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Substitution of Chemical Fertilization using PGRs Evident in Growth and Yield of Tomato

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Abstract

The excessive utilization of synthetic fertilizers and chemicals poses a significant threat to both environment and human well-being. A pot experiment was done between December 2022 and April 2023 using a factorial randomized complete block design, which involved combining fertilizers and plant growth regulators (PGRs). The objective was to decrease the utilization of artificial fertilizers through the application of PGRs. The experiment involved applying fertilizers at 80, 90, 100 and 110% of the recommended doses. The recommended doses consist of 12 grams (g) of urea, 10 g of TSP, 5 g of MoP, 3 g of gypsum, 0.5 g of zinc sulphate, and 0.5 g of boric acid per plant. Furthermore, PGRs including gibberellic acid (GA_3), naphthalene acetic acid (NAA), 4-chlorophenoxy acetic acid (4-CPA), and salicylic acid (SA) were applied at a concentration of 50 ppm. The results showed that there were no significant differences in growth and yield-contributing features when the fertilizer dose was increased from 80% to 110% of the recommended amount. Nonetheless, there were significant differences compared to the control group. However, PGRs showed significant variability in the morphological and reproductive responses of tomatoes under the conditions being researched. The GA_3 treatment resulted in significantly greater plant height, base diameter, number of branches and leaves per plant, canopy spread, and internode length. Moreover, GA_3 at 50 ppm produced the highest number of flowers and fruits/plant, with a single fruit weighing 67.83 g and a total fruit production of 6.61 kg/plant of tomato. Among the other PGRs, salicylic acid showed statistical equivalence to GA_3 treatment. Nonetheless, there was a notable decrease in both vegetative and reproductive features, including yield, when NAA and 4-CPA were used. The interaction between fertilizers and PGRs showed that combining GA_3 and SA with any of the tested fertilizer rates resulted in statistically distinct and improved vegetative and reproductive responses. However, the combination of fertilizer with NAA and 4-CPA produced highly unsatisfactory outcomes. Therefore, GA_3 at 50 ppm and SA at 50 ppm can effectively be employed as substitute of synthetic chemical fertilizers in tomato cultivation.

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Introduction

The tomato (*Solanum lycopersicum* L.) is a very important and extensively grown vegetable crop that has a considerable impact on the economy. It is planted globally and is known for its ability to provide necessary nutrients and flavors to a variety of cuisines. The cultivation of this plant is affected by different environmental elements, and the specific conditions found in sub-tropical Asia pose distinct

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difficulties due to the unpredictable changes in temperature and humidity. The success of tomato growing relies not only on environmental factors but also on the presence of essential nutrient elements to optimize growth and yield.

Optimal nutrient absorption and flawless execution of cellular mechanisms are crucial for the development and productivity of crops. Plant growth regulators (PGRs) are essential for controlling and coordinating important physiological processes in plants, including cell division, elongation, differentiation, and responses to environmental stimuli (Rademacher, 2015; Sourati *et al*., 2022). Gibberellic acid (GA_3), naphthalene acetic acid (NAA), salicylic acid (SA), and chlorophenoxy acetic acid (4-CPA) are being studied for their ability to affect the growth and development of tomatoes, making them noteworthy among other PGRs (Rademacher, 2015; Uddin *et al.*, 2024). These PGRs function as signaling molecules, regulating the expression of genes and metabolic processes, ultimately impacting the physical characteristics and productivity of plants. GA_3, a phytohormone implicated in cellular elongation and seed germination, has been documented to augment stem elongation and amplify fruit dimensions in tomatoes (Dhakal *et al.*, 2023; Gomasta *et al*., 2024). NAA, a synthetic plant hormone, is recognized for its impact on root formation, fruit initiation, and fruit enlargement (Sourati *et al*., 2022). SA, a crucial signaling molecule in the defensive mechanisms of plants, has been linked to the ability of tomatoes to withstand stress and resist pathogens (Ahmad *et al.*, 2019; Liu *et al*., 2022). In addition, the synthetic auxin analog 4-CPA has been linked to enhanced fruit set and higher fruit quality in tomatoes (Sabir *et al*., 2021).

Nevertheless, the crop production in sub-tropical Asian regions is confronted with difficulties due to the varying temperatures and humidity levels. Environmental fluctuations can influence the growth of plants, their ability to absorb nutrients, and their methods for responding to stress. The brief winter characterized by fluctuating temperature and humidity levels occasionally poses a risk to tomato growing, perhaps affecting the optimal production in Bangladesh as well (FAO, 2015). Furthermore, farmers employ synthetic chemical fertilizers to enhance agricultural productivity and mitigate ecological strain on crop production. The excessive use of inorganic fertilizers has resulted in soil, air, and water pollution due to nutrient leaching, degradation of soil physical properties, and the accumulation of harmful chemicals in water bodies (Kayesh *et al.*, 2023). This has led to significant environmental issues and a decline in biodiversity (Savci, 2012; Sultana *et al.*, 2022). In addition, agrochemicals are significant contributors to pollution in developing nations and pose a serious threat to human and livestock health (Sharma and Singhvi, 2017; Kayesh *et al.*, 2023). Consistent and uninterrupted use of inorganic fertilizers results in the frequent absorption and buildup of heavy metals in plant tissues. As a result, the nutritional and grain quality of crops is diminished (Maqbool *et al*., 2020; Abdiani *et al*., 2019). Hence, reducing the use of agrochemicals, particularly artificial fertilizers, in tomato cultivation is critical for improving soil health and producing high-quality vegetable output. PGRs can be the most effective treatment in these cases, because they have the potential to boost tomato productivity by improving fruit set, size, and quality, even in adverse environmental conditions (Serrani *et al.*, 2007). Therefore, this experiment was designed to investigate the effects of using PGRs as substitutes for chemical fertilizers on the development and yield of tomato plants.

Materials and Methods

Experiment Site and Planting Material

The study on tomato production involved the use of fertilizer and PGRs in the vegetable research field of the Department of Horticulture, Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU), Gazipur 1706, Bangladesh (24.02° N latitude and 90.23° E longitude). The experiment took place during the cropping season of 2022–2023, from November 2022 to April 2023. The test crop utilized in this study was Tomato var. BARI Tomato-14. The seeds were obtained from the Olericulture Division of Bangladesh Agricultural Research Institute (BARI), Gazipur, Bangladesh at the beginning of the study.

Experiment Design and Treatments

The experiment was conducted in pots using a factorial randomized complete block design (RCBD) with three replications. Seedlings that were 25 days old were moved to plastic pots measuring 30 cm × 30 cm. These pots had been prepared beforehand using a mixture of cow dung, organic compost and garden soil in a ratio of 2:1:4. The experimental treatments comprised of four distinct doses of fertilizers, in addition to a control group that received no fertilizers (F1), for factor one. The fertilizer rates applied were 110%, 100%, 90%, and 80% of the recommended rates specified in FRG'2018 and denoted as F5, F4, F3, F2, respectively. The 100% dose represents 12 g of urea, 10 g of TSP, 5 g of MoP, 3 g of gypsum, 0.5 g of zinc sulphate ($ZnSO_4$), and 0.5 g of boric acid (H_3BO_4) per plant. For factor two, four types of PGRs were utilized at a concentration of 50 ppm each. These PGRs include Gibberellic acid (GA_3), Naphthalene acetic acid (NAA), 4-Chlorophenoxy acetic acid (4-CPA), and Salicylic acid (SA) and represents as H2, H3, H4, H5, respectively. A control group (H1) was also included where only water was used without any PGRs. Intercultural activities, including weeding, irrigation, mulching, pest and disease management, were performed as required.

Crop Management and Treatment Application

The planting pots were spaced 60 cm apart to facilitate smooth cultural activities. The fertilizers were given in separate portions at the base of the plants by mixing them with the media at 10, 25, and 40 days after transplanting (DAT). Following fertilization, prompt irrigation was consistently implemented. Conversely, the PGRs treatment was administered as a foliar spray during the vegetative growth phase of the plants twice during the third and sixth week after transplantation. The spraying was conducted to ensure thorough wetting of both surfaces of the leaves. The control group of plants were exclusively treated with distilled water as a foliar spray.

Data Collection

The impact of fertilizers and PGRs on the vegetative growth characteristics of tomatoes was evaluated by measuring the plant's height (cm), base diameter (mm), number of branches and leaves per plant, and canopy spread (cm) at full bloom. In addition, the length between nodes (cm) and the level of greenness in the leaves (as SPAD value) were assessed. The study recorded the duration from transplanting to the first flowering and also the quantity of flowers per plant for each replication in the treatment. The harvesting process commenced on February 23, 2023 and concluded on April 9, 2023. The number of fruits per plant was tallied, and the fruit set ratio was determined by dividing the number of flowers by the number of fruits per plant. Following harvest, the fruits were quantified by weighing them (g) and then calculating the total fruit output per plant by multiplying the weight of each individual fruit by the number of fruits per plant.

Statistical Analyses

The data analysis was undertaken using the 'R' program, where a two-way analysis of variance (ANOVA) was performed. A Least Significant Difference (LSD) test was conducted to compare the means of the treatments at a significance level of 5%. Furthermore, a correlation matrix and principal component analysis were performed to ascertain the most remarkable variables contributed in the total variations based on the interrelationships among the growth and yield related factors investigated in the current experiment.

Results and Discussion

Vegetative Growth Behaviour

Among the vegetative growth traits of tomato, plant height, base diameter, number of leaves and canopy spread were significantly affected ($P \leq 0.05$) by the application of fertilizer doses, whereas PGRs alone as well as fertilizer-PGR interactions had significant influences on modulating all the studied growth behaviors of tomato as shown in Table 1 and Table 2.

The plants in the control group (F1) that were treated with no fertilizer had the shortest average plant height (63.41 cm), minimum base diameter (2.13 cm), the lowest leaf number (31.44 per plant) and the narrowest canopy spread (53.39 cm). However, the tomato plants in the other groups (F2 to F5), which were treated with 80% to 110% of the recommended fertilizer doses of FRG'2018, had statistically similar and higher plant heights, base diameters, number of leaves/plant and canopy spreads compared to the control group. In line with these, number of branches, internode length and SPAD value of the tomato plants under the fertilization factor were varied non-significantly and the measurements of these growth parameters ranged from 4.34 to 4.66 per plant, 4.92 to 5.06 cm and 48.59 to 50.21, respectively (Table 1).

Table 1. Vegetative growth of tomato as influenced by fertilizer doses and PGRs

Treatment	Plant height (cm)	Base diameter (cm)	No. of branches /plant	No. of leaves/plant	Canopy spread (cm)	Internode length (cm)	SPAD value
Fertilizer dose							
F1	63.41^{b}	2.13^{b}	4.34	31.44^{b}	53.39^{b}	4.92	48.59
F2	69.38^{a}	2.37^{a}	4.60	34.67^{a}	57.85^{a}	5.08	50.44
F3	70.00^{a}	2.39^{a}	4.90	36.44^{a}	58.49^{a}	5.13	51.34
F4	68.83^{a}	2.37^{a}	4.69	34.13^{a}	57.01^{a}	5.08	49.94
F5	68.53^{a}	2.38^{a}	4.66	33.93^{ab}	56.61^{a}	5.06	50.21
CV (%)	8.25	8.23	13.51	10.72	7.54	10.70	7.49
LS	*	**	Ns	*	*	ns	Ns
Plant growth regulator							
H1	71.20^{b}	2.39^{b}	4.65^{c}	28.11^{c}	56.39^{b}	5.06^{c}	49.42^{bc}
H2	87.90^{a}	2.72^{a}	5.85^{a}	47.13^{a}	69.29^{a}	6.17^{a}	53.08^{a}
H3	47.67^{c}	1.95^{c}	3.67^{d}	26.13^{c}	46.07^{c}	4.32^{d}	47.87^{c}
H4	46.78^{c}	1.91^{c}	3.67^{d}	25.77^{c}	44.09^{c}	4.20^{d}	48.15^{c}
H5	86.61^{a}	2.67^{a}	5.36^{b}	43.47^{b}	67.51^{a}	5.53^{b}	52.01^{ab}
CV (%)	8.25	8.23	13.51	10.72	7.54	10.70	7.49
LS	**	**	**	**	**	**	**

Different letters within the column indicate statistically significant differences among the treatments according to LSD at $P \leq 0.05$. Here, F1, F2, F3, F4 and F5 represent control (no fertilizer), 100, 110, 90 and 80 % of FRG'2018, respectively and H1, H2, H3, H4 and H5 indicate control (no PGR), GA_3, NAA, 4-CPA and SA at 50 ppm, respectively. CV = coefficient of variation, LS = Level of significance.

In account of the PGR doses, the treatment H2 exhibited superiority over the others for plant height (87.90 cm), base diameter (2.72 cm), number of branches (5.85 per plant), number of leaves (47.13 per plant), canopy spread (69.29 cm), internode length (6.17 cm) and SPAD value (53.08) of tomato. The PGR dose H5 demonstrated statistical parity with that of H2 for plant height (86.61 cm), base diameter (2.67 cm), canopy spread (67.51 cm) and SPAD value (52.01) and followed H2 for number of branches (5.36 per plant), number of leaves (43.47 per plant) and internode length (5.53 cm) of the tomato plants under observation. Meanwhile, statistically the lowest measurements on plant height (46.78 cm), base diameter (1.91 cm), number of branches (3.67/plant), number of leaves (25.77 per plant), canopy spread (44.09 cm), internode length (4.20 cm) and SPAD value (48.15) were recorded in the H4 treatment, which exhibited statistically similarity to the H3 PGR. The tomato plants under H1 showed moderate vegetative growth statistically better than H3 and H4 doses (Table 1).

Furthermore, it became apparent through interactions that the tomato plant with the greatest height (90.63 cm) and number of branches (6.13 per plant) were observed in the F3H2 treatment. Whereas the F2H2 combination resulted in the highest number of leaves (49.00 per plant), canopy spread (71.27 cm), and internode length (6.53 cm) of tomato plants. The base diameter (2.83 cm) and SPAD value (55.03) were highest in F5H2 and F4H2 interactions, respectively. In contrast, plants exposed to the F1H4 combination exhibited the lowest base diameter (1.83 cm), number of branches (1.83 per plant) and leaves (21.00 per plant), canopy spread (41.43 cm), internode length (4.03 cm) and SPAD value (45.17). Likely, the F3H4 combination had the shortest plant measuring 46.13 cm (Table 2). It is worth noting that the nutrient doses in treatments H3 and H4 had statistically similar measurements for the inferior plant growth behaviors of tomato (Table 2).

Table 2. Interaction effect of fertilizer and PGRs on vegetative growth of tomato

Treatment interaction		Plant height (cm)	Base diameter (cm)	No. of branches /plant	No. of leaves/plant	Canopy spread (cm)	Internode length (cm)	SPAD value
F1	H1	61.97^{e}	2.13^{fg}	4.00^{ef}	25.20^{de}	52.60^{ef}	4.87^{f-j}	49.50^{a-f}
	H2	80.97^{b-d}	2.43^{d-f}	5.23^{a-d}	45.00^{ab}	64.40^{a-c}	6.00^{a-d}	51.77^{a-e}
	H3	47.90^{f}	1.90^{g}	3.67^{ef}	23.33^{de}	45.90^{fg}	4.40^{h-j}	45.63^{ef}
	H4	46.57^{f}	1.83^{g}	3.67^{ef}	21.00^{e}	41.43^{g}	4.03^{j}	45.17^{f}
	H5	79.67^{cd}	2.37^{ef}	5.13^{a-d}	42.67^{b}	62.63^{b-d}	5.30^{c-g}	50.90^{a-f}
F2	H1	72.00^{d}	2.43^{d-f}	4.57^{c-e}	27.67^{cd}	56.03^{de}	5.13^{d-h}	47.50^{d-f}
	H2	89.93^{ab}	2.77^{a-c}	5.87^{ab}	49.00^{a}	71.27^{a}	6.53^{a}	53.03^{a-d}
	H3	48.43^{f}	2.00^{g}	3.47^{f}	26.00^{de}	47.77^{fg}	4.23^{ij}	49.33^{a-f}
	H4	47.33^{f}	1.97^{g}	3.43^{f}	28.33^{cd}	47.17^{fg}	4.03^{j}	49.73^{a-f}
	H5	89.20^{ab}	2.70^{a-d}	5.67^{ab}	42.33^{b}	67.00^{ab}	5.47^{b-f}	52.60^{a-d}
F3	H1	76.83^{d}	2.50^{b-e}	5.67^{ab}	33.00^{c}	59.97^{cd}	5.30^{c-g}	52.33^{a-d}
	H2	90.63^{a}	2.80^{ab}	6.13^{a}	47.67^{ab}	71.10^{a}	6.07^{a-c}	54.93^{av}
	H3	47.63^{f}	1.97^{g}	3.67^{ef}	28.33^{cd}	47.30^{fg}	4.30^{h-j}	48.37^{c-f}
	H4	46.13^{f}	1.90^{g}	3.57^{ef}	27.20^{cd}	44.33^{g}	4.27^{h-j}	47.77^{d-f}
	H5	88.77^{a-c}	2.77^{a-c}	5.47a^{-c}	46.00^{ab}	69.77^{a}	5.73^{a-f}	53.30^{a-d}
F4	H1	73.23^{d}	2.47^{c-e}	4.57^{c-e}	27.67^{cd}	57.17^{de}	5.03^{e-i}	47.93^{d-f}
	H2	89.20^{ab}	2.77^{a-c}	5.90^{ab}	46.33^{ab}	69.97^{a}	6.23^{ab}	55.03^{a}
	H3	47.30^{f}	1.93^{g}	3.87^{ef}	26.67^{de}	44.97^{g}	4.43^{g-j}	48.30^{c-f}
	H4	47.60^{f}	1.93^{g}	4.00^{ef}	26.33^{de}	44.20^{g}	4.40^{h-j}	49.27^{a-f}
	H5	86.83^{a-c}	2.77a^{-c}	5.10^{b-d}	43.67^{ab}	68.73^{ab}	5.30^{c-g}	49.17^{a-f}
F5	H1	71.97^{d}	2.43^{d-f}	4.43^{d-f}	27.00^{c-e}	56.17^{de}	4.97^{e-i}	49.83^{a-f}
	H2	88.77^{a-c}	2.83^{a}	6.10^{ab}	47.67^{ab}	69.70^{a}	6.00^{a-d}	50.63^{a-f}
	H3	47.10^{f}	1.93^{g}	3.67^{ef}	26.33^{de}	44.43^{g}	4.23^{ij}	47.70^{d-f}
	H4	46.27^{f}	1.93^{g}	3.67^{ef}	26.00^{de}	43.30^{g}	4.27^{h-j}	48.80^{b-f}
	H5	88.57^{a-c}	2.77^{a-c}	5.43^{a-d}	42.67^{b}	69.43^{ab}	5.83^{a-e}	54.10^{a-c}
CV (%)		8.25	8.23	13.51	10.72	7.54	10.70	7.49
LS		**	**	**	**	**	**	**

Different letters within the column indicate statistically significant differences among the treatments according to LSD at *P≤0.05*. Here, F1, F2, F3, F4 and F5 represent control (no fertilizer), 100, 110, 90 and 80 % of FRG'2018, respectively and H1, H2, H3, H4 and H5 indicate control (no PGR), GA_3, NAA, 4-CPA and SA at 50 ppm, respectively. CV = coefficient of variation, LS = Level of significance. CV = coefficient of variation, LS = Level of significance.

Light, temperature, and humidity are the primary environmental elements that significantly impact plant physiological functions, *e.g.*, photosynthesis and hormonal balance, as well as crucial events in plant life, including the transition between developmental stages (Dinu *et al*., 2022; Upadhyay *et al*., 2022). From the present findings, it was notable that growth and yield-related characteristics did not show statistically significant fluctuations between 80% and 110% of the recommended fertilizer doses. However, the fertilizer doses significantly differed from the control, highlights the subtle reaction of tomato plants to varying fertilizer levels. Vegetative growth improvement in the fertilizer applied plants over control plants might be due to added uptake of nutrient elements from the additional nutrient sources as observed by Howlader *et al.* (2019), Apu *et al.* (2022) and Rahman *et al.* (2023). This observation is consistent with the notion of precision fertilization, which highlights the need of optimizing nutrient delivery for the purpose of achieving sustainable agriculture (Smith *et al*., 2018).

In contrast, the GA_3 treatment exhibited remarkable vegetative growth, surpassing other treatments in terms of plant height, base diameter, branch quantity, leaf count per plant, canopy expansion, and internode length. The results align with other research that emphasizes the function of GA_3 in stimulating cell elongation and overall vegetative growth resulting in enhanced vegetative growth (Dhakal *et al*., 2023; Davies, 2010).

Reproductive Growth Behavior

Fertilizer dose, PGR, and their interactions all had a substantial impact on the reproductive growth behaviors of the tomato under study, with the exception of fertilization, which had no effect on the number of days it took for tomato plants to blossom (Table 3, Table 4). As a result of fertilizer application at various doses from 80% to 110% of the recommended dose plus control, maximum number of flowers (100.86 per plant) and fruits (65.98 per plant), the heaviest fruit (61.72 g) and the highest yield (4.29 kg per plant) was obtained in F3 treatment having statistical unanimity with F2, F4 and F5 fertilizer doses. However, greater fruit set rate (68.13%) was noted in F5 fertilizer dose which had statistical parity with F3 and F4 treatments. In comparison, the lowest flower and fruit count (85.44 and 55.52 per plant, respectively), minimum fruit set (64.73%) and the lightest fruit (57.47 g) was record in control treatment resulting in the lowest yield (3.40 kg per plant) of tomato (Table 1).

While considering the PGRs, superiority in the number of flowers (148.12 per plant) and fruits (97.33 per plant), single fruit weight (67.53 g) and yield (6.57 kg per plant) of tomato were noticed in H2 treatment. The PGR treatment showed statistical unity with H2 in respect of the number of flowers (142.23 per plant) and fruits (92.94 per plant) and single fruit weight (66.81 g) and followed H2 for yield (6.19 kg per plant). Fruit set rate was estimated the highest in H3 treatment (65.98%) having statistical harmony with H4 (65.74%). However, these two PGR treatments, though produced flowers in the earliest duration in 44.27 and 44.02 days after transplanting, respectively, had statistical similarity to demonstrate inferior flowering, fruiting, fruit weight and yield in tomato under observation (Table 3).

Table 3. Reproductive behavior and yield of tomato as influenced by the application of fertilizers and PGRs

Treatment	Days required to flowering	No. of flowers per plant	No. of fruits per plant	Fruit set rate (%)	Single fruit weight (g)	Yield (kg/per plant)
Fertilizer dose						
F1	47.33	85.44^{b}	55.52^{b}	64.73^{c}	57.47^{b}	3.40^{b}
F2	48.07	97.55^{a}	63.64^{a}	65.74^{bc}	61.07^{a}	4.10^{a}
F3	48.44	100.86^{a}	65.98^{a}	66.17^{a-c}	61.72^{a}	4.29^{a}
F4	48.28	100.32^{a}	65.74^{a}	67.07^{ab}	60.04^{a}	4.21^{a}
F5	48.25	98.53^{a}	65.07^{a}	68.13^{a}	60.06^{a}	4.15^{a}
CV (%)	6.21	8.94	11.25	4.34	5.72	9.34
LS	Ns	**	**	*	*	**
Plant growth regulator						
H1	50.05^{a}	124.96^{b}	79.02^{b}	63.12^{c}	62.91^{b}	4.97^{c}
H2	50.68^{a}	148.12^{a}	97.33^{a}	65.67^{b}	67.53^{a}	6.57^{a}
H3	44.27^{b}	33.38^{c}	23.26^{c}	69.54^{a}	51.35^{c}	1.20^{d}
H4	44.02^{b}	34.00^{c}	23.40^{c}	68.29^{a}	51.77^{c}	1.22^{d}
H5	51.35^{a}	142.23^{a}	92.94^{a}	65.22^{bc}	66.81^{a}	6.19^{b}
CV (%)	6.21	8.94	11.25	4.34	5.72	9.34
LS	**	**	**	**	**	**

Different letters within the column indicate statistically significant differences among the treatments according to LSD at $P \leq 0.05$. Here, F1, F2, F3, F4 and F5 represent control (no fertilizer), 100, 110, 90 and 80 % of FRG'2018, respectively and H1, H2, H3, H4 and H5 indicate control (no PGR), GA_3, NAA, 4-CPA and SA at 50 ppm, respectively. CV = coefficient of variation, LS = Level of significance.

Table 4. Fertilizer and plant growth regulator interactions influencing the yield and yield contributing traits of tomato

Treatment combination		Days required to flowering	No. of flowers per plant	No. of fruits per plant	Fruit set rate (%)	Single fruit weight (g)	Fruit yield (kg per plant)
F_1	H_1	49.00^{a-c}	112.17^{f}	71.47^{d}	63.68^{fg}	58.70^{cd}	4.18^{g}
	H_2	49.67^{ab}	132.67^{c-e}	87.97^{bc}	66.32^{c-g}	65.73^{ab}	5.78^{cd}
	H_3	43.00^{d}	27.46^{g}	17.83^{e}	64.73^{e-g}	48.83^{e}	0.88^{h}
	H_4	43.67^{d}	28.33^{g}	18.34^{e}	64.23^{e-g}	49.90^{e}	0.91^{h}
	H_5	51.33^{a}	126.57^{de}	81.97^{cd}	64.68^{e-g}	64.20^{a-c}	5.24^{d-f}
F_2	H_1	50.00^{ab}	120.67^{ef}	74.67^{d}	61.72^{g}	62.37^{bc}	4.66^{fg}
	H_2	50.67^{a}	153.56^{a}	101.96^{a}	66.36^{c-g}	68.57^{a}	6.98^{a}
	H_3	44.67^{cd}	34.71^{g}	23.01^{e}	66.42^{c-g}	53.53^{de}	1.23^{h}
	H_4	43.67^{d}	35.56^{g}	24.52^{e}	68.57^{b-e}	53.77^{de}	1.33^{h}
	H_5	51.33^{a}	143.22^{a-c}	94.05^{ab}	65.61^{d-g}	67.13^{ab}	6.31^{bc}
F_3	H_1	50.67^{a}	136.57^{b-d}	87.14^{bc}	63.68^{fg}	66.30^{ab}	5.74^{c-e}
	H_2	51.43^{a}	152.94^{a}	100.44^{a}	65.57^{d-g}	67.47^{ab}	6.74^{ab}
	H_3	44.57^{cd}	34.94^{g}	23.96^{e}	68.67^{b-e}	53.87^{de}	1.29^{h}
	H_4	44.43^{cd}	33.42^{g}	22.80^{e}	67.80^{b-f}	53.13^{de}	1.23^{h}
	H_5	51.10^{a}	146.41^{a-c}	95.57^{ab}	65.14^{e-g}	67.83^{ab}	6.45^{ab}
F_4	H_1	50.10^{ab}	127.85^{de}	80.85^{cd}	63.20^{fg}	63.73^{a-c}	5.15^{d-f}
	H_2	51.30^{a}	154.75^{a}	101.62^{a}	65.59^{d-g}	67.87^{ab}	6.92^{ab}
	H_3	43.77^{d}	36.45^{g}	26.08^{e}	71.29^{b}	50.20^{e}	1.31^{h}
	H_4	44.57^{cd}	35.12^{g}	24.92^{e}	70.74^{bc}	50.83^{e}	1.28^{h}
	H_5	51.67^{a}	147.44^{ab}	95.24^{ab}	64.55^{e-g}	67.57^{ab}	6.42^{ab}
F_5	H_1	50.47^{a}	127.54^{de}	80.94^{cd}	63.32^{fg}	63.47^{a-c}	5.11^{ef}
	H_2	50.33^{a}	146.65^{a-c}	94.65^{ab}	64.50^{e-g}	68.00^{ab}	6.44^{ab}
	H_3	45.33^{b-d}	33.36^{g}	25.43^{e}	76.57^{a}	50.30^{e}	1.28^{h}
	H_4	43.77d	37.57^{g}	26.42^{e}	70.11^{b-d}	51.20^{e}	1.35^{h}
	H_5	51.33^{a}	147.51^{ab}	97.88^{ab}	66.14^{c-g}	67.33^{ab}	6.56^{ab}
CV (%)		6.21	8.94	11.25	4.34	5.72	9.34
LS		**	**	**	**	**	**

Different letters within the column indicate statistically significant differences among the treatments according to LSD at $P \leq 0.05$. Here, F1, F2, F3, F4 and F5 represent control (no fertilizer), 100, 110, 90 and 80 % of FRG'2018, respectively and H1, H2, H3, H4 and H5 indicate control (no PGR), GA_3, NAA, 4-CPA and SA at 50 ppm, respectively. CV = coefficient of variation, LS = Level of significance.

Furthermore, the interactions revealed that F2H2 combination had maximum number of flowers (153.56 per plant) and fruits (101.96 per plant) as well as heavier fruits (68.57 g) and consequently the greatest yield (6.98 kg per plant) in tomato. H2 and H5 PGRs in combination with F2 to F5 fertilizer doses displayed statistical similarity for better reproductive performances in tomato. Meanwhile, H3 and H4 PGRs interacted with all the fertilizer treatments had the statistically similar worst results in terms of flowering, fruiting and yield of tomato at the present study (Table 4).

Here, the application of GA_3 resulted in the highest number of flowers and fruits per plant, as well as a considerable increase in the weight of individual fruits. Consequently, the fruit yield per plant was much greater at 6.61 kg. GA_3's impressive results establish it as a powerful growth regulator capable of improving both the amount and quality of tomato harvests. The application of SA was found to have similar beneficial effects, as demonstrated by Khan *et al.* (2019). This highlights the importance of SA in enhancing plant defense mechanisms and facilitating reproductive characteristics in tomatoes. The discrepancy in plant vegetative and reproductive characteristics, such as yield, observed in the NAA and 4-CPA treatments, indicates that not all PGRs may have the same level of effectiveness in enhancing tomato growth. The observed variation in PGR responses is consistent with previous research, highlighting the significance of meticulous PGR selection according to specific crop and environmental circumstances (Mansouri and Modarres-Sanavy, 2017). The deliberate application of PGRs in tomato farming has been crucial in enhancing growth, maximizing yields, and improving fruit quality, thereby effectively tackling significant issues in contemporary agriculture (Kaur *et al.*, 2020). The improvement in the plant structure has a beneficial effect on the effectiveness of photosynthesis and the absorption of nutrients, ultimately affecting the quantity and quality of the fruit produced. The study conducted by Khan *et al*. (2019) highlights the many effects of GA_3, showing that it enhances flower and fruit formation, increases the weight of individual fruits, and ultimately leads to higher overall fruit yield of horticultural crops (Uddin *et al.*, 2024). The enhancements in output are not exclusively quantitative; tomatoes treated with GA_3 have improved nutritional profiles, increased fruit size, and superior marketable attributes. Additionally, it has been documented that GA_3 has a beneficial impact on the maturity and ripening of fruits, promoting consistency and desirable characteristics (Davies, 2010).

In addition to GA_3, SA shows potential as an alternative PGR, with comparable effects to GA_3 in enhancing both vegetative and reproductive characteristics. The research conducted by Khan *et al*. (2019) provides evidence for the effectiveness of SA, demonstrating its ability to activate plant defense mechanisms and have a positive influence on reproductive processes. Incorporating these PGRs into accurate fertilizer management techniques not only enhances crop production but also supports sustainable agriculture objectives by decreasing dependence on synthetic inputs. This interaction between fertilizers and PGRs provided an important aspect to the research. The combination of PGRs and lower amounts of chemical fertilizers has the potential to enhance tomato production by producing the best possible results. In contrast, the unfavorable outcomes reported in the interaction between fertilizers and NAA or 4-CPA highlight the importance of exercising caution when mixing specific PGRs with fertilizers. The successful implementation of GA_3 and SA in tomato cultivation has shown great potential in lowering the reliance on synthetic chemical fertilizers, hence promoting sustainable agriculture. This is in line with international initiatives to reduce the environmental effects caused by excessive use of fertilizers (FAO, 2015). The study's findings provide useful insights into the practical application of PGRs to optimize fertilizer usage, promote environmentally friendly practices, and ensure food security amidst increasing environmental concerns. Moreover, further study is needed to be carried out for more optimization of the PGRs application in combination with the fertilizer doses under different abiotic stress conditions.

Correlation Coefficient Analysis

The Pearson correlation coefficient was used to assess the correlations between thirteen variables, including growth and yield characteristics of tomatoes, in response to fertilizer and PGRs treatment (Figure 1). The study observed that plant height (PH), base diameter (BD), number of branches (BN) and leaves (LN) per plant, as well as canopy spread (CS), showed moderate to very strong positive correlations with the reproductive and yield traits, specifically the number of flowers (FlPP) and fruits (FPP) per plant, the weight of a single fruit (SFW), and the overall yield (YPP). This suggests that the combined use of fertilizer and PGRs effectively enhanced tomato plant growth, leading to improved yield and related characteristics. There was a slight positive association between vegetative growth and SPAD value, indicating that the leaf SPAD value was minimally affected by the treatment's impact on plant growth. This context explains that enhanced vegetative growth due to interacted use of fertilizers and plant growth regulators significantly and positively influenced the reproductive attributes and yield of tomato.

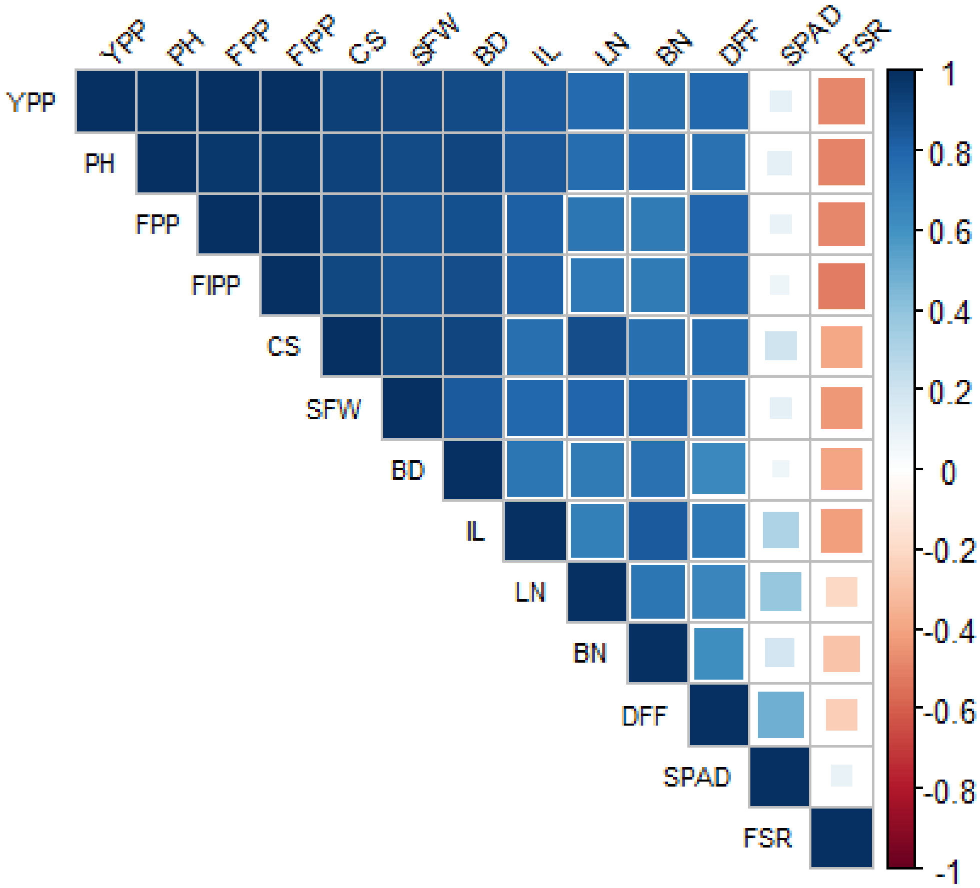

Figure 1. Correlation matrix among the growth and yield traits as influenced by fertilization and PGRs application.

Here, PH, BD, BN, LN, CS, IL, SPAD, DFF, FlPP, FPP, FSR, SFW and YPP represent plant height, base diameter, number of branches per plant, number of leaves per plant, canopy spread per plant, internode length, leaf SPAD value, days required to flowering, number of flowers per plant, number of fruits per plant, fruit set rate, individual fruit weight and fruit yield per plant, respectively.

Principal Component Analysis

Principal component analysis (PCA) was used to illustrate the correlation and influence of various fertilizer treatments and PGRs types on the growth and yield of tomatoes. The initial two principal components (PC1 to PC2) encompass 82.3% of the overall variance in the dataset (Figure 2). The PCA-biplot analysis showed that the different fertilizer treatments overlapped with each other without forming distinct separate clusters (Figure 2a). There was a slight deviation of F2, F3, F4, and F5 from F1 in relation to the Dim1 and Dim2 axes. This indicates that these fertilizers had minimal or no influence on the growth and yield of tomatoes under the conditions of the study (Figure 2a). From the Figure 2b, it has been demonstrated that the five PGR treatments, including the control, can be categorized into three distinct clusters: cluster I (H3 and H4), cluster II (control), and cluster III (H2 and H5). Notably, H2 is positioned separately in the positive quadrant in relation to Dim1 and Dim2.

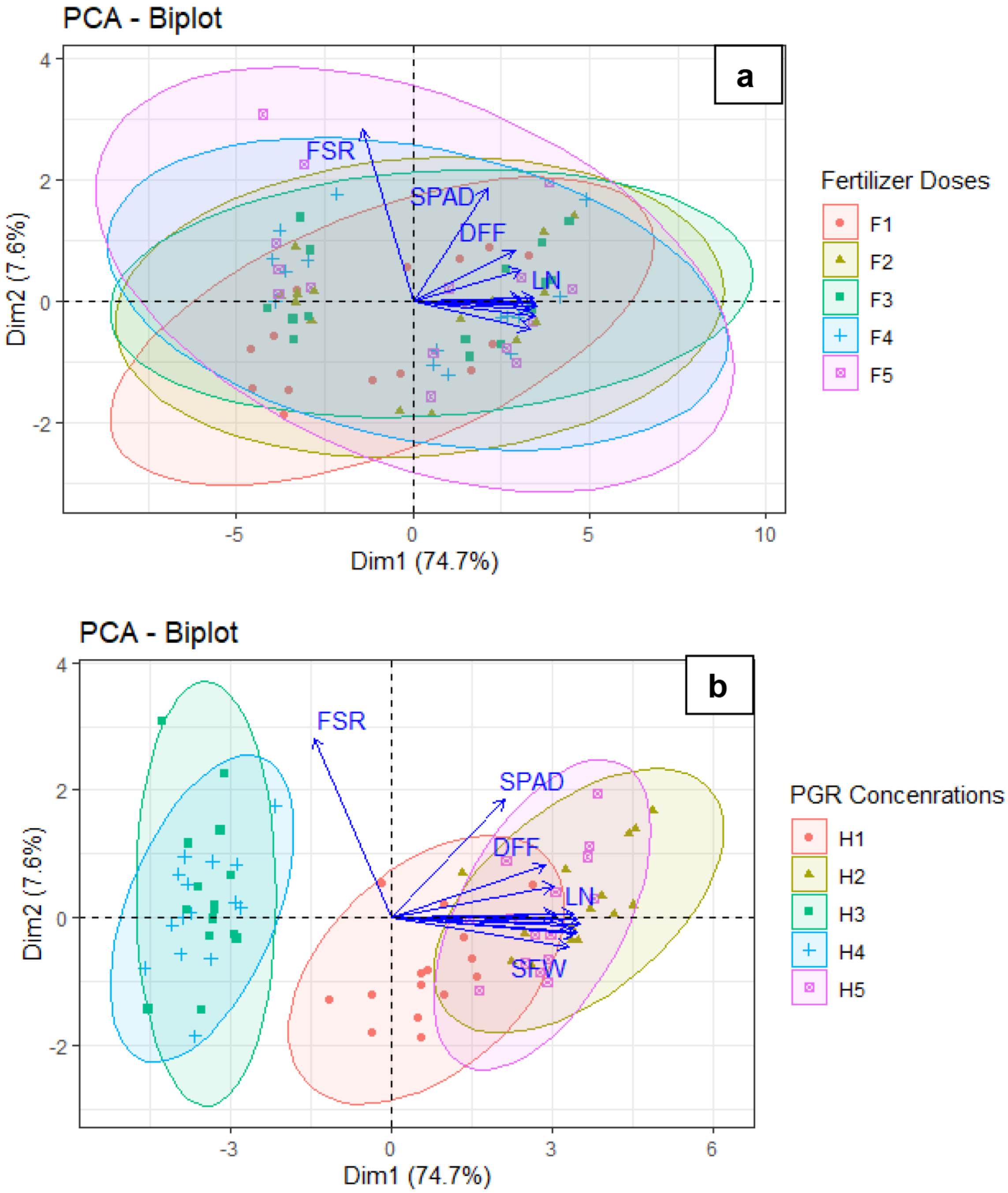

Figure 2 (a–b). Principal Component Analysis (PCA) of growth and yield traits of tomato as influenced by a) fertilization and b) PGRs application respectively.

Here, PH, BD, BN, LN, CS, IL, SPAD, DFF, FlPP, FPP, FSR, SFW and YPP represent plant height, base diameter, number of branches per plant, number of leaves per plant, canopy spread per plant, internode length, leaf SPAD value, days required to flowering, number of flowers per plant, number of fruits per plant, fruit set rate, individual fruit weight and fruit yield per plant, respectively.

The treatment H5 and H2 show overlapping effects in the right quadrants (Q1 and Q2), indicating a significant statistical similarity with positive correlations between the plant growth and yield contributing characteristics in tomato. Meanwhile, H3 and H4, which were positioned on the left side of the PCA-biplot, had a distinct relationship with each other. This positioning indicates that these two PGRs (PGRs) had a detrimental effect on tomatoes under the conditions of the study. H1 occupied the middle position in the PCA and was present in all quadrants, with a minor overlap with H2 and H5 on the right side. This indicates that the treatment had a beneficial effect on most of the parameters. Moreover, the increased magnitude of the parameter vectors more accurately captures the essence of PC1 and PC2. The findings are supported by the confirmation of the angle between the two vectors, where a positive correlation is represented by an angle between 0° and 90°, no correlation is shown by an angle of 0°, and a negative correlation is depicted by an angle between 90° and 180°. Thus, it can be inferred that the H2 and H5 treatments exerted a substantial impact on enhancing tomato growth and yield in field circumstances.

Conclusions

Present work elucidates the correlation between different levels of fertilizer, the application of PGRs, and the resulting reactions of tomato plants. The findings revealed that the utilization of GA_3 and SA has the capacity to decrease the reliance on synthetic chemical fertilizers in tomato farming, while maintaining both growth and production. The subtle and intricate reactions observed emphasize the significance of meticulously evaluating both the amount of fertilizer used and the choice of suitable PGRs for the purpose of sustainable and ecologically responsible agricultural methods.

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Decleration

The authors declare no conflict of interests.

Authors' Contributions

JH and JG conceptualized the study, developed the experimental design, carried out the investigation, examined the data, provided a rationale, and drafted, reviewed, and revised the manuscript; JH, JG, and HS assisted with data collection, methodology, and laboratory analyses; and JH, EK, and HS provided resources, funds, and supervised the study. Each author has thoroughly reviewed, amended, and provided their agreement to submit the work.

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