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Optimization of Plant Growth Regulators Use for Improved Growth, Yield, and Economic Returns from Tomato (*Solanum lycopersicum* L.) in Arid Regions

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Abstract: A field experiment was conducted to optimize the application of plant growth regulators in tomato cultivation during rabi, 2021-22. The objective was to assess their effects on growth, yield attributes, fruit yield, and economics. The experiment included 10 treatments with three plant growth regulators (GA_3, 4-CPA, and NAA), each applied at three levels (25, 50, and 75 µg mL^{-1}), along with a control (water). The experimental design was a randomized block with three replications. Results indicated that GA_3 and NAA significantly enhanced plant height, the number of branches, fruit yield, and economic returns. Conversely, 4-CPA adversely affected yield and consequently economic returns. Optimal dosages for GA_3 and NAA were identified at 53.5 µg mL^{-1} and 63.1 µg mL^{-1}, respectively, using second-order polynomial regression ($y=ax^2+bx+c$). This resulted in tomato yields of 29.55 and 29.69 t ha^{-1}, respectively. NAA treatments stood out, providing the highest net returns (Rs. 4,80,447 ha^{-1}) and a favourable B:C ratio of 4.26:1, making it a promising choice for tomato cultivation.

Key words: 4-CPA, Economic Optimum Dose, Fruit Yield, GA_3, NAA.

Tomato (*Solanum lycopersicum* L.) is the second most important solanaceous vegetable crop in India, surpassed only by potatoes, both in terms of cultivated area and production. This versatile crop finds its way into a variety of culinary applications, from salads and cooked dishes to processed products. Beyond its culinary versatility, tomato also plays a crucial role in human nutrition, offering a rich source of antioxidants such as lycopene, vitamin A, vitamin B, and essential minerals (Ali *et al*., 2020).

Tomato, being a warm-season crop, is sensitive to severe frost. Hence, temperature plays a vital role in the fruit set and pigmentation of tomato. The optimal temperature for fruit setting ranges between 21-28°C, while lycopene synthesis is most efficient between 21-24°C (Rehman *et al*., 2015). Therefore, comparatively warm and sunny weather during the winter season in western Rajasthan provides the ideal conditions for *Rabi* cultivation of tomato. However, during winter high diurnal temperature variations, dry winds, and intense sunlight, contribute to poor fruit set and thus reduced fruit yield. To overcome these abiotic stresses caused by weather-related factors, the application of plant growth regulators (PGRs) through foliar sprays can be a promising solution.

Plant growth regulators are a group of compounds that have the potential to regulate pre-harvest fruit drops, enhance flower bud formation, and promote fruit ripening. Among these, gibberellic acid (GA_3) is known to stimulate stem elongation, facilitate flower maturation, and enhance overall plant growth, all of which have a direct impact on tomato yield and quality (Chaudhury *et al*., 2013). 4-chlorophenoxy acetic acid (4-CPA) is an auxin that influences the ripening process of tomatoes by affecting sucrose metabolism. Notably, the application of 4-CPA after anthesis, increases fruit set percentage, the number of fruits per plant, fruit weight, fruit diameter, fruits per cluster, and yield per cluster in tomatoes, particularly at lower temperatures (Chishti *et al*., 2020). Naphthalene acetic acid (NAA) also plays a role in reducing pre-harvest fruit drops, resulting in an increased number of fruits per plant when applied at the flowering stage (Alam and Khan, 2002). However, it is important to note that the effectiveness of different growth regulators in improving crop yield and quality can vary significantly depending on their concentration, timing and method of application.

Prior research has delved into the application of growth regulators in diverse crops. However, their distinct impact on tomato cultivation in the arid regions of western Rajasthan remains relatively unexplored. Recognizing this knowledge gap, the current study was undertaken to evaluate the effects of GA_3, 4-CPA, and NAA application on crop growth, yield attributes, fruit production, and the overall economics of cultivation in the arid regions of western Rajasthan. This research aims to contribute valuable insights into optimizing tomato cultivation practices in arid environments.

Materials and Methods

An experiment was conducted during the *Rabi* 2021-22 at the Instructional Farm, College of Agriculture, Jodhpur, which is located at an altitude of 231 meters above mean sea level. The experimental site is located between 26°15′ to 26°45′ North latitude and 73°00′ to 73°29′ East longitude. This region is situated within the agro-climatic zone known as the 'Arid Western Plains Zone' of Rajasthan. Jodhpur typically experiences an arid climate characterized by dry, warm, and sunny winters, with an average annual precipitation of approximately 367 mm. During the experimental period (early December to mid-April), the daily maximum and minimum temperatures ranged between 16.1°C and 40.3°C and 10.9°C and 36.6°C, respectively. The mean daily relative humidity varied from 88.1% to 27.1%. Soil of the experimental field was sandy-loam in texture, slightly alkaline (pH 8.2), low in organic carbon (0.13%; Walkley and Black, 1934), and had 174 kg ha^{-1} of available nitrogen (Subbaiah and Asija, 1956), 20.2 kg ha^{-1} of available phosphorus (Olsen, 1954), and 325 kg ha^{-1} of available potassium (Westerman, 1990).

The experiment involved ten different treatments, including three different levels of gibberellic acid (GA_3; 25, 50, and 75 µg mL^{-1}), 4-chlorophenoxy acetic acid (4-CPA; 25, 50, and 75 µg mL^{-1}), and naphthalene acetic acid (NAA; 25, 50, and 75 µg mL^{-1}), as well as a control treatment involving water spray. The experiment was designed using a randomized block design with three replications. The experimental field was prepared for cultivation by two cross-harrowing followed by planking. Additionally, 25 t ha^{-1} of FYM was thoroughly mixed into the soil during harrowing. At the time of transplanting, a uniform dose of 120 kg P_2O_5 ha^{-1} through diammonium phosphate (DAP), 80 kg K_2O ha^{-1} through muriate of potash (MoP), and 60 kg N ha^{-1} through urea were applied approximately 3-4 cm deep in the soil. The remaining nitrogen dose (60 kg ha^{-1} as urea) was split into two halves and applied after 35 and 60 days of transplanting as spot application.

Tomato seedlings (cv. Ansal F_1), aged 30 days, were transplanted on December 1, 2021, with a row-to-plant spacing of 60 cm x 45 cm on flatbeds, organized in plots measuring 3.15 m × 4.20 m. Soil moisture was maintained through consistent irrigation, and manual weeding was performed twice. The recommended plant protection measures were followed as per need. For the application of growth regulators,

Table 1. Effect of different concentrations (µg mL^{-1}) of GA_3, 4-CPA, and NAA on growth, yield attributes, and fruit yield of tomato

Treatment	Plant height (cm)	No. of branches $plant^{-1}$	No. of fruits $plant^{-1}$	Fruit weight (g)	Fruit yield $plant^{-1}$ (kg)	Fruit yield (t ha^{-1})
GA_3 25	68.7	17.6	29.1	74.1	2.04	28.7
GA_3 50	77.8	18.9	32.5	77.7	2.35	29.0
GA_3 75	80.9	19.4	35.3	81.7	2.45	29.3
4-CPA 25	61.9	15.3	26.7	65.1	1.85	25.7
4-CPA 50	57.5	14.4	25.9	63.2	1.75	23.7
4-CPA 75	53.9	13.4	23.0	61.6	1.55	22.7
NAA 25	63.8	16.3	30.5	78.1	2.15	28.7
NAA 50	69.3	17.6	35.0	81.5	2.45	28.8
NAA 75	71.3	18.2	38.1	84.3	2.55	29.7
Control	57.4	15.2	24.2	65.0	1.76	25.3
SEm±	2.58	0.75	1.12	2.39	0.084	1.10
CD (p=0.05)	7.7	2.2	3.3	7.1	0.25	3.3

GA_3= Gibberellic Acid; 4-CPA= 4-Chlorophenoxy Acetic Acid; NAA= Naphthalene Acetic Acid

a stock solution of 1000 µg mL^{-1} of GA_3, 4-CPA, and NAA was prepared using distilled water. Working solutions of 25, 50, and 75 µg mL^{-1} of each of these growth regulators were then prepared by diluting the stock solutions with distilled water. Three foliar sprays of these PGRs were carried out at 30, 45 and 60 days after transplanting with 500 L of water per ha. The sprays were done in the early morning hours to prevent rapid drying of the spray solution due to transpiration.

Observations were recorded on plant height, the number of branches per plant, and the number of fruits per plant from five randomly selected plants in each treatment. Fruit weights were also recorded from five randomly chosen fruits in each treatment. Fruits were harvested when they reached the desired marketable size, and the weight of ripe fruits harvested in each picking was recorded until the final harvest, providing the total yield per plant. The data from periodic harvests throughout the experiment were summed to obtain the fruit yield ha^{-1}. For economic analysis, the average treatment yield, current market rates, and input costs were used to calculate net returns and the benefit-cost ratio. For determining the optimum dosages of PGRs the second-order polynomial regression ($y=ax^2+bx+c$) was fitted between levels of PGRs applied and the fruit yield of tomato. The economically optimum PGR dose was determined by marginal analysis through the quadratic function. The PGR level where the marginal returns are equal to marginal cost was defined as economically optimum dosage.

The data recorded for various parameters were analyzed with the help of the Analysis of Variance technique (Gomez and Gomez 1984) for RBD design using OPSTAT Software (Sheoran, 2023), and regression analysis was performed by using MS Excel. The determination of significant differences between the treatment means was conducted using the critical difference (CD) at a 5% probability level.

Results and Discussion

Growth attributes

The results in Table 1 shows that GA_3 and NAA significantly improved tomato plant height and branches per plant compared to control, while deleterious effects of 4-CPA on plant morphology hindered growth assessment. The effect of GA_3 on plant height (80.9 cm) and number of branches per plant (19.4 cm) were significantly highest at 75 µg mL^{-1}, with no statistical difference with GA_3 at 50 µg mL^{-1}. Similar results were observed by Naz *et al*. (2020) with foliar spray of GA_3 100 µg mL^{-1}. This enhancement is attributed to effect of GA_3 on stem elongation through rapid cell multiplication and antimitotic action, fostering apical growth and branch proliferation (Arivazhagan *et al*., 2018). In the case of NAA, application of 75 µg mL^{-1} was at par with that of 50 µg mL^{-1} (Table 1) for plant height and number of branches at final harvest. Similar results were observed by Naz *et al*. (2020) and Ujjwal *et al.* (2018) in tomato with NAA (30 µg mL^{-1}). The positive response to NAA is likely due to its role in augmenting photosynthesis,

Table 2. Effect of different concentrations ($\mu g\ mL^{-1}$) of GA_3, 4-CPA and NAA on the economics of tomato cultivation

Treatment	Variable cost (Rs. ha^{-1})	*Total Cost (Rs. ha^{-1})	**Gross Return (Rs. ha^{-1})	Net returns (Rs. ha^{-1})	B:C ratio	Additional returns over control (Rs. ha^{-1})
GA_3 25	8288	117409	5,73,267	4,55,858	3.88	61313
GA_3 50	13575	122697	5,80,667	4,57,970	3.73	63425
GA_3 75	18863	127984	5,86,667	4,58,683	3.58	64138
4-CPA 25	3568	112690	5,13,333	4,00,644	3.56	6099
4-CPA 50	4136	113258	4,73,333	3,60,075	3.18	-34470
4-CPA 75	4704	113826	4,53,333	3,39,507	2.98	-55038
NAA 25	3255	112377	5,74,600	4,62,223	4.11	67678
NAA 50	3510	112632	5,76,667	4,64,035	4.12	69490
NAA 75	3765	112887	5,93,333	4,80,447	4.26	85902
Control (water spray)	3000	112122	5,06,667	3,94,545	3.52	-

*Fixed cost of tomato cultivation- Rs.1.09 lakh/ha
**Sale price of tomato- Rs. 20/kg

translocation, and utilization of photosynthates, stimulated by enhanced cell division in apical regions.

Yield attributes

The application of 75 $\mu g\ mL^{-1}$ GA_3, though at par with 50 $\mu g\ mL^{-1}$ GA_3, produced highest values of the number of fruits per plant at final harvest (35.3) and fruit weight (81.7 g) of tomato (Table 1). Similar results were observed by Singh *et al*. (2019) and Bhosale, (2000). The more production of flower primordia (Ujjawal *et al*., 2018) and efficient photosynthate allocation to reproductive parts attributes to these trends. Similarly, the significantly maximum number of fruits per plant at final harvest (38.1) and highest fruit weight (84.3 g) were observed with NAA (75 $\mu g\ mL^{-1}$), and it was at par with NAA (50 $\mu g\ mL^{-1}$). Similar results were observed by Bokade (2004). This might be due NAA application likely increased fruit weight by accumulating sufficient nutrients for larger fruit development.

Due to the potential of 4-CPA to check flowers and fruit drops the number of fruits per plant (25.9) was observed to be significant up to 4-CPA@50 $\mu g\ mL^{-1}$. Similar results were observed by Naz *et al*. (2020), and Bokade, (2004) in tomato. Application of 4-CPA at higher concentration promoted fruit formation but caused deformities and parthenocarpy, resulting in lower fruit weight due to puffiness.

Fruit yield

The fruit yield of tomato was influenced significantly at all levels of GA_3 and NAA over control (Table 1). However, the fruit yield of tomato could not be influenced significantly among 4-CPA levels over control. With GA_3, significantly highest fruit yield per plant (2.5 kg) and fruit yield ha^{-1} (29.3 t) over control was observed with 75 $\mu g\ mL^{-1}$, which incidentally was at par with application of 50 $\mu g\ mL^{-1}$. These findings are in agreement with the findings of Singh *et al*. (2019) and Ranjeet *et al*. (2014). The application of GA_3 augments photosynthesis, leading to increased plant biomass which resulted in an increased fruit set, which ultimately led to more fruit set percentage, more fruit per plant, and higher fruit yield.

Results further revealed that tomato fruit yield decreased with the increase in the 4-CPA levels, attributed to the lower fruit set percent and low fruit weight. These results contradict the findings of Baliyan (2013), who reported a positive relationship between 4-CPA and fruit yield of tomato at 75 $\mu g\ mL^{-1}$. Further, with the application of NAA, significantly maximum fruit yield per plant (2.6 kg) and fruit yield ha^{-1} (29.7 t) over control was observed with NAA@75 $\mu g\ mL^{-1}$, and at par with NAA@50 $\mu g\ mL^{-1}$. Similar results were reported by Ranjeet *et al*. (2014). The application of NAA boosted yield by enhancing physiological activity, leading to more flowers and fruits resulting in higher fruit set and yield.

Economics

The data (Table 2) indicates that the application of GA_3 and NAA at all levels increased perceptibly the net returns from tomato; while with application 50 and 75 $\mu g\ mL^{-1}$ of 4-CPA net returns declined *vis a vis* control. The highest net returns (Rs. 4,80,447 ha^{-1}) and B:C ratio (4.26:1) were recorded with the application of NAA (75 $\mu g\ mL^{-1}$) followed

Table 3. Fruit yield of tomato (Y) as a function of PGR application and economic optimum dose.

Parameters	GA_3	NAA
Economic optimum dose (μg mL^{-1})	53.5	63.1
Yield at economic optimum dose (t ha^{-1})	29.55	29.69
Response at economic optimum dose (t ha^{-1} μg mL^{-1})	0.552	0.470

by NAA (50 μg mL^{-1}) (Rs. 464,035 ha^{-1} and 4.12:1). The Application of NAA at 75 μg mL^{-1} and 50 μg mL^{-1} resulted into additional net returns of RS. 85,902 ha^{-1} and Rs. 69,490 ha^{-1}, respectively over control. Similar results were also reported by Singh *et al.* (2017) and Ramesh, (2019). The difference in net retunes among different treatments was mainly due to the difference in fruit yield and partly the treatment cost also contributed as NAA is much cheaper than GA_3 and 4-CPA.

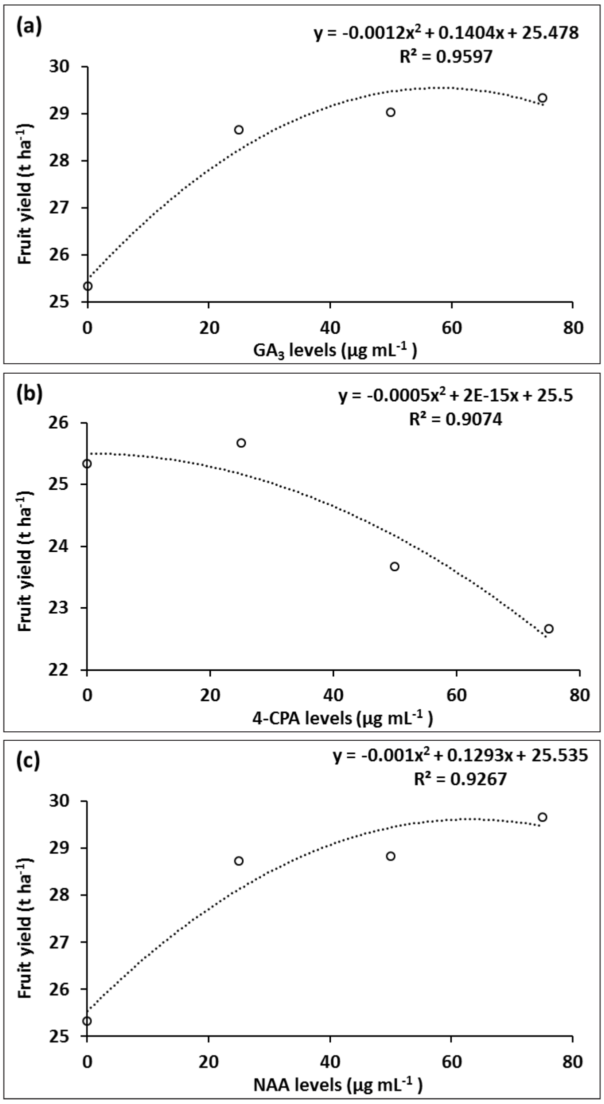

Fig. 1. Quadratic regression between fruit yield (t ha^{-1}) of tomato and levels of a) GA_3 b) 4-CPA and c) NAA.

Economic optimum dose of PGRs

In determining the optimum dosage of PGRs, the relationship between yield and PGR levels was found to be defined best by the quadratic model with R^2 values of 0.959, 0.907, and 0.926 of GA_3, 4-CPA, and NAA, respectively (Fig. 1). As the yield trends with increasing levels of 4-CPA were negative, the economic optimum dosage of only GA_3 and NAA were attempted. The economic optimum dose for GA_3 was estimated to be 53.5 μg mL^{-1} and for NAA it was 63.1 μg mL^{-1}. The fruit yield at the economic optimum dose GA_3 and NAA were 29.55 t ha^{-1} and 29.69 t ha^{-1}, respectively (Table 3). However, the response at the economic optimum dose in NAA (0.470 t ha^{-1} μg mL^{-1}) is less as compared to GA_3 (0.552 t ha^{-1} μg mL^{-1}) because of higher fruit yield with GA_3 levels due to higher growth enhancement.

Conclusion

In conclusion, the study demonstrated the significant impact of GA_3 and NAA on the growth, yield, and economic returns from tomato cultivation. GA_3 (53.5 μg mL^{-1}) and NAA (63.1 μg mL^{-1}) emerged as the economic optimum levels, maximizing yields to 29.55 t ha^{-1} and 29.69 t ha^{-1} respectively. The economic analysis revealed that NAA, in particular, offered the highest net returns, making it an economically viable choice for tomato cultivation. These findings highlight the potential of these growth regulators in enhancing tomato production.

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