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RESEARCH ARTICLE

Synergistic effects of nutrient management and plant density on modulating the growth, yield and quality of broccoli (*Brassica oleracea* var. *italica*) hybrids

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Abstract

Integrated recommendations on hybrid selection, planting density and nutrient management for broccoli are still lacking for the eastern dry zone of Karnataka, representing a key research gap. The study evaluated the influence of hybrid, planting density and nutrient management on broccoli growth, yield and quality over two consecutive Rabi seasons (2023-24 and 2024-25) at Sanjeevini Vatika, Department of Horticulture, University of Agricultural Sciences, Gandhi Krishi Vigyana Kendra (GKVK), Bengaluru, Karnataka. The experiment was conducted using a factorial randomized complete block design (FRCBD) with three replications, involving three factors. The study assessed morphological, yield and quality parameters, including plant height, leaf area, chlorophyll content, head diameter, stalk thickness, vitamin C, total soluble solids and physiological weight loss. The NS1250 and Saki hybrids under optimal spacing and higher fertilization consistently outperformed the Lucky hybrid, showing superior growth traits, earlier harvest, higher yields and enhanced nutritional quality, such as elevated vitamin C and total soluble solids. Wider spacing promoted larger leaf area and head size, while closer spacing expedited harvest. High nutrient input favoured overall plant vigor and reduced physiological weight loss. Overall, the findings highlight the importance of integrated management strategies for maximizing broccoli productivity and quality, offering robust recommendations for sustainable cultivation across similar agro-climatic regions.

Keywords: broccoli; hybrid; nutrient; quality; spacing; yield

Introduction

Broccoli (*Brassica oleracea* var. *italica*) is a temperate vegetable belonging to the family Brassicaceae, originally native to the Mediterranean region and later introduced into India as an exotic crop. This Italian-origin vegetable produces green heads as the economic part and was historically cultivated in Italy, where its consumption spread among Romans and later across the world. Broccoli's popularity has grown globally owing to its rich nutritional profile and health-promoting properties-it is low in calories, fat and sodium, while boasting high concentrations of vitamin C and providing notable amounts of calcium, vitamin A and vitamin B2 (1).

Fertilizers have played a vital role for centuries in restoring essential nutrients to soil, improving crop productivity, supporting plant growth and ensuring global food security through enhanced agricultural yields. To enhance the production of this valuable and highly nutritious vegetable, farmers have increasingly resorted to applying excessive quantities of chemical fertilizers. However, crop yields have risen at a much slower pace than the escalation in fertilizer usage, particularly when large amounts are continually applied over time. This underscores the importance of investigating efficient fertilizer management strategies that can improve or maintain crop output while also sustaining soil fertility. Among the many elements that affect broccoli development and yield, plant density is a crucial component of crop production.

Crop growth and yield are strongly influenced by genotype and plant spacing. Despite its importance, limited research has been conducted in this region of India to explore the combined effects of planting density, fertilization management and hybrid selection suitable for this region on broccoli production. Given the critical role that planting density plays in optimizing resource use and maximizing yield, alongside the influence of balanced fertilization in improving soil fertility and crop performance, it is essential to investigate how these factors interact in local conditions. Therefore, this study aimed to evaluate the effects of varying planting densities, nutrient regimes and hybrids on the growth, yield and quality of broccoli under the specific agro-climatic conditions of the study region.

Materials and Methods

The field experiments were conducted during Rabi seasons of the year 2023-24 and 2024-25 at Sanjeevani Vatika, Department of Horticulture, University of Agricultural Sciences, Gandhi Krishi Vignyan Kendra, Bengaluru. The site is situated in the eastern dry zone of Karnataka at an elevation of 930 m above mean sea level. During the cropping period, the average maximum and minimum temperatures were 26.40 °C and 18.38 °C, respectively. The experimental soil was red sandy loam with uniform topography and its characteristics were as follows: acidic in reaction (pH 5.76), normal electrical conductivity (0.31 dS m^{-1}) and low organic carbon content (0.44 %). The soil was analyzed for available nutrient content before planting. The results indicated that the initial nitrogen, phosphorus and potassium levels were 169.28 kg ha^{-1}, 47.68 kg ha^{-1} and 157.49 kg ha^{-1}, respectively.

The experimental field was prepared by thorough ploughing with a tractor-drawn cultivator, followed by cross harrowing, rotavating and levelling. Farmyard manure at 25 t ha^{-1} was incorporated during land preparation. The experiments were laid out in a factorial randomized complete block design (FRCBD) with three replications. Treatments comprised three factors: plant hybrids (3 levels: H_1- Lucky; H_2- NS1250 and H_3-Saki), plant spacings (2 levels: S_1- 45 cm × 45 cm and S_2- 60 cm × 45 cm) and nutrient application (2 levels: N_1- 120:80:60 kg NPK ha^{-1} and N_2- 150:100:75 kg NPK ha^{-1}). Fertilizer application included 50 % of nitrogen with full doses of phosphorus and potassium as basal, while the remaining 50 % nitrogen was top-dressed 30 days after transplanting (DAT). Twenty-five-day-old healthy, uniform broccoli seedlings were transplanted as per treatments, followed by irrigation and gap filling was completed within a week to maintain uniform plant population.

To assess the crop growth pattern at 60 DAT, five plants were randomly selected from the net plot area in each treatment. Leaf length and width were measured and leaf area (LA) was estimated using the formula (2):

LA = 0.63 × Leaf length (cm) × Leaf width (cm) (Eqn. 1)

The average leaf area of selected plants was calculated. Chlorophyll content was assessed non-destructively with a portable SPAD-502Plus meter (Konica Minolta), which estimates total chlorophyll content with high accuracy (3). Measurements were taken on five leaves per replicate at harvest and the mean was calculated. Days to first harvest were recorded by counting days from transplanting to harvest of five tagged plants in each plot and averaged per treatment. Head compactness was calculated using the formula (4):

Head compactness (g/cm) = Head weight (g) ÷ Head diameter (cm) (Eqn. 2)

Vitamin C content (mg/100 g) was determined by the dichlorophenol indophenols (DCPIP) titration method (5). Total soluble solids (°Brix) were measured by extracting juice from crushed broccoli head samples, placing drops on the prism of a hand refractometer and reading the value at the boundary of shaded and unshaded areas. Physiological loss in weight (%) was calculated (6):

PLW (%) = [(Initial weight - Final weight after 4 days) ÷ Initial weight] ×100 (Eqn. 3)

The averages for all measurements were computed per treatment. All data were collected for two consecutive Rabi seasons (2023-24 and 2024-25). Year-wise values for each treatment were tabulated for detailed comparison. For concise reporting in the results section, mean (pooled) values across seasons were calculated and presented in the text, while individual yearly data are shown in tables. This approach enables both concise interpretation and clear seasonal comparison of measured parameters. Statistical analysis was performed using OPSTAT software at a significance level of $p < 0.05$.

Results

Growth and development parameters of broccoli were evaluated over two consecutive Rabi seasons (2023-24 and 2024-25) to determine the effects of hybrid, plant spacing and nutrient level treatments (Table1). Hybrid NS1250 (H_2) exhibited significantly greater plant height (57.48 cm), larger leaf area (259.95 cm^2) and higher chlorophyll content (51.54 SPAD) compared to Lucky (H_1), which produced more leaves (25.03) and achieved wider plant spread in both north-south (71.38 cm) and east-west (68.13 cm) orientations. Closer spacing (45 cm×45cm) promoted increased plant height (55.69 cm), while wider spacing (S_2: 60cm×45cm) resulted in more leaves (24.38), greater leaf area (255.92 cm^2), higher chlorophyll content (51.08 SPAD) and enhanced plant spread over both years. Increased nutrient input (N_2: 150:100:75 kg NPK ha^{-1}) significantly improved all measured growth parameters compared to lower nutrient input (N_1: 120:80:60 kg NPK ha^{-1}).

Significant two-way interaction effects between broccoli hybrids and plant spacing were observed for growth parameters during both Rabi seasons (2023 and 2024) and presented in Table 2. The hybrid and spacing combination H_2S_1 (NS1250 at 45 cm × 45 cm) produced statistically highest plants (59.32 cm). In contrast, the higher number of leaves was found in plants grown under the H_1S_2 combination (29.08 leaves). Maximum plant spread was recorded in both the north–south (73.09 cm) and east–west (70.23 cm) directions for H_1S_2 combination. The larger leaf area was observed in H_2S_2 (283.14 cm^2), which also showed the higher chlorophyll content (54.89 SPAD units).

The interaction between hybrids and nutrient levels significantly influenced broccoli growth parameters (Table 2). Pooled mean values indicated that the H_2N_2 treatment resulted in the greater plant height (58.43 cm), larger leaf area (272.95 cm^2) and higher chlorophyll content (52.62 SPAD). Conversely, H_1N_2 exhibited the maximum number of leaves (26.09) and wider plant spread. Regarding the interaction between plant spacing and nutrient levels, S_1N_2 produced the taller plants (58.88 cm), while S_2N_2 recorded the larger leaf area (262.22 cm^2), higher chlorophyll content (52.01 SPAD) and significantly greater plant spread. Differences in leaf number were not statistically significant ($p > 0.05$), whereas all other noted parameters showed significance at $p < 0.05$.

Growth and development in broccoli responded significantly to the combined influence of hybrid, spacing and nutrient levels (Table 3). Based on pooled mean values, the maximum plant height (60.88 cm) was recorded in the $H_2S_1N_2$ treatment (T_6). The $H_2S_2N_2$ combination (T_8) exhibited the larger leaf

Table 1. Effect of plant spacing and nutrient levels on growth parameters of broccoli hybrids at 60 days after transplanting

Treatments	Plant height (cm)		Number of leaves		Leaf area (cm^2)		Chlorophyll content (SPAD)		Plant spread (N-S)		Plant spread (E-W)	
	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
Hybrids (H)												
H_1	48.66	50.93	24.65	25.41	208.28	209.35	47.81	39.11	71.69	71.07	68.72	67.54
H_2	55.49	59.47	19.49	18.33	260.97	258.93	53.07	50.00	64.41	64.17	61.55	59.95
H_3	53.45	56.79	19.50	20.36	253.17	256.54	51.68	45.82	68.82	68.86	65.96	64.64
SEm±	0.44	0.42	0.21	0.28	1.78	1.73	0.17	0.19	0.38	0.37	0.37	0.34
CD (5 %)	1.29	1.24	0.62	0.82	5.21	5.06	0.49	0.56	1.11	1.09	1.09	0.98
Plant spacings (S)												
S_1	54.13	57.24	17.08	17.98	225.66	227.33	48.99	40.52	65.68	65.39	62.75	61.17
S_2	50.94	54.22	24.01	24.75	255.96	255.88	52.71	49.44	70.93	70.68	68.07	66.91
SEm±	0.36	0.35	0.17	0.23	1.50	1.41	0.14	0.16	0.31	0.30	0.30	0.27
CD (5 %)	1.05	1.01	0.51	0.67	4.25	4.14	0.40	0.46	0.91	0.89	0.89	0.80
Nutrient levels (N)												
N_1	50.12	53.54	19.22	19.94	231.31	232.54	49.63	43.18	67.16	66.87	64.23	62.93
N_2	54.95	57.92	21.88	22.79	250.31	250.67	52.07	46.78	69.45	69.20	66.59	65.16
SEm±	0.36	0.35	0.17	0.23	1.45	1.41	0.14	0.16	0.31	0.30	0.30	0.27
CD (5 %)	1.05	1.01	0.51	0.67	4.25	4.14	0.40	0.46	0.91	0.89	0.89	0.80

H_1: Lucky; H_2: NS1250; H_3: Saki; S_1: 45 cm x 45 cm; S_2: 60 cm x 45 cm; N_1: 120:80:60 kg NPK per hectare; N_2: 150:100:75 kg NPK per hectare.

Table 2. Two-way interaction effects of broccoli hybrids, plant spacing and nutrient levels on growth parameters at 60 days after transplanting

Treatments	Plant height (cm)		Number of leaves		Leaf area (cm^2)		Chlorophyll content (SPAD)		Plant spread (N-S)		Plant spread (E-W)	
	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
(H × S)												
H_1S_1	48.31	51.06	20.60	21.37	195.38	196.66	45.14	35.19	69.72	69.62	66.64	65.43
H_1S_2	49.02	50.80	28.71	29.44	221.19	222.03	50.47	43.04	73.66	72.52	70.80	69.66
H_2S_1	57.70	60.93	14.52	15.27	237.75	235.78	51.35	45.00	60.60	59.79	57.74	55.57
H_2S_2	53.28	57.98	20.47	21.39	284.20	282.07	54.78	55.00	68.21	68.55	65.35	64.33
H_3S_1	56.37	59.71	16.14	17.30	243.85	249.54	50.49	41.35	66.72	66.75	63.86	62.53
H_3S_2	50.53	53.87	22.86	23.41	262.50	263.53	52.87	50.29	70.92	70.97	68.06	66.75
SEm±	0.62	0.60	0.30	0.40	2.51	2.44	0.24	0.27	0.54	0.53	0.52	0.47
CD (5 %)	1.82	1.75	0.88	1.16	7.36	7.16	0.70	0.79	1.57	1.54	1.54	1.39
(H × N)												
H_1N_1	44.64	46.07	23.50	24.44	197.37	197.99	45.61	38.32	71.22	70.80	68.15	67.42
H_1N_2	52.69	55.79	25.80	26.38	219.20	220.70	50.00	39.90	72.15	71.34	69.29	67.67
H_2N_1	53.92	59.15	16.15	16.83	247.85	246.05	52.08	48.80	61.58	61.42	58.72	57.20
H_2N_2	57.07	59.79	18.84	19.84	274.10	271.80	54.05	51.20	67.24	66.92	64.38	62.70
H_3N_1	51.80	55.40	18.00	18.54	248.73	253.56	51.20	42.40	68.69	68.39	65.83	64.17
H_3N_2	55.10	58.17	21.00	22.17	257.62	259.52	52.16	49.24	68.95	69.33	66.09	65.11
SEm±	0.62	0.60	0.30	0.40	2.51	2.44	0.24	0.27	0.54	0.53	0.52	0.47
CD (5 %)	1.82	1.75	-	-	7.36	7.16	0.70	0.79	1.57	1.54	1.54	1.39
(S × N)												
S_1N_1	50.70	54.27	16.23	17.27	213.10	215.36	47.06	38.28	63.92	63.62	60.92	59.42
S_1N_2	57.55	60.21	17.94	18.69	238.22	239.30	50.92	42.75	67.43	67.15	64.57	62.93
S_2N_1	49.54	52.81	22.20	22.60	249.53	249.71	52.19	48.08	70.40	70.12	67.54	66.44
S_2N_2	52.35	55.62	25.82	26.90	262.39	262.05	53.22	50.80	71.46	71.24	68.60	67.38
SEm±	0.51	0.49	0.25	0.32	2.05	1.99	0.19	0.22	0.44	0.43	0.43	0.39
CD (5 %)	1.49	1.43	0.72	0.95	6.01	5.85	0.57	0.65	1.29	1.26	1.26	1.13

H_1: Lucky; H_2: NS1250; H_3: Saki; S_1: 45 cm × 45 cm; S_2: 60 cm × 45 cm; N_1: 120:80:60 kg NPK per hectare; N_2: 150:100:75 kg NPK per hectare.

Table 3. Three-way interaction effects of broccoli hybrids, plant spacing and nutrient levels on growth parameters at 60 days after transplanting

Treatments	Plant height (cm)		Number of leaves		Leaf area (cm²)		Chlorophyll content (SPAD)		Plant spread (N-S)		Plant spread (E-W)	
	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024
(H × S × N)												
$T_1 - H_1S_1N_1$	42.44	43.88	19.44	20.57	186.76	188.46	40.83	34.79	68.98	69.37	65.70	65.21
$T_2 - H_1S_1N_2$	54.18	58.23	21.75	22.18	203.99	204.86	49.44	35.59	70.45	69.86	67.59	65.64
$T_3 - H_1S_2N_1$	46.85	48.25	27.56	28.31	207.97	207.52	50.39	41.85	73.46	72.22	70.60	69.64
$T_4 - H_1S_2N_2$	51.19	53.35	29.86	30.57	234.40	236.54	50.56	44.22	73.86	72.82	71.00	69.69
$T_5 - H_2S_1N_1$	55.17	60.37	13.85	14.55	216.51	213.58	50.47	43.22	56.20	55.55	53.34	51.33
$T_6 - H_2S_1N_2$	60.22	61.53	15.18	15.99	259.00	257.99	52.24	46.79	65.01	64.03	62.15	59.81
$T_7 - H_2S_2N_1$	52.66	57.93	18.44	19.11	279.19	278.53	53.69	54.39	66.95	67.29	64.09	63.07
$T_8 - H_2S_2N_2$	53.91	58.04	22.50	23.68	289.20	285.62	55.87	55.61	69.46	69.80	66.60	65.58
$T_9 - H_3S_1N_1$	54.50	58.55	15.38	16.70	236.02	244.03	49.89	36.82	66.59	65.94	63.73	61.72
$T_{10} - H_3S_1N_2$	58.24	60.86	16.90	17.90	251.67	255.05	51.08	45.89	66.84	67.56	63.98	63.34
$T_{11} - H_3S_2N_1$	49.10	52.25	20.61	20.38	261.43	263.09	52.50	47.99	70.79	70.84	67.93	66.62
$T_{12} - H_3S_2N_2$	51.95	55.48	25.10	26.44	263.56	263.98	53.24	52.59	71.06	71.11	68.20	66.89
SEm±	0.88	0.84	0.42	0.56	3.55	3.45	0.34	0.38	0.76	0.74	0.74	0.67
CD (5 %)	2.57	2.48	1.24	1.64	10.41	10.13	0.98	1.12	2.23	2.18	65.70	1.97

H_1: Lucky; H_2: NS1250; H_3: Saki; S_1: 45 cm × 45 cm; S_2: 60 cm × 45 cm; N_1: 120:80:60 kg NPK per hectare; N_2: 150:100:75 kg NPK per hectare.

area (287.41 cm²) and the higher chlorophyll concentration (55.74 SPAD). Meanwhile, the $H_1S_2N_2$treatment (T_4) was superior in producing the higher number of leaves (30.22) along with the greater plant spread in both directions. These diverse responses among morphological traits highlight the intricate interaction of broccoli hybrids with specific nutrient regimes and planting densities.

Days to first harvest

It is evident that NS1250 (H_2) reached harvest earlier, with a pooled mean of 49.73 days, while Lucky (H_1) required 68.14 days (Table 4). Closer spacing (S_1: 45 cm × 45 cm) promoted earlier harvest (58.07 days) compared to wider spacing (S_2:60.21 days). Lower nutrient input (N_1:120:80:60 kg NPK ha^{-1}) also hastened harvest (57.56 days), whereas higher input (N_2) delayed it to 60.72 days.

In the two-factor interaction, the earlier harvest was recorded in H_2S_1 (49.30 days), H_2N_1(49.08 days) and S_1N_1 (55.90 days), while longer durations occurred in H_1S_2 (68.62 days), H_1N_2 (69.03 days) and S_2N_2(61.19 days) (Table 5). The three-factor interaction presented in Table 6 showed that treatment $H_2S_1N_1$ (T_5) recorded the earlier harvest (48.52 days pooled) (Table 6), followed closely by $H_2S_2N_1$ (T_7:49.63 days), whereas Lucky under wider spacing with higher nutrients (T_4:$H_1S_2N_2$) exhibited the longer duration to harvest (69.68 days).

Head diameter

Among hybrids, NS1250 (H_2) produced consistently larger head diameters (13.75 cm pooled) compared to Lucky (H_1, 11.52 cm) (Table 4). S_2 encouraged greater head size (13.35 cm pooled), while S_1 limited it (12.31 cm). N_2 notably promoted larger diameters (13.18 cm) in contrast to N_1 (12.48 cm).

Table 4. Effect of plant spacing and nutrient levels on yield and quality parameters of broccoli hybrids

Treatments	Days to first harvest		Head diameter		Stalk diameter		Head yield (q/ha)		Head compactness (g cm^{-1})		Vitamin C (mg 100 g^{-1})		TSS (°Brix)		PLW (%)	
	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
Hybrids (H)																
H_1	67.88	68.40	10.94	12.10	1.99	2.19	75.45	76.33	22.36	24.63	87.34	87.53	5.77	6.01	22.76	29.36
H_2	49.69	49.76	13.20	14.29	3.06	3.25	95.59	97.29	27.20	29.34	95.37	95.30	6.25	6.49	18.24	18.39
H_3	59.61	59.48	12.69	13.73	2.81	3.00	92.63	93.66	25.62	27.76	97.34	97.65	6.03	6.27	19.81	24.09
SEm±	0.19	0.44	0.05	0.04	0.03	0.03	0.43	0.39	0.43	0.43	0.29	0.36	0.03	0.03	0.15	0.14
CD (5 %)	0.55	1.30	0.14	0.11	0.10	0.09	1.27	1.15	1.26	1.26	0.86	1.07	0.08	0.08	0.45	0.42
Plant spacings (S)																
S_1	57.96	58.18	11.75	12.86	2.26	2.46	96.15	97.63	23.23	25.42	91.66	91.75	5.98	6.22	20.97	25.54
S_2	60.16	60.25	12.81	13.89	2.97	3.16	79.63	80.56	26.90	29.06	95.03	95.23	6.05	6.29	19.57	22.36
SEm±	57.96	58.18	0.04	0.03	0.03	0.03	0.35	0.32	0.35	0.35	0.24	0.30	0.02	0.02	0.12	0.12
CD (5 %)	60.16	60.25	0.11	0.09	0.08	0.08	1.04	0.94	1.03	1.03	0.70	0.87	0.06	0.06	0.36	0.34
Nutrient levels (N)																
N_1	57.54	57.57	11.93	13.01	2.46	2.66	84.09	84.54	23.95	26.15	91.65	91.75	5.85	6.09	21.55	26.73
N_2	60.58	60.85	12.62	13.74	2.78	2.97	91.69	93.65	26.17	28.34	95.04	95.23	6.19	6.43	18.99	21.16
SEm±	0.15	0.36	0.04	0.03	0.03	0.03	0.35	0.32	0.35	0.35	0.24	0.30	0.02	0.02	0.12	0.12
CD (5 %)	0.45	1.06	0.11	0.09	0.08	0.08	1.04	0.94	1.03	1.03	0.70	0.87	0.06	0.06	0.36	0.34

H_1: Lucky; H_2: NS1250; H_3: Saki; S_1: 45 cm × 45 cm; S_2: 60 cm × 45 cm; N_1: 120:80:60 kg NPK per hectare; N_2: 150:100:75 kg NPK per hectare.

Table 5. Two-way interaction effects of broccoli hybrids, plant spacing and nutrient levels on yield and quality parameters of broccoli hybrids

Treatments	Days to first harvest		Head diameter		Stalk diameter		Head yield (q/ha)		Head compactness (g cm^{-1})		Vitamin C (mg 100 g $^{-1}$)		TSS (°Brix)		PLW (%)	
	2023	2024	2023	2024	023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
(H × S)																
H_1S_1	67.25	68.08	10.64	11.78	1.91	2.14	84.24	85.58	22.26	24.58	84.24	84.34	5.79	6.03	24.06	31.18
H_1S_2	68.51	68.71	11.24	12.42	2.06	2.25	66.65	67.08	22.46	24.68	90.43	90.71	5.75	5.99	21.46	27.55
H_2S_1	49.35	49.24	12.59	13.72	2.45	2.64	102.67	104.58	23.79	25.93	94.43	94.33	6.18	6.42	18.30	18.96
H_2S_2	50.03	50.28	13.82	14.87	3.68	3.87	88.50	90.00	30.61	32.75	96.31	96.27	6.33	6.57	18.19	17.81
H_3S_1	57.27	57.21	12.02	13.09	2.43	2.62	101.54	102.73	23.63	25.77	96.32	96.60	5.99	6.23	20.55	26.47
H_3S_2	61.95	61.75	13.36	14.36	3.18	3.37	83.73	84.59	27.61	29.75	98.36	98.71	6.07	6.32	19.06	21.71
SEm±	0.26	0.62	0.07	0.05	0.05	0.05	0.61	0.56	0.61	0.61	0.41	0.52	0.04	0.04	0.22	0.12
CD (5 %)	0.77	1.83	0.19	0.15	0.14	0.13	1.80	1.63	1.79	1.78	1.21	1.51	0.11	0.11	0.63	0.34
(H × N)																
H_1N_1	67.01	67.49	10.46	11.64	1.75	1.97	70.02	70.00	22.19	24.50	85.02	85.12	5.60	5.84	24.72	32.17
H_1N_2	68.76	69.30	11.41	12.56	2.23	2.42	80.87	82.66	22.54	24.76	89.65	89.93	5.94	6.18	20.80	26.56
H_2N_1	49.11	49.04	12.89	13.96	2.93	3.12	92.79	93.43	25.48	27.62	94.41	94.37	6.22	6.46	18.85	20.26
H_2N_2	50.27	50.48	13.52	14.63	3.20	3.39	98.38	101.15	28.91	31.05	96.33	96.23	6.29	6.53	17.64	16.51
H_3N_1	56.52	56.18	12.44	13.43	2.70	2.89	89.46	90.18	24.18	26.32	95.52	95.76	5.72	5.96	21.09	27.76
H_3N_2	62.71	62.78	12.94	14.02	2.91	3.10	95.81	97.14	27.06	29.20	99.15	99.54	6.33	6.58	18.52	20.42
SEm±	0.26	0.62	0.07	0.05	0.05	0.05	0.61	0.56	0.61	0.61	0.41	0.52	0.04	0.04	0.22	0.20
CD (5 %)	0.77	1.83	0.19	0.15	0.14	0.13	1.80	1.63	1.79	1.78	1.21	1.51	0.11	0.11	0.63	0.59
(S × N)																
S_1N_1	56.00	55.79	11.48	12.60	2.17	2.38	93.83	95.06	23.26	25.47	89.36	89.27	5.71	5.95	22.67	28.57
S_1N_2	59.92	60.56	12.01	13.12	2.36	2.55	98.47	100.20	23.19	25.38	93.96	94.24	6.26	6.50	19.27	22.51
S_2N_1	59.09	59.35	12.38	13.42	2.75	2.94	74.36	74.01	24.64	26.83	93.93	94.23	5.99	6.23	20.44	24.89
S_2N_2	61.23	61.14	13.23	14.35	3.20	3.39	84.90	87.10	29.15	31.29	96.13	96.23	6.11	6.36	18.70	19.82
SEm±	0.21	0.51	0.05	0.04	0.04	0.04	0.50	0.45	0.50	0.49	0.34	0.42	0.03	0.03	0.18	0.16
CD (5 %)	0.63	1.50	0.16	0.12	0.11	0.11	1.47	1.33	1.46	1.45	0.99	1.24	0.09	0.09	0.51	0.48

H_1: Lucky; H_2: NS1250; H_3: Saki; S_1: 45 cm × 45 cm; S_2: 60 cm × 45 cm; N_1: 120:80:60 kg NPK per hectare; N_2: 150:100:75 kg NPK per hectare.

In the two-way interactions, the H_2S_2 combination gave the largest heads (14.35 cm pooled), while H_1S_1produced the smallest (11.21 cm) (Table 5). Likewise, greater diameters were obtained with H_2N_2 (14.08 cm) and S_2N_2 (13.77 cm), whereas H_1N_1 and S_1N_1 recorded smaller heads (11.06 cm and 12.05 cm pooled, respectively).

The three-way effect was maximized in T_8 ($H_2S_2N_2$: NS1250 + 60 cm × 45 cm + 150:100:75 NPK kg/ha), achieving the greater head diameter of 14.87 cm, closely followed by T_{12} (Saki-based combination) (Table 6). The smaller heads were found in T_1 ($H_1S_1N_1$: Lucky + 45 cm × 45 cm + 120:80:60 NPK kg/ha), with a pooled diameter of 10.70 cm.

Stalk diameter

NS1250 (H_2) exhibited a greater stalk thickness, with a pooled mean of 3.16 cm compared to 2.10 cm for Lucky (H_1) (Table 4). S_2 and higher nutrient application (N_2) favored stalk thickening, yielding pooled means of 3.07 cm and 2.88 cm, respectively, whereas closer spacing (S_1: 45 cm × 45 cm) and reduced nutrient levels (N_1: 120:80:60 NPK kg/ha) resulted in thinner stalks, averaging 2.37 cm and 2.56 cm.

Among two-factor interactions, the H_2S_2 and H_2N_2 combinations produced the thicker stalks (3.78 cm and 3.30 cm pooled), while H_1S_1 and H_1N_1 recorded the smaller diameters (2.03 cm and 1.86 cm pooled) (Table 5). The S_2N_2 combination achieved the maximum stalk thickness among spacing–nutrient pairings (3.30 cm pooled), whereas S_1N_1 had the lower stalk thickness (2.28 cm pooled).

The most robust stalks were obtained in treatment T_8 ($H_2S_2N_2$: NS1250 + 60 cm × 45 cm + 150:100:75 NPK kg/ha), with a pooled mean diameter of 4.08 cm (Table 6). Conversely, T_1 ($H_1S_1N_1$: Lucky + 45 cm × 45 cm + 120:80:60 NPK kg/ha) consistently produced the thinnest and weakest stalks, averaging 1.74 cm (pooled).

Fresh weight of head (g)

The mean data for fresh head weight over two consecutive seasons as presented in Fig 1. NS1250 (H_2) recorded a higher pooled mean

Table 6. Three-way interaction effects of broccoli hybrids, plant spacing and nutrient levels on yield and quality parameters of broccoli hybrids

Treatments	Days to first harvest		Head diameter		Stalk diameter		Head yield (q/ha)		Head compactness (g cm^{-1})		Vitamin C (mg 100 g^{-1})		TSS (°Brix)		PLW (%)	
	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
(H × S × N)																
$T_1 - H_1S_1N_1$	66.96	66.95	10.12	11.26	1.61	1.87	78.04	78.82	22.08	24.43	80.85	80.77	5.39	5.63	26.09	32.61
$T_2 - H_1S_1N_2$	67.54	69.21	11.15	12.30	2.21	2.40	90.44	92.34	22.44	24.73	87.62	87.90	6.19	6.43	22.03	29.76
$T_3 - H_1S_2N_1$	67.05	68.03	10.80	12.02	1.88	2.07	62.01	61.18	22.29	24.58	89.18	89.46	5.81	6.05	23.35	31.73
$T_4 - H_1S_2N_2$	69.97	69.39	11.67	12.82	2.25	2.44	71.30	72.98	22.64	24.78	91.68	91.96	5.68	5.92	19.57	23.36
$T_5 - H_2S_1N_1$	48.73	48.31	12.43	13.61	2.48	2.67	102.40	103.92	24.40	26.54	92.71	92.23	6.15	6.39	19.35	22.58
$T_6 - H_2S_1N_2$	49.98	50.17	12.75	13.82	2.41	2.60	102.95	105.25	23.17	25.31	96.14	96.42	6.20	6.44	17.25	15.35
$T_7 - H_2S_2N_1$	49.50	49.77	13.35	14.31	3.38	3.57	83.19	82.94	26.56	28.70	96.10	96.51	6.30	6.54	18.34	17.94
$T_8 - H_2S_2N_2$	50.55	50.79	14.29	15.44	3.98	4.17	93.82	97.05	34.66	36.80	96.51	96.03	6.37	6.61	18.03	17.68
$T_9 - H_3S_1N_1$	52.30	52.12	11.90	12.94	2.41	2.60	101.04	102.44	23.29	25.43	94.53	94.81	5.58	5.82	22.57	30.52
$T_{10} - H_3S_1N_2$	62.24	62.30	12.13	13.24	2.45	2.64	102.03	103.02	23.97	26.11	98.11	98.39	6.39	6.63	18.54	22.41
$T_{11} - H_3S_2N_1$	60.73	60.24	12.98	13.92	2.98	3.17	77.88	77.91	25.07	27.21	96.51	96.72	5.86	6.10	19.62	25.00
$T_{12} - H_3S_2N_2$	63.17	63.26	13.74	14.79	3.38	3.57	89.58	91.26	30.14	32.28	100.20	100.69	6.28	6.54	18.49	18.42
SEm±	0.37	0.88	0.09	0.07	0.07	0.06	0.87	0.79	0.86	0.86	0.58	0.73	0.05	0.05	0.30	0.28
CD (5 %)	1.09	2.59	0.27	0.21	0.20	0.19	2.54	2.31	2.53	2.51	1.71	2.14	0.15	0.16	0.89	0.83

H_1: Lucky; H_2: NS1250; H_3: Saki; S_1: 45 cm × 45 cm; S_2: 60 cm × 45 cm; N_1: 120:80:60 kg NPK per hectare; N_2: 150:100:75 kg NPK per hectare.

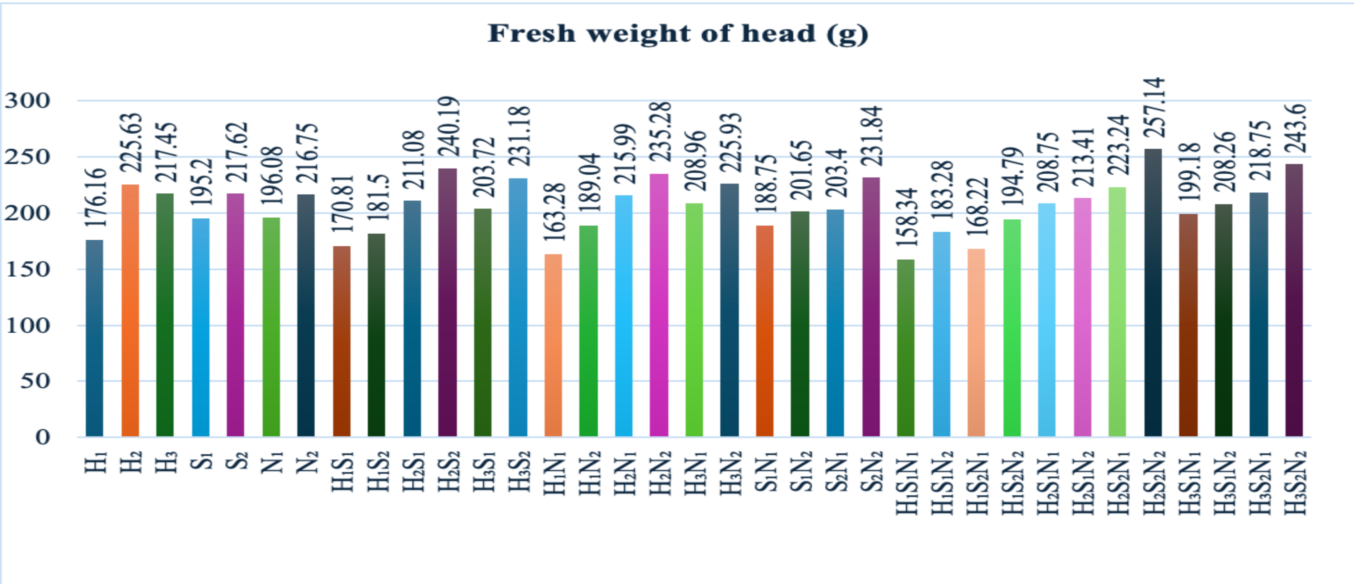

Fig. 1. Effect of plant spacing and nutrient levels on fresh weight of head (g) of broccoli hybrids.

head weight of 225.63 g, whereas Lucky (H_1) produced lighter heads averaging 176.16 g. Wider spacing (S_2:60 cm × 45 cm) promoted heavier heads with a pooled mean of 217.62 g, while closer spacing (S_1:45cm x 45cm) resulted in a lower mean of 195.20 g. Among nutrient levels, the higher input (N_2:150:100:75 kgNPKha^{-1}) produced greater head weight (216.75 g), compared with lower input (N_1:120:80:60 kgNPKha^{-1}) which averaged 196.08g.

In two-factor combinations, H_2S_2 recorded the highest pooled mean head weight (240.19 g), followed by H_2N_2 (235.28 g) and S_2N_2 (231.84g), while H_1S_1 (170.81 g), H_1N_1 (163.28g) and S_1N_1 (188.75g) produced lighter heads. Among all three-factor interactions, the maximum pooled mean head weight was obtained in treatment T_8 ($H_2S_2N_2$) with 257.14g, whereas the lower head weight was recorded in treatment T_1 ($H_1S_1N_1$) with 158.34g.

Head yield (q/ha)

The hybrid NS1250 (H_2) produced the highest pooled mean yield of 96.44qha^{-1}, while Lucky (H_1) recorded a lower mean yield of 75.89qha^{-1} (Table 4). Closer spacing (S_1) achieved a pooled mean yield of 96.89 qha^{-1}, whereas wider spacing (S_2) observed reduced yield of 80.09qha^{-1}. Higher nutrient application (N_2:150:100:75kgNPKha^{-1}) enhanced yield to 92.67qha^{-1}, compared with the lower dose (N_1:120:80:60kgNPKha^{-1}) which recorded 84.32qha^{-1}.

Among two-factor interactions, H_2S_1 yielded the maximum (103.63qha^{-1}), followed by H_2N_2 (99.77qha^{-1}) and S_1N_2 (99.34qha^{-1}), while H_1S_2 (66.87qha^{-1}), H_1N_1 (70.02qha^{-1}) and S_2N_1 (74.17qha^{-1}) resulted in lower yields (Table 5). The highest overall yield was obtained under T_6 ($H_2S_1N_2$) with a pooled mean of 104.10qha^{-1}, statistically comparable to T_5 ($H_2S_1N_1$) at 103.16qha^{-1} (Table 6). The lower yield was observed in T_3 ($H_1S_2N_1$), which recorded 61.60 q ha^{-1}.

Head compactness (g cm^{-1})

Lucky (H_1) recorded the lower pooled mean head compactness at 23.49 g cm^{-1}, while NS1250 (H_2) produced denser heads averaging 28.27 g cm^{-1} (Table 4). S_2 enhanced compactness to 27.98 g cm^{-1}, whereas S_1 reduced it to 24.32 g cm^{-1}. N_2 resulted in 27.25 g cm^{-1}, compared with 25.05 g cm^{-1} for the N_1.

In two-factor interactions, S_2N_2 achieved 30.22 g cm^{-1}, H_2N_2 recorded 29.98 g cm^{-1} and H_2S_2 reached the higher value of 31.68 g cm^{-1}, whereas S_1N_1 (24.36 g cm^{-1}), H_1N_1 (23.34 g cm^{-1}) and H_1S_1 (23.42 g cm^{-1}) showed lower compactness (Table 5). The maximum pooled mean was observed in T_8 ($H_2S_2N_2$) with 35.73 g cm^{-1}, while the lowest compactness was recorded in T_1 ($H_1S_1N_1$) with 23.25 g cm^{-1} (Table 6).

Vitamin C (mg 100 g^{-1})

Broccoli head vitamin C content showed notable variation depending on hybrid, spacing and nutrient management practices. The Saki hybrid (H_3) yielded the highest pooled mean vitamin C content at 97.49 mg 100 g^{-1}, surpassing the Lucky hybrid (H_1), which averaged 87.43 mg 100 g^{-1} (Table 4). S_2 had greater ascorbic acid content (95.13 mg 100 g^{-1}) compared to those at the S_1 (91.71 mg 100 g^{-1}). N_2 further boosted vitamin C levels (95.14 mg 100 g^{-1}), while N_1 (91.70 mg 100 g^{-1}).

Greater concentrations were observed with the pairing of Saki and wider spacing (H_3S_2, 98.53 mg 100 g^{-1}), as well as with Saki and high nutrient input (H_3N_2, 99.35 mg 100 g^{-1}) and the combination of S_2N_2 (96.18 mg 100 g^{-1}) (Table 5). In contrast, the lowest vitamin C content consistently appeared in Lucky under closer spacing (H_1S_1, 84.29 mg 100 g^{-1}), in Lucky with lower fertilization (H_1N_1, 85.07 mg 100 g^{-1}) and in S_1N_1 (89.32 mg 100 g^{-1}).

Among three-factor treatments, the integration of Saki hybrid, wider spacing and higher nutrient application (T_{12}: H3S2N2) produced the maximum vitamin C concentration at 100.45 mg 100 g^{-1}, closely followed by T_{10} (H3S1N2) at 98.25 mg 100 g^{-1} (Table 6).

Total soluble solids (°Brix)

Total soluble solids (TSS) content in broccoli was influenced by hybrid selection, plant spacing and nutrient levels, with significant differences across treatments. The NS1250 hybrid demonstrated significantly higher pooled TSS (6.37 °Brix) compared to Lucky (5.89° Brix) at $p < 0.05$ (Table 4). Wider spacing (60 cm × 45 cm) resulted in a pooled mean TSS of 6.17 °Brix, slightly exceeding the closer spacing (45 cm × 45 cm) at 6.10 °Brix. Application of a higher nutrient dose (150:100:75 kg NPK ha^{-1}) led to a raised pooled mean TSS (6.31 °Brix), while reduced nutrients (120:80:60 kg NPK ha^{-1}) corresponded to lower TSS (5.97 °Brix).

In two-factor combinations, TSS was higher in H_2S_2 (6.45° Brix), H_3N_2 (6.46 °Brix) and S_1N_2 (6.38 °Brix), with lower values in H_1S_2 (5.87 °Brix), H_1N_1 (5.72 °Brix) and S_1N_1 (5.83 °Brix) (Table 5). For three-factor interactions, the greater pooled TSS was measured in T_{10} ($H_3S_1N_2$) at 6.51 °Brix, followed by T_8 ($H_2S_2N_2$) at 6.49 °Brix, while the lowest was observed in T_1 ($H_1S_1N_1$) at 5.51 °Brix (Table 6).

Physiological loss in weight (PLW %)

Moisture retention and post-harvest quality, as indicated by physiological weight loss (PLW), varied significantly across hybrids, plant spacing and nutrient levels. Lucky showed the higher pooled PLW (26.06 %), whereas NS1250 exhibited lower loss (18.31 %), demonstrating better shelf life (Table 4). S_2 reduced PLW (20.96 %), compared to higher loss at S_1 (23.25 %). Optimal fertilization (N_2) resulted in lower PLW (20.07 %), while N_1 led to greater loss (24.14 %).

Among two-factor combinations, the lower PLW was found in H_2S_2 (17.99 %), H_2N_2 (17.08 %) and S_2N_2 (19.26 %), while higher PLW occurred in H_1S_1 (27.62 %), H_1N_1 (28.44 %) and S_1N_1 (25.62 %) (Table 5). The lowest PLW was observed in treatment T_6 ($H_2S_1N_2$), yielding a pooled mean of 16.30 %, whereas the higher loss was recorded in T_1 ($H_1S_1N_1$) at 29.35 % (Table 6).

Discussion

The growth and development of broccoli were significantly influenced by hybrid, plant spacing and nutrient levels over two consecutive Rabi seasons (2023-24 and 2024-25). NS1250 demonstrated superior plant height, larger leaf area and greater chlorophyll content, while Lucky produced a higher leaf number and wider plant spread in both the north–south and east-west directions. Closer spacing (45 cm x 45 cm) encouraged increased plant height, but wider spacing (60 cm x 45 cm) enhanced leaf number, leaf area, chlorophyll content and plant spread. The combined effect of closer spacing (45 cm x 45 cm) and higher nutrient application (150:100:75 kg NPK ha^{-1}) on the NS1250 hybrid produced the tallest plants, likely due to increased competition for light and limited resources at closer spacing making it grow taller in search of sunlight. This increased light competition induced elongation growth for sunlight, stimulating plants to grow taller to maximize photosynthesis (7).

Higher nutrient levels further supported physiological processes and biomass accumulation, allowing efficient nutrient utilization despite limited space. Conversely, the Lucky hybrid showed increased leaf number and plant spread under wider spacing, benefiting from reduced competition and optimal nutrient availability, which promoted robust vegetative growth. Expanded leaf area under wider spacing and higher nutrients aligns with enhanced photosynthesis and cell growth stimulated by genotypic potential and nutrients. The increased plant spread may result from improved metabolic activity, aided by greater nutrient availability and spatial freedom (8). Chlorophyll content peaked in NS1250 under wider spacing and elevated fertilization, likely due to better light penetration, nitrogen's role in chlorophyll synthesis and the hybrid's superior nutrient use efficiency (9, 10). These findings align with prior research demonstrating that hybrid genetics, planting density and fertilization interact complexly to influence broccoli development, morphology and productivity. Optimizing these factors is essential to maximizing yield and quality, as evidenced by this study's superior performance of NS1250 under tailored spacing and nutrient regimes.

Yield-related traits mirrored growth trends. The NS1250 hybrid matured earlier than Lucky, with earlier harvest observed under closer spacing and lower nutrient input. Head diameter and stalk thickness were consistently greater in NS1250, being favored by wider spacing and higher fertilization levels. The larger heads and thicker stalks were found in $H_2S_2N_2$, while Lucky with closer spacing and lower nutrients produced the smaller heads. Similarly, NS1250 delivered heavier head weight and greater yield compared to Lucky. Closer spacing and higher nutrition improved yield, with maximum performance in $H_2S_1N_2$, statistically paralleled by $H_2S_1N_1$, while Lucky in wider spacing and lower nutrients recorded lower yields. The early head maturity observed in the NS1250 hybrid under closer spacing (45 cm x 45 cm) with lower nutrient application may be attributed to stress-induced conditions which accelerated developmental processes and triggered a faster transition to maturity of broccoli heads. The stress signals the plant to transition more quickly from the vegetative stage to forming the edible head, so the heads mature faster than they might under optimal conditions. This aligns with previous findings reporting the influence of competitive environments on the speed of crop growth (11-13).

Conversely, wider spacing (60 cm x 45 cm) combined with higher NPK doses enhanced nitrogen availability for the NS1250 hybrid, stimulating chlorophyll production, amino acid synthesis and efficient carbohydrate use, ultimately increasing head diameter and weight. These improvements reflect the effects of higher dosage of nutrient supply and spatial freedom on assimilate allocation, vegetative growth and organic compound development, as supported by earlier studies (13-17). Furthermore, overall broccoli yield per hectare was significantly greater with higher nutrient levels and closer spacing, mainly due to increased plant population and improved nutrient uptake leading to enhanced photosynthesis, leaf area and translocation of assimilates (18, 19). The optimal treatment ($H_2S_1N_2$) achieves high yield without severely compromising head size by integrating a high-yielding hybrid (H_2), planting at a moderately close spacing (S_1) and supplying higher nutrient levels (N_2), which collectively support both greater plant density and sustained head development; the closer spacing boosts the number of marketable heads per area, while the superior hybrid vigor and nutrient availability help maintain adequate head size despite higher plant population, thus striking a balance between maximizing total yield and preserving acceptable individual head size for market quality.

Quality parameters such as head compactness, vitamin C content and TSS were significantly enhanced in Saki and NS1250 hybrids compared to Lucky. Wider spacing and higher nutrient application also increased these quality traits, with the highest values observed in combined treatments involving Saki or NS1250, wider spacing and higher fertilization. Physiological weight loss (PLW), reflecting postharvest moisture retention, was lower in NS1250 and higher nutrient applications, aligning with improved shelf life. Wider spacing mitigated PLW compared to denser planting. Two and three-factor combinations confirmed T_6 (NS1250, closer spacing and higher nutrients) as the most effective in reducing weight loss, whereas T_1(Lucky, closer spacing and lower nutrients) showed the greater losses. Overall, these results emphasize the interactive influence of genotype, planting density and nutrient management on broccoli growth, yield and quality, with NS1250 and Saki hybrids combined with optimized spacing and nutrient regimes consistently outperforming Lucky across parameters. These findings align with previous studies highlight the importance of integrated agronomic practices for maximizing broccoli productivity and postharvest quality.

Optimal head compactness, vitamin C content and total soluble solids in broccoli were achieved through strategic combinations of hybrid selection, plant spacing and nutrient application, underscoring the integration of genetic potential with favourable agronomic conditions. Treatments involving the NS1250 hybrid, particularly under wider spacing and higher nutrient doses reduced inter-plant competition and improved nutrient availability, promoting robust vegetative growth and efficient nutrient uptake, which led to the development of larger, more compact heads (11). The Saki hybrid exhibited elevated vitamin C levels under wider spacing and sufficient nutrients due to better absorption and utilization of micronutrients such as boron, zinc and manganese, enhancing ascorbic acid synthesis (20). Higher nutrient doses enhanced total soluble solids, likely through improved carbohydrate translocation (21). The lowest physiological weight loss was recorded with the NS1250 hybrid under optimal nutrition and spacing, reflecting strengthened plant vigor, compact head structure and improved water retention, enhancing shelf life (12, 18). Collectively, these results emphasize the critical interactions of genotype, planting density and nutrient management to maximize broccoli yield, quality and postharvest performance.

Conclusion

The study concludes that the growth, yield and quality of broccoli are significantly influenced by hybrid selection, planting density and nutrient management. Among the evaluated treatments, the NS1250 hybrid, when combined with a plant spacing of 45 cm × 45 cm and a higher nutrient dose of 150:100:75 kg NPK ha^{-1}, consistently exhibited superior performance across growth, yield and quality traits. These findings highlight that matching high genetic potential with optimal agronomic inputs directly supports both productivity and product quality. Overall, the results provide practical recommendations: adopt superior hybrids, maintain ideal spacing and ensure sufficient nutrient supply for achieving specific production goals, whether higher yield, enhanced quality or balanced outcomes.

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Authors' contributions

A carried out the studies, analysed and interpretated the data, participated in the sequence alignment and drafted the manuscript. SKN conceptualized and designed the study and was also involved in drafting the manuscript and revising it critically for important intellectual content. KGG conceptualized and participated in the design of the study and critically revised the manuscript. HBG participated in its design and coordination. MB participated in its design, provided expert monitoring throughout the study and manuscript revising. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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