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Plant Growth Regulators for Improved Fruit Quality and Profitability of Capsicum (*Capsicum annuum* L.) under Naturally Ventilated Polyhouse

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Abstract

The present investigation was conducted during the kharif seasons of 2024 and 2025 under a naturally ventilated polyhouse at the Vegetable Research Farm, CSKHPKV, Palampur, to evaluate the influence of plant growth regulators on capsicum productivity and economics. The experiment was laid out in a Randomised Block Design with three replications, comprising 13 treatments involving foliar application of GA_3 and NAA at 50 and 75 ppm during different crop growth stages. The results revealed that NAA @ 75 ppm applied as four sprays at vegetative stage, flower initiation, and 30 and 60 days after flower initiation significantly improved pericarp thickness (5.94 mm), total soluble solids (6.9°B), ascorbic acid content (126.17 mg/100g) and titratable acidity (0.206%) whereas, GA_3 applied @ 75 ppm with four sprays at the same stages recorded highest yield (22.81 q/250m²) and its attributes, making it the most economically rewarding treatment for commercial cultivation of capsicum variety 'Indra' under naturally ventilated polyhouse conditions of mid hills of Himachal Pradesh.

Keywords: Capsicum, Economics, Naturally Ventilated Polyhouse, PGRs, Quality, Yield

Capsicum (*C. annuum* L.), also known as bell pepper, is a globally cultivated high-value vegetable crop prized for its nutritional quality, sensory attributes, and economic returns. Its fruits are rich in vitamins (A, C and E), antioxidants, dietary fibre, and essential minerals, making them highly desirable for fresh consumption, processing, and export markets[1]. In recent years, research has emphasised not only yield but also fruit quality traits such as pericarp thickness, total soluble solids, ascorbic acid content, firmness, and shelf life, which are pivotal for consumer acceptance, post-harvest performance, and market pricing[2]. In India, capsicum cultivation covers approximately 39.23 thousand hectares with an annual production of 607.06 thousand tonnes and an average productivity of 15.47 t ha^{-1} [3]. Himachal Pradesh contributes significantly to this production, with 2.96 thousand hectares under cultivation, producing 51.77 thousand tonnes at a productivity of 17.4 t ha^{-1}. As a high-value cash crop, its economic significance is increasing, especially under protected cultivation that offers opportunities for off-season production, higher quality standards, and enhanced profitability[4].

The performance of capsicum is substantially influenced by environmental conditions and crop-management strategies. Under open-field conditions,

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particularly in mid-hill regions such as Palampur, capsicum productivity and quality are often constrained by erratic rainfall, high humidity and temperature fluctuations, which can lead to an increased incidence of physiological disorders, diseases, microbial spoilage, and poor fruit quality[5]. Protected structures, such as naturally ventilated polyhouses, provide controlled environmental conditions that mitigate biotic and abiotic stresses, encourage uniform fruit development, and improve key quality attributes, including colour, flesh thickness, soluble solids, and post-harvest life. Recent studies have shown that polyhouse cultivation not only stabilises climatic extremes but also enhances fruit biochemical properties by influencing microclimate-related physiological processes[6]. These quality attributes not only determine market acceptance but also directly influence the economic returns of the product. High-quality capsicum fetches premium prices in fresh markets and processing industries, increasing gross returns, net returns, and benefit-cost ratio[7]. However, consistently achieving superior quality depends on precise physiological regulation throughout crop growth. This has led to increased interest in the use of Plant Growth Regulators (PGRs) as practical tools for modulating plant developmental processes and optimising fruit quality outcomes.

Plant Growth Regulators are organic compounds, either natural or synthetic, that modify specific physiological processes in plants. They play a critical role in assimilate partitioning, source-sink relationships, and reproductive development[8,9]. Among the PGRs, Naphthalene Acetic Acid (NAA) and Gibberellic Acid (GA_3) have been widely investigated for their beneficial effects on fruit set, growth, and biochemical quality. NAA has been reported to enhance fruit uniformity, pericarp thickness, and soluble solids by improving cell division and fruit retention, as well as stabilising carbohydrate metabolism during fruit development. It also helps reduce premature fruit drop under stress conditions, thereby maintaining fruit quality and enhancing marketable yields potential[10]. GA_3, on the other hand, is known to promote cell elongation, delay senescence, and improve fruit size and shelf life, which contributes to reduced post-harvest losses and improved economic returns[11]. Recent research has also highlighted the role of PGRs in improving physiological and biochemical quality parameters, such as antioxidant capacity, lycopene concentration, firmness, and nutrient density, which are increasingly linked to consumer health benefits and export quality standards[2,6]. Additionally, studies suggest that structured PGR application schedules tailored to crop growth stages can synergistically enhance fruit quality traits while maintaining economic efficiency. Effective PGR regimes may also reduce the dependency on high fertiliser inputs by improving internal hormonal balance and assimilate-use efficiency, contributing to more sustainable production systems.

Despite these potential benefits, the response of capsicum to PGRs is influenced by several factors, including concentration, frequency, and timing of application, cultivar specificity and environmental conditions. Improper or excessive use can lead to undesirable effects, such as fruit deformities, uneven ripening, and physiological disorders, which may negatively impact market value and profitability[8]. Furthermore, region-specific research under protected cultivation systems, such as naturally ventilated polyhouses in the mid-hill agro-climatic conditions of Himachal Pradesh, remains limited, particularly in terms of integrating quality outcomes with economic analysis. Therefore, a systematic evaluation of the effects of PGRs on fruit yield, quality parameters and economic returns is essential to develop practical recommendations for growers. The present study aimed to assess the impact of different PGR treatments on fruit yield and quality attributes, and to evaluate the economic viability of these treatments to identify the most effective combination for profitable capsicum production under protected conditions.

MATERIALS AND METHODS

The present investigation was carried out during the *kharif* seasons of 2024 and 2025 at the Vegetable Research Farm of the Department of Vegetable Science and Floriculture, CSK Himachal Pradesh Krishi Vishvavidyalaya (CSK HPKV), Palampur, Himachal Pradesh, India. The experiment was laid out in a Randomised Block Design (RBD) with three replications under a Quonset-type naturally ventilated polyhouse. The experimental site is situated in the mid-hill agro-climatic zone (Zone II) of Himachal Pradesh at an altitude of 1290.8 m above mean sea level, with geographical coordinates of 32°06′ N latitude and 76°32′ E longitude. The capsicum hybrid 'Indra' was used as the experimental material to evaluate the response of plant growth regulators in protected cultivation. The treatments comprised foliar application of GA_3 and NAA at two concentrations (50 and 75 ppm), applied at the vegetative stage, flower initiation, and 30 and 60 days after flower initiation. The polyhouse provided a favourable microclimate with day temperatures ranging from 28-30°C and a relative humidity of 60-80 per cent. Seedlings were transplanted at a spacing of 70 cm × 30 cm, and plants in each replication were trained to four stems using nylon threads.

Before transplanting, vermicompost (1.0 kg m^{-2}) and a basal application of chemical fertilisers (50 kg ha^{-1} each of nitrogen, phosphorus, and potassium) were incorporated into the soil. Neem cake @ 30 g per pit was applied 15 days prior to transplantation, and adequate moisture was maintained to avoid phytotoxicity and manage nematode infestation. Fertigation was initiated 21 days after transplanting using a water-soluble fertiliser (NPK 19:19:19) @ 2.2 g m^{-2}, applied twice a week through the drip irrigation system. Fertigation was discontinued 15 days before the final harvest. Seeds were sown on February 2 in 2024 and 2025, in plug trays containing a soilless growing medium composed of cocopeat, perlite, and vermiculite (3:1:1) under controlled growth chamber conditions to produce healthy and disease-free seedlings. Seedlings at the 3-4 leaf stage were transplanted in the polyhouse on April 8 during the respective years. All recommended cultural practices, including hoeing, earthing-up, irrigation, fertigation, pruning, training, staking, and weed management, were followed uniformly as per the standard package of practices for capsicum. Irrigation was provided through a drip irrigation system three to four times per week, depending on the crop requirements.

Solutions of GA_3 and NAA at 50 and 75 ppm concentrations were prepared by dissolving 50 mg and 75 mg of the respective growth regulators in a small quantity of ethanol (approximately 20 ml), followed by dilution to a final volume of one litre with distilled water. Foliar sprays were applied during the evening hours at the specified crop stages. For recording data, five plants from each treatment in each replication were randomly selected and tagged for observations. Fruits harvested from these tagged plants were used to assess quality parameters, namely pericarp thickness (mm), total soluble solids (°Brix) as per AOAC[12], ascorbic acid content (mg/100 g) following Ranganna[13], titratable acidity (%) according to AOAC[14], and shelf life (days), following standard analytical procedures. The economics of the different treatments were also determined based on yield and the cost of cultivation. The cost of inputs such as PGRs, labour and other operational expenses remained uniform across both years of experimentation and therefore was considered constant for economic analysis. The data obtained were subjected to an Analysis of Variance (ANOVA) appropriate for a Randomised Block Design (RBD) using OPSTAT statistical software, following the procedure outlined by Gomez and Gomez[15]. As the year × treatment interaction was non-significant, data were pooled over two years for analysis. Treatment means were compared using the Critical Difference (CD) at the 5% level of significance.

RESULTS AND DISCUSSION

In capsicum, a thicker pericarp contributes to better firmness, shelf life, transportability and overall

Table 1. Effects of plant growth regulators on quality parameters of Capsicum pooled over two years (2024 and 2025)

Treatment		Pericarp thickness (mm)	TSS (°Brix)	Ascorbic acid (mg/100g)	Titratable acidity (%)	Shelf life (days)
T_1	Two sprays* of GA_3 @ 50 ppm	5.09	5.03	94.73	0.317	11.43
T_2	Three sprays** of GA_3 @ 50 ppm	5.37	5.40	96.05	0.298	12.47
T_3	Four sprays*** of GA_3 @ 50 ppm	5.65	5.70	99.91	0.282	13.90
T_4	Two sprays of GA_3 @ 75ppm	5.32	5.50	101.09	0.297	11.70
T_5	Three sprays of GA_3 @ 75 ppm	5.57	5.70	103.71	0.277	12.60
T_6	Four sprays of GA_3 @ 75 ppm	5.83	6.03	108.83	0.260	14.23
T_7	Two sprays of NAA @ 50 ppm	5.23	6.20	108.40	0.248	10.90
T_8	Three sprays of NAA @ 50 ppm	5.43	6.27	114.93	0.241	11.70
T_9	Four sprays of NAA @ 50 ppm	5.67	6.53	119.87	0.225	13.60
T_{10}	Two sprays of NAA @ 75 ppm	5.45	6.30	116.50	0.232	11.50
T_{11}	Three sprays of NAA @ 75 ppm	5.72	6.60	119.43	0.224	13.20
T_{12}	Four sprays of NAA @ 75 ppm	5.94	6.90	126.17	0.206	13.60
T_{13}	Control	4.83	4.77	85.40	0.326	10.27
SE(m)±		0.03	0.03	1.80	0.002	0.30
CD (P=0.05)		0.10	0.10	5.27	0.006	0.88

* At vegetative and flower initiation stage; **At vegetative, flower initiation and 30 days after flower initiation; *** At vegetative, flower initiation, 30 days and 60 days after flower initiation

quality, making the fruits more suitable for both fresh consumption and export. In the present study (Table 1), the thickest pericarp (5.94 mm) was observed in the treatment comprising four sprays of NAA @ 75 ppm applied at the vegetative, flower initiation, and 30 and 60 days after flower initiation stages (T_{12}) followed by T_6 (four sprays of GA_3 @ 75 ppm) and T_{11} (three sprays of NAA @ 75 ppm), while the thinnest pericarp (4.83 mm) was recorded in the control (T_{13}), reflecting limited growth activity. The application of NAA increased pericarp thickness by promoting cell division in the fruit wall and directing extra nutrients to the developing fruits, resulting in a comparatively thicker pericarp than that observed in the other treatments. Enhanced pericarp thickness with foliar application of NAA has also been observed in capsicum[16], contributing to the firmness and storability of capsicum fruits. The Total Soluble Solids (TSS) reflect the sweetness and overall flavour quality of the fruit. The highest value (6.90 °B) was observed in the treatment comprising four sprays of NAA @ 75 ppm (T_{12}), followed by T_{11} (three sprays of NAA @ 75 ppm) and T_9 (four sprays of NAA @ 50 ppm), whereas the lowest TSS content (4.77 °B) was observed in the control (T_{13}). NAA applications improved TSS content in capsicum by increasing leaf area and photosynthesis, improving fruit set and retention and promoting efficient translocation of sugars to fruits, as reported by Pal[17] and Baghel and Singh[18]. Among other quality parameters, ascorbic acid, an antioxidant also known as vitamin C, is a vital nutritional component of capsicum and also enhances the taste of food. The highest content (126.17 mg/100 g) was recorded in T_{12} (four sprays of NAA at 75 ppm), followed by T_9 (119.87 mg/100 g) and T_{11} (119.43 mg/100 g), while the lowest value (85.40 mg/100 g) was recorded in the control (T_{13}). The foliar application of NAA enhances ascorbic acid content in capsicum, as it is a synthetic auxin that stimulates metabolic activity and the biosynthesis of antioxidants. Similar results for ascorbic acid with NAA were reported by Anbarasi and Venkatraman[19], Howard *et al.*[20], and Bosland and Votava[21].

The titratable acidity refers to the total amount of organic acids present in the fruit, which contributes to its sourness and plays a role in the overall flavour and shelf stability. Higher acidity can give the fruit a sharper taste, whereas moderate acidity enhances overall palatability. In the present investigation (Table 1), the lowest titratable acidity (0.206%) was observed in treatment T_{12} (comprising four sprays of NAA at 75 ppm applied at the vegetative, flower initiation, and 30 and 60 days after flower initiation stages), followed by T_{11} (0.224%) and T_9 (0.225%), in contrast the highest acidity (0.326%) was recorded in the control (T_{13}). The lower acidity in T_{12} indicates improved flavour balance and potential storability. This is because NAA enhances fruit ripening processes, leading to the conversion of organic acids (such as citric and malic acids) into sugars and other metabolites. This metabolic shift decreases the acid concentration, so titratable acidity declines while sweetness and ascorbic acid increase. The results of the present investigation are also supported by the work of Pal[17]. The shelf life of capsicum fruits is a key trait for marketability and storage. The longest shelf life of (14.23 days) was recorded in treatment T_6 comprising four sprays of GA_3 @ 75 ppm, applied at vegetative, flower initiation, and 30 and 60 days after flower initiation stages. This treatment was statistically at par with T_3, T_9, and T_{12}, where four sprays of GA_3 and NAA were applied at both concentrations, whereas the shortest shelf life (10.27 days) was observed in the control (T_{13}). The shelf life of capsicum fruits was typically assessed under ambient atmospheric conditions (20-25˚C temperature and 60-70% RH). Ahmed *et al.*[22] also reported that GA_3 delayed ripening and senescence by reducing respiration and ethylene production and minimising water loss, shrivelling, and softening, thus maintaining texture and colour.

The data pertaining to the number of fruits per plant, average fruit weight, yield and economics of capsicum are presented in Table 2. The maximum number of fruits per plant (27) was recorded in T_6 (comprising four sprays of GA_3 @ 75 ppm), followed by T_5 (25.67 fruits), i.e. three sprays of GA_3 @ 75 ppm and T_4 (24.33 fruits), i.e. two sprays of GA_3 @ 75 ppm. On the other hand, the lowest number of fruits (19.33 per plant) was recorded in the control (T_{13}). The highest average fruit weight (97.60 g) was observed in treatment T_6 (comprising four sprays of GA_3 @ 75 ppm) and was statistically at par with T_3 (96.85 g, four sprays of GA_3

Table 2. Effects of plant growth regulators on yield and economics of capsicum pooled over two years (2024 and 2025)

Treatment		Fruits per plant (No.)	Average fruit weight (g)	Fruit yield			Cost of cultivation (Rs)	Gross return (Rs)	Net return (Rs)	B:C ratio
				(kg/ plant)	(kg/ m^2)	(q/ 250m^2)				
T_1	Two sprays* of GA_3 @ 50 ppm	21.33	94.40	2.01	9.45	17.37	39324	86833	47509	2.21
T_2	Three sprays** of GA_3 @ 50 ppm	22.00	95.92	2.11	9.92	18.23	39446	91151	51705	2.31
T_3	Four sprays*** of GA_3 @ 50 ppm	23.00	96.85	2.23	10.48	19.27	39569	96336	56767	2.43
T_4	Two sprays of GA_3 @ 75ppm	24.33	93.55	2.28	10.72	19.70	39332	98496	59164	2.50
T_5	Three sprays of GA_3 @ 75 ppm	25.67	95.10	2.44	11.47	21.08	39459	105408	65949	2.67
T_6	Four sprays of GA_3 @ 75 ppm	27.00	97.60	2.64	12.40	22.81	39586	114048	74462	2.88
T_7	Two sprays of NAA @ 50 ppm	20.67	89.80	1.86	8.74	16.07	39308	80351	41043	2.04
T_8	Three sprays of NAA @ 50 ppm	21.67	90.35	1.96	9.21	16.93	39422	84671	43089	2.09
T_9	Four sprays of NAA @ 50 ppm	21.00	91.00	1.91	8.98	16.50	39537	82511	42974	2.09
T_{10}	Two sprays of NAA @ 75 ppm	22.00	91.60	2.02	9.49	17.45	39308	87266	47958	2.22
T_{11}	Three sprays of NAA @ 75 ppm	22.67	92.35	2.09	9.82	18.06	39423	90288	50865	2.29
T_{12}	Four sprays of NAA @ 75 ppm	23.33	93.20	2.17	10.20	18.75	39538	93743	54205	2.37
T_{13}	Control	19.33	89.00	1.72	8.08	14.86	39079	74303	35224	1.90
SE(m)±		0.45	0.44	0.44	0.04	0.16	-	-	-	-
CD (P=0.05)		1.32	1.28	1.28	0.12	0.47	-	-	-	-

* At vegetative and flower initiation stage; **At vegetative, flower initiation and 30 days after flower initiation; *** At vegetative, flower initiation, 30 days and 60 days after flower initiation, Sale rate of capsicum: Rs 50/kg

@ 50 ppm), followed by T_2 (95.92 g, three sprays of GA_3 @ 50 ppm). In contrast, the lowest average fruit weight (89 g) was recorded in the control (T_{13}). The highest fruit yield per plant, per m^2 and per polyhouse (250 m^2 size) was recorded in T_6 (four sprays of GA_3 @ 75 ppm) with values of 2.64 kg, 12.40 kg and 22.81 q, respectively. This was followed by T_5 and T_4 (three and two sprays of GA_3 @ 75 ppm, respectively), whereas these parameters were recorded lowest in the control (T_{13}). The economic analysis revealed that the highest gross return (Rs. 1,14,048/-), net return (Rs. 74,462/-) and B: C ratio (2.88) were recorded in T_6 (comprising four sprays of GA_3 at vegetative, flower initiation, and 30 days and 60 days after flower initiation stages). This was followed by T_5 (three sprays of GA_3@ 75 ppm) and T_4 (two sprays of GA_3 @ 75 ppm), whereas the lowest returns were recorded in T_{13} (control).

CONCLUSION

The application of NAA at 75 ppm, applied as four sprays at the vegetative stage, flower initiation, and 30 and 60 days after flower initiation, was found to be superior in improving quality attributes such as pericarp thickness, total soluble solids, ascorbic acid content, and titratable acidity, which are highly desirable for premium fresh markets and processing industries. In contrast, GA_3 applied @ 75 ppm with four sprays (at the vegetative stage, flower initiation, and 30 and 60 days after flower initiation) recorded the highest yield and related attributes, making it the most economically rewarding treatment for commercial cultivation of capsicum variety 'Indra' under naturally ventilated polyhouse under mid-hill conditions of Himachal Pradesh.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest among the authors in this research paper.

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AUTHORS CONTRIBUTION

SG: Conducted the experiment and analyzed the data. NS: Wrote the original manuscript and revised submission. SN: Collected and compiled literature, helped in data recording. RS: Finalized the research programme, methodology, provided resources and edited the manuscript