome to promote the growth of agricultural crops. Microbiol. Res. 245: 126690.

Zhishen J, Mengcheng T & Jianming W 1999 The determination of flavonoid contents in mulberry and their scavenging effects on superoxide radicals. Food Chem. 64(4): 555-559.