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Maximizing productivity in onion bulb cultivation through crop geometry and NPKS nutrient management

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Abstract

A study was conducted to determine the optimal dosage of NPKS fertilizer and the most suitable crop geometry to enhance both productivity and bulb quality of kharif onion (*Allium cepa* L.). The research was laidout using a split plot design, incorporating three levels of NPKS fertilizer in the main plot and five different crop geometries in the subplot, with three replications spanning from August to November in the years 2020-21 and 2021-22. Among the various combinations tested, the widest crop geometry (15 cm x 15 cm) coupled with the application of 140 N: 80 P: 80 K: 40 S kg ha^{-1} dose of nutrients exhibited superior results. This combination resulted in the highest values for plant height (97.88 cm), number of leaves per plant (19), leaves' weight per plant (74.15 g), average bulb weight (133.97 g), and harvest index (51.24). Conversely, the closest spacing (7.5 x 7.5 cm) with the highest fertilizer dose led to the maximum biological yield (125.89 t ha^{-1}) and bulb yield (61.89 t ha^{-1}). Notably, the spacing of 10 x 10 cm with the application of 140 N: 80 P: 80 K: 40 S kg ha^{-1} emerged as the optimal combination for achieving the highest marketable yield (43.62 t ha^{-1}), gross return (₹ 5.23 lakhs), net return (₹ 4.23 lakhs), and benefit-cost ratio (4.23). Consequently, we conclude that, for maximizing the production of marketable bulbs of kharif onion, a crop geometry of 10 x 10 cm with a nutrient dose of 140 N: 80 P: 80 K: 40 S kg ha^{-1} is recommended. This information contributes valuable insights for optimizing onion cultivation practices, thereby enhancing both yield and economic returns.

Key word: Biological yield, bulb, geometry, harvest index, nutrient, quality attributes

Introduction

Onion (*Allium cepa* L.), a member of the Amaryllidaceae family, holds the distinction of being the second most widely cultivated and one of the oldest food crops globally. Revered for its indispensable role in enhancing flavor and pungency, this versatile crop serves as a vegetable, spice, and medicinal plant (Muhie, 2022). Its significance extends beyond domestic consumption, with India ranking among the foremost contributors to the international trade of fresh agricultural produce, notably earning substantial foreign exchange (Muhie, 2022; Anonymous, 2021).

The characteristic pungency of onions is attributed to the presence of allyl-propyl disulphide, a sulfur-bearing compound found in the volatile oil of the vegetable ($C_6H_{12}S_2$). Leading global onion producers include China, India, and Egypt (Muhie, 2022), with India contributing significantly to the global export market. In the fiscal year 2020-21, India exported 1.58 million metric tons of fresh onions, amounting to a noteworthy 378.49 USD million (Anonymous, 2021). Worldwide, onion bulb production in 2017 reached 97.80 million metric tons from 5.20 million hectares, yielding an average of 18.80 t ha^{-1}. India, as the second-largest onion producer globally, harvested 26.64 million tons from 1.62 million hectares in the year 2021-22. However, the productivity of onions in India remains comparatively low at 16.44 t ha^{-1}, underscoring the potential for improvement through enhanced agro-techniques, specifically nutrient management and optimized crop geometry.

Notably, better agricultural practices, particularly refined nutrient management and strategic crop geometry, have the potential to elevate both productivity and bulb quality. Existing data demonstrate that the application of NPK fertilizer with sulfur positively influences bulb yield and quality. Conversely, imbalances in nutrient application negatively impact onion productivity and bulb quality. Studies, such as that by Sandana *et al.* (2020), emphasize the detrimental effects of subordinate fertilization, particularly with phosphorus, which can lead to a significant reduction in yield, up to 70 percent.

The optimal fertilizer requirements for onions have been established within a broad range: 95 to 150 kg N, 13 to 57 kg P, and 42 to 150 kg K ha^{-1}, as reported by various researchers (Lee *et al.*, 2011; Meher *et al.*, 2016; Khokhar, 2019; Mazumder *et al.*, 2019; Mandal *et al.*, 2020), resulting in yields ranging from 10 to 30 t ha^{-1}. Khokhar (2019) underscores the onion bulb's substantial nutrient uptake, removing 108 kg of nitrogen, 21 kg of phosphorus, and 120 kg of potassium per hectare to produce 60 t ha^{-1} of onions.

Beyond nutrition, crop geometry plays a pivotal role in determining onion productivity and marketability. Efficient utilization of available crop land without wastage is achieved through carefully considered crop spacing, avoiding competition among plants for essential growth factors such as water, nutrients, CO_2, and light. Acknowledging the critical influence of nutrient management and crop geometry on onion cultivation, this experiment was undertaken with the hypothesis that a balanced NPKS fertilization regimen, coupled with appropriate crop geometry, can significantly enhance the productivity and bulb quality of onions.

Materials and methods

The field experiment was conducted at Agricultural Research Substation, Sumerpur- Pali (Rajasthan) during *kharif* season of the two successive years of 2020-21 and 2021-22. The centre is located at 73° 05' East longitude and 25° 09' North latitude with an altitude of 272 m above Mean Sea Level. The centre is grouped under arid region with rainfall of 356.8 mm, signify RH 48.25 per cent and means maximum temperature of 33° C and minimum 19.5° C during first year of experimentation (August to November, 2020-21) and average rainfall of 147.0 mm, signify RH 55.75 per cent and means maximum temperature of 47.5° C and minimum 18.5° C during second year of experimentation (August to November, 2021-22). The soil analysis result showed that the experimental site had a soil pH of 8.2, EC 0.30 ds/m with 0.25 per cent organic carbon. It has 28 kg P_2O_5 ha^{-1}, 139 kg K_2O ha^{-1}, 0.16 ppm Zn, 1.26 ppm Fe, 0.20ppm Cu and 0.82 ppm Mn. The soil was 8, 30 and 62 per cent clay, silt and sand respectively, which gave sandy-loamy soil texture. The 15 treatment combinations were comprise with three levels of NPKS fertilizer ($F_1$100 N: 40 P: 40 K: 20 S; F_2 120 N: 60 P: 60 K: 30 S; F_3 140 N: 80 P: 80 K: 40 S) kg ha^{-1}, and five crop geometries ($S_1$7.5 x 7.5 cm, S_2 10 cm x 10 cm, S_3 12.5 cm x 12.5 cm, S_4 15 cm x 15 cm and S_5 12.5 cm x 10 cm).

The two factor experiment was laid out in Split Plot Design by means of NPKS levels as main plot and crop geometry as subplot with three replications. Onion seeds of variety Agrifound Dark Red, suitable for kharif season production were sown in nursery on a well prepared seed bed in first week of June. The experimental plot size was 3m × 90 cm on raised bed with drip irrigation and adjacent plots and blocks were 1.0 m and 1.5 m apart, respectively.

Data were recorded from the middle rows of each plot left one plant at both ends of rows. The entire amount of well decompose FYM (25 t ha^{-1}), and treatment wise full dose of phosphorus, potash, sulphur, 1/3 of N were applied during land preparation and 50 days old seedlings were used for transplanting. The doses of nitrogen fertilizer as Urea (46% N), phosphorus fertilizer as DAP (48% P_2O_5 + 18% N), potassium fertilizer as Muriate of Potash (60% K_2O), and sulphur as Sulfex Gold (Sulphur 80% w/w) were used. The rest of N applied in two equal splits as top dress at 30 and 60 days after transplanting. All other recommended cultural practices including irrigation, gap filling, weeding, diseases and pest management concerning onion production were done as and when required. Transplanting of seedlings on 28 to 29 July and harvesting was done on 13th November to 15th November of both years of experimentation, when bulbs were mature. The plant height was measured from ground level to the tip of the longest leaf. The number of fully grown, green and photosynthetically active leaves were recorded. The neck diameter below the joint of leaf lamina was measured with the help of digital vernier caliper. Bulb weight leaves weight, leaf: bulb ratio, root length, root weight, number of roots were recorded by using standard methods from randomly selected ten bulbs and averaged. Bulb yield, split bulb yield, unmarketable bulb, biological yield and marketable yield per ha was computed from the yield obtained per hectare. The TSS was determined by hand refractometer (ATAGO TC-1E) with a range of 0 to 32 °Brix and resolutions of 0.2 °Brix by placing 1 to 2 drops of clear juice on the prism. The refractometer was standardized against distilled water (0% TSS). A semi-trained judge used a 10-point hedonic scale to determine the overall quality score (taste, pungency, size, shape, consumer preference, *etc.*) and color score of the bulb (Amerine *et al.*, 1965). By dividing the bulb length (polar diameter) by the bulb width (equatorial diameter), the bulb shape index was calculated. Bulb with index value 1 is considered globular, bulb with less than 1 is considered flat, and bulb with more than 1 is considered torpedo. The harvest index was calculated as a percentage by dividing economic (bulb) yield per hectare by total biological yield per hectare on a fresh weight basis. Unmarketable bulbs are determined subjectively and recorded as the weight of diseased, decayed, insect-attacked, and abnormal bulbs at harvest, including multiple bulbs, thick necked bulbs, too small bulbs (less than 30 g weight), too large bulbs, and so on. The gross return was calculated by multiplying the yield by the average market rate during the investigation period. In addition, the net return was calculated by deducting the cost of each treatment from the gross return. The benefit cost ratio was computed by dividing net return by total cultivation cost. All data for each parameter were collected from ten randomly selected plants in each unit plot, and data were pooled from two consecutive growing years and analyzed using Statistical Analysis System (SAS) software (Version 9.1) for analysis of variance, and differences among means were compared at $P<0.05$.

Results

Effect of crop geometry: Results revealed that wider crop spacing, particularly at 15 x 15 cm, significantly enhanced vegetative growth parameters, resulting in the highest plant height, number of leaves per plant, and overall plant vigor. Optimal bulb weight was achieved at 10 x 10 cm spacing, whereas 7.5 x 7.5 cm spacing produced smaller and unmarketable bulbs (Table 1). Closer spacing intensified premature bolting, reaching 10.04% at 7.5 x 7.5 cm, while 15 x 15 cm spacing demonstrated the lowest bolting rate of 6.17%. Decreasing crop geometry significantly increased total bulb yield and biological fresh matter yield, with the highest values observed at 7.5 x 7.5 cm.

Higher plant population density (7.5 x 7.5 cm) resulted in a substantial increase in the number and weight of unmarketable bulbs, leading to a significant reduction in economic yield. Quality parameters, such as total soluble solids, bulb color score, and overall quality, favored precisely populated plots (10 x 10 cm and 12.5 x 10 cm). The marketable yield, gross return, net return, and B: C ratio were optimal at 10 x 10 cm spacing. The highest biological yield and total bulb yield were recorded in closer spacing at 7.5 x 7.5 cm, albeit with a notable quantity of unmarketable bulbs. Increasing crop geometry from 7.5 x 7.5 cm to 10 x 10 cm enhanced marketable fresh bulb yield, gross return, net return, and B: C ratio by approximately 33%, indicating the suitability of 10 x 10 cm spacing for optimal onion production.

Effect of NPKS fertilizer levels: Different NPKS fertilizer combinations significantly influenced all vegetative growth parameters (Table 1). The highest values for plant height (77.83 cm), number of leaves per plant (14.43), neck diameter (18.61 mm), leaves weight per plant (63.19 g), leaf bulb ratio (0.80), root length (7.80 cm), number of roots per plant (139.99), and root weight per plant (4.33) were observed with the highest fertilizer rate (F3: 140 N: 80 P: 80 K: 40 S kg ha^{-1}), followed by F2 (120 N: 60 P: 60 K: 30 S kg ha^{-1}), while the lowest values were recorded with F1 (100 N: 40 P: 40 K: 20 S kg ha^{-1}). Bulb shape index was not significantly affected, exhibiting a globular shape in F3 and 'torpedo' shapes in other treatments (index 1.03 to 1.05).

Table 1. Effect of onion crop geometry and NPKS fertilizer levels on vegetative growth parameters

Treatments	Plant Height (cm)	No. of leaves plant^{-1}	Neck dia-meter (mm)	Leaves weight plant^{-1} (g)	Root length (cm)	No. of roots plant^{-1}	Root weight plant^{-1} (g)
Crop geometry							
S1	58.52	9.46	14.53	48.20	5.90	110.91	2.88
S2	69.21	11.25	16.81	54.97	6.78	121.75	3.38
S3	75.38	14.00	18.77	63.46	7.59	124.25	4.47
S4	86.57	16.58	20.33	71.58	9.28	134.41	6.02
S5	71.14	13.37	16.80	56.66	7.40	125.91	3.76
S. Em$\pm$	1.04	0.16	0.29	0.58	0.08	0.99	0.06
C.D. (P=0.05)	3.03	0.47	0.87	1.71	0.24	2.91	0.19
NPKS fertilizer levels							
F1	65.46	11.28	15.94	54.59	6.95	122.27	3.72
F2	73.2	13.09	17.8	59.14	7.42	117.08	4.25
F3	77.83	14.43	18.61	63.19	7.80	130.99	4.33
S. Em$\pm$	1.39	0.21	0.40	0.79	0.11	1.34	0.09
C.D. (P=0.05)	5.48	0.85	1.56	3.10	0.43	5.26	0.36
Interaction between crop geometry and NPKS fertilizer levels							
S1F1	52.09	8.00	13.04	44.53	5.63	107.87	2.84
S2F1	63.31	9.63	14.47	50.04	6.62	119.37	2.97
S3F1	69.73	12.63	16.89	57.23	7.03	123.87	3.91
S4F1	76.65	14.13	19.60	68.25	8.59	135.87	5.51
S5F1	65.50	12.00	15.70	52.89	6.87	124.37	3.37
S1F2	59.44	10.87	15.00	48.70	6.22	117.89	3.01
S2F2	71.04	12.74	17.23	53.79	6.93	132.39	3.63
S3F2	77.07	13.74	18.54	62.06	8.52	134.39	4.64
S4F2	85.18	16.62	20.29	72.34	9.26	127.48	6.23
S5F2	73.28	13.49	17.13	58.81	7.35	130.39	4.07
S1F3	64.01	10.50	15.56	51.35	5.84	106.98	2.78
S2F3	73.29	12.38	18.73	61.08	6.80	113.48	3.53
S3F3	79.32	15.63	20.13	71.10	7.23	114.48	4.86
S4F3	97.88	19.00	21.09	74.15	9.98	139.89	6.33
S5F3	74.64	14.63	17.58	58.27	7.98	122.98	3.83
S. Em$\pm$	0.28	0.28	0.51	1.02	0.14	1.73	0.11
C.D. (P=0.05)	0.82	0.82	1.50	2.91	0.42	5.05	0.34

S1 : 7.5 x 7.5 cm; S2 : 10.0 cm x 10.0 cm; S3 : 12.5 cm x 12.5 cm; S4 : 15.0 cm x 15.0 cm; S5 : 12.5 cm x 10.0 cm; F1: 100 N: 40 P: 40 K: 20 S; F2: 120 N: 60 P: 60 K: 30 S; F3: 140 N: 80 P: 80 K: 40 S, NS: not significant

Table 2. Effect of onion crop geometry and NPKS fertilizer levels on yield parameters

Treatments	Leaf: bulb ratio	Bulb weight-1 (g)	Bulb yield (t ha^{-1})	Biological yield (t ha^{-1})	Harvest Index
Crop geometry					
S1	0.97	49.47	58.47	118.73	25.49
S2	0.81	67.97	45.19	83.92	47.94
S3	0.80	78.81	33.54	62.40	50.28
S4	0.57	125.74	37.16	60.07	50.31
S5	0.79	71.32	37.93	70.02	49.62
S. Em$\pm$	0.01	0.89	0.50	1.06	0.01
C.D. (P=0.05)	0.02	2.60	1.461	3.09	0.02
NPKS fertilizer levels					
F1	0.78	73.36	39.57	73.19	44.64
F2	0.78	79.38	42.85	79.72	44.93
F3	0.80	83.26	44.96	84.18	44.62
S. Em$\pm$	0.01	1.19	0.67	1.42	0.01
C.D. (P=0.05)	NS	4.69	2.63	5.59	0.05
Interaction between crop geometry and NPKS fertilizer levels					
S1F1	0.95	46.56	55.04	110.70	25.10
S2F1	0.81	61.67	41.01	76.07	47.70
S3F1	0.77	74.07	31.52	57.42	51.20
S4F1	0.58	117.85	34.83	56.55	49.59
S5F1	0.79	66.63	35.45	65.22	49.59
S1F2	0.98	49.48	58.49	119.60	25.68
S2F2	0.78	68.71	45.69	83.86	48.61
S3F2	0.77	80.28	34.16	62.53	51.08
S4F2	0.57	125.42	37.07	60.31	50.10
S5F2	0.80	73.02	38.84	72.29	49.16
S1F3	0.98	52.38	61.89	125.89	25.68
S2F3	0.83	73.52	48.87	91.84	47.50
S3F3	0.87	82.10	34.93	67.26	48.55
S4F3	0.55	133.97	39.59	63.34	51.24
S5F3	0.79	74.31	39.51	72.56	50.10
S.Em$\pm$	0.01	1.54	0.86	1.83	0.01
C.D. (P=0.05)	0.03	NS	NS	NS	0.048

Premature bolting was most pronounced (8.11%) with the lowest nutrient combination (F1) and least (7.36%) with the highest nutrient combination (F3) (Table 3). The data in Table 2 underscore the significant impact of varying NPKS fertilizer levels on bulb weight, bulb yield per hectare, and biological yield per hectare. Increasing from F1 to F2 led to substantial increases in bulb weight (8.21%), bulb yield per hectare (8.29%), and biological yield per hectare (8.92%). Further escalation from F2 to F3 resulted in incremental increases of 4.89, 4.92, and 5.59%, respectively. Beyond F3 (140 N: 80 P: 80 K: 40 S kg ha^{-1}), no significant improvement in yield parameters was noted, indicating saturation.

The lowest harvesting index (44.62) at F3 may be attributed to a non-significant decline in fresh marketable bulb yield in response to escalating nutrient levels. This overdose or supra-optimal supply of nutrients might have induced excessive vegetative growth at the expense of bulb development.

NPKS combinations significantly influenced onion bulb quality parameters (TSS, bulb color score, and quality score) (Table 3). F2 treatment (120 N: 60 P: 60 K: 30 S kg ha^{-1}) demonstrated superior performance with higher TSS (12.86 °Brix), bulb color score (8.21), and quality score (8.48) compared to other combinations. The highest (F3) and lowest (F1) nutrient levels resulted in suboptimal values due to nutrient deficiency and excess, respectively.

Statistical analysis (Table 4) revealed significant differences among treatments for marketable yield, gross return, net return, and B: C ratio. The highest marketable yield (35.48 t ha^{-1}), gross return (₹ 4.26 lakhs), net return (₹ 3.26 lakhs), and B: C ratio (3.26) were achieved with F3 treatment (140 N: 80 P: 80 K: 40 S kg ha^{-1}). Increasing from F1 to F2 significantly boosted marketable fresh bulb yield (9.94%), gross return (10.03%), net return (12.82%), and B: C ratio (10.18%). Further escalation from F2 to F3 resulted in incremental increases, albeit in a diminishing pattern (4.88, 4.93, 5.84, and 3.82%, respectively). F3 treatment emerged as optimal, suggesting no need for further increases in NPKS nutrients beyond this rate.

Interaction effect of crop geometry and levels of fertilizers: Table 1 and Fig.1 demonstrate the significant impact of varying NPKS fertilizers and crop geometry on onion vegetative growth parameters. The most effective treatment, S4F3 (15 cm x 15 cm + 140 N: 80 P: 80 K: 40 S kg ha^{-1}), surpassed others, closely followed by S4F2 (15 cm x 15 cm + 120 N: 60 P: 60 K: 30 S kg ha^{-1}), while S1F1 (7.5 x 7.5 cm + 100 N: 40 P: 40 K: 20 S kg ha^{-1}) exhibited the lowest growth parameters. Maximum values for plant height (97.88 cm), number of leaves per plant (19.0), neck diameter (21.09 mm), leaves weight per plant (74.15 g), root

Table 3 Effect of onion crop geometry and NPKS fertilizer levels on physicochemical qualities

Treatments	Bulb Shape Index	Bolting per cent	Split bulb (t ha^{-1})	TSS (º Brix)	Bulb colour score (10 marks)	Quality Score (10 marks)
Crop geometry						
S1	1.08	10.04	1.27	12.26	7.52	7.12
S2	0.98	8.19	3.68	13.09	8.09	9.00
S3	1.00	7.13	3.95	12.72	7.97	8.70
S4	1.03	6.17	6.21	12.76	7.84	7.91
S5	1.05	7.52	3.01	12.84	8.07	8.75
S. Em±	0.01	0.06	0.05	0.11	0.08	0.07
C.D.(*P*=0.05)	NS	0.19	0.16	0.33	0.25	0.22
NPKS fertilizer levels						
F1	1.03	8.11	3.33	12.81	7.40	7.99
F2	1.05	7.96	3.65	12.86	8.21	8.48
F3	1.00	7.36	3.89	12.54	8.08	8.42
S. Em±	0.02	0.09	0.07	0.15	0.11	0.10
C.D.(*P*=0.05)	NS	0.36	0.28	NS	0.46	0.39
Interaction between crop geometry and NPKS fertilizer levels						
S1F1	1.13	10.60	1.20	12.24	7.00	6.74
S2F1	0.97	8.14	3.58	12.76	7.25	8.49
S3F1	1.02	7.39	3.80	12.76	7.75	8.49
S4F1	1.03	6.64	5.42	12.26	7.50	7.49
S5F1	1.02	8.14	2.65	13.01	7.50	8.74
S1F2	1.10	10.26	1.31	13.28	7.76	7.24
S2F2	0.98	8.25	3.39	13.26	8.51	9.26
S3F2	1.00	7.13	3.88	12.91	8.26	8.87
S4F2	1.08	6.13	6.52	12.28	8.01	7.99
S5F2	1.10	7.68	3.12	13.03	8.50	8.99
S1F3	1.02	9.25	1.28	12.74	7.79	7.38
S2F3	1.00	8.18	4.07	12.36	7.76	8.76
S3F3	0.99	6.88	4.17	12.86	8.01	8.76
S4F3	0.97	5.75	6.68	12.24	8.39	8.26
S5F3	1.03	6.75	3.26	12.49	8.44	8.87
S. Em±	0.02	0.12	0.09	0.19	0.15	0.13
C.D.(*P*=0.05)	0.05	0.35	0.28	NS	0.45	NS

Table 4. Effect of onion crop geometry and NPKS fertilizer levels on economics parameters

Treatments	Un-marketable (t ha^{-1})	Marketable yield (t ha^{-1})	Gross return (Rs lakh)	Net return (Rs. lakhs)	B:C Ratio
Crop geometry					
S1	28.20	30.27	3.63	2.65	2.70
S2	4.96	40.22	4.83	3.85	3.92
S3	2.21	31.33	3.76	2.78	2.83
S4	6.93	30.23	3.63	2.65	2.70
S5	3.19	34.75	4.17	3.19	3.25
S. Em±	0.15	0.30	0.05	0.02	0.02
C.D.(*P*=0.05)	0.43	0.89	0.75	0.06	0.06
NPKS fertilizer levels					
F1	8.80	30.77	3.69	2.73	2.85
F2	9.02	33.83	4.06	3.08	3.14
F3	9.47	35.48	4.26	3.26	3.26
S. Em±	0.10	0.41	0.07	0.02	0.26
C.D.(*P*=0.05)	0.41	1.60	0.27	0.10	0.10
Interaction between crop geometry and NPKS fertilizer levels					
S1F1	27.26	27.79	3.33	2.37	2.47
S2F1	4.72	36.29	4.35	3.39	3.54
S3F1	2.13	29.39	3.53	2.57	2.67
S4F1	6.79	28.03	3.36	2.40	2.50
S5F1	3.10	32.34	3.88	2.92	3.04
S1F2	27.78	30.70	3.68	2.70	2.76
S2F2	4.91	40.77	4.89	3.91	3.99
S3F2	2.22	31.94	3.83	2.85	2.91
S4F2	6.86	30.21	3.62	2.64	2.70
S5F2	3.30	35.54	4.26	3.28	3.35
S1F3	29.55	32.33	3.88	2.88	2.88
S2F3	5.25	43.62	5.23	4.23	4.23
S3F3	2.27	32.66	3.92	2.92	2.92
S4F3	7.12	32.46	3.90	2.90	2.90
S5F3	3.16	36.35	4.36	3.36	3.36
S. Em±	0.25	0.52	0.09	0.03	0.03
C.D.(*P*=0.05)	0.75	1.54	NS	0.09	0.09

For treatment details refer Table 1

length (9.98 cm), number of roots per plant (139.89), and root weight per plant (6.33) were observed in S4F3, with the lowest bulb shape index (0.97) and leaf bulb ratio (0.55).

Closer crop geometry and lower nutrient combinations (S1F1: 7.5 x 7.5 cm + 100 N: 40 P: 40 K: 20 S kg ha^{-1}) resulted in the highest premature bolting (10.6%), while wider spacing with higher nutrient levels (S4F3: 15 cm x 15 cm + 140 N: 80 P: 80 K: 40 S kg ha^{-1}) exhibited the least (5.75%) (Table 3). Increasing NPKS levels and spacing correlated with a significant increase in average bulb weight. The maximum bulb weight (133.97 g) was achieved in S4F3, followed by S4F2 (125.42 g). Notably, the closest spacing with the highest nutrient dose (S1F2: 7.5 x 7.5 cm + 140 N: 80 P: 80 K: 40 S kg ha^{-1}) produced the highest bulb yield (61.89 t ha^{-1}), biological yield (125.89 t ha^{-1}), and unmarketable bulb yield (29.55 t ha^{-1}), outperforming other treatments.

Wider crop geometry with the highest nutrient dose (S4F3: 15 cm x 15 cm + 140 N: 80 P: 80 K: 40 S kg ha^{-1}) significantly increased the quantity of split bulbs (6.68 t ha^{-1}), followed by S4F2 (6.52 t ha^{-1}) and S4F1 (5.42 t ha^{-1}), while S1F1 exhibited the minimum (1.20 t ha^{-1}) (Table 3). The highest harvest index (51.24) was achieved in S4F3, closely followed by S3F1 (51.20) and S3F2 (51.08), showing increases of about 104.14, 103.98, and 103.51% compared to the control.

TSS and quality score were insignificantly affected by different treatments. Precisely populated plots (10 x 10 cm and 12.5 cm x 10 cm) with a medium fertilizer level (120 N: 60 P: 60 K: 30 S kg ha^{-1}) produced better-quality onion bulbs. The highest values for total soluble solids (13.26 °Brix and 13.03 °Brix), bulb color score (8.51 and 8.50), and quality score (9.26 and 8.99) were observed in S2F2 and S2F5, respectively, while the minimum values were recorded in S1F1 (Table 3).

Significant increases in marketable fresh bulb yield, net return, and B: C ratio were observed with escalating fertilizer levels and optimum crop geometry (Table 4). The highest marketable fresh bulb yields (43.62 t ha^{-1}), gross return (₹ 5.23 lakhs), net return (₹ 4.23 lakhs), and B: C ratio (4.23) were recorded in S2F3, closely followed by S2F2 with marketable fresh bulb yields (40.77 t ha^{-1}), gross return (₹ 4.89 lakhs), net return (₹ 3.91 lakhs), and B: C ratio (3.99). The lowest values were obtained from S1F1, mainly due to additional production (27.26 t ha^{-1}) of unmarketable bulbs (Table 4).

Discussion

The findings of this study unequivocally demonstrate that increased spacing between onion plants positively correlates with enhanced vegetative growth, primarily attributable to greater access to light, space, and air. The augmented photosynthetic activity resulting from these favorable conditions contributes to a substantial increase in leaf area per plant and additional assimilates, fostering the development of larger bulbs (Fig. 1).

This outcome aligns with the observations of Amare *et al.* (2020) and Harris *et al.* (2016) in the context of onion cultivation, where wider spacing facilitated superior vegetative growth.

Conversely, closer spacing intensifies competition among plants for nutrients, space, and light, resulting in stunted bulb sizes that are deemed unmarketable. Comparable conclusions were drawn by Amare *et al.* (2020) and Walle *et al.* (2018), indicating that increased plant density exacerbates competition for essential growth factors, leading to physiological stress, premature bolting, and diminished bulb quality.

The significant increase in total bulb yield and biological fresh matter yield in densely populated plantations can be attributed to the expanded leaf area or the efficient utilization of light energy due to the higher plant population. This increase, as suggested by Harris *et al.* (2016) and Mahala *et al.* (2019), enhances the photosynthetic rate per unit area, resulting in greater assimilate accumulation in both above-ground plant parts and bulbs.

The lowest harvest index and a higher proportion of unmarketable bulbs at higher plant population densities (7.5 x 7.5 cm) are linked to decreased mean bulb sizes, premature bolting, and the production of poorer quality bulbs, including a surge in very small bulbs (cull bulbs). These factors collectively contribute to a significant reduction in economic yield due to intense crop competition for growth factors (Fig. 3). Similar outcomes were reported by Amare *et al.* (2020) and Walle *et al.* (2018), reinforcing the conclusion that a plant spacing of 10 x 10 cm is most conducive to optimal onion production.

Application of an adequate amount of NPKS fertilizers has a positive impact on onion plant growth, influencing processes such as photosynthesis, protein synthesis, carbohydrate metabolism, and the translocation and storage of food materials. The addition of NPKS fertilizers enhances the plant's nutrient absorption capacity by increasing root surface area per unit of soil volume and the rate of nutrient uptake. This is attributed to the roles of nitrogen in chlorophyll, enzymes, and protein synthesis; phosphorus in root growth development, phospho-proteins, and phospho-lipids formation; potassium in enzyme activity promotion and assimilate translocation; and sulfur in root development and increasing the leaf's efficiency in sugar and starch production. These findings are consistent with the research of Islam *et al.* (2008), Barman *et al.* (2013), Kumara *et al.* (2018) and Mahala *et al.* (2019).

Insufficient nutrient levels can lead to premature bolting, as heightened crop competition for nutrients induces growth-related stress and physiological distress, as noted by Harris *et al.* (2016). Therefore, the application of higher levels of NPKS (140 N: 80 P: 80 K: 40 S kg ha^{-1}) with medium crop geometry (10 x 10 cm and 12.5 cm x 10 cm) emerges as a strategic approach to improving marketability or decreasing the quantity of unmarketable onion bulbs, ultimately enhancing returns with the highest benefit-cost ratio. Widening the crop geometry tends to decrease the yield of unmarketable bulbs but linearly reduces total bulb production. Conversely, closer crop geometry produces the highest yield of unmarketable bulbs (small-sized and misshaped) due to stiff interplant competition for growth factors. Notably, the widest crop geometry with the highest dose of fertilizer (15 cm x 15 cm + 140 N: 80 P: 80 K: 40 S kg ha^{-1}) yields a considerable number of excessively large bulbs, contributing to the overall unmarketable fresh bulb yield due to low interplant competition for growth factors. These results echo the findings of Mahala *et al.* (2019).

In conclusion, 15 x 15 cm crop spacing improved onion vegetative growth, while 7.5 x 7.5 cm stunted growth and premature bolting. The optimal onion spacing was 10 x 10 cm, balancing plant density and nutrient availability. For optimal marketable yield, economic returns, and crop quality, use 10 x 10 cm spacing and the highest NPKS fertilizer rate (F3).

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