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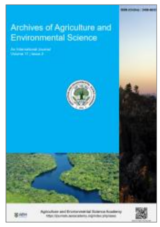

Original Research Article

Effect of different concentrations of gibberellic acid and naphthalene acetic acid on growth, yield and post harvest quality of tomato

Suraj Lamsal[1,*] and Hom Nath Giri[2]

[1] Valley Krishi Campus, Faculty of Agriculture, Agriculture and Forestry University, Rampur, Chitwan, Nepal
[2] Department of Horticulture, Faculty of Agriculture, Agriculture and Forestry University, Rampur, Chitwan, Nepal
[*] Corresponding author's Email: Suraj.lamsal25@gmail.com

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ABSTRACT

A field experiment was carried out in Rukum West, Nepal, from March to June 2025 in order to assess the impact of various concentrations of gibberellic acid (GA_3) and naphthalene acetic acid (NAA) on the growth, yield, fruit quality, and postharvest quality of "Monoprecos" tomato. The experiment was conducted using a randomized complete block design (RCBD) with seven treatments and three replications. Plant height, flowering traits, fruit length, fruit diameter, fruit yield, total soluble solids (TSS), titratable acidity (TA), pH, physiological loss in weight (PLW), and decay loss of tomato were recorded during the experiment. GA_3 @ 75 ppm treatment produced the maximum plant height (165.21 cm) of tomato, whereas GA_3 @ 50 ppm recorded the highest number of flowers per plant (104.29), fruit length (4.42 cm), and fruit yield (24.07 mt ha^{-1}) of tomato. NAA @ 30 ppm treatment produced the highest number of flowers per cluster (10.34) and fruit diameter (4.94 cm) of tomato. GA_3 @ 50 ppm also recorded higher TSS (4.88 °Brix) and pH, while titratable acidity was highest in the control. After 12 days of storage, GA_3 @ 50 ppm showed lower PLW (11.92%), whereas GA_3 @ 25 ppm recorded the lowest decay loss (70.83%). Therefore, GA_3 @ 50 ppm can be recommended as an optimum concentration for growth, yield, and postharvest quality of tomato in the mid-hill region of Nepal.

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INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is one of the most widely cultivated and economically important vegetable crops, belonging to the Solanaceae family, and is valued for its high nutritional content as well as its versatile use in fresh consumption and processed products. Tomato is rich in vitamins A and C, minerals, and bioactive compounds such as lycopene, a powerful antioxidant associated with reduced risk of cardiovascular diseases and certain cancers (Motlhalamme *et al*., 2025). Despite its importance, tomato productivity is often limited by several biotic and abiotic factors, including temperature stress, poor agronomic management, and nutrient imbalance. High temperatures during flowering and fruit-setting stages can reduce pollen viability and fruit set, ultimately lowering yield and fruit quality (Jerca *et al*., 2024). In Nepal, tomato is cultivated across diverse agro-ecological regions from the Terai to mid-hills, contributing substantially to household income and nutritional security. However, the national productivity remains relatively low compared with global standards due to limited adoption of improved cultivation technologies, several disease and pest outbreak, and inadequate crop management practices (Ministry of Agriculture & Livestock Development [MOALD, 2024]; Pandit *et al*., 2022).

Plant growth regulators (PGRs) are widely used in horticulture to regulate plant growth, development, and productivity. Among them, Gibberellic acid (GA_3) and naphthalene acetic acid (NAA) are commonly applied to enhance vegetative growth, flowering, fruit set, and yield in tomato. GA_3 promotes cell elongation, stem growth, and reproductive development, thereby improving plant height, flowering, and fruit formation (Luo *et al*., 2024; Poonia *et al*., 2024). Similarly, NAA, a synthetic Auxin, plays an important role in cell division, fruit retention, and reduction of flower and fruit drop, leading to increased yield and improved fruit quality (Khan & Nabi, 2023). Although GA_3 and NAA have demonstrated beneficial effects on tomato growth and productivity, their optimal concentrations vary across different agro-ecological conditions and previous studies have examined separate production and post-harvest treatment (Bhattarai *et al.*, 2025; Khadka & Sapkota, 2025) rather than jointly evaluating growth, yield, and post harvest quality in the mid-hill regions of Nepal. Therefore, this study aimed to evaluate the effects of different concentrations of GA_3 and NAA on the growth, yield, and post harvest quality of tomato under the agro-ecological conditions of Rukum West, Nepal.

MATERIALS AND METHODS

Location of the experiment

The experiment was conducted in the year 2025 A.D at Musikot Municipality, at Vegetable Seed Production Centre (VSPC), Rukum West, Nepal. The area is situated in Karnali Province of Nepal. The experimental site is situated at 28.618495 °N latitude and 82.4618433 °E longitude, with an elevation between 754 meters above sea level (masl) and 6,070 (masl) to the north. Rukum West district covers an area of 1213.50 square kilometers. The elevation of the experimental site is 1440 masl. Geographically, the experimental site is in a hilly region of Nepal.

Weather data of the experimental site

The climate of the experimental site is characterized as a sub-tropical climate with dry summer and cold winter. The south-facing topography is suitable for the production of vegetables and vegetable seed. It covers a wide range of Agro-climatic conditions, receiving an average annual temperature of 20.3°C with an average annual rainfall of 1,639 mm. The meteorological data for the year 2025 A.D experimental period were recorded from the meteorological station of vegetable seed production center, Rukum West (Figure 1).

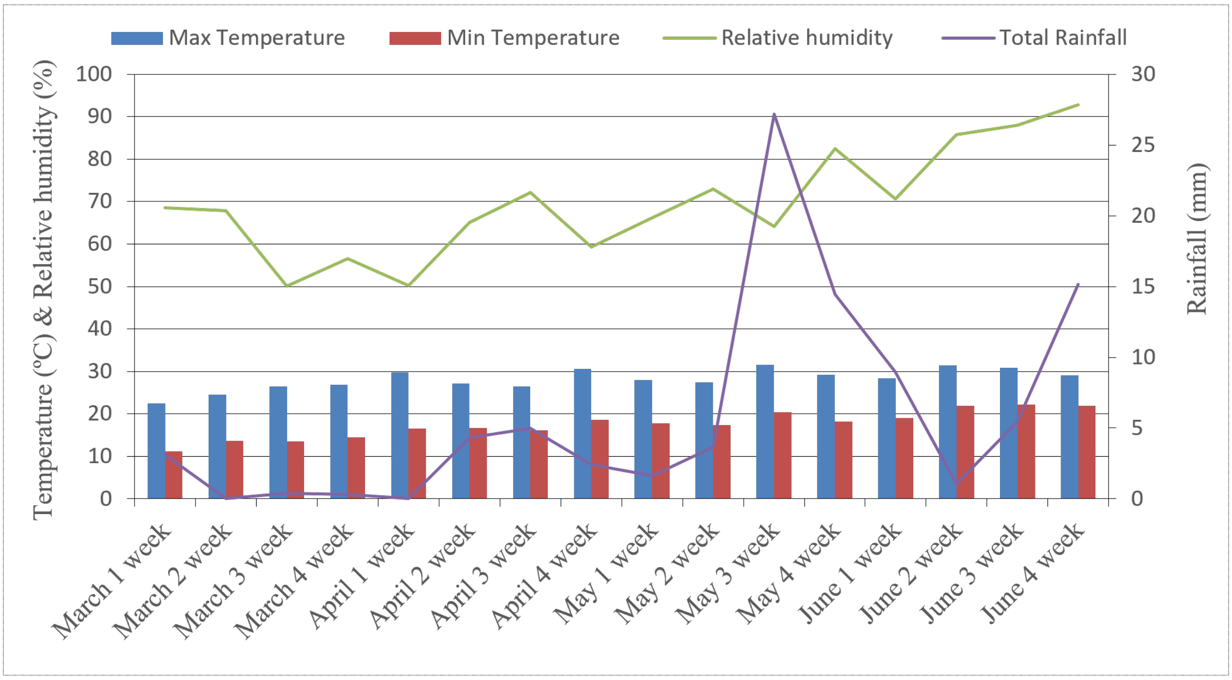

Figure 1. *Weather parameters of the research location during the tomato growing period 2025 (Source: Meteorological Station, Chapa, Rukum West).*

Soil properties of the experimental field

Soil samples were collected from the experimental field before transplanting seedlings and were tested at Integrated Agriculture Lab, Surkhet, Karnali Province, Nepal. The experimental field's soil was neutral in reaction (pH 7.5), medium in soil organic matter content (4.8%), high in total nitrogen (0.24%), and low in available potassium (60.78 kg/ha) and phosphorus (23.4 kg/ha).

Experimental design and treatment details

Altogether seven treatments were laid out in a randomized complete block design with three replications.

Preparation and spray of plant growth regulator solutions

At first, Stock solution of 1000 ppm was prepared. To prepare the stock solution, 1 gram of GA_3 or NAA was mixed with 1 liter of distilled water. Then, a working solution was prepared by using the formula from the stock solution.

$$C_1V_1 = C_2V_2 \quad (1)$$

Where, C_1 is the concentration (ppm) of the stock solution, V_1 is the volume of the stock solution, C_2 is the desired concentration (ppm) of the working solution, V_2 is the final volume of the working solution.

Only the freshly prepared solutions were sprayed during evening time so as to prevent evaporation during intense sunlight. The spray was done at an interval of 15 days from 15 (Days after transplanting) DAT and ending at 45 DAT with a hand pump sprayer fitted with a fine nozzle. To avoid drift and cross contamination from one plot to another, a polythene sheet was stretched between the plants of two adjacent plots.

Name of the treatments

Three different doses of Gibberellic acid i.e., 25, 50 and 75 ppm and three different doses of NAA i.e., 10, 20 and 30 ppm along with one control treatment were used in this experiment. T_1= GA_3 @ 25 ppm, T_2= GA_3 @ 50 ppm, T_3= GA_3 @ 75 ppm, T_4= NAA @ 10 ppm, T_5= NAA @ 20 ppm, T_6= NAA @ 30 ppm, T_7= Control (Distilled water).

Crop management practices

Raised nursery beds were prepared by sterilization of the nursery beds with Bavistin @ 1 g/liter of water, Basal application of farm yard manure (FYM) @ 5 kg/m^2 and Urea, DAP, and Potash @ 5 g of each per m^2 were applied. The tomato seeds were sown about 1.5 to 2 cm deep and 5 cm apart in February. After complete germination, healthy 28 days old seedlings were transplanted to the main field in the late afternoon. The experimental field was well prepared by ploughing and harrowing twice. The recommended dose of Urea, DAP, and MOP fertilizer for tomato is 10: 5: 4 kg/ropani, and FYM was applied at the rate of 30 mt/ha (Agriculture and livestock Diary: AITC, 2024). Urea was applied in three split doses first as a basal dose which is applied at the time of transplanting and remaining half doses were applied at 25 DAT and 45 DAT. Weeding and earthing up were done at 25 and 45 days after transplanting (DAT). Training was done by removing suckers, and staking was done when the plant height increased to prevent the plants from creeping out on the ground and to keep them standing. As the vines grew, they were loosely connected to stakes, bamboo or poles that were placed near the plant. Insecticide and fungicide were sprayed for control of insects and fungus. Irrigation was given as and when required.

Observation and measurement

Data were collected from six randomly selected plants out of 20 plants from each plot, and following observations were studied in the successive stages of crop growth.

Growth parameter: Plant height at 30, 45, 60 and 75 days after transplanting (DAT) was collected from six sample plants in each plot.

Yield parameter: Yield attributes data included Numbers of flowers per cluster and Numbers of flowers per plant at 60 DAT and 75 DAT, Numbers of flowers per plant, Days to 50% flowering, and Fruit length, diameter, and individual fruit weight were collected.

Chemical parameters: Fruit quality was assessed by measuring Total soluble solids (TSS), titratable acidity (TA), and pH of tomato. TSS was determined by using a hand refractometer expressed in °Brix, TA was determined by titration against 0.01N sodium hydroxide (NaOH) solution expressed as percentage acidity by following standard methods (Latimer, 2023) and Fruit juice pH was measured using a digital pH meter.

Post-harvest quality: Post-harvest quality attributes included Physiological loss in weight at 3, 6, 9 and 12 days of storage (DAS). The initial and subsequent fruit weights were recorded using a weighing balance, and PLW was expressed as a percentage.

$$\mathrm{PLW}(\%) = \frac{\text{Initial weight} - \text{Final weight}}{\text{Initial weight}} \times 100\% \qquad (2)$$

Decay loss of tomato at 3, 6, 9, 12 and 15 days of storage (DAS) was recorded when fruits showing visible symptoms of decay were counted, and decay loss was expressed as a percentage of the total number of stored fruits.

$$\text{Decay loss}(\%) = \frac{\text{Number of decayed fruits}}{\text{Total number of fruits}} \times 100\% \qquad (3)$$

Data analysis

The data obtained from the experimental plots for growth, yield and post harvest attributing characters of tomatoes were entered, and organized in Microsoft Excel and statistically analyzed to find out statistical significance. The treatment means were calculated, and analysis of variance (ANOVA) was performed in R software (version 4.5.1) according to the experimental design. The significance of treatment effects was tested using the F (variance ratio) test. When significant differences were observed, the treatment means were compared using Duncan's Multiple Range Test (DMRT) at the 5% probability level. The grand mean and coefficient of variation were also calculated from the ANOVA results.

Plant height

During the study, the effect of different concentrations of GA_3 and NAA was tested. At 30 days after transplanting (DAT), plant height was significantly different. The tallest plant height was obtained by GA_3 @ 75 ppm (51.96 cm), which was statistically similar to GA_3 @ 50 ppm, GA_3 @ 25 ppm, and NAA @ 30 ppm (Table 1). At 45 DAT, tallest plant height was obtained by GA_3 @ 75 ppm (101.81 cm), which was statistically similar to GA_3 @ 50 ppm and GA_3 @ 25 ppm. Plant height was significantly different at 60 DAT, where the tallest plant height was obtained by GA_3 @ 75 ppm and GA_3 @ 50 ppm. At 75 DAT, there was a significant difference in plant height (Table 1). The tallest plant height was obtained by GA_3 @ 75 ppm (165.21 cm), which was statistically similar to GA_3 @ 50 ppm, the results are in conformity with those of (Kavitha *et al.*, 2023). As GA_3 binds to the GID1 (Gibberellin Insensitive Dwarf 1) receptor, forming a GA_3 GID1 complex and degrading a DELLA protein which normally stops cell division , this degradation enhances cell division in the apical meristem and longitudinal expansion of internodal cells and resulting in a taller plant (Shi *et al.*, 2024).

Number of flowers and days to flowering

At 75 DAT, the number of flowers per cluster showed highly significant differences, where the highest number of flowers per cluster (10.34) was recorded with NAA @ 30 ppm, which was statistically at par with GA_3 @ 50 ppm (Table 2). Similarly, for the number of flowers per plant, a highly significant difference was observed among treatments. The maximum number of flowers per plant (104.29) was observed with GA_3 @ 50 ppm, which was statistically at par with NAA @ 30 ppm. This result is in line with the finding of Jha *et al.* (2022) and confirmed that GA_3 @ 50 ppm significantly enhances flowering traits and yield attributing characters too. This may be due to balance concentration of GA_3 which support miR156 and SISBP pathway and activate the flower gene SFT and AP1 and resulting in the highest number of flowers (Ferigolo *et al.*, 2023). The effect of different concentrations of GA_3 and NAA has been observed clearly on days to 50% flowering. GA_3 @ 75 ppm had earlier flowering on 29.33 days which shows highly significant difference among other treatments which was statistically at par with NAA @ 30 ppm at 31.67 days (Table 2). A higher concentration of GA_3 promotes cell division and elongation which accelerates the vegetative phase and encourages an earlier reproductive growth, resulting in early emergence of inflorescence (Chowdhury *et al.*, 2023).

Table 1. Effect of different concentration of GA_3 and NAA on plant height of tomato.

Plant height (cm)				
Treatments	**30 DAT**	**45 DAT**	**60 DAT**	**75 DAT**
GA_3 @ 25 ppm	48.05^{ab}	100.91^{a}	131.22^{ab}	157.59^{abc}
GA_3 @ 50 ppm	48.73^{ab}	97.36^{a}	138.08^{ab}	159.64^{ab}
GA_3 @ 75 ppm	51.96^{a}	101.81^{a}	144.20^{a}	165.21^{a}
NAA @ 10 ppm	42.02^{bc}	77.42^{bc}	120.83^{b}	138.57^{cd}
NAA @ 20 ppm	44.25^{bc}	79.53^{bc}	124.45^{b}	141.19^{bcd}
NAA @ 30 ppm	47.02^{abc}	88.94^{ab}	129.50^{ab}	148.32^{abcd}
Control	40.27^{c}	72.25^{c}	102.44^{c}	130.32^{d}
Grand mean	46.04	88.32	127.24	148.69
SEM(±)	0.85	1.79	2.05	2.18
F- test	*	**	**	**
$LSD_{(0.05)}$	6.96	14.66	16.72	17.77
CV, (%)	8.49	9.33	7.38	6.73

Mean followed by common letter(s) within columns are non-significantly different based on DMRT P = 0.05, '*' significant at 5% (P<0.05), **Significant at 0.01 P level, SEM: Standard Error of Mean, CV: Coefficient of Variance, LSD: Least significant difference, DAT: Days after transplanting.

Table 2. Effect of different concentration of GA_3 and NAA on number of flowers and days to 50% flowering.

Treatments	**Number of flowers/cluster at 75 DAT**	**Number of flowers/plant at 75 DAT**	**Days to 50% flowering**
GA_3 @ 25 ppm	7.98^{cd}	81.65^{bc}	33.00^{cd}
GA_3 @ 50 ppm	9.61^{ab}	104.29^{a}	32.67^{cd}
GA_3 @ 75 ppm	7.82^{cd}	78.70^{bc}	29.33^{d}
NAA @ 10 ppm	7.32^{cd}	65.44^{cd}	37.67^{b}
NAA @ 20 ppm	8.36^{bc}	74.14^{cd}	33.67^{c}
NAA @ 30 ppm	10.34^{a}	94.21^{ab}	31.67^{cd}
Control	6.94^{d}	60.83^{d}	43.33^{a}
Grand mean	8.34	79.89	34.42
SEM(±)	0.17	1.94	0.42
F-test	***	***	***
$LSD_{(0.05)}$	1.3	15.78	3.42
CV, (%)	8.71	11.12	5.58

Mean followed by common letter(s) within columns are non-significantly different based on DMRT P = 0.05, ***Significant at 0.001 P level. SEM: Standard Error of Mean, CV: Coefficient of Variance, LSD: Least significant difference, DAT: Days after transplanting.

Yield and yield parameters

A significant difference was seen in fruit length on the application of different concentrations of plant growth regulators on tomatoes. GA_3 @ 50 ppm resulted in the largest fruit length (4.42 cm), which was statistically similar to GA_3 @ 75 ppm and GA_3 @ 25 ppm. When compared to untreated plants it was (3.37 cm) fruit length, this shows that the treatment of GA_3 greatly increased fruit growth and cell elongation (Table3). NAA @ 30 ppm shows a highly significance difference among other treatment on fruit diameter (4.94 cm), which was statistically at par with NAA @ 20 ppm. As compared to other treatments, GA_3 @ 50 ppm produced the highest fruit length (4.42 cm), where lowest in the control (Figure 2). GA_3 @ 50 ppm shows significantly increased in fruit length as compared to others (Paikra *et al.*, 2022) Gibberellins promote cell expansion during early fruit growth stages which collectively increases fruit size (Guo *et al.*, 2022). NAA @ 30 ppm recorded the widest fruits, which aligns with similar result (Kumar *et al.*, 2025). NAA @ 30 ppm improved physical fruit traits and yield compared with lower auxin or control. Effect of different concentrations of GA_3 and NAA was tested. GA_3 @ 50 ppm produced the highest yield (24.07 mt ha^{-1}), which was statistically similar to NAA @ 30 ppm which aligns with tomato experiments Hassan *et al.* (2024) as it is influence by the fruit length. Furthermore, GA_3 @ 50 ppm greatly improved yield parameters by increasing photosynthetic efficiency and nutrient translocation (Shoaib *et al.*, 2025).

Table 3. Effect of different concentrations of GA_3 and NAA on yield parameters of tomato.

Treatments	Fruit length (cm)	Fruit diameter (cm)
GA_3 @ 25ppm	4.10^{abc}	4.68^{b}
GA_3 @ 50 pm	4.42^{a}	4.70^{b}
GA_3 @ 75 pm	4.22^{ab}	4.58^{b}
NAA @ 10 pm	3.62^{de}	4.57^{b}
NAA @ 20ppm	3.70^{cde}	4.78^{ab}
NAA @ 30 ppm	3.91^{bcd}	4.94^{a}
Control	3.46^{e}	4.37^{c}
Grand mean	3.91	4.65
SEM(±)	0.05	0.023
F- test	**	**
$LSD_{(0.05)}$	0.41	0.19
CV, (%)	5.8	2.32

Mean followed by common letter(s) within columns are non-significantly different based on DMRT P = 0.05, **Significant at 0.01 P level, . SEM: Standard Error of Mean, CV: Coefficient of Variance, LSD: Least significant difference.

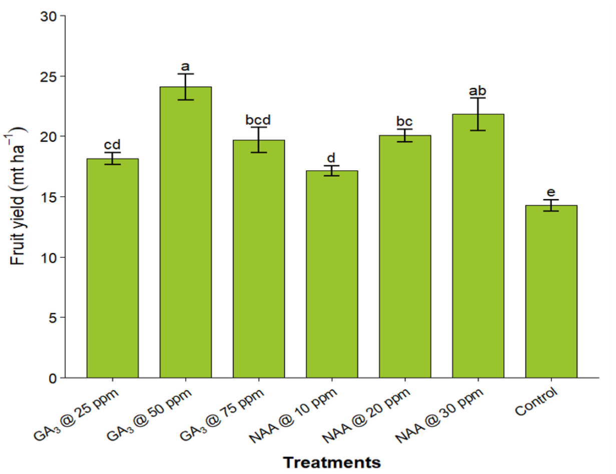

Figure 2. *Effect of different concentrations of GA_3 and NAA on yield of tomato.*

Chemical parameters

Total soluble solids (TSS), pH, and titratable acidity of tomato fruits were significantly influenced by different concentrations of GA_3 and NAA. The TSS content was observed to be significantly different among treatments. The maximum TSS (4.88 °Brix) was observed with GA_3 @ 50 ppm, which was statistically at par with GA_3 @ 75 ppm, GA_3 @ 25 ppm, NAA @ 10 ppm, and NAA @ 30 ppm (Table 4). Fruit pH also showed significant differences among the treatments. The highest pH value (4.58) was obtained with GA_3 @ 50 ppm, which was statistically at par with GA_3 @ 75 ppm and NAA @ 20 ppm. Similarly, titratable acidity was also significantly affected by the treatments. The minimum titratable acidity (0.430%) was recorded with GA_3 @ 75 ppm, which was statistically at par with GA_3 @ 50 ppm, NAA @ 20 ppm, and NAA @ 30 ppm (Table 4). These results are in accordance with those of Rebollo & Rosales (2023), who found that tomato fruit acidity was decreased and TSS was considerably raised by GA_3 50 ppm, whereas low or high doses showed less effect.

Table 4. Effect of different concentration of GA_3 and NAA on chemical composition of tomato.

Treatments	TSS (°Brix)	pH	TA (%)
GA_3 @ 25 ppm	4.6^{abc}	4.29^{bc}	0.463^{ab}
GA_3 @ 50 ppm	4.88^{a}	4.58^{a}	0.439^{bc}
GA_3 @ 75 ppm	4.73^{ab}	4.49^{ab}	0.430^{c}
NAA @ 10 ppm	4.65^{ab}	4.35^{bc}	0.457^{ab}
NAA @ 20 ppm	4.23^{bc}	4.39^{ab}	0.451^{bc}
NAA @ 30 ppm	4.36^{abc}	4.35^{bc}	0.455^{abc}
Control	4.08^{c}	4.16^{c}	0.477^{a}
Grand mean	4.51	4.38	0.45
SEM(±)	0.06	0.026	0.003
F- test	*	*	*
$LSD_{(0.05)}$	0.49	0.21	0.02
CV, (%)	6.19	2.71	2.99

Mean followed by common letter(s) within columns are non-significantly different based on DMRT P = 0.05, '*' significant at 5% (P<0.05), SEM: Standard Error of Mean, CV: Coefficient of Variance, LSD: Least significant difference, TSS: Total soluble solids, TA: Titratable Acidity.

Physiological loss in weight

Highly significant differences were observed in the physiological loss in weight of tomato fruits during 15 days of storage, recorded at 3 days' intervals. At 3 and 6 days of storage, the highest physiological weight loss (3.72% and 8.92%) respectively was recorded in the control, on the 9th day of storage, NAA @ 30 ppm (12.60%) recorded the highest physiological loss in weight, which was statistically at par with NAA @ 10 ppm and the control (Table 5). At 12th days of storage, the greatest physiological loss in weight (17.42%) was observed with NAA @ 30 ppm, which was statistically at par with NAA @ 10 ppm and the control, whereas GA_3 @ 50 ppm resulted in comparatively lower physiological loss in weight (11.92)%. A similar trend of physiological loss in weight was found (Başak *et al.*, 2025). The physiological loss in weight was rapid on control while GA_3 @ 50 ppm showed slow losses which is closely similar with Park & Malka (2022), this may be due to GA_3 suppress ethylene pathway and slow down cell wall degradation (Yang *et al.*, 2023).

Table 5. Effect of different concentration of GA_3 and NAA on physiological loss in weight of tomato.

Physiological loss in weight (%)				
Treatments	**3 days**	**6 days**	**9 days**	**12 days**
GA_3 @ 25 ppm	2.14^{de}	4.59e	9.53^{b}	13.64^{bc}
GA_3 @ 50 ppm	1.82^{e}	4.25^{e}	7.77^{c}	11.92^{c}
GA_3 @ 75 ppm	2.6^{bcd}	5.25^{d}	9.15^{bc}	14.05^{bc}
NAA @ 10 ppm	2.80^{bc}	5.92^{c}	11.46^{a}	15.79^{ab}
NAA @ 20 ppm	2.27^{cde}	4.5^{e}	8.39^{bc}	12.07^{c}
NAA @ 30 ppm	2.93^{b}	6.94^{b}	12.6^{a}	17.42^{a}
Control	3.72^{a}	8.92^{a}	12.24^{a}	14.59^{abc}
Grand mean	2.61	5.77	10.16	14.21
SEM(±)	0.067	0.046	0.196	0.391
F- test	***	***	***	*
$LSD_{(0.05)}$	0.55	0.38	1.60	3.2
CV, (%)	11.79	3.72	8.86	12.63

Mean followed by common letter(s) within columns are non-significantly different based on DMRT P = 0.05, '*' significant at 5% (P<0.05), , ***Significant at 0.001 P level. SEM: Standard Error of Mean, CV: Coefficient of Variance, LSD: Least significant difference.

Decay loss

Highly significant differences were observed in the decay loss of tomato fruits during storage, recorded at 6, 9, 12, and 15 days after storage. At 6^{th} day of storage, the highest decay percentage (45.83%) was recorded in the control, which was statistically followed by NAA @ 30 ppm and NAA @ 20 ppm (Figure 3). At 9^{th} day of storage, maximum decay loss (70.83%) was recorded in the control, which was statistically at par with NAA @ 30 ppm. At 12^{th} day of storage, the highest decay percentage (79.17%) was recorded in the control which were statistically at par with NAA @ 20 ppm and NAA @ 30 ppm. At 15^{th} day of storage, the maximum decay loss (100%) was observed in NAA @ 30 ppm and the control, which were statistically at par with each other. The minimum decay loss (70.83%) was recorded with GA_3 @ 25 ppm. (Chen *et al.*, 2023; Wang *et al.*, 2024) reported that higher NAA concentration induce ethylene producing and cell wall degrading gene which accelerate rapid fruit softening and make fruits more prone to microbial invasion, thereby increasing decay incidence.

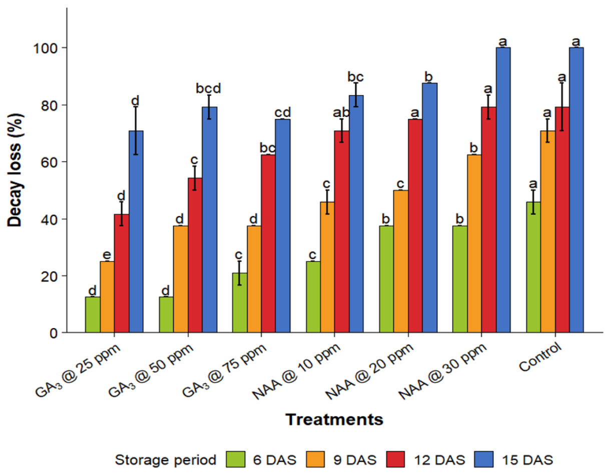

Figure 3. *Effect of different concentration of GA_3 and NAA on decay loss of tomato.*

Conclusion

In conclusion, the application of GA_3 and NAA significantly influenced tomato growth, flowering, yield, fruit quality, and postharvest performance under the protected conditions. GA_3 @ 75 ppm recorded the greatest plant height and earlier 50% flowering, while GA_3 @ 50 ppm produced the highest number of flowers per plant, fruit length, and fruit yield. NAA @ 30 ppm resulted in the highest number of flowers per cluster and fruit diameter. GA_3 @ 50 ppm recorded highest TSS and pH, where TA was highest in the control and less physiological loss in weight was on GA_3 @ 50 ppm, whereas GA_3 @ 25 ppm recorded the lowest decay loss during storage. These findings indicate that GA_3 @ 50 ppm performed favorably for several important traits, but its effectiveness should be interpreted within the specific location, season, and experimental conditions of this study. Since the experiment was conducted at a single location and during one growing season, further multi-location and multi-season studies are needed to validate these responses before making broader recommendations.

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DECLARATIONS

Author contribution statement: Conceptualization: S.L. and H.N.G.; Methodology and design of experiment: S.L. and H.N.G.; Software and validation: S.L. and H.N.G.; Formal analysis: S.L.; Investigation: H.N.G.; Data curation: S.L.; Writing—original draft preparation: S.L.; Writing—review and editing: S.L. and H.N.G.; Visualization: S.L.; Supervision: H.N.G. All authors have read and agreed to the published version of the manuscript.

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Ethics approval: This study was conducted in view of the institutional ethical guidelines and does not harm the human participants.

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