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RESEARCH ARTICLE

Synergistic effects of FYM and *Azotobacter* on Brassicaceae growth and yield at different altitudes

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Abstract

Bio-organic farming plays a crucial role in ensuring environmental sustainability by fostering plant growth and yield, particularly in challenging abiotic stress conditions. The study aims to investigate the influence of farm yard manure (FYM) and *Azotobacter*, at varying altitudes, on the growth and yield performance of Brassicaceae vegetables, including cabbage, cauliflower and radish. The open-field study was carried out using a factorial experiment within a randomized block design. The first variable consisted of different treatments: T_1 (FYM), T_2 (*Azotobacter*), T_3 (FYM + *Azotobacter*) and T_4 (control). The second variable was the location factor (such as high-altitude (3340 m, Leh-Ladakh) and low altitude (321 m, Chandigarh), India. In general, the T_3 treatment (FYM + *Azotobacter*) exhibited superior crop growth and yield attributes as compared to the control. At 90 days after transplanting (DAT) or 60 days after sowing (DAS), the T_3 treatments demonstrated increased plant height, leaf length, leaf width, leaf area, plant spread, stem diameter, leaf chlorophyll content and leaf anthocyanin content at HA, whereas a higher number of leaves and greater radish plant height and leaf area were observed at LA. Further, T_3 treatment of HA cultivated Brassicaceae vegetables demonstrated a higher yield, such as cabbage (494.75 ± 4.97 q/ha), cauliflower (259.05 ± 10.34 q/ha) and radish (390.64 ± 4.65 q/ha) than LA. Overall, this study concludes that bio-organic farming of sustainable Brassicaceae vegetable production at HA gets more yields as compared to LA cultivated samples.

Keywords: *Azotobacter*; Brassicaceae vegetable; farm yard manure; Ladakh; yield

Introduction

At present, the global agricultural industry's most pressing issues are energy crisis, environmental safety, food and nutritional security (1). The world's population has been growing steadily over the past few decades, which has raised the need for high-quality food. This need has largely been addressed through the use of chemical fertilizers. However, their prolonged application has resulted in a reduction of natural soil fertility, deterioration of soil structure, loss of beneficial microbes and insects, soil acidification, chemical burns and depletion of essential minerals. As a result, there has been a decline in the nutritional content of food which led to a rise in a number of health issues, such as asthma, birth deformities, neurological impacts, cancer and hormone disruption (1, 2). Thus, there is an increased focus on improving the yield and nutritional profiles of food crops. The most efficient way to accomplish this is through bio-organic farming (3). Bio-organic farming is a sustainable agricultural approach that reduces or entirely eliminates the use of synthetic fertilizers, pesticides, growth regulators and artificial additives in animal feed. Along with crop yield, it prioritizes healthy food, soils, plants and habitats. Furthermore, it is well known that bio-organic inputs such as FYM and bio fertilizers like *Azotobacter* help decrease reliance on chemical fertilizers while supplying plants with essential nutrients required for their growth (4, 5). However, its effectiveness in challenging high-altitude environments remains largely unexplored. Therefore, the present study bridges the gap of studying the implementation of FYM and *Azotobacter* in high-altitude and simultaneously comparing with Lower altitude (6).

Furthermore, the Brassicaceae family, including widely consumed vegetables in the Leh region, comprises about 3500 species, such as bokchoy, broccoli, Brussels sprouts, cabbage, cauliflower, radish, knol-khol and more, known for their natural richness in bioactive compounds with numerous health benefits (7, 8). It encompasses a diverse range of economically significant species and cultivars used for vegetables, oilseeds, forages and ornamental purposes. These plants are rich in dietary fiber, essential minerals and vitamins A, B and C, while remaining low in calories and fat. They are also an excellent source of health-enhancing phytochemicals, including carotenoids, chlorophylls, flavonoids and glucosinolates, along with essential elements such as potassium and calcium (9). However, adverse climatic conditions at high altitudes, such as atmospheric pressure, temperature, moisture, daylight hours, UV radiation, wind, season duration and geology, along with a short cultivation period, lead to the degradation of the yield and nutritional value of these vegetables over time (10, 11). As a consequence, providing nutrient-rich food to the locals becomes challenging. Therefore, the implementation of biofertilizer could support the plant in harnessing the essential nutrients to efficiently regulate its cellular mechanisms for higher production of primary and secondary metabolites to support its better growth and survivability in such adverse climatic conditions (7).

Thus, to bridge the knowledge gap on cultivating nutrient-rich vegetables in extreme high-altitude conditions of high altitudes, the current study compares the growth and yield of cruciferous vegetables cultivated at high and low altitudes, especially under the treatment with organic biofertilizers, namely FYM and *Azotobacter*. The selection of these 2 stations (HA *vs*. LA) for the present experimental study is motivated by the fact that most fresh food supply to meet the nutritional requirements of local natives in high-altitude regions is sourced from low-altitude areas and nearby locations. This results in significant air-transportation costs along with the loss of nutritional quality of fresh produce. Hence, the planned study undertakes a comparative examination of how organic farming practices impact the growth of crops. Additionally, the study gave a specific emphasis on evaluating the yield performance of cruciferous vegetables in the environments of both altitudes.

Materials and Methods

Experimental field and condition

Field trials were conducted over 2 consecutive years (2020-2021 and 2021–2022) in open-field conditions at both high-altitude (HA) and low-altitude (LA) locations. The HA site was the Agriculture Research Unit (ARU) at the Defence Institute of High Altitude Research (Leh), India (elevation: 3,340 m, 34° 08.2'N; 77°34.3'E), while the LA site was the Defence Institute of High Altitude Research base lab in Chandigarh, India (30° 41'31'' N; 76°47'10'' E, 321 m above mean sea level) (Fig. 1).

Temperature and relative humidity were recorded daily at both locations using a hygro-thermometer (445702, Extech Instruments). The average maximum and minimum temperatures at HA were 25.74 ± 2.03 °C and 4.40 ± 1.07 °C, respectively, whereas at LA, they were 33.34 ± 1.65 °C and 10.64 ± 1.90 °C. The maximum relative humidity recorded was 59.77 ± 3.10 % at HA and 87.11 ± 3.22 % at LA, while the minimum relative humidity was 14.24 ± 2.40 % at HA and 62.26 ± 1.15 % at LA (Fig. 2).

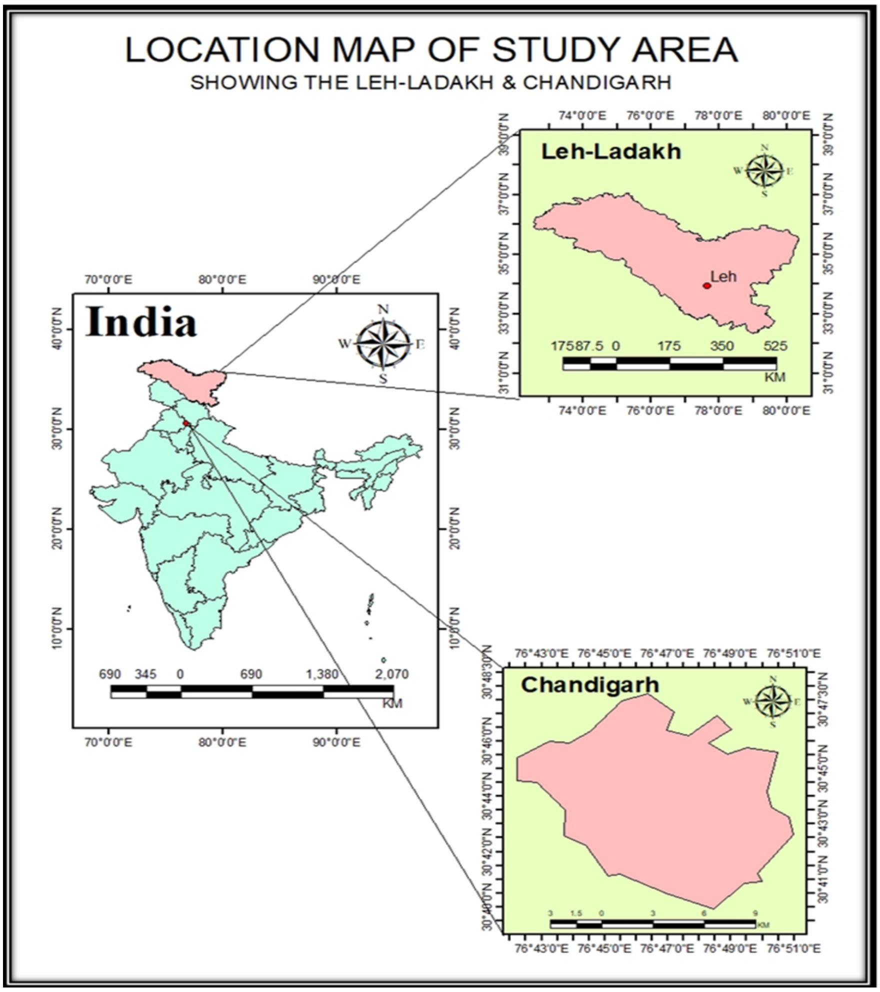

Fig. 1. Location of the study area.

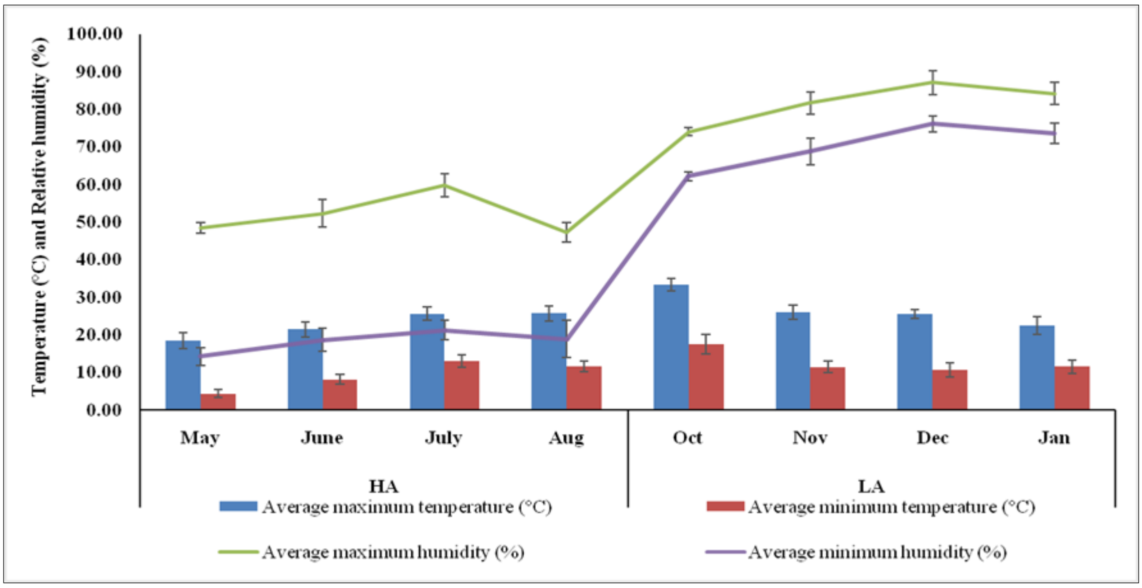

Fig. 2. Average means minimum and maximum temperatures, as well as relative humidity, at high and low altitudes during crop growth period. HA: High altitude and LA: low altitude.

Experimental design

The study was carried out using cabbage (*Brassica oleracea* L. var. *capitata*) cv. F_1 Videshi, cauliflower (*B. oleracea* L. var. *botrytis*) cultivar WS909 and radish (*Raphanus sativus* L.) cultivar Pusa Himani at both high and low altitude sites. The field experiment consisted of 12 plots and was designed using a two-factorial randomized block design (RBD). It included 4 treatments: T_1 (FYM at 150q/ha), T_2 (*Azotobacter* at 8.6 kg/ha), T_3 (a combination of FYM at 150q/ha and *Azotobacter* at 8.6 kg/ha) and T_4 (Control), each replicated 3 times. Each plot measured 1.62 m^2 (1.35 m in length × 1.20 m in width), with a 0.5 m gap maintained between both the blocks and individual plots. Cabbage and cauliflower seedlings were transplanted at the 2 - 3 true leaf stage when they reached a height of 15 - 18 cm. The radish seeds were directly sown in the experimental field at both the locations (HA and LA). Plant spacing of cabbage and cauliflower (60 cm × 45 cm) and radish (30 cm × 10 cm) was maintained in all plots. FYM and biofertilizer were incorporated into each plot prior to seedling transplantation. Irrigation was carried out using the flooding method, with a 3-day interval at the high-altitude (HA) site and a 6 – 7 day interval at the low-altitude (LA) site during the initial plant establishment phase. As the plants matured, irrigation frequency was adjusted to once a week at HA and every 2 weeks at LA. No synthetic pesticides or fertilizers were used at any location (LA & HA). Weeds were manually removed 2 - 3 times throughout the growing season.

Vegetative growth attributes

Five plants were randomly selected from each treatment and tagged for further observations. Growth parameters were recorded at 30, 45, 60, 75 and 90 days after transplantation (DAT) in cabbage and cauliflower and 30, 45, 60 days after sowing (DAS) in radish.

Plant height (cm)

Plant height was recorded by measuring from the ground level to the tip of the longest leaf using a measuring scale. The recorded vine length was presented as the mean value.

Number of leaves per plant

The leaf count was determined by counting the leaves of randomly selected plants at different successive stages of growth.

Leaf length with petiole (cm)

Leaf length with petiole was recorded from the leaf petiole up to the leaf apex at different growth stages with the help of measuring scale.

Leaf width (cm)

The broadest portion of the leaves was measured by measuring scale at different growth stages.

Leaf area (cm²)

Leaf area (cm²) was calculated by multiplying the length of the leaf without petiole and width of the leaf.

Plant spread (cm)

Plant spread was recorded from middle portion of the head/ curd/ knob to outer leaf of the plant with the help of measuring scale.

Stem diameter (mm)

Stem diameter was recorded from the first secondary root level to the position of first leaves in cabbage and cauliflower at different growth stages with the help of vernier calipers (12).

Leaf chlorophyll content

A portable chlorophyll meter was used to determine the chlorophyll content of the leaves (CCM-200 plus, ADC Bioscientific, UK). The results were expressed as chlorophyll content index (cci).

Leaf anthocyanin content

A portable anthocyanin meter was used to determine the anthocyanin content (ACI) of the leaves (ACM-200 plus, ADC Bioscientific, UK). The results were expressed as anthocyanin content index (aci).

Yield attributes

Number of inner leaves

The number of inner leaves was determined by counting the openings of the cabbage head (13).

Polar and equatorial diameter (mm)

To record the polar and equatorial diameter, the heads/curds were vertically sectioned at the center and the widest horizontal distance across the cut section was measured using digital vernier calipers (14).

Compactness rate

Cabbage and cauliflower compactness rate was recorded by the formula given in an earlier report (15). A compactness value of 1 indicates that the head is exceedingly compact and does not contain any air. A lower compaction rate results in a more compact cranium, while a higher compaction rate leads to less compactness.

$$\text{Compactness rate} = \frac{\text{Head volume } \left(3/4\ \pi \text{ radius}^3\right)}{\text{Head weight (g)}} \qquad \text{(Eqn. 1)}$$

Root length (cm)

In radish, length of root was recorded with the help of measuring scale.

Root diameter (mm)

In case of radish, the root diameter was measured at 3 distinct locations namely, the stalk end, middle section and floral end utilizing a vernier caliper. The average diameter was then calculated from these measurements.

Yield per plant (g)

The weight of heads, curds, roots per plant was recorded using a weighing balance. The weight of the average result was then reported as the yield per plant (16).

Yield (q/ha)

The weight of head, curd, roots per plot (kg) was recorded and converted to a per-ha basis. The final yield was expressed as total production (q/ha).

Statistical analysis

All experimental data were collected in triplicate and presented as mean ± standard deviation (SD). Data from both study years were pooled for analysis. To determine statistical significance, an independent t-test was conducted for samples from HA and LA, while one-way ANOVA followed by Duncan's multiple range test ($p \leq 0.05$) was used for comparisons. A two-way ANOVA was performed to assess the effects of altitude, treatment and their interaction. Statistical analyses were carried out using SPSS 16.0 (SPSS Corporation, Chicago, IL).

Results and Discussion

Effect on plant height

Observations were recorded at 5 growth stages (30, 45, 60, 75 and 90 DAT). Among the treatments (T_1, T_2, T_3 and T_4), T_3 significantly influenced plant height at both HA and LA (Table 1). This effect is likely attributable to the presence of free-living nitrogen-fixing bacteria, such as *Azotobacter*, play a dual role by fixing atmospheric nitrogen and producing phytohormones like GA3, IAA and cytokinins. These

Table 1. Comparative effect of location and treatments on plant height (cm) of *Brassica* vegetables grown at HA *vs.* LA

ALT	TRE	Cabbage					Cauliflower					Radish		
		30 DAT	45 DAT	60 DAT	75 DAT	90 DAT	30 DAT	45 DAT	60 DAT	75 DAT	90 DAT	30 DAS	45 DAS	60 DAS
HA	T_1	17.18 ± 0.70^{b***}	27.41 ± 0.88^{b}	29.05 ± 0.21^{b}	30.46 ± 0.88^{b}	32.39 ± 0.88^{b*}	12.13 ± 0.37^{b***}	18.42 ± 0.64^{c***}	29.10 ± 1.27^{b**}	35.16 ± 0.54^{b}	44.34 ± 0.76^{c**}	11.11 ± 0.41^{b***}	17.13 ± 0.80^{b***}	21.77 ± 0.87^{b***}
	T_2	17.17 ± 0.85^{b***}	27.24 ± 0.57^{b}	28.77 ± 0.38^{b}	30.63 ± 0.63^{b}	32.79 ± 0.99^{b*}	11.59 ± 0.54^{b***}	17.03 ± 0.72^{b***}	28.73 ± 0.35^{b*}	34.00 ± 0.55^{b}	42.04 ± 0.61^{b***}	10.53 ± 0.62^{b***}	16.93 ± 0.65^{b***}	21.58 ± 0.24^{b***}
	T_3	18.33 ± 0.42^{c***}	29.05 ± 0.23^{c}	31.97 ± 0.71^{c}	33.93 ± 0.42^{c**}	35.96 ± 0.61^{c**}	12.82 ± 0.10^{c***}	21.02 ± 0.28^{d***}	32.67 ± 0.42^{c***}	38.74 ± 1.11^{c}	48.14 ± 0.69^{d**}	12.04 ± 0.40^{c***}	21.19 ± 0.35^{c***}	24.20 ± 0.54^{c***}
	T_4	13.53 ± 0.28^{a***}	20.58 ± 0.47^{a**}	25.55 ± 0.68^{a}	27.19 ± 0.50^{a*}	28.46 ± 0.68^{a*}	9.68 ± 0.35^{a***}	14.35 ± 0.26^{a***}	26.22 ± 0.69^{a}	28.89 ± 0.80^{a}	33.47 ± 1.34^{a}	9.42 ± 0.41^{a***}	13.51 ± 0.16^{a***}	18.98 ± 0.31^{a***}
LA	T_1	23.92 ± 1.08^{b}	26.9 ± 1.01b	28.39 ± 0.84^{b}	29.05 ± 0.60^{b}	29.93 ± 0.51^{b}	28.34 ± 1.21^{b}	30.68 ± 1.51^{b}	33.75 ± 0.95^{b}	36.45 ± 0.86^{b}	39.82 ± 0.79^{b}	18.73 ± 0.75^{b}	26.12 ± 0.61^{b}	28.62 ± 0.73^{b}
	T_2	23.97 ± 0.98^{b}	26.65 ± 0.90^{b}	28.29 ± 0.99^{b}	28.92 ± 0.91^{b}	29.99 ± 1.04^{b}	26.83 ± 0.95^{b}	29.29 ± 1.61^{b}	32.72 ± 1.52^{b}	35.39 ± 1.19^{b}	39.03 ± 0.20^{b}	17.79 ± 1.11^{b}	24.99 ± 1.29^{b}	28.63 ± 0.61^{b}
	T_3	26.11 ± 0.48^{c}	29.38 ± 0.32^{c}	30.69 ± 0.40^{c}	31.29 ± 0.54^{c}	32.27 ± 0.60^{c}	30.74 ± 0.34^{c}	33.98 ± 0.40^{c}	36.37 ± 0.28^{c}	39.84 ± 0.28^{c}	43.89 ± 1.26^{c}	21.29 ± 0.79^{c}	29.05 ± 0.95^{c}	31.71 ± 0.47^{c}
	T_4	21.88 ± 0.56^{a}	24.07 ± 0.67^{a}	25.33 ± 0.40^{a}	25.73 ± 0.37^{a}	26.69 ± 0.40^{a}	21.76 ± 1.04^{a}	24.79 ± 0.55^{a}	26.76 ± 0.28^{a}	29.22 ± 0.32^{a}	31.79 ± 1.06^{a}	15.50 ± 0.87^{a}	20.83 ± 0.54^{a}	22.81 ± 0.70^{a}
ALT		***	NS	NS	***	***	***	***	***	**	***	***	***	***
TRE		***	***	***	***	***	***	***	***	***	***	***	***	***
ALT×TRE		NS	***	NS	NS	NS	***	NS	**	NS	NS	*	NS	***

HA- high altitude and LA- low altitude, Values presented as means ± SD, ALT: Altitude, TRE: Treatment, T_1= FYM at 150 q/ha, T_2= *Azotobacter* at 8.6 kg/ha, T_3= FYM at 150 q/ha+ *Azotobacter* at 8.6 kg/ha and T_4= Control. ALT x TRE - interaction of altitude and treatment.DAT: days after transplanting, DAS: days after sowing.

Values in columns with different lowercase letters indicate significant differences at $P < 0.05$, based on Duncan's multiple range test among treatments. Mean values within each column (between groups) were analyzed using an independent *t*-test, showing significant differences. A two-way ANOVA was conducted to assess the interaction between altitude and treatments, significance levels: *** $P \leq 0.001$; ** $P \leq 0.01$; * $P \leq 0.05$; NS = not significant.

hormones contribute to plant growth and improve nutrient accessibility to the roots by facilitating nutrient dissolution (17, 18). These findings align well with previous studies on plant height conducted by other researchers on cabbage, broccoli and tomato(19-22).

Furthermore, during the early stage (30 DAT/DAS), cabbage, cauliflower and radish plants were found to be taller at LA (26.11 ± 0.48 cm, 30.74 ± 0.34 cm, 21.29 ± 0.79 cm). However, at HA the plant height has been 18.33 ± 0.42 cm, 12.82 ± 0.10 cm, 12.04 ± 0.40 cm respectively. This initial effect on plant height may result from abiotic stress factors such as cold, frost, drought, low oxygen levels, strong winds and intense UV radiation commonly experienced at high altitudes (23). At 60 DAS, LA grown radish had more plant height (31.71 ± 0.47 cm) than HA-grown radish (24.20 ± 0.54 cm). The interaction between altitude and treatment on radish was also found significant. It might have appeared due to the difference in species and environmental factors. However, during later stage such as 90 DAT, the higher plant height in cabbage (35.96 ± 0.61 cm) and cauliflower (48.14 ± 0.69 cm) was observed at HA than LA grown cabbage and cauliflower, respectively. It might be because of cumulative effect of bio-organic treatment, combined with prolonged sunlight exposure at high altitudes, typically boosts the photosynthesis rate and promotes plant growth. According to previous study, plants that grown under high light intensity exhibited a greater growth rate and biomass compared to those cultivated in low light conditions (24).

Effect on number of leaves per plants

This study assessed the impact of different treatments (T_1, T_2, T_3 and T_4) on the number of leaves per plant. The treatments were applied at various intervals after transplanting, as shown in Table 2. Notably, treatment T_3, involving the application of FYM and *Azotobacter*, exhibited the highest number of leaves per plant across different days after transplanting (30 - 90) and sowing (30 - 60) for both high altitude (HA) and low altitude (LA) Brassicaceae vegetables. The observed increase in leaf count could be attributed to the synergistic effect of FYM and *Azotobacter*. FYM acts as a substrate and energy source for *Azotobacter*, helping it survive and multiply in the soil. This leads to an increase in the microbial count as well as activity in fixing nitrogen. Therefore, the combination leads to a better uptake and plant growth (7). These results align with previous studies (20, 25, 26).

Moreover, at 90 days after transplanting (DAT), LA-grown cabbage had a higher maximum leaf count per plant (17.56 ± 0.10) compared to HA-grown cabbage (16.11 ± 0.19). This difference in leaf count between altitudes could potentially be attributed to the differential environmental influences, with low altitudes exhibiting a more pronounced effect compared to high altitudes. Interestingly, no significant disparity was noted in cauliflower leaf count at 90 DAT across both altitudes. In radish, at 60 DAS, the highest leaf count (17.83 ± 0.29) was recorded at HA, as compared to LA (14.94 ± 0.59). This could be due to the combined influence of bio-organic fertilizer, which enhanced nitrogen availability and increased light intensity, which promoted leaf growth. These findings are consistent with prior research highlighting the effect of elevated light intensity and ultraviolet radiation in the high alpine region of Leh Ladakh (27, 28).

Table 2. Comparative effect of location and treatments on number of leaves of *Brassica* vegetables grown at HA *vs.* LA

ALT	TRE	Cabbage					Cauliflower					Radish		
		30 DAT	45 DAT	60 DAT	75 DAT	90 DAT	30 DAT	45 DAT	60 DAT	75 DAT	90 DAT	30 DAS	45 DAS	60 DAS
HA	T_1	9.06 ± 0.34b***	13.28 ± 0.19^{b}	13.83 ± 0.44^{b}	14.44 ± 0.42^{b}	14.72 ± 0.25^{b***}	6.55 ± 0.25^{b***}	11.67 ± 0.60^{b**}	13.11 ± 0.48^{b*}	15.89 ± 0.35b*	17.5 ± 0.33^{b**}	7.33 ± 0.34^{b}	14.83 ± 0.6^{b***}	15.06 ± 0.54^{b**}
	T_2	8.83 ± 0.44^{b***}	13.06 ± 0.20^{b**}	13.72 ± 0.25^{b*}	14.22 ± 0.39^{b*}	14.61 ± 0.26^{b**}	6.72 ± 0.09^{b***}	11.39 ± 0.38^{b**}	12.94 ± 0.20^{b**}	15.72 ± 0.25b**	17.28 ± 0.19^{b**}	7.61 ± 0.10^{b}	14.72 ± 0.58^{b***}	15.67 ± 0.88^{b**}
	T_3	10.17 ± 0.17^{c***}	14.28 ± 0.25^{c**}	15.17 ± 0.29^{c}	15.72 ± 0.09^{c***}	16.11 ± 0.19^{c***}	7.46 ± 0.08^{c***}	13.33 ± 0.44^{c**}	14.72 ± 0.09^{c***}	18.34 ± 0.29c	20.44 ± 0.42^{c}	9.39 ± 0.42^{c}	16.72 ± 0.68^{c***}	17.83 ± 0.29^{c**}
	T_4	7.39 ± 0.35^{a***}	9.50 ± 0.29^{a***}	10.72 ± 0.09^{a***}	11.00 ± 0.00^{a***}	11.39 ± 0.26^{a***}	5.44 ± 0.20^{a***}	8.39 ± 0.10^{a***}	10.83 ± 0.17^{a**}	12.72 ± 0.69a**	14.05 ± 0.25^{a***}	6.16 ± 0.29^{a}	10.89 ± 0.54^{a*}	12.17 ± 0.60^{a*}
LA	T_1	12.33 ± 0.17^{b}	13.78 ± 0.48^{b}	14.17 ± 0.34^{b}	14.89 ± 0.10^{b}	15.94 ± 0.10^{b}	11.45 ± 0.25^{b}	13.50 ± 0.00^{b}	14.56 ± 0.42^{b}	17.11 ± 0.38^{b}	18.72 ± 0.25^{b}	8.11 ± 0.51^{b}	11.55 ± 0.25^{b}	12.56 ± 0.34^{b}
	T_2	12.39 ± 0.10^{b}	14.11 ± 0.19^{b}	14.50 ± 0.17^{b}	15.11 ± 0.38^{b}	15.89 ± 0.35^{b}	11.33 ± 0.17^{b}	13.28 ± 0.58^{b}	14.39 ± 0.35^{b}	16.83 ± 0.29^{b}	18.56 ± 0.34^{b}	7.89 ± 0.42^{b}	11.33 ± 0.44^{b}	12.50 ± 0.67^{b}
	T_3	13.78 ± 0.35^{c}	15.28 ± 0.25^{c}	15.39 ± 0.26^{c}	16.39 ± 0.10^{c}	17.56 ± 0.10^{c}	12.83 ± 0.44^{c}	14.72 ± 0.09^{c}	15.94 ± 0.10^{c}	19.00 ± 0.33^{c}	20.89 ± 0.26^{c}	9.83 ± 0.17^{c}	13.22 ± 0.25^{c}	14.94 ± 0.59^{c}
	T_4	11.28 ± 0.09^{a}	12.67 ± 0.17^{a}	13.17 ± 0.00^{a}	13.44 ± 0.10^{a}	14.17 ± 0.00^{a}	9.61 ± 0.51^{a}	11.50 ± 0.44a	12.72 ± 0.42^{a}	15.17 ± 0.44^{a}	16.72 ± 0.35^{a}	6.22 ± 0.35^{a}	9.39 ± 0.35^{a}	10.45 ± 0.39^{a}
ALT		***	***	***	***	***	***	***	***	***	***	*	***	***
TRE		***	***	***	***	***	***	***	***	***	***	***	***	***
ALT×TRE		NS	***	***	***	***	*	**	NS	**	***	NS	*	NS

HA- high altitude and LA- low altitude, Values presented as means ± SD, ALT: Altitude, TRE: Treatment, T_1= FYM at 150 q/ha, T_2= *Azotobacter* at 8.6 kg/ha, T_3= FYM at 150 q/ha+ *Azotobacter* at 8.6 kg/ha and T_4= Control. ALT x TRE - interaction of altitude and treatment.DAT: days after transplanting, DAS: days after sowing.

Values in columns with different lowercase letters indicate significant differences at $P < 0.05$, based on Duncan's multiple range test among treatments. Mean values within each column (between groups) were analyzed using an independent *t*-test, showing significant differences. A two-way ANOVA was conducted to assess the interaction between altitude and treatments, significance levels: *** $P \leq 0.001$; ** $P \leq 0.01$; * $P \leq 0.05$; NS = not significant.

Effect on leaf length with petiole

Leaf length is a critical growth trait in cruciferous vegetables and was significantly influenced by different treatments and locations (Table 3). Among the treatments, T_3treatment exhibited a significant influence on leaf length compared to control at both locations. It has been reported that biofertilizer treatments alone or in combination with organic manure resulted in the enhancement of vegetative growth as compared to untreated plants (29). These results align with previous studies on broccoli (19–21).

Moreover, during the initial stage of the plant growth (30 DAT) the maximum leaf length with petiole was recorded in cabbage (24.63 ± 0.58 cm) and cauliflower (27.72 ± 0.50 cm) at LA as compared to HA-grown samples. This could be due attributed to abiotic stress conditions at high altitude, such as low temperatures and reduced oxygen levels. Our findings align with those of (30). At 90 DAT, the maximum leaf length with petiole was recorded in cabbage (33.21 ± 0.89 cm) and cauliflower (44.36 ± 1.04 cm) at HA. In contrast, the lowest values were observed in LA-grown cabbage (30.29 ± 0.44 cm) and cauliflower (40.95 ± 1.03 cm). It could be due to the strong effect of FYM and *Azotobacter* and high rate of photosynthesis at high altitude location than low altitude. At high altitudes, stronger light can enhance photosynthesis, but lower CO_2 levels from reduced atmospheric pressure limit carbon fixation. To cope, some plants develop more chlorophyll, higher stomatal density, or improved CO_2 uptake. Lower ambient temperatures help by reducing photorespiration, allowing certain species to maintain good photosynthetic performance (28). Earlier studies reported that plant cultivated in high light intensity and ultra violet radiation resulted in increased leaf size (28, 30).

Effect on leaf width

Leaf width is crucial parameter for proper head and curd development in Brassicaceae crops. In our study, Table 4 showed that the treatment (T_3) with FYM + *Azotobacter* significantly ($p \leq 0.05$) increased the leaf width compared to control at both locations (HA and LA). This increase in leaf width could be attributed to the combined application of FYM and biofertilizers, which likely enhanced microbial biomass and nutrient mineralization. The results were similar to the findings of (31, 12).

Furthermore, at 30 DAT, the maximum leaf width in cabbage (14.16 ± 0.18 cm) and cauliflower (11.10 ± 0.47cm) was measured at LA whereas; minimum leaf width (10.04 ± 0.08 cm and 5.55 ± 0.14 cm) was measured at HA-grown crop. The initial reduction in leaf width at high altitudes could be attributed to lower temperatures and oxygen availability, leading to slower cell expansion. However, at 90 DAT, the maximum leaf width was recorded at HA-grown cabbage (26.97 ± 0.25 cm) and cauliflower (23.14 ± 0.51 cm) as compared to LA-grown cabbage (20.11 ± 0.04 cm) and cauliflower (16.46 ± 0.24 cm). A notable interaction between altitude and treatments (ALT×TRE) was observed at 30, 45 and 90 DAT. This suggests that the response to treatments varied significantly depending on altitude, likely due to differences in environmental stressors and nutrient availability. The leaf width might have increased as a result of increased exposure to sunlight and light intensity. The result aligns with the findings of (27, 28).

Table 3. Comparative effect of location and treatments on leaf length with petiole (cm) of *Brassica* vegetables grown at HA *vs.* LA

ALT	TRE	Cabbage					Cauliflower					Radish
		30 DAT	45 DAT	60 DAT	75 DAT	90 DAT	30 DAT	45 DAT	60 DAT	75 DAT	90 DAT	
HA	T_1	$15.72 \pm 0.52^{b***}$	25.02 ± 0.54^{b}	26.75 ± 0.23^{b}	$28.10 \pm 0.37^{b**}$	$29.40 \pm 0.58^{b**}$	$10.77 \pm 0.34^{b***}$	$16.65 \pm 0.59^{b***}$	$25.69 \pm 1.13^{b**}$	32.6 ± 1.27^{b}	$40.47 \pm 1.32^{b**}$	NO
	T_2	$15.69 \pm 0.63^{b***}$	24.99 ± 0.34^{b}	26.67 ± 0.67^{b}	28.31 ± 0.31^{b}	$30.33 \pm 0.81^{b*}$	$10.00 \pm 0.40^{b***}$	$15.95 \pm 0.66^{b***}$	$25.61 \pm 0.31^{b*}$	31.05 ± 0.83^{b}	$39.30 \pm 0.73^{b**}$	
	T_3	$17.13 \pm 0.42^{c***}$	26.98 ± 0.38^{c}	$30.02 \pm 0.54^{c*}$	31.05 ± 1.15^{c}	$33.21 \pm 0.89^{c**}$	$11.19 \pm 0.27^{c***}$	$18.57 \pm 0.37^{c***}$	$29.72 \pm 0.41^{c**}$	$35.27 \pm 0.52^{c*}$	$44.36 \pm 1.04^{c*}$	
	T_4	$12.74 \pm 0.19^{a***}$	$18.75 \pm 0.60^{aa***}$	22.38 ± 0.34^{a}	$24.95 \pm 0.56^{a**}$	$26.11 \pm 0.33^{a**}$	$8.62 \pm 0.34^{a***}$	$13.24 \pm 0.20^{a***}$	23.15 ± 0.71^{a}	25.80 ± 1.23^{a}	30.39 ± 1.34^{a}	
LA	T_1	22.21 ± 0.82^{b}	24.95 ± 0.60^{b}	25.99 ± 0.50^{b}	26.62 ± 0.37^{b}	27.73 ± 0.26^{b}	24.40 ± 1.41^{b}	27.65 ± 1.53^{b}	29.70 ± 0.70^{b}	32.53 ± 0.70^{b}	36.43 ± 0.32^{b}	
	T_2	22.07 ± 1.11^{b}	24.86 ± 0.91^{b}	26.19 ± 1.06^{b}	26.75 ± 0.95^{b}	27.77 ± 0.93^{b}	22.83 ± 0.47^{b}	27.16 ± 1.35^{b}	29.54 ± 1.57^{b}	32.32 ± 1.45^{b}	35.50 ± 0.52^{b}	
	T_3	24.63 ± 0.58^{c}	27.39 ± 0.63^{c}	28.77 ± 0.47^{c}	29.36 ± 0.48^{c}	30.29 ± 0.44^{c}	27.72 ± 0.50^{c}	31.11 ± 0.41^{c}	33.10 ± 0.64^{c}	36.46 ± 0.44^{c}	40.95 ± 1.03^{c}	
	T_4	20.19 ± 0.37^{a}	22.28 ± 0.50^{a}	23.12 ± 0.46^{a}	23.79 ± 0.38^{a}	24.85 ± 0.21^{a}	18.92 ± 1.10^{a}	22.10 ± 0.55^{a}	23.90 ± 0.20^{a}	26.02 ± 0.43^{a}	28.75 ± 0.46^{a}	
ALT		***	***	NS	***	***	***	***	***	NS	***	
TRE		***	***	***	***	***	***	***	***	***	***	
ALT×TRE		NS	***	NS	NS	NS	***	*	*	NS	NS	

HA- high altitude and LA- low altitude, Values presented as means ± SD, ALT: Altitude, TRE: Treatment, NO: not observed, T_1= FYM at 150q/ha, T_2= *Azotobacter* at 8.6 kg/ha, T_3= FYM at 150 q/ha+ *Azotobacter* at 8.6 kg/ha and T_4= Control. ALT x TRE - interaction of altitude and treatment.DAT: days after transplanting.

Values in columns with different lowercase letters indicate significant differences at $P < 0.05$, based on Duncan's multiple range test among treatments. Mean values within each column (between groups) were analyzed using an independent *t*-test, showing significant differences. A two-way ANOVA was conducted to assess the interaction between altitude and treatments, significance levels: *** $P \leq 0.001$; ** $P \leq 0.01$; * $P \leq 0.05$; NS = not significant.

Table 4. Comparative effect of location and treatments on leaf width (cm) of *Brassica* vegetables grown at HA *vs.* LA

ALT	TRE	Cabbage					Cauliflower					Radish
		30 DAT	45 DAT	60 DAT	75 DAT	90 DAT	30 DAT	45 DAT	60 DAT	75 DAT	90 DAT	
HA	T_1	$9.61 \pm 0.17^{b***}$	$18.34 \pm 0.08^{b***}$	$20.71 \pm 0.65^{b***}$	$22.83 \pm 0.38^{b***}$	$23.34 \pm 0.39^{b***}$	$4.84 \pm 0.04^{b***}$	$9.02 \pm 0.15^{b***}$	$12.93 \pm 0.15^{c*}$	$14.53 \pm 0.17^{b***}$	$21.97 \pm 0.38^{b***}$	
	T_2	$9.53 \pm 0.09^{b***}$	$18.01 \pm 0.12^{b***}$	$20.87 \pm 0.44^{b***}$	$22.55 \pm 1.26^{b**}$	$23.30 \pm 0.31^{b***}$	$4.73 \pm 0.08^{b***}$	$8.61 \pm 0.41^{b***}$	$12.44 \pm 0.15^{b*}$	$14.73 \pm 0.59^{b**}$	$21.93 \pm 0.29^{b***}$	
	T_3	$10.04 \pm 0.08^{c***}$	$19.52 \pm 0.26^{c***}$	$23.32 \pm 0.45^{c***}$	$25.24 \pm 0.25^{c***}$	$26.97 \pm 0.25^{c***}$	$5.55 \pm 0.14^{c***}$	$11.34 \pm 0.29^{c**}$	14.13 ± 0.27^{d}	$16.15 \pm 0.28^{c*}$	$23.14 \pm 0.51^{c***}$	
	T_4	$8.05 \pm 0.10^{a***}$	$13.52 \pm 0.36^{a*}$	$18.23 \pm 0.06^{a***}$	$20.34 \pm 0.34^{a***}$	$22.24 \pm 0.06^{a***}$	$4.51 \pm 0.06^{a***}$	$6.80 \pm 0.10^{a***}$	$10.63 \pm 0.20^{a**}$	$12.39 \pm 0.26^{a***}$	$17.31 \pm 0.09^{a***}$	
LA	T_1	12.89 ± 0.37^{b}	14.44 ± 0.69^{b}	16.78 ± 0.16^{b}	17.32 ± 0.05^{b}	18.10 ± 0.11^{b}	9.96 ± 0.53^{c}	11.29 ± 0.41^{b}	12.07 ± 0.32^{b}	13.16 ± 0.16^{b}	14.4 ± 0.38^{c}	NO
	T_2	12.66 ± 0.38^{b}	14.38 ± 0.50^{b}	16.42 ± 0.72^{b}	17.00 ± 0.73^{b}	17.91 ± 0.74^{b}	9.08 ± 0.55^{b}	10.89 ± 0.18^{b}	11.75 ± 0.25^{b}	12.79 ± 0.31^{b}	13.85 ± 0.24^{b}	
	T_3	14.16 ± 0.18^{c}	16.30 ± 0.13^{c}	18.57 ± 0.17^{c}	19.13 ± 0.15^{c}	20.11 ± 0.04^{c}	11.10 ± 0.47^{d}	13.05 ± 0.28^{c}	13.84 ± 0.31^{c}	15.24 ± 0.34^{c}	16.46 ± 0.24^{d}	
	T_4	10.88 ± 0.04^{a}	12.51 ± 0.50^{a}	14.20 ± 0.11^{a}	14.64 ± 0.14^{a}	15.45 ± 0.09^{a}	6.69 ± 0.2^{a}	8.70 ± 0.13^{a}	9.29 ± 0.31^{a}	10.32 ± 0.22^{a}	11.44 ± 0.04^{a}	
ALT		***	***	***	***	***	***	***	***	***	***	
TRE		***	***	***	***	***	***	***	***	***	***	
ALT×TRE		***	***	NS	NS	***	***	NS	*	*	***	

HA- high altitude and LA- low altitude, Values presented as means ± SD, ALT: Altitude, TRE: Treatment, NO: not observed, T_1= FYM at 150q/ha, T_2= *Azotobacter* at 8.6 kg/ha, T_3= FYM at 150 q/ha+ *Azotobacter* at 8.6 kg/ha and T_4= Control. ALT x TRE - interaction of altitude and treatment.DAT: days after transplanting.

Values in columns with different lowercase letters indicate significant differences at $P < 0.05$, based on Duncan's multiple range test among treatments. Mean values within each column (between groups) were analyzed using an independent *t*-test, showing significant differences. A two-way ANOVA was conducted to assess the interaction between altitude and treatments, significance levels: *** $P \leq 0.001$; ** $P \leq 0.01$; * $P \leq 0.05$; NS = not significant.

Effect on leaf area

As shown in Table 5, leaf area was significantly higher in the T_3 treatment compared to the control (T_4) at both locations and across different growth stages. This increase in leaf area could be attributed due improved nutrient availability, enhanced root development and potential synergistic interactions between FYM and *Azotobacter* on plant growth. Additionally, at 30 (DAT/DAS), cabbage (299.70 ± 1.64 cm^2), cauliflower (264.82 ± 10.86 cm^2) and radish (117.43 ± 0.97 cm^2) displayed the maximum leaf area at LA, contrasting with those at HA where cabbage (137.02 ± 3.98 cm^2), cauliflower (49.99 ± 2.25 cm^2) and radish (47.07 ± 1.11 cm^2) showed lower values. This could be due to the greater leaf length and width observed at low altitude, which directly contributes to a larger leaf area. Moreover, in radish, at 60 DAS, the maximum leaf area (227.26 ± 5.04 cm^2) was recorded at LA as compared to HA (151.61 ± 4.87 cm^2). The altitude and treatments interaction was found significant ($p \leq 0.05$) at 30, 45 and 60 DAS. It might have appeared due to the difference in species and crop characteristics (30). At 90 DAT, the higher leaf area in cabbage (811.16 ± 10.11 cm^2) and cauliflower (837.54 ± 26.29 cm^2) was recorded at HA than to LA grown vegetables. A significant interaction between altitude and treatments was observed in cabbage and cauliflower at 30, 45, 60, 75 and 90 DAT. It might be due to the result that the maximum leaf length and width was found at high altitude as compared to low altitude. Our result is similar to the finding of (31, 30).

Effect on plant spread

At different growth stages, plant spread was significantly influenced by altitude and bio-organic treatments (Table 6). The treatment (T_3) showed the greatest plant spread, whereas the control group showed the least amount of plant spread at both locations. Our findings are consistent with (12, 19). Furthermore, at 30 DAT, the maximum plant spread for cabbage (23.22 ± 0.31cm); cauliflower (20.58 ± 1.19 cm) was recorded at LA, whereas, minimum plant spread was found in HA-grown cabbage (16.32 ± 0.24 cm) and cauliflower (10.99 ± 0.29 cm), respectively. The reduced plant spread at high altitudes could be attributed to abiotic stress factors such as lower temperatures, reduced oxygen levels and limited soil nutrient availability. However, during the later stage of plant growth, *i.e.*, 90 DAT, the higher plant spread was recorded at HA-grown cabbage (36.59 ± 0.27 cm) and cauliflower (43.02 ± 0.62 cm) as compared to LA-grown cabbage (31.33 ± 0.79 cm) and cauliflower (35.11 ± 0.65 cm). The interaction effect of altitude and bio-fertilizer treatments on plant spread was found to be significant at 30, 45 and 90 DAT. The greater plant spread observed at high altitudes during later growth stages could be due to increased light intensity and improved nutrient availability, which promote vegetative growth. According to previous reports, the crop's plant spread enhances by high nutrient availability and high light intensity (28, 31).

Effect on stem diameter

Table 7 shows a significant difference in stem diameter across all growth stages based on treatments (T_1, T_2, T_3 and T_4) and altitude (HA & LA). Among the treatments, T_3treatment resulted in the highest stem diameter across different days after transplanting at both locations. These findings are consistent with previous reported studies by (20, 25). Moreover, during the

Table 5. Comparative effect of location and treatments on leaf area (cm^2) of *Brassica* vegetables grown at HA *vs.* LA

ALT	TRE	Cabbage					Cauliflower					Radish		
		30 DAT	45 DAT	60 DAT	75 DAT	90 DAT	30 DAT	45 DAT	60 DAT	75 DAT	90 DAT	30 DAS	45 DAS	60 DAS
HA	T_1	119.49 ± 3.12^{b***}	391.43 ± 16.13^{b**}	465.93 ± 6.95^{b***}	561.22 ± 1.36^{b***}	623.18 ± 9.41^{b***}	41.57 ± 1.60^{c***}	114.5 ± 3.88^{c***}	267.61 ± 10.12^{b**}	376.40 ± 15.80^{b}	729.00 ± 21.02^{b***}	39.31 ± 1.19^{b***}	95.67 ± 3.68^{b***}	122.62 ± 4.42^{b***}
	T_2	117.76 ± 4.26^{b***}	386.16 ± 15.24^{b**}	467.06 ± 7.24^{b***}	554.9 ± 21.87^{b***}	626.3 ± 12.52^{b***}	38.05 ± 1.75^{b***}	106.97 ± 5.41^{b***}	262.66 ± 7.62^{b**}	375.14 ± 16.71^{b}	713.97 ± 8.17^{b***}	39.06 ± 1.67^{b***}	95.04 ± 3.72^{b***}	121.84 ± 3.77^{b***}
	T_3	137.02 ± 3.98^{c***}	455.92 ± 16.13^{c**}	581.85 ± 18.52^{c***}	678.94 ± 14.54^{c***}	811.16 ± 10.11^{c***}	49.99 ± 2.25^{d***}	154.47 ± 0.96^{d***}	340.89 ± 10.94^{c**}	494.02 ± 18.16^{c}	837.54 ± 26.29^{c***}	47.07 ± 1.11^{c***}	126.06 ± 1.63^{c***}	151.61 ± 4.87^{c***}
	T_4	85.33 ± 0.35a***	198.93 ± 4.06^{a**}	336.96 ± 14.67^{a**}	424.05 ± 20.95^{a***}	530.17 ± 8.68^{a***}	34.76 ± 1.22^{a***}	69.03 ± 1.37^{a***}	192.25 ± 2.93^{a}	274.89 ± 6.30^{a***}	491.03 ± 6.94^{a***}	26.59 ± 0.94^{a***}	60.64 ± 1.34^{a***}	84.43 ± 2.58^{a***}
LA	T_1	235.63 ± 9.28^{b}	305.21 ± 13.59^{b}	377.11 ± 6.14^{b}	397.43 ± 6.60^{b}	432.89 ± 7.34^{b}	201.11 ± 8.60^{c}	273.01 ± 11.68b	324.68 ± 7.56^{b}	396.15 ± 7.27^{c}	494.18 ± 11.31^{c}	92.83 ± 3.24^{c}	159.98 ± 3.93^{c}	184.34 ± 4.62^{b}
	T_2	236.31 ± 12.07^{b}	304.16 ± 13.17^{b}	367.29 ± 16.74^{b}	392.37 ± 14.46^{b}	431.77 ± 18.54^{b}	178.61 ± 8.06^{b}	262.33 ± 10.15b	312.49 ± 14.84^{b}	371.75 ± 11.17^{b}	458.56 ± 10.27^{b}	83.90 ± 2.14^{b}	150.09 ± 3.82^{b}	176.51 ± 4.62^{b}
	T_3	299.70 ± 1.64^{c}	379.32 ± 9.7^{c}	447.31 ± 5.20^{c}	474.59 ± 5.25^{c}	525.87 ± 11.34^{c}	264.82 ± 10.86^{d}	365.45 ± 12.20c	415.74 ± 13.68^{c}	508.29 ± 16.38^{d}	628.34 ± 13.4^{d}	117.43 ± 0.97^{d}	184.95 ± 7.19^{d}	227.26 ± 5.04^{c}
	T_4	176.59 ± 4.58^{a}	235.51 ± 10.99^{a}	278.63 ± 4.55^{a}	299.19 ± 5.31^{a}	331.13 ± 2.34^{a}	101.86 ± 2.36^{a}	162.15 ± 0.98a	189.68 ± 1.37^{a}	231.81 ± 3.60a	292.04 ± 2.71^{a}	60.70 ± 2.43^{a}	87.78 ± 2.75^{a}	109.95 ± 2.95^{a}
ALT		***	***	***	***	***	***	***	***	NS	***	***	***	***
TRE		***	***	***	***	***	***	***	***	***	***	***	***	***
ALT×TRE		***	***	***	***	***	***	***	***	**	*	***	***	***

HA- high altitude and LA- low altitude, Values presented as means ± SD, ALT: Altitude, TRE: Treatment, T_1= FYM at 150q/ha, T_2= *Azotobacter* at 8.6 kg/ha, T_3= FYM at 150 q/ha+ *Azotobacter* at 8.6 kg/ha and T_4= Control. ALT x TRE - interaction of altitude and treatment.DAT: days after transplanting, DAS: days after sowing.

Values in columns with different lowercase letters indicate significant differences at $P < 0.05$, based on Duncan's multiple range test among treatments. Mean values within each column (between groups) were analyzed using an independent *t*-test, showing significant differences. A two-way ANOVA was conducted to assess the interaction between altitude and treatments, significance levels: *** $P \leq 0.001$; ** $P \leq 0.01$; * $P \leq 0.05$; NS = not significant.

Table 6. Comparative effect of location and treatments on plant spread (cm) of *Brassica* vegetables grown at HA *vs.* LA

ALT	TRE	Cabbage					Cauliflower					Radish
		30 DAT	45 DAT	60 DAT	75 DAT	90 DAT	30 DAT	45 DAT	60 DAT	75 DAT	90 DAT	
HA	T_1	14.73 ± 0.46^{b***}	26.13 ± 0.81^{b*}	29.85 ± 0.55^{b**}	30.79 ± 1.24^{b*}	34.01 ± 0.14^{c***}	10.23 ± 0.38^{b***}	16.51 ± 0.47^{b**}	26.86 ± 0.99^{b**}	28.68 ± 0.36^{b}	38.72 ± 0.49^{b***}	NO
	T_2	14.51 ± 0.52^{b***}	26.37 ± 0.69^{b*}	29.63 ± 0.68^{b**}	30.67 ± 0.65^{b**}	32.97 ± 0.22^{b**}	9.28 ± 0.19^{a***}	15.97 ± 0.65^{b**}	26.51 ± 0.49^{b**}	28.54 ± 0.10^{b}	37.97 ± 1.26^{b***}	
	T_3	16.32 ± 0.24^{c***}	28.03 ± 0.07^{c***}	31.76 ± 0.58^{c*}	32.97 ± 0.33^{c**}	36.59 ± 0.27^{d***}	10.99 ± 0.29^{c***}	19.30 ± 0.17^{c**}	29.61 ± 1.21^{c*}	33.07 ± 0.85^{c}	43.02 ± 0.62^{c***}	
	T_4	12.7 ± 0.13^{a***}	20.14 ± 0.66^{a}	25.06 ± 0.63^{a*}	26.43 ± 0.26^{a**}	26.90 ± 0.25^{a*}	8.88 ± 0.21^{a**}	13.46 ± 0.26^{a**}	23.06 ± 0.56^{a***}	26.25 ± 0.38^{a***}	28.81 ± 0.31^{a***}	
LA	T_1	21.25 ± 0.91^{b}	23.60 ± 0.68^{b}	26.09 ± 0.90^{b}	26.89 ± 0.88^{b}	27.93 ± 0.73^{b}	17.57 ± 0.70^{b}	19.94 ± 1.06^{b}	23.89 ± 0.53^{b}	29.38 ± 0.96^{b}	32.04 ± 0.54^{c}	
	T_2	21.16 ± 0.95^{b}	23.72 ± 0.87^{b}	25.98 ± 1.17^{b}	26.83 ± 1.29^{b}	27.89 ± 1.21^{b}	16.70 ± 0.64^{b}	19.66 ± 0.57^{b}	23.34 ± 1.05^{b}	28.39 ± 0.83^{b}	30.84 ± 0.76^{b}	
	T_3	23.22 ± 0.31^{c}	25.96 ± 0.28^{c}	29.41 ± 0.70^{c}	30.30 ± 0.82^{c}	31.33 ± 0.79^{c}	20.58 ± 1.19^{c}	22.66 ± 0.94^{c}	27.37 ± 0.69^{c}	31.93 ± 0.25^{c}	35.11 ± 0.65^{d}	
	T_4	16.92 ± 0.47^{a}	19.55 ± 0.65^{a}	22.07 ± 1.19^{a}	22.84 ± 1.21^{a}	23.80 ± 1.24^{a}	13.13 ± 1.00^{a}	14.76 ± 0.40^{a}	17.56 ± 0.36^{a}	20.39 ± 0.36^{a}	24.18 ± 0.52^{a}	
ALT		***	***	***	***	***	***	***	***	***	***	
TRE		***	***	***	***	***	***	***	***	***	***	
ALT×TRE		**	*	NS	NS	*	***	*	*	***	**	

HA- high altitude and LA- low altitude, Values presented as means ± SD, ALT: Altitude, TRE: Treatment, NO: not observed, T_1= FYM at 150q/ha, T_2= *Azotobacter* at 8.6 kg/ha, T_3= FYM at 150 q/ha+ *Azotobacter* at 8.6 kg/ha and T_4= Control. ALT x TRE - interaction of altitude and treatment. DAT: days after transplanting.

Values in columns with different lowercase letters indicate significant differences at $P < 0.05$, based on Duncan's multiple range test among treatments. Mean values within each column (between groups) were analyzed using an independent *t*-test, showing significant differences. A two-way ANOVA was conducted to assess the interaction between altitude and treatments, significance levels: *** $P \leq 0.001$; ** $P \leq 0.01$; * $P \leq 0.05$; NS = not significant.

initial stage of plant growth (30 DAT), LA-grown cabbage (13.12 ± 0.68 mm) and cauliflower (10.32 ± 0.23 mm) exhibited larger stem diameters compared to their counterparts grown at HA, which recorded 8.43 ± 0.32 mm for cabbage and 5.33 ± 0.02 mm for cauliflower. This could be due to abiotic stress factors such as lower temperatures, reduced oxygen levels and nutrient limitations at higher altitudes. Our results align well with those reported in earlier report (31). However, at 90 DAT, the maximum stem diameter was observed in cabbage (25.25 ± 0.34 mm) and cauliflower (24.30 ± 0.50 mm) grown at HA, while the minimum stem diameter was noted in LA-grown cabbage (19.16 ± 0.66 mm) and cauliflower (20.94 ± 0.85 mm). These variations could be influenced by differences in treatment effects, soil nutrient availability and the increased photosynthetic efficiency observed at higher altitudes.

Effect on leaf chlorophyll content

Chlorophyll, the primary light-absorbing pigment in plants, plays a crucial role in metabolic activity (31). In the current study, the highest leaf chlorophyll content of Brassicaceae vegetables was recorded in treatment (T_3) compared to (T_1, T_2 and T_4) at both HA and LA locations (Table 8). Earlier study reported that high availability of N due to application of FYM and *Azotobacter* significantly increased the chlorophyll content in cabbage (29). Furthermore, at 90 DAT, higher chlorophyll content of cabbage (64.53 ± 1.81 cci) and cauliflower (59.27 ± 0.39 cci) was recorded at HA as compared to LA-grown cabbage (50.21 ± 1.33 cci) and cauliflower (45.96 ± 0.36 cci) respectively. In radish at 60 DAS, a similar trend was found at HA as in the LA-grown sample. The combined influence of altitude and treatments on leaf chlorophyll content was found to be significant in cabbage (45 and 75 DAT), cauliflower (30 DAT) and radish (45 and 60 DAS). The higher chlorophyll content observed at HA could be attributed to increased light intensity, which enhances chlorophyll synthesis and photosynthetic efficiency. Our findings are consistent with previous study, in which it was reported that white and blue light significantly enhance the photosynthetic efficiency and chlorophyll content of Welsh onions (32).

Effect on leaf anthocyanin content

Anthocyanins play a crucial role in protecting leaves from photo-inhibitory damage by absorbing excess photons. In our investigation, treatment (T_3) with FYM and *Azotobacter* at various growth stages in both the HA and LA locations had a greater leaf anthocyanin content of Brassicaceae vegetables (Table 9). At 90 DAT, the highest leaf anthocyanin content was recorded in HA-grown cabbage (24.76 ± 0.36 aci) and cauliflower (16.87 ± 0.22 aci), compared to their LA-grown counterparts. In a two-way analysis, the interaction effect of altitude and bio-fertilizer treatments on leaf anthocyanin content of Brassicaceae vegetable was found to be significant at 30, 45, 60, 75 and 90 DAT/DAS, which could be due to high ultraviolet radiation. These findings are in agreement with previous study, which reported that UV-B and UV-C enhanced anthocyanin accumulation in leaves of *Capsicum* (33).

Altitude and treatments had a significant effect ($p \leq 0.05$) on various yield parameters of cabbage and cauliflower, including the number of inner leaves, head/curd diameter, length, weight per plant, compactness rate and total yield (q/ha) (Fig. 3 and 4). The effect of treatments on cabbage and cauliflower at both locations was validated by One-way ANOVA.

Table 7. Comparative effect of location and treatments on stem diameter (mm) of *Brassica* vegetables grown at HA *vs.* LA

ALT	TRE	Cabbage					Cauliflower					Radish
		30 DAT	45 DAT	60 DAT	75 DAT	90 DAT	30 DAT	45 DAT	60 DAT	75 DAT	90 DAT	
HA	T_1	$7.35 \pm 0.15^{b***}$	12.63 ± 0.36^{b}	13.07 ± 0.58^{b}	$17.12 \pm 0.30^{b**}$	$22.14 \pm 0.37^{b***}$	$4.21 \pm 0.16^{b***}$	$7.71 \pm 0.12^{c***}$	$9.85 \pm 0.36^{b**}$	$13.3 \pm 0.18^{b*}$	$20.37 \pm 0.19^{b***}$	NO
	T_2	$7.00 \pm 0.13^{b***}$	12.58 ± 0.19^{b}	12.90 ± 0.22^{b}	$17.01 \pm 0.42^{b***}$	$22.09 \pm 0.23^{b***}$	$4.11 \pm 0.07^{b***}$	$7.17 \pm 0.32^{b***}$	$9.83 \pm 0.27^{b*}$	13.27 ± 0.63^{b}	$20.46 \pm 0.16^{b***}$	
	T_3	$8.43 \pm 0.32^{c***}$	15.09 ± 0.25^{c}	15.79 ± 0.16^{c}	$20.25 \pm 0.46^{c**}$	$25.25 \pm 0.34^{c***}$	$5.33 \pm 0.02^{c***}$	$9.45 \pm 0.39^{d***}$	$11.3 \pm 0.14^{c**}$*	16.83 ± 0.74^{c}	$24.30 \pm 0.50^{c**}$	
	T_4	5.46 ± 0.22a***	$8.24 \pm 0.20^{a***}$	$9.96 \pm 0.10^{a*}$	$14.45 \pm 0.12^{a**}$	$19.00 \pm 0.24^{a***}$	$3.73 \pm 0.14^{a***}$	$5.65 \pm 0.12^{a***}$	8.44 ± 0.27^{a}	11.29 ± 0.35^{a}	$16.55 \pm 0.32^{a***}$	
LA	T_1	11.25 ± 0.31^{b}	12.26 ± 0.39^{b}	13.31 ± 0.49^{b}	14.85 ± 0.42^{b}	16.29 ± 0.49^{b}	8.80 ± 0.26^{b}	10.77 ± 0.43^{b}	11.97 ± 0.41^{b}	14.43 ± 0.48^{b}	16.29 ± 0.61^{b}	
	T_2	11.47 ± 0.27^{b}	12.37 ± 0.22^{b}	13.26 ± 0.29^{b}	14.94 ± 0.06^{b}	16.39 ± 0.13^{b}	8.51 ± 0.63^{b}	10.38 ± 0.42^{b}	11.49 ± 0.76^{b}	13.61 ± 0.57^{b}	16.00 ± 0.54^{b}	
	T_3	13.12 ± 0.68^{c}	14.56 ± 0.75^{c}	15.34 ± 1.01^{c}	17.22 ± 0.82^{c}	19.16 ± 0.66^{c}	10.32 ± 0.23^{c}	12.74 ± 0.30^{c}	13.78 ± 0.12^{c}	17.79 ± 0.64^{c}	20.94 ± 0.85^{c}	
	T_4	9.08 ± 0.36^{a}	10.18 ± 0.20^{a}	11.01 ± 0.57^{a}	11.81 ± 0.59^{a}	12.82 ± 0.53^{a}	6.56 ± 0.29^{a}	7.89 ± 0.23^{a}	8.90 ± 0.16^{a}	11.16 ± 0.33^{a}	12.37 ± 0.28^{a}	
ALT		***	***	NS	NS	***	***	***	***	*	***	
TRE		***	***	***	***	***	***	***	***	***	***	
ALT×TRE		NS	***	NS	NS	NS	***	*	***	NS	NS	

HA- high altitude and LA- low altitude, Values presented as means ± SD, ALT: Altitude, TRE: Treatment, NO: not observed, T_1= FYM at 150q/ha, T_2= *Azotobacter* at 8.6 kg/ha, T_3= FYM at 150 q/ha+ *Azotobacter* at 8.6 kg/ha and T_4= Control. ALT x TRE - interaction of altitude and treatment.DAT: days after transplanting.

Values in columns with different lowercase letters indicate significant differences at $P < 0.05$, based on Duncan's multiple range test among treatments. Mean values within each column (between groups) were analyzed using an independent *t*-test, showing significant differences. A two-way ANOVA was conducted to assess the interaction between altitude and treatments, significance levels: *** $P \leq 0.001$; ** $P \leq 0.01$; * $P \leq 0.05$; NS = not significant.

Table 8. Comparative effect of location and treatments on leaf chlorophyll content (cci) of *Brassica* vegetables grown at HA *vs.* LA

ALT	TRE	Cabbage					Cauliflower					Radish		
		30 DAT	45 DAT	60 DAT	75 DAT	90 DAT	30 DAT	45 DAT	60 DAT	75 DAT	90 DAT	30 DAS	45 DAS	60 DAS
HA	T_1	27.42 ± 0.32^{b}	46.47 ± 1.61^{b***}	49.70 ± 1.47^{b***}	53.25 ± 1.08^{b***}	57.04 ± 0.85^{b***}	25.60 ± 1.33^{b}	42.70 ± 0.79^{b***}	44.51 ± 0.15^{b***}	47.39 ± 0.94^{b***}	53.48 ± 0.77^{b***}	32.31 ± 1.11^{b***}	42.13 ± 0.86^{b***}	42.9 ± 0.63^{b***}
	T_2	27.35 ± 0.63^{b}	47.05 ± 0.72b***	49.58 ± 1.30^{b***}	53.36 ± 0.95^{b***}	57.05 ± 0.37^{b***}	25.41 ± 1.23^{b}	42.93 ± 1.22^{b***}	44.35 ± 1.51^{b***}	47.12 ± 0.61^{b***}	53.53 ± 1.43^{b***}	33.08 ± 1.33^{b***}	42.37 ± 1.32^{b***}	42.79 ± 0.60^{b***}
	T_3	33.33 ± 1.16^{c}	55.69 ± 2.26^{c***}	56.16 ± 0.02^{c***}	61.63 ± 2.33^{c***}	64.53 ± 1.81^{c***}	32.26 ± 1.22^{c*}	49.18 ± 1.28^{c***}	50.42 ± 0.55^{c***}	53.15 ± 1.54^{c***}	59.27 ± 0.39^{c***}	36.23 ± 1.64^{c***}	49.31 ± 0.65^{c***}	49.72 ± 0.16^{c***}
	T_4	22.6 ± 1.04^{a}	38.73 ± 0.87^{a***}	43.06 ± 2.04^{a***}	47.71 ± 0.48^{a***}	49.69 ± 0.50^{a***}	21.25 ± 0.50^{b*}	38.47 ± 1.05^{a***}	38.99 ± 0.08^{a***}	41.16 ± 0.73^{a***}	44.84 ± 1.19^{a***}	27.28 ± 1.02^{a***}	36.23 ± 0.71^{a***}	36.49 ± 1.06^{a***}
LA	T_1	28.33 ± 0.47^{b}	34.36 ± 1.56^{b}	38.34 ± 0.67^{b}	41.79 ± 0.83^{b}	44.86 ± 0.84^{b}	26.78 ± 0.79^{b}	31.18 ± 0.21^{b}	35.14 ± 0.36^{b}	38.82 ± 1.09^{b}	41.79 ± 0.35^{b}	21.96 ± 0.18^{b}	25.62 ± 0.43^{b}	29.2 ± 0.42^{b}
	T_2	28.40 ± 0.72^{b}	33.47 ± 0.96b	38.58 ± 0.23^{b}	41.67 ± 0.64^{b}	44.59 ± 1.07^{b}	26.83 ± 0.71^{b}	31.12 ± 0.28^{b}	35.24 ± 0.37^{b}	39.02 ± 0.17^{b}	41.99 ± 1.27^{b}	21.11 ± 1.22^{b}	25.69 ± 0.54^{b}	28.43 ± 0.20^{b}
	T_3	32.86 ± 0.30^{c}	39.13 ± 0.74^{c}	42.22 ± 0.60^{c}	45.64 ± 0.53^{c}	50.21 ± 1.33^{c}	30.16 ± 0.48^{c}	35.94 ± 1.05^{c}	39.48 ± 0.88^{c}	43.66 ± 0.68^{c}	45.96 ± 0.36^{c}	24.59 ± 0.91^{c}	28.49 ± 0.75^{c}	32.83 ± 0.72^{c}
	T_4	24.58 ± 0.67^{a}	29.62 ± 0.37^{a}	31.39 ± 0.50^{a}	33.58 ± 0.49^{a}	36.51 ± 0.67^{a}	22.55 ± 0.06^{a}	27.27 ± 0.38^{a}	30.40 ± 0.63^{a}	32.99 ± 1.20^{a}	34.34 ± 0.18^{a}	17.69 ± 0.01^{a}	20.77 ± 0.65^{a}	24.58 ± 0.54^{a}
ALT		**	***	***	***	***	NS	***	***	***	***	***	***	***
TRE		***	***	***	***	***	***	***	***	***	***	***	***	***
ALT×TRE		NS	***	NS	**	NS	**	NS	NS	NS	NS	NS	***	***

HA- high altitude and LA- low altitude, Values presented as means ± SD, ALT: Altitude, TRE: Treatment, T_1= FYM at150q/ha, T_2= *Azotobacter* at 8.6 kg/ha, T_3= FYM at 150q/ha+ *Azotobacter* at 8.6 kg/ha and T_4= Control. ALT x TRE - interaction of altitude and treatment.DAT: days after transplanting, DAS: days after sowing.

Values in columns with different lowercase letters indicate significant differences at $P < 0.05$, based on Duncan's multiple range test among treatments. Mean values within each column (between groups) were analyzed using an independent *t*-test, showing significant differences. A two-way ANOVA was conducted to assess the interaction between altitude and treatments, significance levels: *** $P \leq 0.001$; ** $P \leq 0.01$; * $P \leq 0.05$; NS = not significant.

Table 9. Comparative effect of location and treatments on leaf anthocyanin content (aci) of *Brassica* vegetables grown at HA *vs.* LA

ALT	TRE	Cabbage					Cauliflower					Radish		
		30 DAT	45 DAT	60 DAT	75 DAT	90 DAT	30 DAT	45 DAT	60 DAT	75 DAT	90 DAT	30 DAS	45 DAS	60 DAS
HA	T_1	9.66 ± 0.15^{b***}	14.77 ± 0.67^{b***}	15.09 ± 0.28^{b***}	19.35 ± 0.45^{b***}	21.47 ± 0.51^{b***}	8.47 ± 0.23^{b***}	8.93 ± 0.47^{b}	11.41 ± 0.23^{b***}	12.81 ± 0.35^{b*}	14.63 ± 0.31^{b***}	9.07 ± 0.37^{b***}	12.63 ± 0.48^{a***}	13.55 ± 0.58^{b***}
	T_2	9.71 ± 0.24^{b***}	14.74 ± 0.42^{b***}	14.98 ± 0.27^{b***}	19.02 ± 0.23^{b***}	21.73 ± 0.44^{b***}	8.48 ± 0.14^{b***}	8.88 ± 0.52^{b}	11.25 ± 0.21^{b*}	12.76 ± 0.28^{b*}	14.54 ± 0.19^{b***}	9.78 ± 0.18^{c***}	12.63 ± 0.28^{a***}	13.41 ± 0.30^{b***}
	T_3	11.28 ± 0.20^{c***}	17.00 ± 0.21^{c***}	17.79 ± 0.22^{c***}	21.75 ± 0.48^{c***}	24.76 ± 0.36^{c***}	10.53 ± 0.15^{c***}	11.33 ± 0.11^{c***}	13.03 ± 0.37^{c*}	14.62 ± 0.35^{c**}	16.87 ± 0.22^{c***}	10.74 ± 0.28^{d***}	15.08 ± 0.52^{b***}	16.28 ± 0.15^{c***}
	T_4	9.25 ± 0.07^{a***}	11.59 ± 0.30^{a***}	12.00 ± 0.34^{a***}	14.22 ± 0.30^{a***}	15.29 ± 0.07^{a***}	6.71 ± 0.29^{a***}	8.09 ± 0.08^{a***}	10.13 ± 0.20^{a***}	11.59 ± 0.09^{a***}	13.06 ± 0.15^{a***}	7.58 ± 0.09^{a***}	11.84 ± 0.27^{a***}	11.95 ± 0.13^{a***}
LA	T_1	6.61 ± 0.26^{b}	9.12 ± 0.27^{b}	11.85 ± 0.41^{b}	13.32 ± 0.50^{b}	15.16 ± 0.35^{b}	6.43 ± 0.11^{b}	8.47 ± 0.24^{b}	10.70 ± 0.11^{b}	11.88 ± 0.22^{b}	12.78 ± 0.26^{b}	3.76 ± 0.08^{b}	4.43 ± 0.12^{b}	6.57 ± 0.06^{b}
	T_2	6.73 ± 0.05^{b}	9.41 ± 0.29^{b}	12.10 ± 0.58^{b}	13.52 ± 0.13^{b}	15.19 ± 0.40^{b}	6.31 ± 0.06^{b}	8.17 ± 0.47^{b}	10.34 ± 0.49^{b}	11.51 ± 0.44^{b}	12.37 ± 0.38^{b}	3.59 ± 0.19^{b}	4.43 ± 0.22^{b}	6.52 ± 0.23^{b}
	T_3	7.97 ± 0.17^{c}	10.92 ± 0.27^{c}	13.75 ± 0.40^{c}	15.51 ± 0.25^{c}	17.54 ± 0.16^{c}	7.89 ± 0.18^{c}	10.35 ± 0.11^{c}	12.04 ± 0.14^{c}	13.39 ± 0.22^{c}	14.36 ± 0.34^{c}	4.49 ± 0.14^{c}	5.58 ± 0.06^{c}	7.75 ± 0.10^{c}
	T_4	5.26 ± 0.05^{a}	7.29 ± 0.14^{a}	9.98 ± 0.11^{a}	10.98 ± 0.05^{a}	12.23 ± 0.17^{a}	3.87 ± 0.18^{a}	5.51 ± 0.18^{a}	7.19 ± 0.24^{a}	8.98 ± 0.26^{a}	10.10 ± 0.18^{a}	2.71 ± 0.06^{a}	3.36 ± 0.05^{a}	4.47 ± 0.08^{a}
ALT		***	***	***	***	***	***	***	***	***	***	***	***	***
TRE		***	***	***	***	***	***	***	***	***	***	***	***	***
ALT×TRE		***	**	***	***	***	**	***	***	***	*	***	**	***

HA- high altitude and LA- low altitude, Values presented as means ± SD, ALT: Altitude, TRE: Treatment, T_1= FYM at 150q/ha, T_2= *Azotobacter* at 8.6 kg/ha, T_3= FYM at 150 q/ha+ *Azotobacter* at 8.6 kg/ha and T_4= Control. ALT x TRE - interaction of altitude and treatment.DAT: days after transplanting, DAS: days after sowing.

Values in columns with different lowercase letters indicate significant differences at $P < 0.05$, based on Duncan's multiple range test among treatments. Mean values within each column (between groups) were analyzed using an independent *t*-test, showing significant differences. A two-way ANOVA was conducted to assess the interaction between altitude and treatments, significance levels: *** $P \leq 0.001$; ** $P \leq 0.01$; * $P \leq 0.05$; NS = not significant.

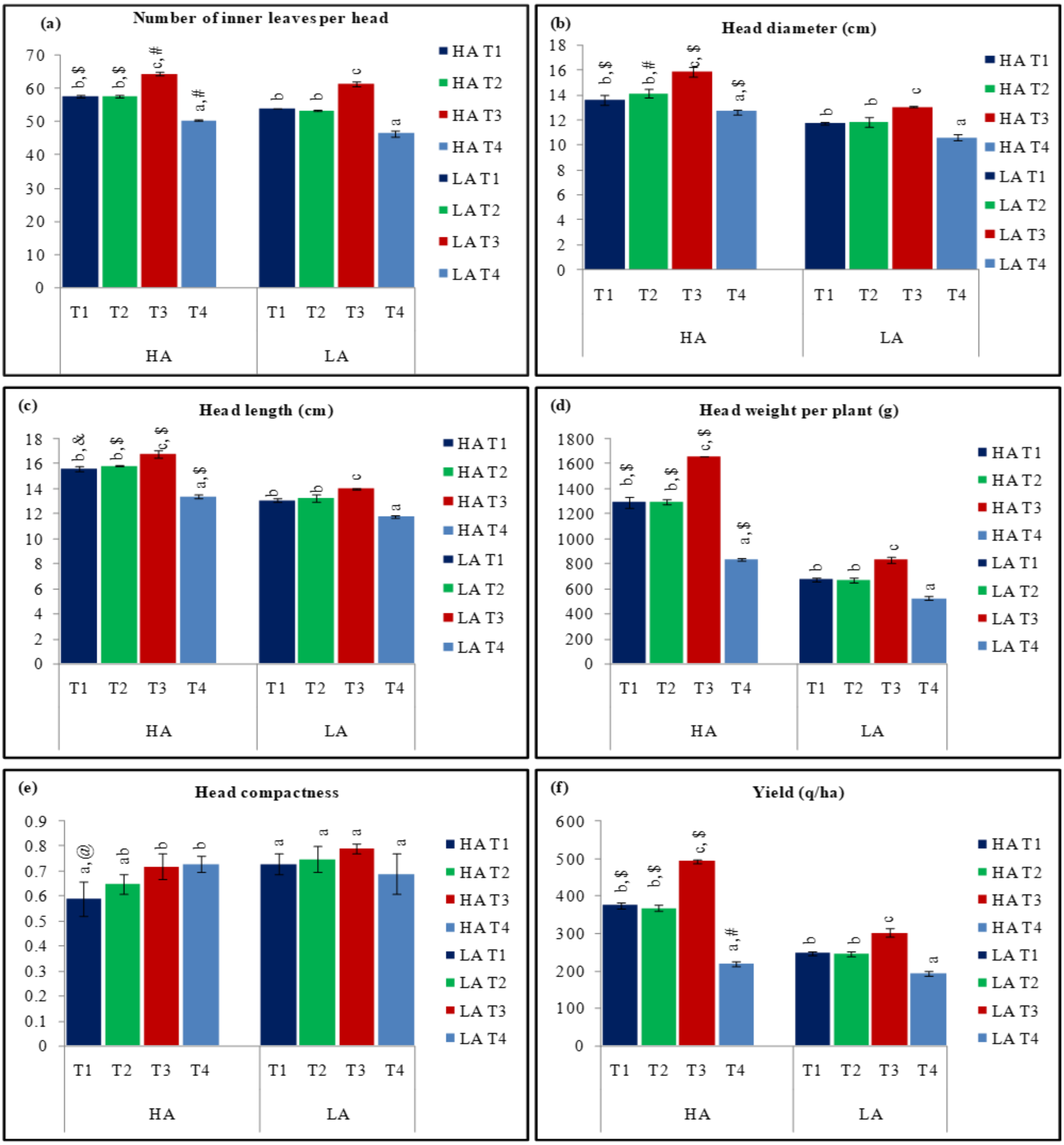

Fig. 3. Effect of altitudes and treatments on: (a) number of inner leaves per head, (b) head diameter, (c) head length, (d) head weight per plant, (e) head compactness (f) yield. Data presented as mean (± SD) over replicates. Different lowercase letters indicate significant differences among treatments at $P < 0.05$, as determined by Duncan's multiple range test. Statistically different between high and low altitude treatments consider at $ $p \leq 0.001$; # $p \leq 0.01$ and at $p \leq 0.05$ analyzed by independent t test. HA = High altitude and LA = Low altitude. T_1= FYM at 150 q/ha, T_2= *Azotobacter* at 8.6 kg/ha, T_3= FYM at 150 q/ha+ *Azotobacter* at 8.6 kg/ha and T_4= Control.

The current study showed that the treatment T_3 enhanced the head/curd yield in comparison to the control at both locations. This could be attributed to the influence of organic manure (FYM), which enhances soil biological activity and facilitates nutrient mobilization from applied sources. The increase in yield and related attributes due to *Azotobacter* inoculation could be attributed to enhanced nitrogen fixation, which promoted vegetative growth and improved overall yield characteristics of cabbage and cauliflower. These outcomes are consistent with the earlier findings of (19, 20, 31).

Furthermore, the maximum number of inner leaves in cabbage head (64.55 ± 0.48) was found at HA than at LA (61.33 ± 0.73). Head compactness was higher at HA in the treatment T_1 (cabbage) and T_4 (cauliflower). According to a study, head compactness of head or curd depends on the ratio of head or curd volume and weight. In both cabbage and cauliflower, the maximum head/curd diameter, length, weight per plant and total yield were observed at HA, while the lowest values were recorded at LA. In a two-factor study, the impact of altitude and treatment (ALT×TRE) was examined on head/curd weight, compactness rate and yield were also found significantly

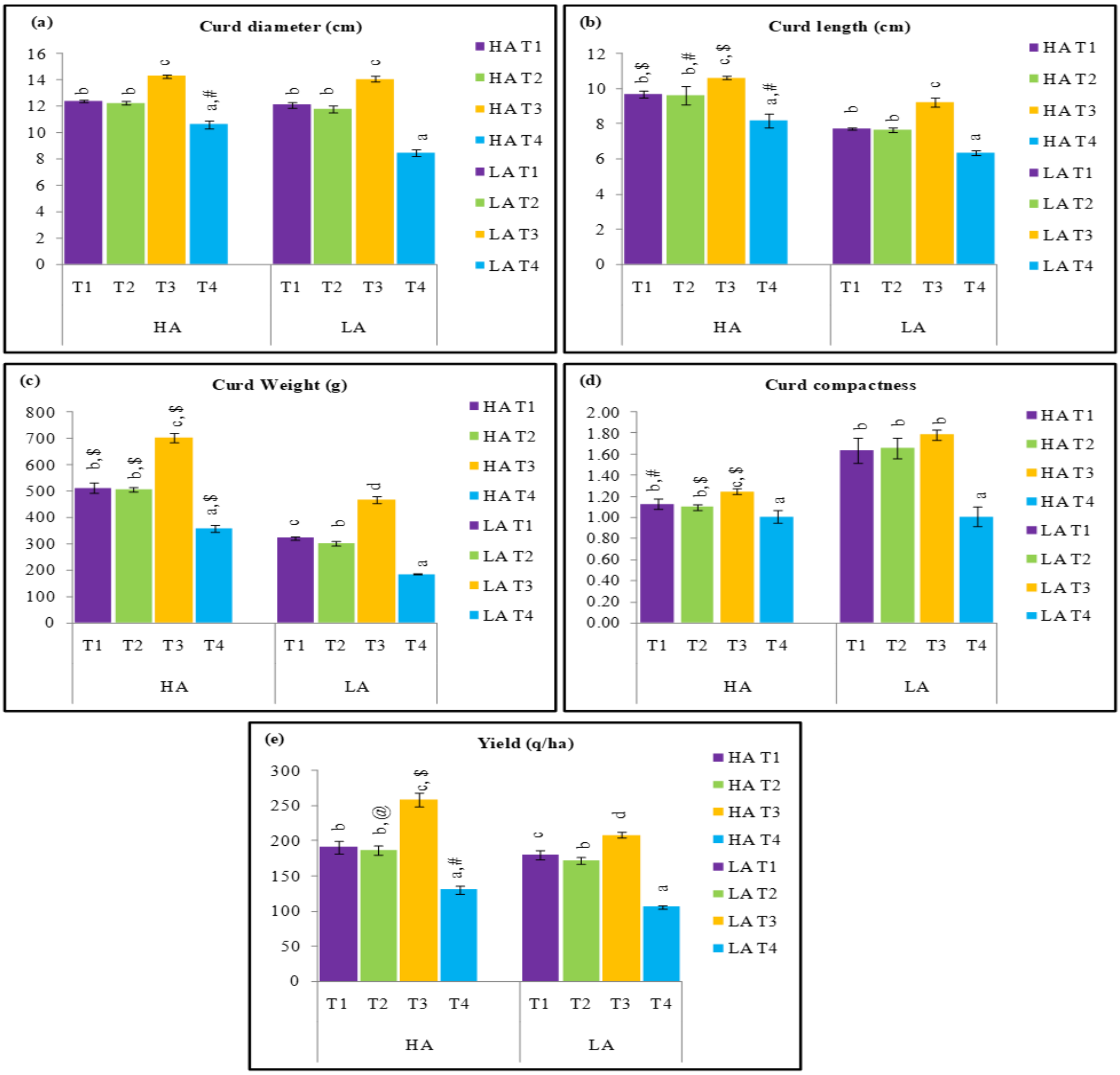

Fig. 4. Effect of altitudes and treatments on: (a) curd diameter, (b) curd length, (c) curd weight per plant, (d) curd compactness (e) yield. Data presented as mean (± SD) over replicates. Different lowercase letters indicate significant differences among treatments at $P < 0.05$, as determined by Duncan's multiple range test. Statistically different between high and low altitude treatments consider at \$ $p \leq 0.001$; # $p \leq 0.01$ and at $p \leq 0.05$ analyzed by independent t test. HA= High altitude and LA= Low altitude. T_1= FYM at 150 q/ha, T_2= *Azotobacter* at 8.6 kg/ha, T_3= FYM at 150 q/ha+ *Azotobacter* at 8.6 kg/ha and T_4= Control.

higher (Table S1). Recent studies have demonstrated that longer photoperiod and improved photosynthesis can increase agricultural output at high altitude (28). Additionally, high head/curd yield and better physical properties of cabbage and cauliflower this could also be attributed to enhanced plant growth parameters at high altitude, which likely improved the photosynthetic rate and the assimilation of biosynthetic products into storage tissues such as the cabbage head, ultimately leading to superior physical attributes of cabbage and cauliflower head at HA compared with those grown at LA experimental field (34, 35).

Effect on yield parameters of radish

The yield attributes of radish, including root diameter, root length, root weight and total yield, showed statistically significant difference (*p ≤ 0.05*) among treatments at both locations (Fig. 5). At both locations, the T_3 (a combination of FYM and *Azotobacter*) produced the best results compared to other treatments. The increased root yield with FYM and Azotobacter could be attributed to improved nutrient availability and nitrogen fixation, which enhanced plant growth and dry matter production. These factors subsequently enhanced root diameter, length and weight, which in turn improved root yield. Our result is consistent with (36, 37).

Furthermore, radish grown at HA exhibited the highest root diameter (35.24 ± 0.79 mm), root weight per plant (200.20 ± 6.41 g) and total yield (390.64 ± 4.65 q/ha) compared to those grown at LA. No significant difference was observed in root length at both locations. In a two-factor study, the impact of altitude and treatment were found to have a significantly higher (*p ≤ 0.05*) on root weight (Table S1). The increased root diameter, root weight and root yield at HA may be attributed to

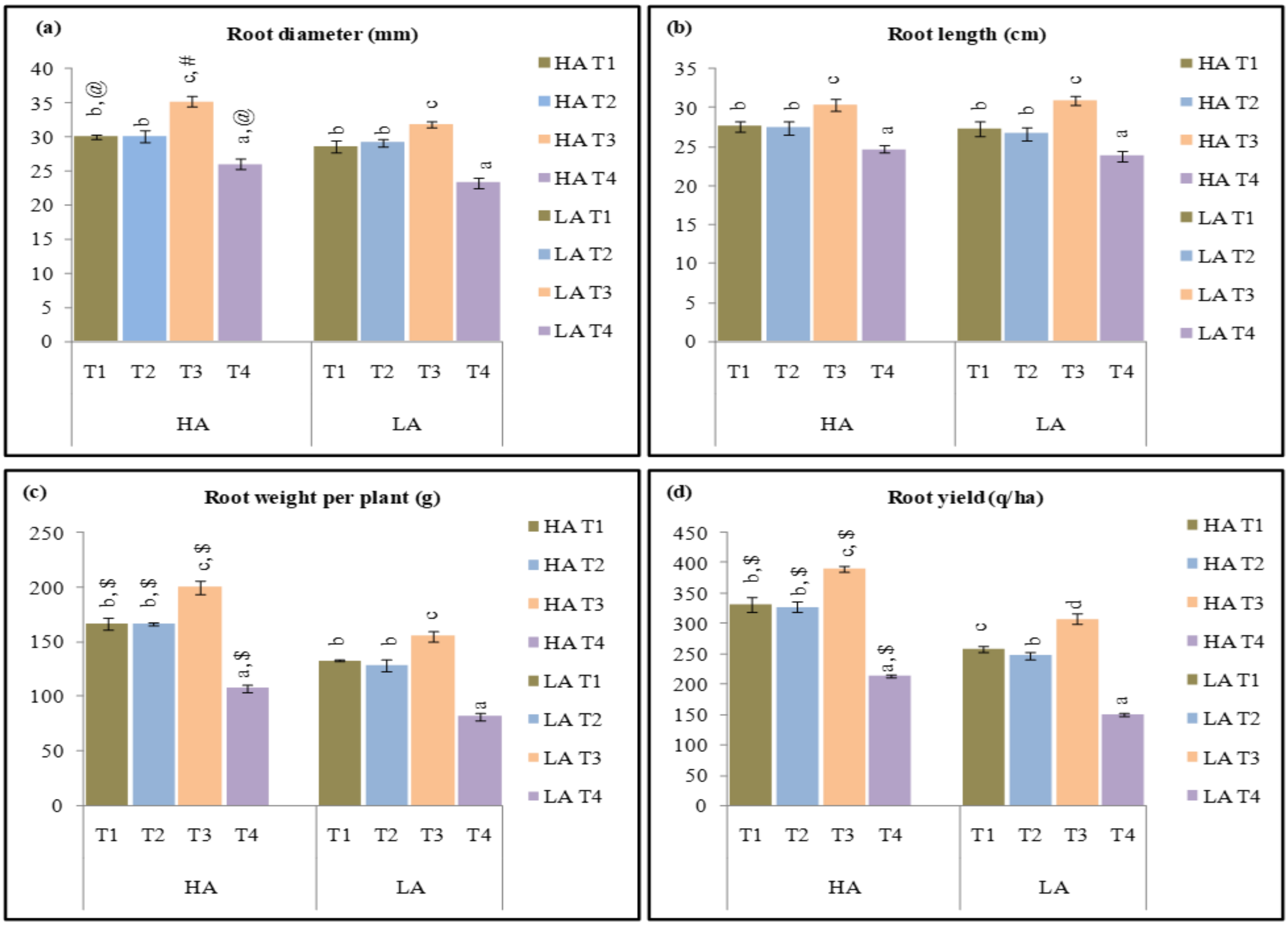

Fig. 5. Effect of altitudes and treatments on: (a) root diameter, (b) root length, (c) root weight per plant, (d) yield. Data presented as mean (± SD) over replicates. Different lowercase letters indicate significant differences among treatments at $P < 0.05$, as determined by Duncan's multiple range test. Statistically different between high and low altitude treatments consider at $\$\ p \leq 0.001$; # $p \leq 0.01$ and at $p \leq 0.05$ analyzed by independent t test. HA = High altitude and LA = Low altitude. T_1= FYM at 150 q/ha, T_2= *Azotobacter* at 8.6 kg/ha, T_3= FYM at 150 q/ha+ *Azotobacter* at 8.6 kg/ha and T_4= Control.

lower soil bulk density and improved soil porosity and water retention, facilitated by the application of organic manure. Another contributing factor may be the presence of *Azotobacter*, which could enhance the solubilization of plant nutrients, particularly at higher altitudes. This, in turn, may lead to greater uptake of NPK from the soil, ultimately resulting in increased yield. Our results are in good agreement with previous study (36).

Biofertilizers are being actively explored as a sustainable alternative to minimize chemical fertilizer use, offering environmentally friendly and safe solutions. The present study demonstrates that under the challenging environmental conditions of high-altitude regions, the application of FYM and *Azotobacter* significantly improved the growth and yield performance of cruciferous vegetables, including cabbage, cauliflower and radish across different growth stages. At 90 DAT and 60 DAS, our results confirm the positive influence of *Azotobacter* at high altitudes, enhancing key morphological attributes such as plant height, leaf area, plant spread, chlorophyll content and anthocyanin accumulation. In addition, HA-grown Brassicaceae vegetables were found to have higher head/curd/root diameter, head/ curd/root weight per plant and increased crop yields, in comparison to LA-grown Brassicaceae vegetables. Based on the findings of this study, we recommend that growers use combination of organic manure and biofertilizers to enhance the productivity of Brassicaceae vegetables at high altitudes. This approach can help local farmers maximize their benefits by producing high-quality crops and potentially increasing their income, despite the challenging environmental conditions at higher altitude.

Conclusion

Biofertilizers are being actively explored as a sustainable alternative to minimize chemical fertilizer use, offering environmentally friendly and safe solutions. The present study demonstrates that under the challenging environmental conditions of high-altitude regions, the application of FYM and *Azotobacter* significantly improved the growth and yield performance of cruciferous vegetables, including cabbage, cauliflower and radish across different growth stages. At 90 DAT and 60 DAS, our results confirm the positive influence of *Azotobacter* at high altitudes, enhancing key morphological attributes such as plant height, leaf area, plant spread, chlorophyll content and anthocyanin accumulation. In addition, HA-grown Brassicaceae vegetables were found to have higher head/curd/root diameter, head/curd/root weight per plant and increased crop yields, in comparison to LA-grown Brassicaceae vegetables. Based on the findings of this study, we recommend that growers use combination of organic manure and biofertilizers to enhance the productivity of Brassicaceae vegetables at high altitudes. This approach can help local farmers maximize their benefits by producing high-quality crops and potentially increasing their income, despite the challenging environmental conditions at higher altitude.

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Authors' contributions

SS prepared the original draft preparation and conducted the experiments. MR supervised the work and edited the manuscript. NK contributed to the methodology, experimentation and data analysis. AV and MKP assisted in sample collection. SP and MK contributed to the methodology and edited the manuscript. SS also conceptualized the study, provided overall supervision, guidance and was involved in manuscript correction and editing. All authors have seen the draft copy and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: There is no conflict of interest among the authors.

Ethical issues: None

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