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Research Article

Influence of Planting Density and Nutrient Regimes on Plant Macronutrient Uptake and Soil Nutrient Dynamics in Broccoli (*Brassica oleracea* var. *italica*) Hybrids Grown Under Polyhouse Condition

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Abstract

A polyhouse experiment at Sanjeevini Vatika, UAS, GKVK, Bengaluru (Rabi 2023–2024) evaluated planting density and nutrient regimes on broccoli hybrid nutrient uptake and soil dynamics. The experiment used a factorial randomized complete block design (RCBD). NS1250, under wider spacing with higher NPK application, showed increased nitrogen, phosphorus, and potassium uptake, while Lucky hybrid at closer spacing with lower inputs achieved superior nutrient use efficiency. Results indicate that strategic adjustment of planting and nutrient management under polyhouse conditions enhances both nutrient absorption and efficiency in broccoli, supporting greater sustainable production and soil health.

Keywords: Broccoli; Efficiency; Hybrid; Nutrient; Soil; Spacing

Abbreviations

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 ha^{-1}; N_2: 150:100:75 kg NPK ha^{-1}; N: Nitrogen; P: Phosphorus; K: Potassium; NUE: Nitrogen Use Efficiency; PUE: Phosphorus Use Efficiency; KUE: Potassium Use Efficiency.

Introduction

Broccoli (*Brassica oleracea* var. *italica*), an important member of the Cruciferae family, is cultivated worldwide for its highly nutritious immature flower heads. Celebrated for its abundant vitamins and minerals, broccoli is often described as a superfood, providing vitamin A in quantities far surpassing that of cauliflower (by 130 times) and cabbage (by 22 times) [1], as well as generous amounts of thiamin, riboflavin, niacin, vitamin C, calcium, phosphorus, potassium, and iron [1]. Regular consumption of broccoli has been reported to lower the risk of various cancers, largely due to the presence of sulforaphane—a compound known to boost the body's natural defense mechanisms and improve disease resistance [2]. Given its rich nutrient composition, broccoli contributes significantly to enhancing the nutritional well-being of populations. To maximize yields and quality, the crop demands an appropriate supply of essential nutrients. Mineral nutrient absorption by the aboveground portions of plants varies significantly both across different plant species and among cultivars within a single species [3]. Yet, there remains a knowledge gap regarding the influence of planting density and nutrient regimes on nutrient uptake and soil nutrient dynamics in broccoli. This study was conducted to evaluate the effects of planting density and nutrient regimes on macronutrient uptake and soil nutrient status in broccoli hybrids grown under polyhouse conditions.

Materials and Methods

Polyhouse experiments were undertaken during the *Rabi* seasons of 2023 and 2024 at *Sanjeevani Vatika*, Department of Horticulture, University of Agricultural Sciences, GKVK, Bengaluru. The experimental location, positioned in Karnataka's Eastern Dry Zone at 930 m AMSL, experiences an average maximum temperature of 26.40 °C and a minimum of 18.38 °C during the crop growth period. Prior to establishing the experiment, composite soil samples were randomly collected from the polyhouse at a depth of 0–30 cm. The samples were air-dried, finely ground, sieved through a 2 mm mesh, and stored in glass bottles for analysis. The polyhouse soil exhibited a uniform red coloration and topography, with a nearly neutral pH (6.47), normal electrical conductivity (0.75 dS m^{-1}) and a low organic carbon content (0.46%). Nutrient analysis revealed that available N levels (235.59 kg ha^{-1}) were low, P (49.47 kg ha^{-1}) and K (268.74 kg ha^{-1}) were present in medium amounts. Micronutrient assessment found sufficient levels of iron (4.96 mg kg^{-1}), manganese (3.74 mg kg^{-1}), and copper (2.49 mg kg^{-1}), while zinc (0.49 mg kg^{-1}) and boron (0.38 mg kg^{-1}) were deficient.

The field was initially prepared through deep ploughing using a tractor-drawn cultivator, followed by cross harrowing, rotavation and levelling to ensure a fine seedbed. During land preparation, farmyard manure was incorporated at a rate of 25 t ha^{-1}. The experiment was established following a factorial randomized complete block design (FRCBD) and included three replications. Treatments involved three factors: broccoli hybrids (H_1: Lucky; H_2: NS1250; H_3: Saki), two plant spacings (S_1: 45 cm × 45 cm; S_2: 60 cm × 45 cm) and two nutrient regimes (N_1: 120:80:60 kg NPK ha^{-1}; N_2: 150:100:75 kg NPK ha^{-1}). For fertilizer application, 50% of the total nitrogen and the full doses of phosphorus and potassium were applied as a basal dose, while the remaining nitrogen was top-dressed 30 days after transplanting.

Following crop harvest, composite soil samples were obtained from each plot at a depth of 0–30 cm. Standard protocols were utilized in the chemical analysis of these samples. Soil pH and electrical conductivity (EC) were assessed with a digital meter, as outlined by Jackson (1973) [4] and organic carbon was estimated using the Walkley and Black method (1934) [5]. Determination of available nitrogen, phosphorus and potassium in the soil was performed using the procedures described by Subbaiah (1956) [6], Bray and Kurtz (1945) [7] and Jackson [4], respectively. Micronutrient concentrations were quantified according to Lindsay and Norwell [8], while boron content was measured by the method described by John and co-workers (1975) [9]. Assessment of plant nutrient uptake samples were taken from recently expanded leaves and heads of each treatment plots. In order to determine the mineral contents of leaves and heads, plants samples were oven-dried at 60°C for 48 h and then ground, sample analysis involved several techniques: nitrogen was estimated via the micro-Kjeldahl method; phosphorus was measured by the vanado-molybdo phosphoric acid yellow color test [4]; and potassium was determined using the same approach as for available potassium in soil analysis. All data were collected for two consecutive *Rabi* seasons (2023 and 2024). Season-wise values for each treatment were tabulated for detailed comparison. The averages for all measurements were computed per treatment and subjected to the analysis of variance (ANOVA) to compare the effects using software OPSTAT. For concise reporting in the results and discussion section, mean (pooled) values across seasons were calculated and presented in the text, while individual seasonal data are shown in respective tables.

Results and Discussion

After harvesting the broccoli crop, analysis of soil pH, electrical conductivity and organic carbon content revealed no statistically significant variation among the combinations of hybrids, plant spacing and nutrient regimes under polyhouse condition. Detailed results for these soil attributes are provided in Table 1. Significant effects were observed for each of the individual factors—hybrid type, plant spacing, and nutrient levels—on post-harvest soil availability of nitrogen, phosphorus, and potassium, as well as on nutrient uptake by broccoli hybrids. The corresponding data are detailed in Table 2. Of the hybrids evaluated, Saki (H_3) resulted in the lower residual levels of available soil nitrogen (114.16 kg ha^{-1}), phosphorus (36.49 kg ha^{-1}) and potassium (181.04 kg ha^{-1}) after harvest. In contrast, the NS1250 hybrid (H_2) maintained higher concentrations of these nutrients in the soil at the end of the cropping cycle. Notably, Saki (H_3) absorbed significantly greater amounts of nitrogen (228.46 kg ha^{-1}), phosphorus (123.48 kg ha^{-1}) and H_2 absorbed significantly greater amounts potassium (171.98 kg ha^{-1}) compared to the other hybrids. When comparing plant spacing treatments, closer spacing (45 cm × 45 cm) resulted in lower post-harvest residual levels of nitrogen (113.81 kg ha^{-1}), phosphorus (36.45 kg ha^{-1}), and potassium (179.88 kg ha^{-1}) in the soil. In contrast, wider spacing (60 cm × 45 cm) maintained the higher soil nutrient availability after harvest. Additionally, the uptake of nitrogen (241.64 kg ha^{-1}), phosphorus (68.54 kg ha^{-1}) and potassium (181.69 kg ha^{-1}) by broccoli plants reached its maximum under the wider spacing. Application of the lower nutrient dose (N_1: 120:80:60 kg NPK ha^{-1}) resulted in the lower residual concentrations of available nitrogen (111.68 kg ha^{-1}), phosphorus (35.78 kg ha^{-1}) and potassium (177.78 kg ha^{-1}) in the soil, compared to treatments receiving higher fertilizer rates. In contrast, maximum nutrient uptake by broccoli plants was observed under N_2 (150:100:75 kg NPK ha^{-1}), with uptake values of 234.67 kg ha^{-1} for nitrogen, 64.85 kg ha^{-1} for phosphorus and 176.37 kg ha^{-1} for potassium. Variations in nutrient uptake and residual soil nutrients are due to genetic absorption abilities and planting density effects on roots and competition. Closer spacing limits roots and uptake, while wider spacing improves both. Higher fertilizer increases uptake and residual nutrients, balancing supply with crop demand. The findings are further supported by other investigators in broccoli [10,11].

Treatments	NUE (kg kg^{-1})		PUE (kg kg^{-1})		KUE (kg kg^{-1})	
	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024
$T_1 – H_1S_1N_1$	37.61	38.43	38.26	39.20	72.76	71.19
$T_2 – H_1S_1N_2$	36.92	37.06	35.43	36.30	60.90	59.48
$T_3 – H_1S_2N_1$	28.77	29.16	29.69	30.55	49.44	47.87
$T_4 – H_1S_2N_2$	28.23	28.95	29.67	30.53	47.46	46.04
$T_5 – H_2S_1N_1$	37.58	38.02	37.53	38.03	68.44	66.87
$T_6 – H_2S_1N_2$	37.06	37.12	36.79	37.83	67.77	65.41
$T_7 – H_2S_2N_1$	28.95	29.42	32.38	31.47	55.22	53.65
$T_8 – H_2S_2N_2$	33.00	33.00	34.26	33.14	57.81	56.39
$T_9 – H_3S_1N_1$	35.28	35.28	35.28	35.54	60.55	58.98
$T_{10} – H_3S_1N_2$	34.06	34.06	34.80	33.45	59.45	58.03
$T_{11} – H_3S_2N_1$	27.40	27.40	22.39	23.25	45.73	45.23
$T_{12} – H_3S_2N_2$	23.22	24.01	20.82	21.68	45.24	44.14

Table 1: Interaction effect of hybrids, plant spacing and nutrient levels on nutrient use efficiency under polyhouse condition.

NUE- Nitrogen Use Efficiency; PUE- Phosphorus Use Efficiency; KUE- Potassium Use Efficiency; NUE, PUE, KUE refer to nutrient use efficiency values calculated as kg of nutrient uptake per kg of applied fertilizer;

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 ha^{-1}; N_2: 150:100:75 kg NPK ha^{-1}.

Treat-ments	Available nutrients in the soil (kg ha^{-1})						Nutrient uptake (kg ha^{-1})					
	N		P_2O_5		K_2O		N		P_2O_5		K_2O	
	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_1	115.72	116.60	37.59	36.88	181.15	182.78	221.20	221.07	60.09	58.97	167.06	166.87
H_2	115.91	117.09	37.64	37.55	183.70	184.03	226.10	226.61	60.92	59.41	171.81	172.14
H_3	114.07	114.24	36.79	36.18	180.07	182.00	227.91	229.00	62.13	61.35	171.53	171.80
S.Em±	0.37	0.35	0.19	0.15	0.42	0.23	1.72	1.46	0.54	0.42	0.66	0.67
CD (5%)	1.07	1.04	0.55	0.44	0.87	0.69	5.03	4.28	1.60	1.24	1.93	1.95
S_1	113.37	114.25	36.99	35.91	178.90	180.86	208.58	209.40	52.98	51.86	158.65	158.78
S_2	117.10	117.70	37.69	37.83	184.38	185.01	241.57	241.71	69.11	67.97	181.62	181.76
S.Em±	0.30	0.29	0.15	0.12	0.24	0.19	1.40	1.19	0.45	0.35	0.54	0.54
CD (5%)	0.88	0.85	0.45	0.36	0.71	0.56	4.11	3.49	1.30	1.01	1.58	1.60
N_1	111.37	111.99	36.15	35.41	176.89	178.66	215.77	216.14	56.66	55.56	163.89	164.16
N_2	119.10	119.96	38.53	38.33	186.39	187.21	234.37	234.97	65.43	64.26	176.38	176.36
S.Em±	0.30	0.29	0.15	0.12	0.24	0.19	1.40	1.19	0.45	0.35	0.54	0.54
CD (5%)	0.88	0.85	0.45	0.36	0.71	0.56	4.11	3.49	1.30	1.01	1.58	1.60

Table 2: Effect of hybrids, plant spacing and nutrient levels on post-harvest soil availability of nitrogen, phosphorus and potassium and on plant nutrient uptake under polyhouse condition.

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 ha^{-1}; N_2: 150:100:75 kg NPK ha^{-1}.

The two-way interaction between broccoli hybrids, plant spacings and nutrient regimes summarized in Table 3. The combination of NS1250 hybrid at wider spacing (H_2S_2: NS1250 + 60 cm × 45 cm) resulted in the higher soil nutrient retention, yielding available nitrogen at 119.85 kg ha^{-1}, phosphorus at 39.06 kg ha^{-1} and potassium at 189.62 kg ha^{-1} after harvest. Conversely, the lower available nitrogen was found in H_3S_1 (Saki + 45 cm × 45 cm + 112.58 kg ha^{-1}) and phosphorus (35.76 kg ha^{-1}), while H_2S_1 showed the lower post-harvest potassium (178.11 kg ha^{-1}) levels. The greater nutrient uptake by broccoli was achieved with NS1250 hybrid at wider spacing, resulting in nitrogen, phosphorus and potassium uptake of 247.89 kg ha^{-1}, 70.08 kg ha^{-1} and 185.65 kg ha^{-1}, respectively. In contrast, the combination of Lucky and closer spacing recorded the lower uptake, with 203.47 kg ha^{-1} nitrogen and 154.52 kg ha^{-1} potassium whereas, NS1250 and closer spacing recorded lower phosphorus uptake of 50.25 kg ha^{-1}.

Among hybrid and fertilizer level combinations (Table 3), NS1250 supplied with the higher NPK rate left the higher residual soil nutrients post-harvest (N: 121.02 kg ha^{-1}, P: 39.68 kg ha^{-1}, K: 189.86 kg ha^{-1}). In contrast, Saki under the lower NPK dosage had the lower residual N: 111.04 kg ha^{-1} and P: 35.52 kg ha^{-1}) while, H_1N_1 had the lower residual K: 177.91 kg ha^{-1}). For nutrient uptake, H_3N_2 (Saki + 150:100:75 kg NPK ha^{-1}) recorded the higher uptake values (N: 235.07 kg ha^{-1}, P: 65.85 kg ha^{-1}, K: 177.33 kg ha^{-1}), while H_1N_1 (Lucky + 120:80:60 kg NPK ha^{-1}) showed the lower uptake (N: 208.19 kg ha^{-1}, P: 53.59 kg ha^{-1} and K: 158.47 kg ha^{-1}).

Evaluating spacing and nutrient applications (Table 3), the higher post-harvest soil nutrient availability recorded in S_2N_2 with nitrogen, phosphorus and potassium at120.53 kg ha^{-1}, 38.82 kg ha^{-1} and 189.83 kg ha^{-1}, respectively. S_1N_1 had the lower nutrient availability (N: 109.09 kg ha^{-1}, P: 34.86 kg ha^{-1} and K: 175.99 kg ha^{-1}) in soil at harvest. The combination, S_2N_2 had the higher nutrient uptake (N: 248.59 kg ha^{-1}, P:72.23 kg ha^{-1} and K: 188.73 kg ha^{-1}), while S_1N_1 presented the lower uptake (N: 197.23 kg ha^{-1}, P: 47.38 kg ha^{-1} and K: 153.40 kg ha^{-1}).

Treat-ments	Available nutrients in the soil (kg ha^{-1})						Nutrient uptake (kg ha^{-1})					
	N		P_2O_5		K_2O		N		P_2O_5		K_2O	
	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)												
H_1S_1	115.24	116.17	37.87	37.06	180.80	182.23	203.69	203.25	52.11	50.68	154.59	154.45
H_1S_2	116.20	117.04	37.32	36.70	181.50	183.33	238.71	238.88	68.07	67.27	179.54	179.28
H_2S_1	112.76	113.54	36.77	35.49	177.78	178.44	203.57	206.10	51.01	49.49	158.18	158.45
H_2S_2	119.06	120.64	38.51	39.61	189.61	189.62	248.64	247.13	70.83	69.33	185.45	185.84
H_3S_1	112.11	113.04	36.35	35.17	178.12	181.90	218.48	218.86	55.82	55.40	163.18	163.45
H_3S_2	116.03	115.43	37.23	37.18	182.02	182.09	237.35	239.13	68.45	67.31	179.88	180.15
S.Em±	0.52	0.50	0.26	0.21	0.42	0.33	2.43	2.06	0.77	0.60	0.93	0.77
CD (5%)	1.52	1.46	0.78	0.62	1.23	0.97	7.11	6.05	2.26	1.76	2.73	2.76
(H×N)												
H_1N_1	111.55	112.48	36.37	36.22	176.59	178.53	208.17	208.20	54.10	53.08	158.33	158.60
H_1N_2	119.89	120.72	38.82	37.53	185.72	187.03	234.23	233.93	66.08	64.87	175.80	175.13
H_2N_1	111.52	112.45	36.07	34.98	177.58	178.15	217.64	218.07	57.90	56.33	167.47	167.74
H_2N_2	120.30	121.73	39.22	40.13	189.81	189.90	234.57	235.15	63.93	62.49	176.15	176.55
H_3N_1	111.03	111.05	36.01	35.03	176.52	179.29	221.51	222.16	57.99	57.29	165.86	166.13
H_3N_2	117.12	117.43	37.57	37.32	183.63	184.70	234.31	235.83	66.28	65.42	177.19	177.46
S.Em±	0.52	0.50	0.26	0.21	0.42	0.33	2.43	2.06	0.77	0.60	0.93	0.77
CD (5%)	1.52	1.46	0.78	0.62	1.23	0.97	7.11	6.05	2.26	1.76	2.73	2.76
(S×N)												
S_1N_1	108.62	109.55	35.54	34.17	174.65	177.32	196.79	197.66	47.80	46.95	153.26	153.53
S_1N_2	118.12	118.95	38.44	37.64	183.15	184.40	220.36	221.15	58.16	56.77	164.04	164.04
S_2N_1	114.11	114.44	36.75	36.64	179.13	179.99	234.75	234.63	65.53	64.18	174.52	174.79
S_2N_2	120.08	120.97	38.63	39.01	189.62	190.03	248.38	248.80	72.70	71.75	188.72	188.73
S.Em±	0.42	0.41	0.22	0.17	0.34	0.27	1.98	1.69	0.63	0.49	0.76	0.77
CD (5%)	1.24	1.20	0.63	0.50	1.00	0.79	5.81	4.94	1.84	1.43	2.23	2.26

Table 3: Two-way interaction effect of hybrids, plant spacing and nutrient levels on post-harvest soil availability of nitrogen, phosphorus and potassium and on plant nutrient uptake under polyhouse condition.

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 ha^{-1}; N_2: 150:100:75 kg NPK ha^{-1}.

The three-way interaction of hybrids, plant spacings and nutrient regime's significant outcomes for uptake and residual of NPK are detailed in Table 4. Specifically, the treatment T_5 ($H_2S_1N_1$: NS1250 + 45 cm × 45 cm + 120:80:60 kg NPK ha^{-1}) resulted in the lower soil nutrient levels after harvest, measuring 107.95 kg ha^{-1} nitrogen, 33.98 kg ha^{-1} phosphorus and 173.85 kg ha^{-1} potassium. By contrast, the combination $H_2S_2N_2$ (T_8: NS1250 + 60 cm × 45 cm + 150:100:75 kg NPK ha^{-1}) recorded the higher residual nutrients in soil after the harvest. Macronutrient uptake by plants displayed significant variation. Maximum uptake was observed in combination $H_2S_2N_2$ (T_8: NS1250 + 60 cm × 45 cm + 150:100:75 kg NPK ha^{-1}), with 257.70 kg ha^{-1} nitrogen, 73.71 kg ha^{-1} phosphorus and 193.60 kg ha^{-1} potassium. This was comparable to treatment T_4 ($H_1S_2N_2$: Lucky + 60 cm × 45 cm + 150:100:75 kg NPK ha^{-1}), which had 247.37 kg ha^{-1} nitrogen, 72.27 kg ha^{-1} phosphorus and 186.98 kg ha^{-1} potassium uptake. Conversely, the lower absorption was found in treatment T_1 ($H_1S_1N_1$: Lucky + 45 cm × 45 cm + 120:80:60 kg NPK ha^{-1}), with plant uptake values of 186.15 kg ha^{-1} nitrogen, 44.11 kg ha^{-1} phosphorus and 145.09 kg ha^{-1} potassium. Although closer spacing increases plant density, in this study it led to lower uptake due to root competition. Wider spacing allowed better individual plant uptake, resulting in higher total nutrient absorption. Hybrid vigor, spacing, and fertilizer jointly affect nutrient dynamics, with densely planted, high-demand hybrids and low fertilizer causing greater soil depletion than wider spacings with higher inputs.

Treatments	Available nutrients in the soil (kg ha^{-1})						Nutrient uptake (kg ha^{-1})					
	N		P_2O_5		K_2O		N		P_2O_5		K_2O	
	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024
T_1 – $H_1S_1N_1$	108.93	109.86	36.02	35.88	175.01	175.75	185.62	186.67	44.49	43.73	144.95	145.22
T_2 – $H_1S_1N_2$	121.55	122.48	39.71	38.24	186.59	188.71	221.76	219.83	59.72	57.63	164.23	163.68
T_3 – $H_1S_2N_1$	114.18	115.11	36.72	36.57	178.16	181.31	230.72	229.73	63.71	62.43	171.71	171.98
T_4 – $H_1S_2N_2$	118.22	118.96	37.92	36.82	184.85	185.35	246.70	248.04	72.43	72.11	187.37	186.58
T_5 – $H_2S_1N_1$	107.48	108.41	34.83	33.13	173.39	174.30	196.57	198.72	48.72	46.83	157.39	157.66
T_6 – $H_2S_1N_2$	118.03	118.67	38.71	37.86	182.16	182.58	210.57	213.47	53.29	52.14	158.96	159.23
T_7 – $H_2S_2N_1$	115.55	116.48	37.30	36.82	181.76	181.99	238.71	237.42	67.08	65.83	177.55	177.82
T_8 – $H_2S_2N_2$	122.57	124.79	39.72	42.39	197.46	197.23	258.57	256.83	74.58	72.83	193.34	193.86
T_9 – $H_3S_1N_1$	109.45	110.38	35.78	33.52	175.54	181.90	208.19	207.58	50.17	50.28	157.43	157.70
T_{10} – $H_3S_1N_2$	114.78	115.71	36.91	36.82	180.70	181.90	228.76	230.14	61.47	60.53	168.93	169.20
T_{11} – $H_3S_2N_1$	112.61	111.72	36.23	36.54	177.49	176.67	234.83	236.73	65.81	64.29	174.29	174.56
T_{12} – $H_3S_2N_2$	119.45	119.15	38.23	37.82	186.55	187.51	239.86	241.53	71.08	70.32	185.46	185.73
S.Em±	0.43	0.70	0.36	0.37	0.59	0.47	3.43	2.92	1.09	0.85	1.32	1.33
CD (5%)	1.25	2.07	1.05	1.10	1.73	1.37	10.06	8.56	3.19	2.49	3.86	3.91

Table 4: Three-way interaction effects of broccoli hybrids, plant spacing and nutrient levels on nutrient uptake and post-harvest soil nutrient availability under polyhouse condition.

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 ha^{-1}; N_2: 150:100:75 kg NPK ha^{-1}.

Treatment T_1 (Lucky hybrid at 45 cm × 45 cm spacing with 120:80:60 kg NPK ha^{-1}) resulted in the higher efficiencies for nitrogen, phosphorus and potassium use, with recorded mean values of 38.02 kg kg^{-1} for NUE (Nitrogen Use Efficiency), 38.73 kg kg^{-1} for PUE (Phosphorus Use Efficiency) and 71.98 kg kg^{-1} for KUE (Potassium Use Efficiency) (Table 5). In contrast, treatment T_{12} (Saki hybrid at 60 cm × 45 cm spacing with 150:100:75 kg NPK ha^{-1}) showed the lower macronutrient use efficiencies, achieving only 23.62 kg kg^{-1} for NUE, 21.25 kg kg^{-1} for PUE and 44.69 kg kg^{-1} for KUE. The pronounced nutrient use efficiency in T_1 can be attributed to the Lucky hybrid's superior genetic ability for nutrient uptake in tandem with denser planting, which increases nutrient absorption per unit of fertilizer. These results emphasize that the combination of a genetically nutrient-efficient hybrid, optimal plant population density and adequate nutrient supply yields markedly improved nutrient use efficiency in broccoli cultivation. Other researchers have also observed similar patterns in broccoli [11-13].

The combined effects of hybrid type, plant spacing and major nutrient levels did not result in significant variation in the soil concentrations of zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), or boron (B). Table 6 displays the detailed outcomes for these micronutrients. Evaluation of micronutrient uptake by broccoli hybrids under polyhouse conditions, as shown in Table 7, indicated no statistically significant differences in absorption rates among the tested treatments.

Treatments	Zn (mg ha^{-1})		Fe (mg ha^{-1})		Mn (mg ha^{-1})		Cu (mg ha^{-1})		B (mg ha^{-1})	
	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024
$T_1 – H_1S_1N_1$	0.35	0.36	4.51	4.56	3.32	3.35	2.56	2.60	0.26	0.27
$T_2 – H_1S_1N_2$	0.36	0.36	4.55	4.66	3.35	3.32	2.55	2.60	0.27	0.27
$T_3 – H_1S_2N_1$	0.35	0.36	4.51	4.51	3.37	3.39	2.61	2.62	0.27	0.27
$T_4 – H_1S_2N_2$	0.35	0.35	4.52	4.63	3.34	3.34	2.57	2.61	0.27	0.26
$T_5 – H_2S_1N_1$	0.36	0.35	4.56	4.51	3.32	3.28	2.54	2.62	0.27	0.27
$T_6 – H_2S_1N_2$	0.36	0.35	4.55	4.64	3.34	3.35	2.55	2.64	0.27	0.26
$T_7 – H_2S_2N_1$	0.35	0.35	4.53	4.65	3.37	3.34	2.56	2.63	0.26	0.25
$T_8 – H_2S_2N_2$	0.36	0.36	4.56	4.73	3.33	3.33	2.57	2.64	0.27	0.27
$T_9 – H_3S_1N_1$	0.35	0.35	4.53	4.43	3.31	3.34	2.55	2.64	0.26	0.24
$T_{10} – H_3S_1N_2$	0.35	0.37	4.55	4.63	3.34	3.36	2.56	2.59	0.26	0.26
$T_{11} – H_3S_2N_1$	0.35	0.36	4.57	4.65	3.35	3.43	2.54	2.60	0.28	0.26
$T_{12} – H_3S_2N_2$	0.36	0.36	4.56	4.45	3.37	3.42	2.55	2.64	0.27	0.27
S.Em±	0.01	0.01	0.08	0.06	0.05	0.05	0.03	0.03	0.01	0.01
CD (5%)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 5: Interaction effect of hybrids, plant spacing and nutrient levels on post-harvest soil availability of micronutrients under polyhouse condition.

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 ha^{-1}; N_2: 150:100:75 kg NPK ha^{-1}.

Treatments	Zn (g ha^{-1})		Fe (g ha^{-1})		Mn (g ha^{-1})		Cu (g ha^{-1})		B (g ha^{-1})	
	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024	Rabi 2023	Rabi 2024
$T_1 - H_1S_1N_1$	82.34	83.21	216.29	215.98	121.42	121.32	39.10	39.24	62.09	61.28
$T_2 - H_1S_1N_2$	83.85	85.14	226.35	228.50	125.01	124.36	38.13	38.18	63.13	63.85
$T_3 - H_1S_2N_1$	82.90	83.91	212.77	214.58	120.14	120.99	38.50	38.64	63.74	63.91
$T_4 - H_1S_2N_2$	87.80	88.61	231.42	231.62	126.15	127.00	39.71	39.89	65.12	65.33
$T_5 - H_2S_1N_1$	84.17	85.27	217.15	218.33	123.71	122.69	39.75	39.92	60.52	60.17
$T_6 - H_2S_1N_2$	83.61	84.06	222.52	222.21	124.78	123.51	39.58	39.79	62.46	62.87
$T_7 - H_2S_2N_1$	85.80	86.21	209.13	210.94	120.11	120.70	40.88	41.09	63.88	64.01
$T_8 - H_2S_2N_2$	87.65	88.17	231.25	230.94	125.89	126.22	40.66	40.87	64.97	65.18
$T_9 - H_3S_1N_1$	86.00	86.31	219.51	219.71	124.33	123.39	38.89	39.10	63.08	63.75
$T_{10} - H_3S_1N_2$	84.34	86.11	228.30	228.52	125.12	124.62	40.04	40.25	62.87	63.47
$T_{11} - H_3S_2N_1$	86.61	87.29	218.64	219.32	123.96	122.95	38.78	38.99	64.86	65.04
$T_{12} - H_3S_2N_2$	87.81	89.21	233.99	236.16	126.35	127.56	41.34	41.55	68.45	67.58
S.Em±	1.02	1.31	3.16	3.16	1.38	1.38	0.65	0.65	0.85	1.05
CD (5%)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 6: Interaction effect of hybrids, plant spacing and nutrient levels on plant micronutrient uptake under polyhouse condition.

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 ha^{-1}; N_2: 150:100:75 kg NPK ha^{-1}.

Conclusion

Saki hybrid showed superior nutrient uptake and lower residual soil nutrients. Wider spacing (60 cm × 45 cm) and higher fertilizer rates improved both nutrient retention and absorption. These findings suggest that NS1250 under wider spacing with high NPK is suitable for maximizing uptake, while Lucky under closer spacing with lower NPK achieves the best nutrient use efficiency. These findings highlight the critical synergy between genetic selection and well-managed agronomic practices in optimizing broccoli productivity and nutrient efficiency.

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Conflict of Interest

The authors declare that there is no conflict of interest.

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