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Effect of Foliar Application of GA_3, NAA, and Zinc on Growth, Yield, and Quality of Onion (*Allium cepa* L.)

Gyanendra Singh [a], Lavkush Pandey [a*], Shivkant Singh Chandel [a], Anup Kumar Yadav [a], Akshita Amukhi [a], Aman Kumar Pandey [a], Anant Tiwari [a], Kushagra Kumar Bind [a], Ujjwal Anand [a], Ashish Maurya [a] and Dharmendra Kumar Singh [b]

[a] *Department of Horticulture, Prof. Rajendra Singh (Rajju Bhaiya) University, Naini, Prayagraj (UP), India.*
[b] *Faculty of Agriculture, Udai Pratap Autonomous College (UP College), Varanasi, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Onion (*Allium cepa* L.) is an economically important vegetable crop valued for its culinary, nutritional, and commercial significance. Optimising the foliar application of plant growth regulators and micronutrients may improve onion growth, bulb yield, quality, and production economics. The study aims to evaluate the effects of plant growth regulators and zinc on the growth, yield, and quality of onion. A field experiment was conducted during the rabi season of 2025–26 at the Horticulture Research Field, Prof. Rajendra Singh (Rajju Bhaiya) University, Naini, Prayagraj, Uttar Pradesh, The experiment was arranged in a randomised block

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**Corresponding author: E-mail: lavkush16pandey@gmail.com, lavkushanduat@gmail.com;*

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design with seven treatments and three replications. The treatments comprised GA_3 (100 ppm), NAA (200 ppm), zinc (0.1%), and their combinations, applied as foliar sprays at 30 and 60 days after transplanting (DAT). Among the treatments, T_5 (GA_3 100 ppm + zinc 0.1%) produced the highest plant height (56.57, 60.12, and 66.19 cm), number of leaves per plant (6.87, 8.00, and 13.01), pseudostem length (6.83, 9.32, and 14.74 cm), and pseudostem diameter (1.92, 2.83, and 3.51 cm) at 45, 60, and 90 DAT, respectively. The same treatment also recorded the highest average bulb weight (85.36 g), polar diameter (6.14 cm), equatorial diameter (6.33 cm), yield per plot (11.35 kg plot^{-1}), and yield per hectare (28.38 t ha^{-1}), followed by T_6 (NAA 200 ppm + zinc 0.1%). In contrast, the highest total soluble solids (12.20 °Brix), titratable acidity (0.31%), ascorbic acid (13.43 mg 100 g^{-1}), and total sugar content (6.43%) were recorded under T_4 (GA_3 100 ppm + NAA 200 ppm). The control (T_7) recorded the lowest values for most parameters. In this study, GA_3 (100 ppm) combined with zinc (0.1%) improved onion growth and yield, whereas GA_3 (100 ppm) combined with NAA (200 ppm) improved bulb quality.

Keywords: Allium cepa; GA_3; NAA; zinc; bulb yield; quality; Pusa red.

1. Introduction

Onion (*Allium cepa L.*) is one of the most important vegetable crops in the family Amaryllidaceae (formerly Alliaceae) and has a chromosome number of 2n = 16. It is widely cultivated and consumed because of its culinary, medicinal, and economic importance. Onions are valued for their pungency, flavour, and nutritional properties and are an important component of daily diets in many cultures (Brewster, 2008). The primary centre of origin of onion (*Allium cepa*) is Central Asia, whereas the Near East and Mediterranean regions are considered secondary centres of origin. Onions have been used since ancient times, including around 600 BC in Egypt and India, for food, medicine, and rituals. The genus *Allium* comprises more than 500 species, although only a few are cultivated. Among these, onion (*Allium cepa*) and garlic (*Allium sativum*) are the most important worldwide (Agasimani, 2010).

Onion is a good source of carbohydrates, proteins, vitamins B_6 and C, minerals (phosphorus, calcium, magnesium, iron, manganese, and sulphur), amino acids, and antioxidants. In addition, onion species contain several secondary metabolites, including flavonoids, phenolics, phytosterols, and saponins (Ray *et al.*, 2023; Gomasta *et al.*, 2026), which have been associated with cardiovascular, antidiabetic, antibacterial, antiviral, and antiallergic properties.

Onion bulbs contain 86.84% moisture, 1.2% protein, 0.1% fat, 11.6% carbohydrates, 0.4% minerals, 0.18% calcium, 0.05% phosphorus, 0.7% iron, 0.4% nicotinic acid, and vitamins B and C (Samiksha *et al.*, 2024). However, onion quality and production need to be improved to meet increasing consumer demand. Farmers often apply synthetic agrochemicals indiscriminately to enhance field-level onion productivity. Such practices may contribute to environmental pollution, including greenhouse-gas emissions, water contamination through runoff, and long-term declines in soil fertility caused by nutrient leaching and changes in microbial communities (Kayesh *et al.*, 2023; Gomasta *et al.*, 2024). In this context, plant growth regulators such as gibberellic acid (GA_3) and naphthalene acetic acid (NAA) may offer options for improving onion yield and quality.

GA_3 is an important growth stimulant that promotes cell elongation and division, thereby supporting plant growth and development. However, improvements in crop production and quality largely depend on the concentration of the plant growth regulator and the timing of its application (Thakur et al., 2018).

Naphthalene acetic acid (NAA) plays a key role in cell elongation and division, vascular-tissue differentiation, root initiation, apical dominance, leaf senescence, leaf and fruit abscission, fruit set, and flowering (Singh *et al.*, 2019). Studies have shown that judicious applications of GA_3 and NAA can significantly affect the growth, yield, and quality of horticultural crops, including vegetables and spices (Dhakal *et al.*, 2023; Hassan *et al.*, 2024; Uddin et al., 2024).

In addition to plant growth regulators, the micronutrient zinc plays an important role in plant metabolism, including the transport of water, nutrients, and photosynthates to rapidly growing meristematic tissues. Its combined application with plant growth regulators may also improve onion yield (Panwar *et al.*, 2025). Recent studies on onion indicate that integrated nutrient, microbial, and targeted foliar-input strategies may improve plant growth, nutrient uptake, bulb yield, quality, and production economics under different cultivation conditions (Sitapara et al., 2024; Arunachalam et al., 2024; Mahmoud et al., 2024; Bhardwaj et al., 2025; Harish et al., 2026).

1.1 Research Gap

Although individual effects of plant growth regulators and micronutrients on onion have been reported, limited information is available on the comparative and combined effects of foliar GA_3, NAA, and zinc at the concentrations and application timings used in the present study. Evidence is particularly limited regarding their simultaneous effects on vegetative growth, bulb yield, quality, and production economics of onion cv. Pusa Red under the agroclimatic conditions of Prayagraj.

1.2 Objective

The present study aimed to evaluate the individual and combined effects of foliar GA_3 (100 ppm), NAA (200 ppm), and zinc (0.1%), applied at 30 and 60 days after transplanting, on the growth, yield, quality, and economics of onion cv. Pusa Red.

2. Materials and Methods

The experiment was conducted at the Horticulture Research Field of Prof. Rajendra Singh (Rajju Bhaiya) University, Naini, Prayagraj, Uttar Pradesh, during the rabi season of 2025–26 to determine the effects of plant growth regulators and zinc on the growth, yield, and quality of onion (*Allium cepa* L.). The research field is located at 25.3585671° N latitude and 81.8933582° E longitude, at an elevation of 98 m above mean sea level. During the crop-growth period, the temperature ranged from 5.5 to 35.5 °C, and the relative humidity ranged from 13.9% to 99.7%. The experimental field had well-drained and aerated sandy-loam soil. The soil comprised 59.60% sand, 25.27% silt, and 15.13% clay, as determined using the Bouyoucos hydrometer method (Bouyoucos, 1927). The experiment was arranged in a randomised block design with three replications and seven treatments: T_1, GA_3 at 100 ppm; T_2, NAA at 200 ppm; T_3, zinc at 0.1%; T_4, GA_3 at 100 ppm + NAA at 200 ppm; T_5, GA_3 at 100 ppm + zinc at 0.1%; T_6, NAA at 200 ppm + zinc at 0.1%; and T_7, control. The treatments were applied as foliar sprays at 30 and 60 DAT. The recommended NPK dose for onion (100:50:50 kg ha^{-1}) was supplied through urea, SSP, and MOP, together with 20 t ha^{-1} of FYM. The full doses of FYM, phosphorus, and potash and half of the nitrogen dose were applied to the plots before transplanting. The remaining nitrogen was applied in two equal splits at 30 and 60 DAT. Intercultural operations, including hoeing, weeding, irrigation, and thinning, were performed according to crop requirements and field conditions. Growth parameters (plant height, number of leaves, pseudostem length, and pseudostem diameter) were recorded from five plants per plot at 45, 60, and 90 DAT. Yield parameters (equatorial diameter, polar diameter, average bulb weight, yield per plot, and yield per hectare) and quality parameters (TSS, titratable acidity, ascorbic acid, and total sugar content) were recorded after harvest.

2.1 Statistical Analysis

The experimental data were analysed using analysis of variance (ANOVA) for a randomised block design with three replications, following Panse and Sukhatme (1985). The significance of treatment effects was assessed using the F-test at the 5% probability level. Treatment means were compared using the critical difference (CD) at $P \leq 0.05$ whenever the F-test was significant. The standard error of the mean [SE(m)] and coefficient of variation (CV%) were also calculated.

3. Results and Discussion

3.1 Growth Attributes

The growth attributes assessed were plant height, number of leaves per plant, pseudostem length, and pseudostem diameter, as presented in Table 1.

Plant Height (cm): Plant height was significantly affected by the plant growth regulator and zinc treatments at all growth stages (45, 60, and 90 DAT). The maximum plant heights were recorded under T_5 (GA_3 at 100 ppm + zinc at 0.1%): 56.57, 60.12, and 66.19 cm at 45, 60, and 90 DAT, respectively. These values were significantly higher than those under the other treatments. The next-highest values were recorded under T_6 (NAA at 200 ppm + zinc at 0.1%): 53.44, 58.69, and 63.26 cm at 45, 60, and 90 DAT, respectively. The lowest plant heights were recorded under the control (T_7): 40.09, 42.82, and 47.08 cm at 45, 60, and 90 DAT, respectively.

The improved performance under T_5 during crop growth suggests a complementary effect of GA_3 and zinc on vegetative growth. GA_3 promotes meristematic activity and cell elongation, whereas zinc contributes to protein synthesis, auxin production, and enzyme activation. Together, these physiological processes may have contributed to the greater plant height. Sarkar et al. (2018) reported increased onion plant height following GA_3 application, which is consistent with the present findings. Increased plant height after foliar GA_3 application was also reported by Gomasta *et al.* (2024). Khan et al. (2025) similarly found that combining zinc with growth regulators improved onion growth attributes.

Number of Leaves per Plant: The number of leaves per plant was significantly affected by the application of plant growth regulators and zinc at 45, 60, and 90 DAT. T_5 (GA_3 at 100 ppm + zinc at 0.1%) produced the highest numbers of leaves per plant, with 6.87, 8.00, and 13.01 leaves at 45, 60, and 90 DAT, respectively. This treatment was significantly superior to the other treatments and was followed by T_6 (NAA at 200 ppm + zinc at 0.1%), which produced 6.07, 7.15, and 11.13 leaves per plant at 45, 60, and 90 DAT, respectively. The lowest values were recorded under the control (T_7), with 4.28, 5.07, and 7.13 leaves plant^{-1} at 45, 60, and 90 DAT, respectively.

The greater number of leaves under T_5 may be attributable to the combined effects of the plant growth regulator and micronutrient. Gibberellic acid promotes the formation of new leaves by stimulating meristematic activity, whereas zinc supports chlorophyll formation and photosynthetic efficiency. Increased photosynthetic activity may provide more assimilates for vegetative development and leaf production. These findings are consistent with those of Sarkar et al. (2018) and Khan et al. (2025), who reported that foliar GA_3 and zinc applications improved vegetative growth, particularly leaf number, in onion.

Pseudostem Length (cm): The application of plant growth regulators and zinc significantly affected onion pseudostem length at 45, 60, and 90 DAT. Among the treatments, T_5 (GA_3 at 100 ppm + zinc at 0.1%) recorded the greatest pseudostem lengths: 6.83, 9.32, and 14.74 cm at 45, 60, and 90 DAT, respectively. This treatment was followed by T_6 (NAA at 200 ppm + zinc at 0.1%), which produced pseudostem lengths of 6.36, 8.72, and 13.26 cm, respectively. The shortest pseudostems were recorded under the control treatment, with values of 4.87, 7.20, and 9.07 cm at 45, 60, and 90 DAT, respectively.

The greater pseudostem length under T_5 suggests that GA_3 and zinc supported vegetative development throughout the crop cycle. Zinc contributes to protein synthesis, chlorophyll formation, and photosynthetic activity, whereas GA_3 promotes cell elongation and expansion. These processes may jointly support pseudostem growth and development. The present findings are consistent with those of Sarkar et al. (2018) and Khan et al. (2025), who reported that combined applications of growth regulators and micronutrients improved onion growth attributes.

Pseudostem Diameter (cm): The plant growth regulator and zinc treatments significantly affected onion pseudostem diameter at 45, 60, and 90 DAT. T_5 (GA_3 at 100 ppm + zinc at 0.1%) recorded the greatest pseudostem diameters of 1.92, 2.83, and 3.51 cm at 45, 60, and 90 DAT, respectively. This treatment was followed by T_6 (NAA at 200 ppm + zinc at 0.1%), which recorded pseudostem diameters of 1.49, 2.12, and 3.17 cm, respectively. The smallest pseudostem diameters were recorded under the control (T_7), with values of 0.53, 1.10, and 2.07 cm at 45, 60, and 90 DAT, respectively.

3.2 Yield Attributes

The yield attributes assessed were equatorial diameter, polar diameter, average bulb weight, yield per plot, and yield per hectare, as presented in Table 2.

Equatorial and Polar Diameters: Both the equatorial and polar diameters of onion bulbs were significantly affected by the treatments. The largest equatorial diameter (6.33 cm) and polar diameter (6.14 cm) were recorded under T_5 (GA_3 at 100 ppm + zinc at 0.1%), followed by T_6 (NAA at 200 ppm + zinc at 0.1%), with corresponding values of 6.16 and 5.88 cm. The smallest values were recorded under the control (T_7).

The increase in bulb size under the GA_3 and zinc treatments may be attributed to enhanced cell elongation and division. GA_3 promotes vegetative growth and cell expansion, whereas zinc plays a role in auxin synthesis and enzyme activation. These findings agree with Singh et al. (2019), who reported that GA_3 improved onion bulb size. Similarly, Cakmak (2008) highlighted the role of zinc in plant growth and development through metabolic regulation.

Average Bulb Weight (g): The highest average bulb weight (85.36 g) was recorded under T_5 (GA_3 at 100 ppm + zinc at 0.1%), followed by T_6 (NAA at 200 ppm + zinc at 0.1%), with 81.00 g. The control recorded the lowest average bulb weight (55.01 g).

The increase in bulb weight may be attributable to improved photosynthetic activity and the translocation of assimilates from the leaves to the bulbs. GA_3 may enhance the source–sink relationship, whereas zinc supports carbohydrate metabolism. These results are supported by Khadka et al. (2024), who reported that combined applications of growth regulators and micronutrients increased onion bulb weight.

Yield (kg plot^{-1} and t ha^{-1}): Yield was significantly affected by the treatments. The highest yield was recorded under T_5 (GA_3 at 100 ppm + zinc at 0.1%), with 11.35 kg plot^{-1} and 28.38 t ha^{-1}, followed by T_6 (NAA at 200 ppm + zinc at 0.1%), with 10.78 kg plot^{-1} and 26.95 t ha^{-1}. The lowest yield was recorded under the control, with 7.32 kg plot^{-1} and 18.29 t ha^{-1}.

The higher yield under T_5 may be attributed to the combined effects of GA_3 and zinc on vegetative growth, bulb development, and nutrient uptake. Zinc also supports enzyme activity and protein synthesis, which may contribute to yield formation. These results are consistent with Bista et al. (2022), who reported increased onion yield following the combined use of GA_3 and micronutrients. Similarly, Alloway (2008) emphasised the importance of zinc in crop productivity.

3.3 Quality Parameters

The quality attributes assessed were total soluble solids, titratable acidity, ascorbic acid, and total sugar content, as presented in Table 3.

Total Soluble Solids (TSS): The total soluble solids content of onion bulbs differed significantly among the treatments. The highest value (12.20 °Brix) was recorded under T_4 (GA_3 at 100 ppm + NAA at 200 ppm), followed by T_5 (GA_3 at 100 ppm + zinc at 0.1%), with 11.93 °Brix. The lowest value (10.67 °Brix) was recorded under the control.

The increase in total soluble solids may be attributable to enhanced sugar synthesis and accumulation resulting from the metabolic effects of the plant growth regulators. GA_3 may improve photosynthesis and assimilate transport, whereas NAA may support carbohydrate accumulation in storage organs. These findings are consistent with Sravani et al. (2020), who reported increased total soluble solids in onion following the application of plant growth regulators.

Titratable Acidity (%): Titratable acidity ranged from 0.19% to 0.31%. The highest value (0.31%) was recorded under T_4 (GA_3 at 100 ppm + NAA at 200 ppm), followed by T_5 (GA_3 at 100 ppm + zinc at 0.1%), with 0.29%. The lowest value was recorded under the control.

Trivedi and Dhumal (2017) reported a similar increase in onion acidity following the application of growth regulators.

Ascorbic Acid (mg 100 g^{-1}): Ascorbic acid content differed significantly among the treatments. The highest value (13.43 mg 100 g^{-1}) was recorded under T_4 (GA_3 at 100 ppm + NAA at 200 ppm), followed by T_5 (GA_3 at 100 ppm + zinc at 0.1%), with 12.62 mg 100 g^{-1}. The lowest value (9.93 mg 100 g^{-1}) was recorded under the control.

Table 1. Effect of Plant Growth Regulators and Zinc on growth attributes at 45, 60, and 90 days after transplanting of onion

Treatments	Plant Height (cm)			No. of Leaves per Plant		
	45 DAT	**60 DAT**	**90 DAT**	**45 DAT**	**60 DAT**	**90 DAT**
T_1 – GA_3 @ 100 ppm	47.42±0.78	50.72±0.41	56.19±0.88	5.33±0.41	6.57±0.15	10.07±0.37
T_2 – NAA @ 200 ppm	45.53±0.36	49.13±0.53	54.09±0.95	4.87±0.18	6.17±0.15	9.17±0.29
T_3 – Zinc @ 0.1%	42.17±0.64	45.31±0.33	50.45±0.44	4.52±0.27	5.43±0.20	7.47±0.18
T_4 – GA_3 @ 100 ppm + NAA @ 200 ppm	49.70±0.61	53.56±0.26	58.13±0.69	5.81±0.12	6.90±0.12	10.26±0.53
T_5 – GA_3 @ 100 ppm + Zinc @ 0.1%	56.57±0.44	60.12±0.56	66.19±0.95	6.87±0.07	8.00±0.31	13.01±0.32
T_6 – NAA @ 200 ppm + Zinc @ 0.1%	53.44±1.68	58.69±0.26	63.26±1.21	6.07±0.15	7.15±0.16	11.13±0.18
T_7 – Control	40.09±0.41	42.82±0.71	47.08±0.69	4.28±0.19	5.07±0.09	7.13±0.58
C.D. at 5%	2.62	1.50	2.41	0.74	0.28	1.27
SE(m) ±	0.84	0.48	0.77	0.24	0.09	0.40

Table 1. Effect of Plant Growth Regulators and Zinc on growth attributes at 45, 60, and 90 days after transplanting of onion (Contd.)

Treatments	Length of Pseudo stem (cm)			Diameter of Pseudo stem (cm)		
	45 DAT	**60 DAT**	**90 DAT**	**45 DAT**	**60 DAT**	**90 DAT**
T_1 – GA_3 @ 100 ppm	5.68±0.18	8.18±0.59	11.46±0.32	1.05±0.03	1.62±0.21	2.74±0.56
T_2 – NAA @ 200 ppm	5.33±0.07	7.96±0.58	10.70±0.09	0.85±0.02	1.49±0.20	2.52±0.21
T_3 – Zinc @ 0.1%	5.09±0.02	7.56±0.25	10.13±0.22	0.71±0.03	1.32±0.04	2.25±0.07
T_4 – GA_3 @ 100 ppm + NAA @ 200 ppm	6.15±0.21	8.39±0.82	11.93±0.06	1.22±0.02	1.91±0.40	2.94±0.15
T_5 – GA_3 @ 100 ppm + Zinc @ 0.1%	6.83±0.08	9.32±0.54	14.74±0.28	1.92±0.04	2.83±0.06	3.51±0.34
T_6 – NAA @ 200 ppm + Zinc @ 0.1%	6.36±0.10	8.72±0.36	13.26±1.45	1.49±0.06	2.12±0.14	3.17±0.18
T_7 – Control	4.87±0.08	7.20±0.23	9.07±0.25	0.53±0.02	1.10±0.05	2.07±0.17
C.D. at 5%	0.40	1.17	1.65	0.15	0.55	0.83
SE(m) ±	0.13	0.37	0.53	0.05	0.18	0.27

Table 2. Effect of Plant Growth Regulators and Zinc on Yield Attributes of Onion

Treatments	Equatorial Diameter (cm)	Polar Diameter (cm)	Average bulb Weight (g)	Yield (kg/plot)	Yield (t/ha)
T_1 – GA_3 @ 100 ppm	5.71±0.27	5.26±0.17	76.44±0.65	10.17±0.09	25.43±0.22
T_2 – NAA @ 200 ppm	5.44±0.25	5.14±0.20	73.58±1.05	9.78±0.14	24.46±0.35
T_3 – Zinc @ 0.1%	5.25±0.06	4.93±0.18	68.30±0.58	9.08±0.08	22.71±0.19
T_4 – GA_3 @ 100 ppm + NAA @ 200 ppm	5.98±0.03	5.53±0.09	78.40±1.72	10.43±0.23	26.08±0.57
T_5 – GA_3 @ 100 ppm + Zinc @ 0.1%	6.33±0.23	6.14±0.18	85.36±1.60	11.35±0.21	28.38±0.53

Treatments	Equatorial Diameter (cm)	Polar Diameter (cm)	Average bulb Weight (g)	Yield (kg/plot)	Yield (t/ha)
T_6 – NAA @ 200 ppm + Zinc @ 0.1%	6.16±0.12	5.88±0.04	81.00±1.00	10.78±0.13	26.95±0.33
T_7 – Control	4.37±0.13	4.06±0.07	55.01±1.21	7.32±0.16	18.29±0.40
C.D. at 5%	0.57	0.49	3.45	0.46	1.15
SE(m) ±	0.18	0.16	1.11	0.15	0.37

Table 3. Effect of Plant Growth Regulators and Zinc on Quality Attributes of Onion

Treatments	TSS (Brix)	Titrable Acidity (%)	Ascorbic Acid (mg/100g)	Total Sugar Content (%)
T_1 – GA_3 @ 100 ppm	11.53±0.09	0.25±0.01	11.79±0.14	5.19±0.03
T_2 – NAA @ 200 ppm	11.23±0.15	0.24±0.02	11.34±0.13	5.40±0.07
T_3 – Zinc @ 0.1%	11.00±0.06	0.21±0.01	10.92±0.13	4.96±0.06
T_4 – GA_3 @ 100 ppm + NAA @ 200 ppm	12.20±0.12	0.31±0.01	13.43±0.50	6.43±0.23
T_5 – GA_3 @ 100 ppm + Zinc @ 0.1%	11.93±0.12	0.29±0.01	12.62±0.21	5.84±0.04
T_6 – NAA @ 200 ppm + Zinc @ 0.1%	11.73±0.15	0.27±0.02	11.95±0.03	5.51±0.09
T_7 – Control	10.67±0.03	0.19±0.01	9.93±0.32	4.61±0.13
C.D. at 5%	0.50	0.03	0.73	0.37
SE(m) ±	0.16	0.01	0.24	0.12

Table 4. Effect of plant growth regulators and zinc on economics of onion

Treatment	Common cost of cultivation (₹/ha)	Cost of treatments (₹/ha)	Yield (q/ha)	Rate/ q	Total Cost of Cultivation (₹/ha)	Gross Return (₹/ha)	Net Return (₹/ha)	B:C Ratio
T_1 – GA_3 @ ppm	135862	25000	254.3	1700	160862	432310	271448	1.69:1
T_2 – NAA @200 ppm	135862	8000	244.6	1700	143862	415820	271958	1.89:1
T_3 – Zinc @0.1%	135862	250	227.1	1700	136112	386070	249958	1.84:1
T_4 – GA_3 @100 ppm + NAA @200 ppm	135862	33000	260.8	1700	168862	443360	274498	1.63:1
T_5 – GA_3 @100 ppm+ Zinc @ 0.1%	135862	25300	283.8	1700	161112	482460	321348	1.99:1
T_6 – NAA @200 ppm + Zinc @ 0.1%	135862	8300	269.5	1700	144112	458150	314038	2.18:1
T_7 – Control	135862	0	182.9	1700	135862	310930	175068	1.29:1

The increase in ascorbic acid content may be attributable to improved enzymatic activity and vitamin biosynthesis under GA_3 and NAA application. Zinc also plays an important role in enzyme activation and antioxidant metabolism. These findings are consistent with Babaleshwar et al. (2017), who reported increased vitamin C content in onion following micronutrient and plant growth regulator applications.

Total Sugar Content (%): The application of plant growth regulators and zinc significantly affected the total sugar content of onion bulbs. T_4 (GA_3 at 100 ppm + NAA at 200 ppm) recorded the highest total sugar content (6.43%), followed by T_5 (GA_3 at 100 ppm + zinc at 0.1%) and T_6 (NAA at 200 ppm + zinc at 0.1%), with values of 5.84% and 5.51%, respectively. The control (T_7) recorded the lowest total sugar content (4.61%). Under the conditions of the present study, the combined foliar application of GA_3 at 100 ppm and NAA at 200 ppm was associated with improved total sugar content in onion bulbs.

3.4 Economics and Benefit–Cost Ratio

The economics and benefit–cost ratio of onion production were significantly affected by the treatments. T_5 (GA_3 at 100 ppm + zinc at 0.1%) recorded the highest net return (₹321,348 ha^{-1}), followed by T_6 (NAA at 200 ppm + zinc at 0.1%), with ₹314,038 ha^{-1}. The highest benefit–cost ratio was recorded under T_6 (2.18:1), followed by T_5 (1.99:1). The control (T_7) recorded the lowest net return (₹175,068 ha^{-1}) and benefit–cost ratio (1.29:1) (Table 4 and Fig. 1).

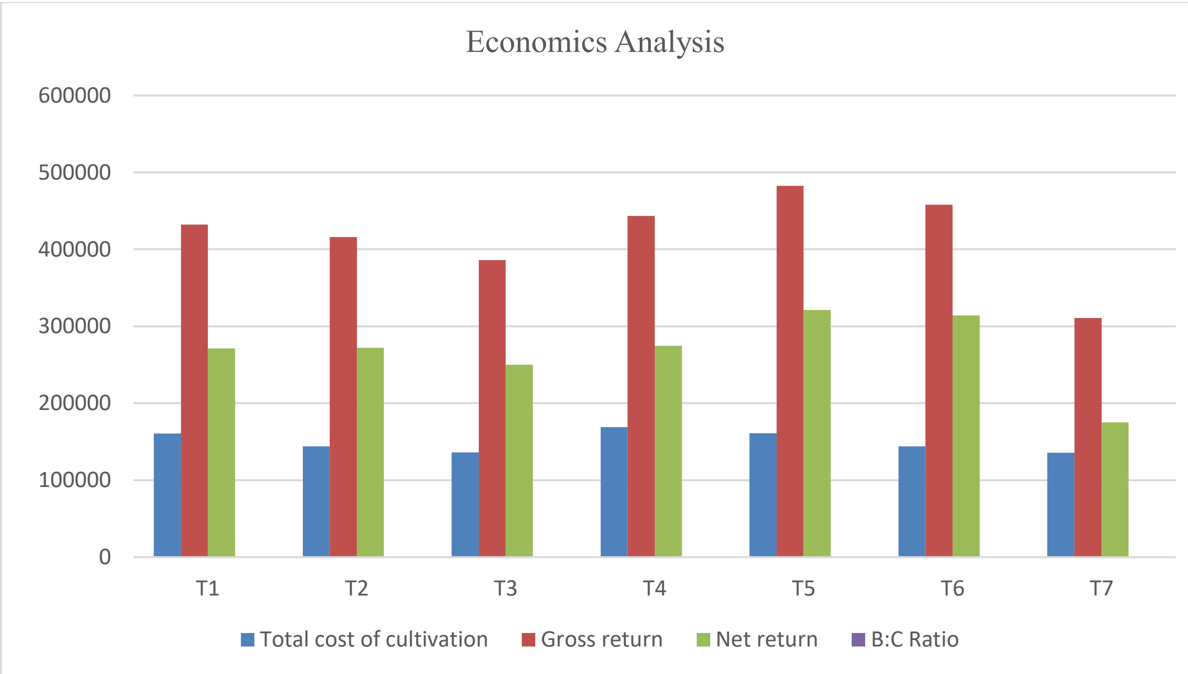

Fig. 1. Graph showing effect of plant growth regulators and zinc on economics and benefit cost ratio of onion

4. Conclusion

The study showed that foliar applications of plant growth regulators and zinc affected the growth, yield, quality, and economics of onion. Among the treatments, GA_3 at 100 ppm combined with zinc at 0.1% recorded the highest values for vegetative growth and yield-related attributes, including plant height, number of leaves, pseudostem length, pseudostem diameter, bulb size, average bulb weight, yield per plot, and yield per hectare. For quality attributes, GA_3 at 100 ppm combined with NAA at 200 ppm recorded the highest total soluble solids, titratable acidity, ascorbic acid, and total sugar content. The economic analysis showed that GA_3 at 100 ppm combined with zinc at 0.1% produced the highest net return, whereas NAA at 200 ppm combined with zinc at 0.1% produced the highest benefit–cost ratio. Under the conditions of this study, combined foliar applications of plant growth regulators and zinc may support the productivity and quality of onion cv. *Pusa Red*.

5. Limitation

The study was conducted during a single rabi season at one location using one onion cultivar, which may limit the wider applicability of the findings. The treatments were evaluated at fixed concentrations and two application timings; therefore, dose–response relationships and alternative spray schedules were not assessed. The experiment also did not examine residual soil effects, storage behaviour, or performance across contrasting environments. Multi-season and multi-location studies are required to confirm the consistency of the observed growth, yield, quality, and economic responses.

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Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper

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