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Optimizing Nitrogen Fertilization and Plant Spacing for Higher Broccoli (*Brassica oleracea* L. var. *italica*) Yield and Quality in Semi-Arid Conditions

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Abstract: Broccoli (*Brassica oleracea* L. var. *italica*) is an emerging high-value vegetable in Pakistan, due to its nutritional and medicinal importance. However, optimized production practices, including recommendations for nitrogen (N) fertilization and plant spacing, for semi-arid subtropical conditions remain limited. A study was conducted to investigate the effects of N doses (0, 125, 250, 375, 500 kg N ha^{-1}) and plant spacings (60×30, 60×45, 75×45 cm) on growth, yield and quality of broccoli cv. Marathon Field experiments were conducted over two consecutive years (2021-2022 and 2022-2023) at the Institute of Horticultural Sciences, University of Agriculture, Faisalabad, Pakistan, using a randomized complete block design (RCBD), with four replications. Results revealed that 250 kg N ha^{-1} significantly enhanced chlorophyll contents, leaf number, stem diameter, curd diameter, secondary curds yield and quality attributed [TA(titratable acidity), TSS (total soluble salts) and vitamin C]. While 500 kg N ha^{-1} maximized leaf area, plant fresh biomass (PFB), plant dry biomass (PDB), curd fresh weight (CFW), curd dry weight (CDW) and primary curd yield. Among plant spacing treatments, 60×45 cm optimized chlorophyll content, number of leaves, leaf area, PFB, PDB, curd diameter, CFW, CDW, yield of primary curds, TSS and TA. Whereas 75×45 cm maximum stem diameter, number and yield of secondary curds, and vitamin C content. Overall, moderate nitrogen application (250 kg N ha^{-1}) combined with 75×45 cm spacing provides a balanced strategy for improving yield and quality. For cultivars producing secondary curds, 75×45 cm spacing with 250 kg N ha^{-1} is recommended for higher yields and good quality curds under semi-arid conditions.

Keywords: Broccoli nitrogen fertilization, broccoli yield optimization, curd yield and quality, plant population density, nitrogen use efficiency, sustainable fertilization.

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1. Introduction

Broccoli (*Brassica oleracea* var. *italica*) is an Italian vegetable that is a rich source of minerals (Ca, K, Fe), vitamins (A, C, K), dietary fiber, antioxidants, polyphenols, and glucosinolates (Andrés et al., 2025; Bussler et al., 2025). It strengthens the human immune system and plays a critical role in preventing cardiac and cancerous diseases (Syed et al., 2023). Its use as a salad is considered excellent for weight loss due to its low-calorie and high fiber content. This vegetable is valued for its large sized head that is used as raw (salad purpose) or cooked (steamed, fried, roasted) (Nagraj et al., 2020). Usually, varieties produce a single head, also termed as the primary head. But, some varieties also produce secondary heads, which increase the yield (Mansour et al., 2023; Shi et al., 2024). According to

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FAO, China and India are the leading producers of broccoli. Broccoli is cultivated on a limited area in Pakistan; during 2023-24, it was cultivated on 1718 ha, producing 22109 tonnes with an average yield of 12.87 tonnes ha^{-1} (FAOSTAT, 2024).

Broccoli, a rich source of minerals and vitamins, is increasingly recognized in Pakistan as a functional food due to its multiple health benefits. However, its production faces several constraints. From a consumption perspective, awareness of broccoli remains low among the general population; only health-conscious people know about it. From a production point of view, only 40% of farmers involved in cultivation of high-value vegetable and medicinal crops are aware of this crop. Among the broccoli growers, one-third of the community is rarely familiar with its varieties (Shakeel et al., 2020). Inadequate awareness about crop-specific production technology is another major constraint. This can be attributed to limited research work about the broccoli production technology, as broccoli growers generally follow cultural practices recommended for cauliflower production (Shakeel et al., 2020).

Umar and Ayub (2024) studied the impact of irrigation levels and timings on broccoli yield grown in Peshawar and recommended that broccoli crop should be irrigated in the morning when 35% of the available water has been depleted. Latif et al. (2019) evaluated the response of two varieties (Galabrease and Rocco F1) to five planting dates and recommended the first week of October as the best planting time for both varieties in Dera Ismail Khan. However, many aspects of production are rarely studied, particularly the fertilizer requirements.

Among plant nutrients, nitrogen (N) is a widely used fertilizer in intensive cropping systems, mainly attributed to its role in plant biomass production. However, its judicious application is crucial, as excessive N use has both economic and environmental consequences (Aziz et al., 2022), and can also deteriorate crop nutritional quality, including lower concentration of vitamin C (Albornoz, 2016).

Optimal crop N requirement is regulated by soil inherent nutritional status, soil type and its properties, cropping system, crop growth stage, irrigation method and several other factors (Ata-Ul-Karim et al., 2017; Bi et al., 2013; Govindasamy et al., 2023). Therefore, scientists have optimized nitrogenous fertilizer for broccoli cultivation in different regions of the world (Ferreira et al., 2023; Kim et al., 2021; Vieira et al., 2025).

Broccoli is sensitive to high N application rates; incidence of hollow stem increases at higher N rates, particularly when applied five weeks after transplanting (Frieman et al., 2026; Kim et al., 2021). Recommended N dose is reportedly around 400 to 600 kg N ha^{-1} to obtain an early broccoli crop and a higher yield. Preplant application of N produced better results than split application. However, Yoldas et al. (2008) obtained the highest broccoli yield by applying 300 kg N ha^{-1}.

Plant spacing is also an important agronomic practice to achieve high yield. An optimum number of plants per unit area contributes and assists plants in using available resources and inputs properly. It is very effective to achieve a high yield of good quality and uniform maturity in broccoli. Change in plant spacing per unit area gives a potential regulated size of curds and also affects several other quality parameters of broccoli (Madhumathi et al., 2017; Tuhin et al., 2025).

Plant spacing varies with soil conditions, climate and cultivar requirements. Generally, wider spacing results in vigorous vegetative growth primarily due to reduced competition for light, moisture and nutrients (Bairwa et al., 2017). Contrarily, closer spacing improves soil coverage, which not only protects soil but also suppresses weeds, enhances fertilizer use efficiency and can increase yield (Neto et al., 2016).

Plant spacing is therefore a critical determinant of yield of Cole crops (Tuhin et al., 2025). The size of the curd is an important marketing characteristic in broccoli and plant population density is one of the main factors affecting the curd size and broccoli quality traits. Competition between broccoli plants not only influences the curd size and overall plant growth but also affects other quality characteristics (Azam et al., 2020; Hasan et al., 2024).

Despite the increasing popularity of broccoli in Pakistan, farmers largely rely on production practices developed for cauliflower (Shakeel et al., 2020). Previous studies in Pakistan have addressed specific aspects such as irrigation management (Umar and Ayub, 2024), planting time (Latif et al., 2019), and foliar application of biostimulants (Iqbal et al., 2023a); however, the combined effects of plant spacing and N nutrition remain insufficiently explored. Therefore, the present study was conducted to determine the optimal N dose and plant spacing for improving growth, curd yield, and quality of broccoli cv. Marathon.

Table 1. Monthly mean Metrological data of experimental site during 2022–23 and 2023–24

Year / Month	Average Daily Air Temperature (°C)			R.H	Rainfall	Sunshine	Wind speed
	Maximum (Tmax)	**Minimum (Tmin)**	**Mean (Tmean)**		**(mm)**	**(h)**	**(km h^{-1})**
October (**2023-24**)	34.5	19.2	26.9	72.7	15.5	8.92	1.97
November	28.3	9.0	20.0	81.3	6.8	7.5	1.1
December	21.0	7.2	14.1	83.8	6.1	5.9	3.2
January	17.8	8.1	13.0	88.5	48.4	8.75	1.5
February	23.9	8.6	16.3	82.9	10.2	7.6	1.7
October (**2023-24**)	32.7	18.1	25.4	73.4	30.7	8.1	3.8
November	27.2	13.8	20.5	68.6	3.8	5.4	1.1
December	23.0	7.2	15.1	70.1	0	6.0	1.3
January	17.2	5.4	11.3	85.0	31.2	5.3	1.6
February	26	10.5	18.3	72.0	14.3	7.4	1.6

Source: **AgroMet Observatory, Department of Agronomy, University of Agriculture, Faisalabad, Pakistan**

2. Materials and Methods

2.1. Experimental Site, Design and Crop Management

Broccoli cv. Marathon (SAKATA) seeds were obtained from a local supplier (Gujranwala, Pakistan). Seedlings were raised in plug trays using UAF Gro soilless media (Rasool et al., 2024) and transplanted (35 days after sowing, on one side of ridges) at the research field of Institute of Horticultural Sciences, University of Agriculture, Faisalabad (31.4336 °N, 73.0683 °E, 186 m a.s.l), Pakistan, on November 22, 2022 and November 21, 2023. Weather data and pre-sowing soil analysis are presented in Table 1, and Table 2.

Two independent experiments were conducted in a randomized complete block design (RCBD) with four replications, without testing N × spacing interaction. In Exp-1, five N levels (0, 125, 250, 375, 500 kg N ha^{-1}) were evaluated at 75×30 cm plant spacing. In Exp-2 three plant spacing treatments (60×30, 60×45, 75×45 cm) were tested at 375 kg N ha^{-1}. Irrigation and recommended pest and disease management were carried out to minimize plant stress.

2.2. Data Collection and Biochemical Analysis

From each replication of every treatment, five plants were randomly selected. Plant height was measured from the base (soil level) to the top of the apical leaf of the plant with the help of a measuring tape. Number of leaves on the main axis (later referred to as primary leaves) and lateral shoots (secondary leaves) per plant were counted. Primary leaves of the selected plants were scanned using a portable leaf area meter to calculate the leaf area per plant. The chlorophyll content index of two healthy leaves from the primary/main axis of each selected plant was determined with the help of a SPAD chlorophyll meter. Plants were uprooted after harvesting curds and excised into shoots and roots with the help of a sickle to measure the fresh weight of the plant by using a digital weighing balance. Stem diameter was recorded with the help of digital Vernier caliper. After harvesting the primary (main) curd, the diameter was measured and weight was noted. The shoots arising from the leaf axils developed secondary curds; number and yield of secondary curds were also recorded.

Total soluble solids (TSS) of broccoli juice were measured using a digital refractometer (ATAGO RS-5000, Japan), calibrated with distilled water. Titratable acidity (TA) was determined by titrating fresh curd juice (10 ml) against 0.1 N NaOH using phenolphthalein as an indicator. Ascorbic acid content was quantified by titrating a filtered aliquot (5 ml) of juice, prepared in 0.4% oxalic acid, against 2,6-dichloroindophenol dye.

2.3. Statistical Analysis

Statistix8.1® software (Analytical Software, Tallahassee, USA) was used to analyze data using the Analysis of Variance (ANOVA) technique, whereas significant differences among treatment means were compared by Tukey's test at 5% probability level (Steel et al., 1997).

Table 2. Soil analysis report of the experimental site

Trait	2022-23	2023-24
Texture	Sandy loam	Sandy loam
pH	7.9	8.0
EC (dSm^{-1})	1.70	1.81
Organic matter (%)	0.59	0.67
Total Nitrogen (%)	0.051	0.059
Available Phosphorus (mg kg^{-1})	27	30
Potassium (mg kg^{-1})	226	253

Table 3. Effect of different nitrogen doses on vegetative growth parameters of broccoli

Nitrogen Level (kg N ha^{-1})	Plant height (cm)		Chlorophyll content (CCI)		Number of leaves Plant^{-1}		Leaf area (cm^2)		Plant fresh biomass (g)		Plant dry biomass (g)		Stem diameter (mm)	
Years	**2022-23**	**2023-24**	**2022-23**	**2023-24**	**2022-23**	**2023-24**	**2022-23**	**2023-24**	**2022-23**	**2023-24**	**2022-23**	**2023-24**	**2022-23**	**2023-24**
T1 (control)	51.25 b	49.11 b	80.4 a	80.29 b	57.51 c	61.25 ab	225.6 c	231.7 c	1177 ab	1138 ab	161 ab	130.3 c	32.27 ab	31.75 a
T2 (125)	52.13 ab	52.13 ab	81.1 a	80.21 b	79.75 ab	69.75 ab	226.9 c	251.3 ab	1111 b	1044 b	149 c	137.5 b	30.96 b	31.12 a
T3 (250)	53.31 a	53.65 a	82.5 a	83.41 a	83.75 a	77.75 a	243.5 bc	250.4 ab	1269 ab	1183 ab	182 ab	158.5 ab	32.52 a	32.79 a
T4 (375)	52.1 ab	52.25 ab	83.5 a	80.61 b	69.75 b	66.25 ab	281.0 ab	232.2 b	1290 ab	1236 ab	153 bc	150.4 bc	31.45 ab	30.75 a
T5 (500)	51.5 ab	52.81 ab	81.3 a	79.47 b	62.05 bc	54.75 b	294.2 a	259.1 a	1483 a	1305 a	190 a	187.1 a	32.05 ab	32.24 a
LSD value (P>0.05)	5.43	3.69	6.66	2.75	39.91	19.70	49.61	53.7	320.3	426.1	36.25	45.36	1.39	3.65

Means followed by the same letter(s) within a column do not differ significantly at $P \leq 0.05$.

Table 4. Effect of different nitrogen doses on reproductive growth parameters of broccoli

Nitrogen Level (kg N ha^{-1})	Curd diameter (mm)		Curd fresh weight (g)		Curd dry weight (g)		Yield of primary curds (g) per plot (130 ft²)		No. of secondary curds		Yield of secondary curds (g)	
Years	**2022-23**	**2023-24**	**2022-23**	**2023-24**	**2022-23**	**2023-24**	**2022-23**	**2023-24**	**2022-23**	**2023-24**	**2022-23**	**2023-24**
T1 (control)	109.92 b	114.72 ab	180.54 c	172.65 b	18.15 b	18.29 ab	7659.5 b	7969.1 b	6.91b	6.66 b	8114.3 b	8004 b
T2 (125)	111.7 ab	112.11 ab	185.93 c	177.17 b	18.49 ab	18.16 ab	8827.1 ab	8812.6 ab	7.25 ab	6.99 ab	11146 ab	11190 ab
T3 (250)	115.2 a	116.29 a	199.01 ab	207.53 ab	20.05 ab	19.55 a	9188.5 ab	9188.3 ab	8.41a	7.58 a	12094.6 a	13080 a
T4 (375)	113.32 ab	109.4 ab	194.15 abc	176.13 b	19.25 ab	17.22 b	8958.1 ab	8980.9 ab	7.08 ab	6.83 ab	11430.2 ab	12020 ab
T5 (500)	114.08 a	114.12 ab	206.45 a	252.31 a	20.67 a	19.91 a	9769.5 a	9977.6 a	6.91b	6.51 b	8138.4 b	8200 b
LSD value (P>0.05)	3.68	5.98	14.83	64.67	3.68	218	1647.2	1487.5	1.36	1.59	4052	2772

Means followed by the same letter(s) within a column do not differ significantly at $P \leq 0.05$.

Table 5. Effect of different nitrogen doses on biochemical properties of broccoli

Nitrogen Level (kg N ha^{-1})	Total Soluble Salts (TSS) (°Brix)		Titratable Acidity (TA) (%)		Ascorbic acid (mg 100g^{-1})	
	2022-23	**2023-24**	**2022-23**	**2023-24**	**2022-23**	**2023-24**
T1 (control)	4.9 a	4.75 b	0.40 ab	0.41 ab	28.92 ab	28.92 ab
T2 (125)	5.25 a	4.91 ab	0.35 b	0.38 b	34.43 a	34.45 a
T3 (250)	5.67 a	5.67 a	0.53 a	0.55 a	35.81 a	35.85 a
T4 (375)	5.37 a	5.37 ab	0.40 ab	0.42 ab	23.41 b	23.37 b
T5 (500)	5.32 a	5.32 ab	0.45 ab	0.43 ab	23.96 b	23.92 b
LSD value (P>0.05)	0.89	0.92	0.09	0.1	9.63	9.78

Means followed by the same letter(s) within a column do not differ significantly at $P \leqslant 0.05$

3. Results

3.1. Experiment 1

3.1.1. Vegetative Growth Attributes in Response to Nitrogen: The application of N showed significant effect on the vegetative parameters of broccoli. Maximum plant height, chlorophyll contents, and number of leaves was achieved in T3 (250 kg N ha^{-1}) during both years of the trial (Table 3). However, highest value for leaf area (294.2 cm^2, 259.11 cm^2), plant fresh biomass (1482.8 g, 1305.1 g) and plant dry biomass (190.3 g, 187.1 g) was recorded from T5 (500 kg N ha^{-1}) during both years, but was statistically similar to T3 (250 kg N ha^{-1}) for these traits, except for leaf area during 1st year. Contrarily, the lowest values for leaf area, plant fresh biomass and dry biomass were noted from T1 (control) (Table 3).

3.1.2. Yield and Related Attributes in Response to Nitrogen Levels: The application of nitrogen significantly improved almost all yield related parameters of broccoli. Maximum diameter of curd (115.2mm, 116.2mm) was attained in T3 (250 kg N ha^{-1}) in both years. Contrarily, the lowest value was recorded from T1 (control). Mean fresh and dry weight of the broccoli curds was increased with increasing the dose of nitrogen fertilizer; maximum from the highest dose T5 (500 kg N ha^{-1}), while the lowest value was noted from T1 (control). Average yield of primary curds was highest (9769.5 g, 9977.6 g 12.1 m^{-2}) from the T5 (500 kg N ha^{-1}) during both years. However, number of secondary curds and their yield was lowest for T5 (500 kg N ha^{-1}), even lower than control although both were statistically similar. Highest value for number of secondary curds (8.41, 7.58) and yield (12094.6 g, 13080 g 12.1 m^{-2}) was observed for T3 (250 kg N ha^{-1}) during both years (Table 4).

3.1.3. Effect of Nitrogen on Biochemical parameters: The application of N also affected the biochemical properties of broccoli. The highest values for TSS, TA and vit. C were noted from the T3 (250 kg N ha^{-1}); being 86.4% and 83.8% higher TSS, 75.5% and 74.5% higher TA, and 80.8% and 80.8% higher vit. C than control during both years. The lowest values for TSS, TA and vit. C were noted from T1 (control), T2 (125 kg N ha^{-1}) and T5 (500 N kg N ha^{-1}) respectively (Table 5).

3.2. Experiment 2

3.2.1. Effect of Plant Spacing on Vegetative Traits

Different plant spacings significantly affected the vegetative growth parameters of broccoli. Maximum plant height was demonstrated in T3 (75×45 cm) during both years of trial, but it was statistically at par with T1 (60×30 cm). However, chlorophyll contents, number of leaves and leaf area of broccoli were significantly higher for T2 (60×45 cm). Maximum value for plant fresh (1734.8 g, 1825.1 g) and dry biomass (166.1 g, 168.4 g) was recorded for T2 (60×45 cm), consistent across experimental years. The lowest values for leaf area, plant fresh and dry biomass were noted from T1 (60×30 cm). Stem diameter of broccoli was increased with increasing the plants spacing; maximum value was noted from the 75×45 plant spacing in across the experimental years (34.16 mm, 33.55 mm) (Table 6).

Different plant spacings significantly impacted on almost all reproductive parameters of broccoli. Maximum curd diameter (125.3mm, 125.6mm) was observed in T2 (60×45 cm) in both years trial, but was statistically similar to T3 (75×45 cm) in both years and with T1 (60×30 cm) during first year. Highest fresh (239.7, 235.9 g) and dry (22.81, 25.30 g) weight of broccoli curds was recorded from T2 (60×45 cm), while the lowest curd fresh and dry weight was attained from T3 (75×45 cm). Yield of primary curds was highest (1750.7 g, 1870.7g) from T2 during both years followed by T1 and the lowest value was noted from T3. Number of secondary curds (6.88, 6.51) and their yield (2648.1, 2648.3 g) was highest for T3 (75×45 cm), while the lowest value was recorded from T1 (60×30 cm) during both years (Table 7).

3.2.2. Yield and Related Attributes of Broccoli in Response to Different Plant Spacings: Different plant spacings significantly affected the biochemical properties of broccoli. The highest values for TSS (5.56, 5.56 °Brix) and TA (0.57%, 0.44%) were achieved under treatment T2 (60×45 cm plant spacing) followed by T3 (75×45 cm). Highest vitamin C (35.76, 36.76 mg 100g^{-1}) was noted from T3 (75×45 cm) followed by (60×45 cm). The lowest values for TSS, TA and vitamin C were noted from T1 (60×30 cm) (Table 8).

4. Discussion

4.1 Effect of Nitrogen Rates

Intensive cropping systems prevailing around the globe demand more fertilizers to produce higher yield; nitrogenous fertilizers are on the top. Nitrogen is the basic building block for amino and nucleic acid. However, its sensible use is necessary because excessive use may not only reduce the profitability but also contributes to soil and water pollution (Aziz et al., 2022).

Table 6. Vegetative growth response of broccoli to different plant spacings

Plant spacing	Plant height (cm)		Chlorophyll content (CCI)		Number of leaves		Leaf area (cm^2)		Plant fresh biomass (PFB, g)		Plant dry biomass (PDB, g)	
Years	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
T1 (60×30 cm)	49.7 ab	48.5 ab	81.73 a	77.6 b	53.66 c	50.33 c	218.0 c	250.3 c	1351.7 b	1046.3 a	125.8 b	135.4 b
T2 (60×45 cm)	48.5 b	44.3 b	83.8 a	83.0 a	78.23 a	76.01 a	271.6 a	296.0 a	1734.0 a	1825.1 a	166.1 a	168.4 a
T3 (75×45 cm)	50.5 a	48.9 a	81.03 a	79.0 b	67.01 b	73.30 b	258.4 b	273.3 b	1561.7 ab	1600.7 a	147.4 ab	157.4 ab
LSD value (P>0.05)	4.5	7.63	8.75	2.64	54.2	21.71	164.5	27	364.8	807.5	25.81	13.31

Means followed by the same letter(s) within a column do not differ significantly at P ≤ 0.05.

Table 7. Effect of different plant spacings on reproductive growth parameters of broccoli

Plant spacing	Stem diameter (mm)		Curd diameter (mm)		Curd fresh weight (g)		Curd dry weight (g)		Yield of primary curds (g)		No. of secondary curds		Yield of secondary curds (g)	
Years	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
T1 (60×30 cm)	30.48 b	31.30 b	122.4 a	117.5 b	232.6 ab	231.6 ab	20.18 ab	19.33 ab	1681.7 ab	1700.1 ab	4.66 c	5.61 c	1227.0 b	1221.7 b
T2 (60×45 cm)	33.83 ab	32.86 ab	125.3 a	125.6 a	239.7 a	235.9 a	22.81 a	25.30 a	1750.7 a	1870.7 a	5.55 b	5.99 b	1927.3 ab	1927.3 ab
T3 (75×45 cm)	34.16 a	33.55 a	120.6 a	124.5 a	207.2 b	210.8 b	19.15 b	19.72 ab	1564.0 b	1620.2 b	6.88 a	6.51 a	2648.1 a	2648.3 a
LSD value (P>0.05)	3.39	2.5	5.89	6.32	22.05	15.85	3.02	3.82	822.6	432.2	0.64	1.26	1272.9	1260.9

Means followed by the same letter(s) within a column do not differ significantly at P ≤ 0.05.

Table 8. Effect of different plant spacings on biochemical properties of broccoli

Plant Spacing	Total Soluble Salts (TSS) (°Brix)		Titratable Acidity (TA) (%)		Ascorbic acid (mg $100g^{-1}$)	
Years	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
T1 (60×30 cm)	3.86 b	2.86 b	0.39 b	0.41 b	24.87 b	23.87 b
T2 (60×45 cm)	5.56 a	5.56 a	0.57 a	0.44 a	34.95 ab	34.89 ab
T3 (75×45 cm)	4.86 ab	4.35 ab	0.41 ab	0.42 ab	35.76 a	36.76 a
LSD value (P>0.05)	0.73	1.54	0.06	0.06	3.34	5.34

Means followed by the same letter(s) within a column do not differ significantly at P ≤ 0.05.

Therefore, it was imperative to investigate proper dose of nitrogenous fertilizer for improved curd yield as well as physio-chemical properties of broccoli. The results of this study revealed that different N doses had significant effect on growth and yield related parameters of broccoli. Highest values for vegetative parameters (leaf area, fresh and dry biomass) were achieved from treatment T5 (500 kg N ha^{-1}) while plant height, chlorophyll content and stem diameter were more in T3 (250 kg N ha^{-1}); both T3 and T5 were statistically similar for most of the traits.

Giri et al. (2013) also reported highest plant height and number of leaves of broccoli for 100 to 200 kg N ha-1 in Nepal. Qadir et al. (2017) did not find any change in chlorophyll content of crop with change in the N doses that support findings of this study. Moniruzzaman et al. (2007) found maximum number of leaves of broccoli for 197.7 kg N ha^{-1} that partially support result of this study. So, increasing N from 250 to 500 kg N ha^{-1} resulted in highest vegetative growth of broccoli. Leaf area increase has been associated with increased photosynthesis (Li et al., 2022) that might have possibly increased fresh and dry weight of broccoli (Gulias et al., 2003), indicating enhanced availability of photosynthates for curd formation.

This likely resulted in higher curd fresh and dry weight 250 to 500 kg N ha^{-1} than control. Similarly, yield of primary and secondary curds was increased with increasing N dose. However, yield of secondary curds was higher from 250 kg N ha^{-1} treatment than all others and it was possibly due to higher number of secondary curds.

Recent studies indicate that optimal N requirements for broccoli are generally lower than previously reported. A study conducted in middle Gujarat, India demonstrated that maximum curd yield was achieved with 200 kg N ha^{-1} combined with 75 kg P and 50 kg K ha^{-1}, consistently outperforming lower fertilization rates across multiple growing seasons (Giri et al., 2013). Similarly, Kim et al. (2021) reported that optimal broccoli yields in California were obtained within the range of 200–250 kg N ha^{-1}, highlighting improved nitrogen use efficiency at moderate application rates.

Surprisingly, higher N application rate i.e., above 250 kg N ha^{-1}, decreased curd vitamin C content. Slosar et al. (2016) also reported reduction in vitamin C content of broccoli curd due to increase in N application rate. Nitrogen application rate were negatively correlated with vitamin C contents of crisphead lettuce, cabbage and potato (Lee and Kader, 2000). Previously, Metwaly (2016) also reported decline in vitamin C content of broccoli curd at N application rate above 173 kg N ha^{-1} that partially corresponds to result of current study.

Plant water uptake was positively correlated with N application rate (Li et al., 2024) and decreasing soil moisture increased vitamin C content of broccoli curd (Erken and Kuzucu, 2013). So, higher nitrogen application rates (150 and 200 kg N $acre^{-1}$) might have increased water uptake by the broccoli plants which possibly had decreased vitamin C content of broccoli curd in current study. TSS and titratable acidity was also increased up to 250 kg N ha^{-1} and then declined that is also in partial accordance with the findings of Metwaly (2016).

4.2 Effect of Plant Spacing

Closer spacing (60×30 cm) decreased number of leaves and leaf area of broccoli compared to wider spacing (60×45 cm and 75×45 cm), maximum at 60×45 cm that is in accordance with the findings earlier reported (Madhumathi et al., 2017). Higher photosynthesis resulting from this enhanced leaf area can be the reason of higher fresh and dry biomass at wider spacings than closer spacing (60×30 cm). However, there was no significant increase in curd fresh and dry weight at wider spacing (60×45 cm), rather decline in values was noted at 75×45 cm. These results are in partial agreement with the findings of previous studies (Kumar et al., 2021). Accordingly yield of primary curds declined at widest spacing (75×45 cm) and was maximum at 60×45 cm. However, number of secondary curds and their yield was highest at widest spacing (75×45 cm) followed by 60×45 cm. So, cultivars with higher number of secondary curds should be planted at widest spacing and those without secondary curds should be planted at closest spacing. High yield of primary curd from 60×45 cm compared to 60×30 cm supports results of this study. Tuhin et al (2025) also demonstrated highest yield of secondary curds at 60×40 cm that partially support findings of this study for 60×45 cm. Findings of Basak et al. (2022) strengthen our view of higher secondary curd yield from wider (60×45 cm) spacing than closer spaced plants (60×30 cm).

Curd quality was improved at wider spacing as evident from higher values of TSS, TA and ascorbic acid at 60×45 cm and 75×45 cm possibly because of increased photosynthesis leading to higher carbohydrate accumulation (Kumar et al., 2021). Therefore, increased levels of TSS and vitamin C as compared to densely grown plants. Singh et al. (2022) also concluded that broccoli curd quality was decreased due to closer spacing that confirm results of present study.

Improving nitrogen use efficiency (NUE) is critical for maintaining productivity while reducing fertilizer inputs and environmental impacts (Ali et al., 2025). Climate-smart and precision nutrient management approaches demonstrate that moderate nitrogen rates (200–300 kg N ha^{-1}), particularly when integrated with organic amendments, can optimize yield, enhance efficiency, and minimize losses. These findings reinforce the importance of sustainable nitrogen management for resilient crop production systems (Iqbal et al., 2023b; Govindasamy et al., 2023).

5. Conclusion

Fertilizer application should be guided by soil fertility status; however, under the studied agroclimatic conditions, nitrogen rates of 250–500 kg ha^{-1} enhanced both primary and secondary curd yield. For improved nutritional quality, particularly higher vitamin C content, lower nitrogen levels (125–250 kg ha^{-1}) are recommended. Optimal plant spacing significantly differs across cultivar types. Farmers can achieve maximum primary curd by using 60×45 cm spacing for varieties producing primary curds, whereas, 75×45 cm favored higher production of secondary curds. Overall, moderate nitrogen application combined with appropriate plant spacing offers a balanced strategy for maximizing yield and quality. Further research should focus on the interactive effects of nitrogen, soil moisture, and plant spacing on curd yield and quality of broccoli for site-specific recommendations.

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