RESEARCH ARTICLE

Enhancing Vegetative Growth Parameters of *Solanum lycopersicum* (Tomato) through Exogenous Hormone Application

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Abstract

Tomato, rich in minerals, vitamin B, vitamin C, essential amino acids, sugars, and dietary fibres, is grown worldwide. The fruit also contains an antioxidant, lycopene, and is known to decrease the risk of cancer. Relatively easy to grow, tomato comprises popular health-related food components. Over the past few years there has been an increased interest in reinforcing local production of crops through organic means. At the same time, it is essential that nutritious food is made available to each household. The present study is an effort to ameliorate the growth of tomato using phytohormones either alone or in combination as a soil drench. The seeds were raised in a nursery, followed by transplantation into garden soil. The transplanted plants were maintained in sets treated with 50, 100, and 200 ppm (three different concentrations) of auxin, cytokinin, and gibberellin. A combination of auxin + cytokinin and auxin + gibberellin was also used at 50, 100, and 200 ppm. The data was collected for root (length), plant height and branch number. Total photosynthetic pigments were also studied. All the treatments resulted in increased growth in vegetative parameters except 50 ppm auxin, which turned out to be a poor performer. The treatments cytokinin and a combination of auxin + gibberellin also resulted in early flowering. The study emphasizes that the growth parameters of tomato can be ameliorated organically using hormone formulations. Further, this simple method of raising tomato can be propagated as a popular technology amongst home gardeners, besides encouraging small scale farmers.

Highlights

- Tomatoes are rich in minerals, vitamins, and antioxidant which help to reduce the risk of cancers.
- Application of phytohormones through soil drench method provides a simple technique of raising tomato crop.
- Besides vegetative growth, exogenous application of phytohormones is also effective for floral initiation and fruit setting in tomatoes.
- Soil drench method is safe for environment and proves to be effective for home gardening and small-scale farming.
- The simple approach can provide impetus to food security as it will be effective for enhancing growth and yield of other vegetable crops.

Keywords: Flowering, Hormones, Soil Drench, Stomatal Frequency, Trichome Density

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Introduction

Tomato (*Solanum lycopersicum* L.) is a common vegetable. Its consumption is renowned for health advantages owing to the abundant nutrients such as vitamin A, ascorbic acid, thiamine, riboflavin, and niacin alongside, magnesium, calcium, lycopene, mineral and carotene (Bose and Som, 1986; Gaied *et al*., 2013; Pramanik *et al*., 2018). Lycopene is known to combat the detrimental impact of free radicals, various cancers, diabetes, heart issues, oxidative stress-related problems, skin and bone ailments, and also reproductive disorders (Imran *et al*., 2020). The fresh and ripened tomato fruit is rich in organic acids such as citric acid, malic acid, and acetic acid, which help in purifying blood besides acting as intestinal antiseptic (Pruthi, 1993). In India, tomato, among other vegetables, ranks fourth in area coverage, while second in production (Pramanik *et al*., 2018). Despite its adaptability to various climates, tomato is highly susceptible to hot and humid cultivation conditions (Ahmad, 2002). Elevated temperatures, salinity stress, and viral attack (diseases) represent primary challenges curtailing the sustained and increased productivity of the crop (Fekadu and Dandena, 2006). Horticulture extensively utilizes plant growth regulators (PGRs) to boost development, enhancing yields through augmenting the quantity and size of fruits set (Serrani *et al*., 2007; Batlang, 2008). Exogenous PGR application has resulted in enhanced production of various vegetable crops, including tomato (Saha, 2009). Phytohormones like auxin, gibberellin, and cytokinin are investigated to have a vital role in parthenocarpy, fruit set, and fruit size (Pramanik and Mohapatra, 2017). The transport of auxin downwards along the stem towards the root triggers root development. With increased branching in the roots, plants take up increased amount of mineral nutrients from

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soil, which accumulate in the plant's storage organs, ultimately amplifying yields (Wang *et al*., 2005).

Auxin, a pivotal plant hormone, stimulates stem cell elongation, root initiation, and lateral root formation, while also regulating apical dominance, phototropism, and gravitropism (Woodward and Bartel, 2005; Ljung, 2013; Teale and Palm, 2018). Auxins are investigated to have a key position in the signaling pathway while interacting with other phytohormones such as brassinosteroids, ethylene, salicylic acid, jasmonic acid, and cytokinin (Ljung, 2013; Teale and Palm, 2018). Cytokinin is crucial for vegetative growth, promoting cell division, leaf expansion, delaying senescence, and encouraging lateral bud development (Hwang and Sheen, 2001; Keiber and Schaller, 2018). Gibberellin significantly impacts plant growth by inducing stem elongation, influencing seed germination, enhancing fruit size in seedless fruits, and regulating flowering in specific plant species (Yamaguchi, 2008; Hedden and Thomas, 2012).

Exogenous application of auxin influences root initiation, lateral root initiation, and overall growth of roots in tomato plants. It also aids in fruit development, promoting increased fruit set and size (Davies, 2010). Exogenously applied gibberellin stimulates stem elongation, enhances internodal length and overall plant height in tomato. It also improves fruit size (Hedden and Thomas, 2012). Exogenously applied cytokinin promotes cell division and enhances leaf expansion and shoot growth in tomato plants. It contributes to increased lateral bud development, thereby impacting overall plant architecture and branching (Suttle, 1998; Davies, 2010).

The interactions among auxin, cytokinin, and gibberellin result in synergistic and/or antagonistic effect on plant growth and yield. Auxin and cytokinin synergistically interact to regulate shoot growth, branching, seed germination processes, embryogenesis and organ development (Hwang and Sheen, 2001; Nordstrom, 2004; Davies, 2010). Auxin and cytokinin exhibit antagonistic effects on root development, with auxin promoting root growth while cytokinin inhibiting it. The urgent issue of food security and availability around the world, and the impact of climate change, presents a challenge to agriculture. This threat entails the challenge of ensuring dependable green practices that maximize productivity and also mitigate environmental effects. In the past few years, there has been a notable rise in stakeholders' preference for organically grown crops globally, driven by the perception of healthier and safer products. Moreover, organic farming reduces off-farm inputs and minimizes harm to the ecosystem (Sani and Yong, 2021). Organic farming incorporating plant hormones holds significance in sustainability by enhancing plant growth, resilience, and productivity without relying on synthetic chemicals. Utilization of natural plant hormones in organic farming promotes root development, tolerance against stresses and thus fruit production (Khan *et al*., 2012). This approach fosters sustainable farming by relieving dependence on age-old synthetic chemical inputs, contributing to ecosystem health and preserving soil fertility (Rouphael *et al.,* 2018).

In the present investigation, phytohormones namely, auxin, cytokinin and gibberellin and their combinations were applied as soil drench. In previous works, phytohormones have been added to the soil as soil-mix (Jan *et al.,* 2022) or foliar application has been done (Upadhyay and Ranjan, 2015; Khan *et al.,* 2018; Wavhale and Salve, 2024). Soil drenching involves targeted delivery of nutrients or treatments directly to the root system, ensuring efficient uptake and utilization by plants. This method enables the roots to access essential elements or treatments more effectively, potentially enhancing overall plant health, nutrient uptake, and growth. This application in drench form is presumed to be more effective as the hormone if given as soil mix, it is a one-time application. The plant requirement keeps changing as it grows hence the drench can be administered at intervals. In the foliar form the hormone application is subject to its absorption through stomata and the rate of transpiration. The drench application is innovative and roots can easily be targeted in the rhizosphere. Present investigation is an attempt to ameliorate the vegetative growth of tomato by exogenous application of hormones in the drench form. The work holds significance in terms of investigating various other combinations of hormones, such as jasmonic acid and brassinosteroids. Extending the studies in ameliorating crop growth and yield under abiotic stress through hormone application would also help us understand the crosstalk that exists amongst the hormones (Rastogi *et al*., 2013). This simple technology can provide impetus to household food security and self-reliance, which has become important in post-COVID times.

Materials and Methods

Plant material

Tomato (*Solanum lycopersicum* L. var. Pusa Ruby) seeds were procured from National Seeds Corporation, Indian Agricultural Research Institute (IARI), Pusa, New Delhi. The experiment was conducted in the Sri Guru Har Rai Botanical Garden of Sri Guru Tegh Bahadur Khalsa College, University of Delhi, during the months of March-July 2023. Tomato seeds were initially grown in pro-trays filled with coco-peat. The nursery-grown seedlings were later transplanted to pots filled with garden soil.

Experimental Design

A nursery of tomato seedlings was raised in pro-trays, followed by transplantation of two-week-old (14 DAS) seedlings into plastic pots filled with garden soil. The experiment was designed in a randomized manner wherein hormones such as auxin- Indole-3-acetic acid (IAA, T_1), cytokinin- 6- furfuryl amino purine (Kinetin, T_2) and gibberellin- gibberellic acid (GA, T_3) alone and in combination of auxin with cytokinin (ACK, T_4) and with gibberellin (AGA, T_5) in varying concentrations of 50 to 200 ppm were used for exogenous application. Tomato seedlings raised in a nursery without any hormone treatment were kept as control (T_0). Various hormone treatments and the concentrations used are given in Table 1. For each treatment (T_0-T_5), five plastic pots (8 inches in diameter) were used. Each pot was first filled with garden soil, and later a single seedling was transplanted to each pot. The plants were subjected to hormone treatment by drenching the soil near their roots every 5 days, with each treatment replicated thrice, while being raised under natural sunlight. The total drench treatments given were six during the vegetative phase, beginning from the day of transplantation,

Table 1: Hormone treatments used in the experimental study

	Treatments			
Hormones	*0 ppm (T_0)*	*50 ppm*	*100 ppm*	*200 ppm*
Auxin (IAA, T_1)	Control (C_1)	A50	A100	A200
Cytokinin (Kn, T_2)	Control (C_2)	CK50	CK100	CK200
Gibberellin (GA, T_3)	Control (C3)	GA50	GA100	GA200
Auxin Cytokinin (IAA+Kn, T_4)	Control (C_4)	ACK50	ACK100	ACK200
Auxin Gibberellin (IAA+GA, T_5)	Control (C_5)	AGA50	AGA100	AGA200

i.e., six treatments in a month (30DAT). The drench treatment 10 mL per pot was given with the help of a syringe to the soil. The drench was given either in the morning or evening in order to minimize any loss due to evaporation under intense sunlight. To study the effect of hormone application either individually or in combination, tomato growth parameters were analysed throughout the period from transplantation until harvest of mature plants. The harvesting was done in field on ice and the samples were then processed for biochemical analysis in laboratory after thawing.

Vegetative Growth Parameters

Various hormone treatments were evaluated for ameliorating morphological growth parameters, including plant height, branch number, leaf number/branch, shoot length, root length, fresh and dry weight of the plant. Traditional methods for calculating the morphological parameters were adopted. Measurements for plant height (from base of the stem near soil surface to the tip of primary stem), number of branches per plant (per node), and number of leaves per branch were taken 30 days post-treatment, while root length (primary stem after carefully uprooting the plant) was assessed during the harvest phase. All measurements were taken with a meter scale (Brunes *et al.,* 2016). Harvested plants (*of one replicate*) were weighed for their fresh weight and were subsequently dried at 70°C for dry data (*of one replicate*).

Physiological Analysis

Effect of hormone application on plant growth was further analysed through physiological analysis such as stomatal frequency, trichome density and relative water content (RWC) analysis. Estimation of various assimilatory–photosynthetic and accessory pigments, such as Chlorophyll a, Chlorophyll b, total chlorophyll, and carotenoid analysis, was done using fresh leaf tissue. On the 20th day, the second leaf from the stem tip of the healthiest replicate was excised and parameters taken.

Stomatal Frequency and Trichome Density

Fresh leaves that were fully expanded on 20 DAT were collected from three plants per treatment. Peel mounts were prepared by treating the peels with cupric sulphate solution and hydrochloric acid, facilitating the measurement of stomatal frequency and trichome density (Ram and Nayyar, 1974). Stomata and trichomes were observed at 400x magnification using light microscope. Stomatal frequency and trichome density were calculated using the equation below:

$$\text{Stomatal Frequency} = \frac{\text{Number of stomata in microscopic field}}{\text{Area of microscopic field (mm}^2\text{)}}$$

$$\text{Trichome Density} = \frac{\text{Number of trichomes in microscopic field}}{\text{Area of microscopic field (mm}^2\text{)}}$$

Relative Water Content

Fully expanded leaves from three plants of each treatment were taken and cut into small pieces. Leaf pieces were immediately weighed for fresh weight (FW) analysis. After 4 hours incubation in water, leaf pieces were reweighed for turgid weight (TW) analysis and then dried for 24 hours in an oven at 70°C for constant dry weight (DW) analysis. Using the fresh and turgid weight data, relative water content was calculated using the equation:

$$\text{Relative Water Content (\%)} = \{\frac{FW-DW}{TW-DW}\} \times 100$$

Total Chlorophyll and Carotenoids Content Analysis

Assimilatory pigments (chlorophyll a, chlorophyll b, total chlorophyll and carotenoids) content in tomato leaf tissue were determined using dimethylsulphoxide (DMSO) as solvent (Hiscox and Israelstam, 1979). Fresh leaf tissue (100 mg) was taken in a test tube containing 10 mL of DMSO. To prevent photo-oxidation, these test tubes were wrapped in aluminium foil and incubated at 65°C for 5 hours. Absorbance of assimilatory pigments- chlorophyll a, chlorophyll b, total chlorophyll and carotenoids was measured at standard wavelengths of 480, 510, 645 and 663 nm, respectively, using DMSO as blank. Assimilatory pigments- chlorophyll a (Chl a), chlorophyll b (Chl b), total chlorophyll and carotenoids content were calculated using standard method of Arnon (1949).

Statistical Analysis

The data recorded for various morphological growth parameters and Physiological analysis with parameters were analysed statistically using one-way analysis of variance. Mean values of the treatment were compared using Duncan's multiple range test (DMRT) post-hoc test at a significance level of 5% ($p < 0.05$). The analysis was made between the parameters obtained for individual hormones (Auxins, cytokinins, and gibberellins), and those between a combination of hormones (Auxins and cytokinins, and auxins and gibberellins).

Results

Effect of Hormones on Vegetative Growth and Flowering

Significant changes in growth parameters were observed after application of individual hormone treatment and in combinations on plant height, branch number per plant and number of leaves per branch.

Plant height

Maximum plant height was recorded with GA100 followed by CK100 and the latter was found to be statistically similar to GA200. Minimum plant height was recorded in the plants treated with auxin at 50 ppm which was almost 50% less than control (Fig. 1A). For the hormone treatments used in combination, a notable increase in plant height was recorded with combination of auxin + cytokinin at 100 ppm (ACK100) followed by AGA and ACK at 200 ppm, respectively. However, hormone treatments, ACK and AGA, each at a 50 ppm concentration, resulted in a 67% reduction in plant height (Fig. 1B).

Number of branches

A significant increase in branch number was recorded for GA200 followed by CK100. A noteworthy reduction in branch number was recorded with A50 with almost half branches as compared to control (Fig. 1C). Though, hormone combination of ACK and AGA both at 100 and 200 ppm concentration resulted in enhanced branching, however this increase was not statistically different

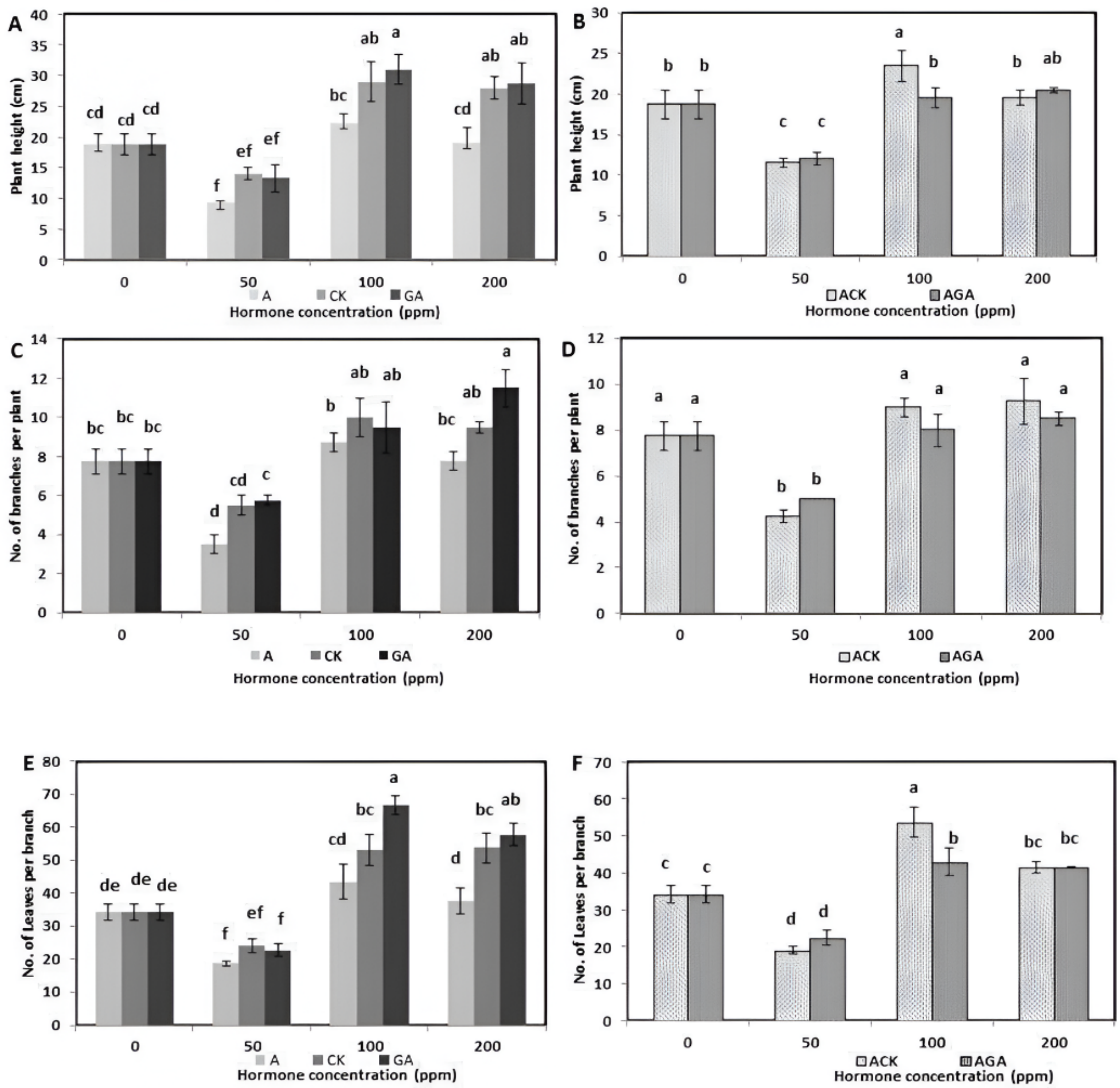

Fig. 1: Effect of hormone treatments on vegetative growth. (A, B) Plant height between individual hormones (A), between combination of hormones (B), (C, D) No. of branches per plant between individual hormones (C), between combination of hormones (D) and (E, F) No. of leaves per branch between individual hormones (E), between combination of hormones (F). Error bars (mean ± S.E.) with different lowercase letters indicate significant difference when analysed with DMRT post-hoc test at significance level of 5% ($p<0.05$)

from the control (Fig. 1D). Hormonal combination of ACK and AGA at 50 ppm resulted in almost 50% reduced branching.

Number of leaves per plant

Maximum increase in leaves per branch was recorded for GA100 followed by GA200. However, a significant reduction in leaf number was recorded at A50 (Fig. 1E). In the case of hormone combination, ACK and AGA each at 100 ppm resulted in a marked increase in leaf number (Fig. 1F).

Shoot Length

The results analysed for hormone treatment on shoot length were significant, where maximum shoot length was recorded for GA at 200 ppm, followed by CK100 and GA100, respectively. Minimum shoot length was recorded for auxin at 50 ppm (Fig. 2A). Among the hormone combinations, increased shoot length was recorded for ACK100 followed by ACK200 and AGA100, however no significant difference was observed for these treatments (Fig. 2B).

Root Length

Among the individual hormone treatments, enhanced root length was recorded for GA at 100 ppm, however, the response was not statistically different from A200 and CK100 (Fig. 3A). Hormone combination ACK at 100 ppm resulted in elongated, much-branched and dense roots than the control (Fig. 3 B and C). Moreover, lower concentrations of both ACK and AGA at 50 ppm also resulted in increased root length than the control.

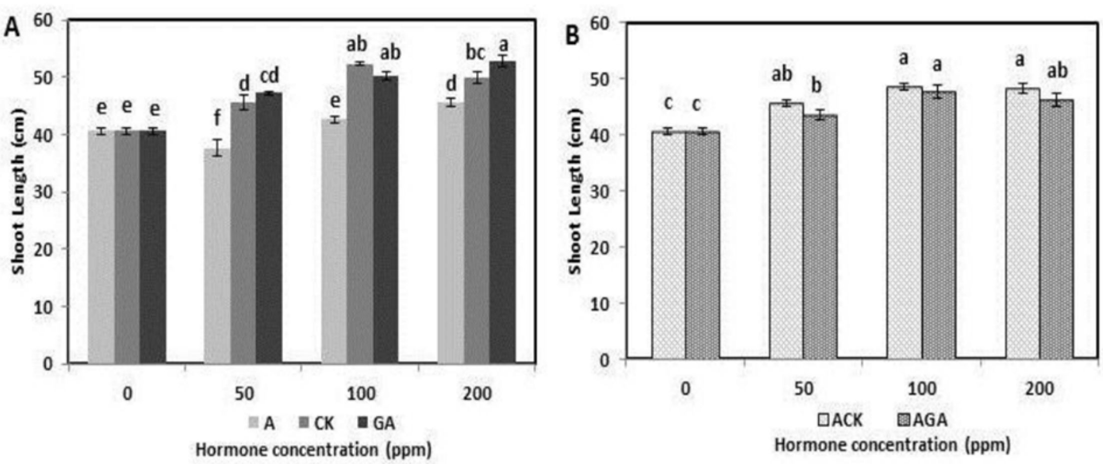

Fig. 2: (A, B) Effect of hormone treatments on shoot length. Error bars (mean ± S.E.) with different lowercase letters indicate significant difference with DMRT (Duncan's Multiple Range Test) post-hoc test at significance level of 5% ($p<0.05$)

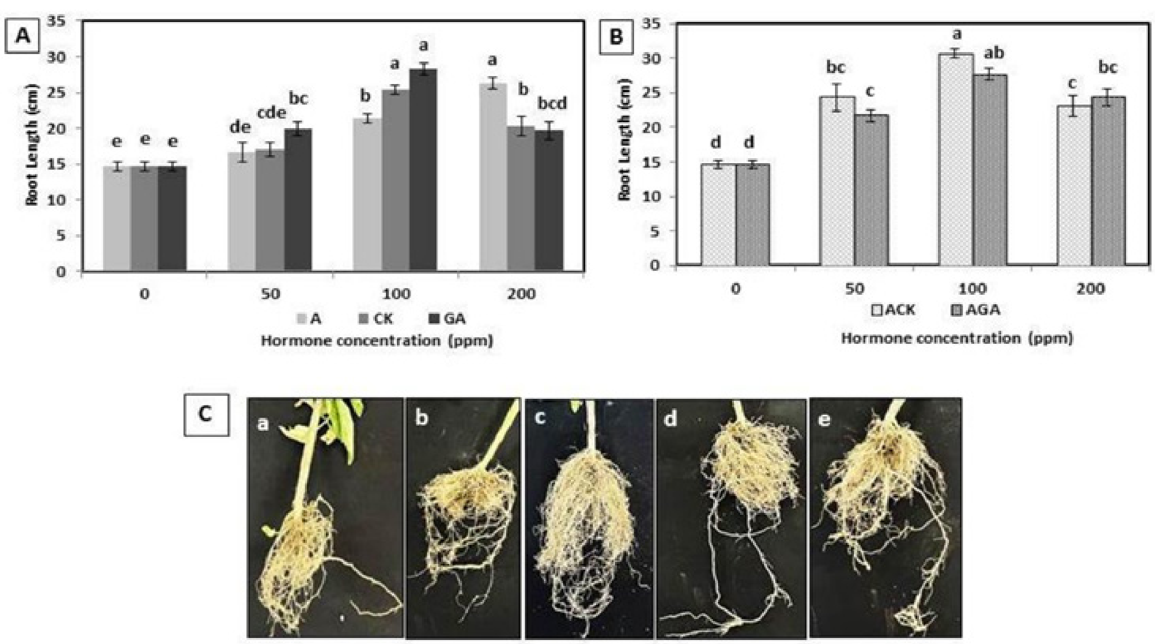

Fig. 3: (A,B) Effect of hormone treatments on root length. Error bars (mean ± S.E.) with different lowercase letters indicate significant difference with DMRT post-hoc test at significance level of 5% ($p<0.05$). (C) Photograph showing morphological comparison in root growth (a) control, (b) A50, (c) CK 100, (d) GA 100 and (e) ACK 100

Fresh and dry weight analysis

Among individual hormone treatment, GA at 200 ppm resulted in enhanced fresh weight (Fig. 4A). For the hormone combinations, maximum plant fresh weight was recorded from ACK100 followed by AGA100 (Fig. 4B). However, decrease in plant fresh weight was observed from auxin treatment at 50 ppm as compared to control.

Gibberellin at 200 ppm concentration resulted in maximum plant dry weight (Fig. 4C). This increase in dry weight was followed by the hormonal combination ACK100 (Fig. 4D). Dry weight was found to be minimal for auxin at 50 ppm.

Besides vegetative growth, the effect of hormone treatments was also observed on flowering and fruiting (Fig. 5 A-C). Early flower initiation was observed with CK100 and AGA100 as compared to other treatments. It was also observed that application of AGA100 resulted in early fruit setting (Fig. 5C).

Effect of Hormones on Physiological Parameters

Stomatal frequency

Data analysed for stomatal frequency showed a significant effect for cytokinin and gibberellin application. Maximum stomatal

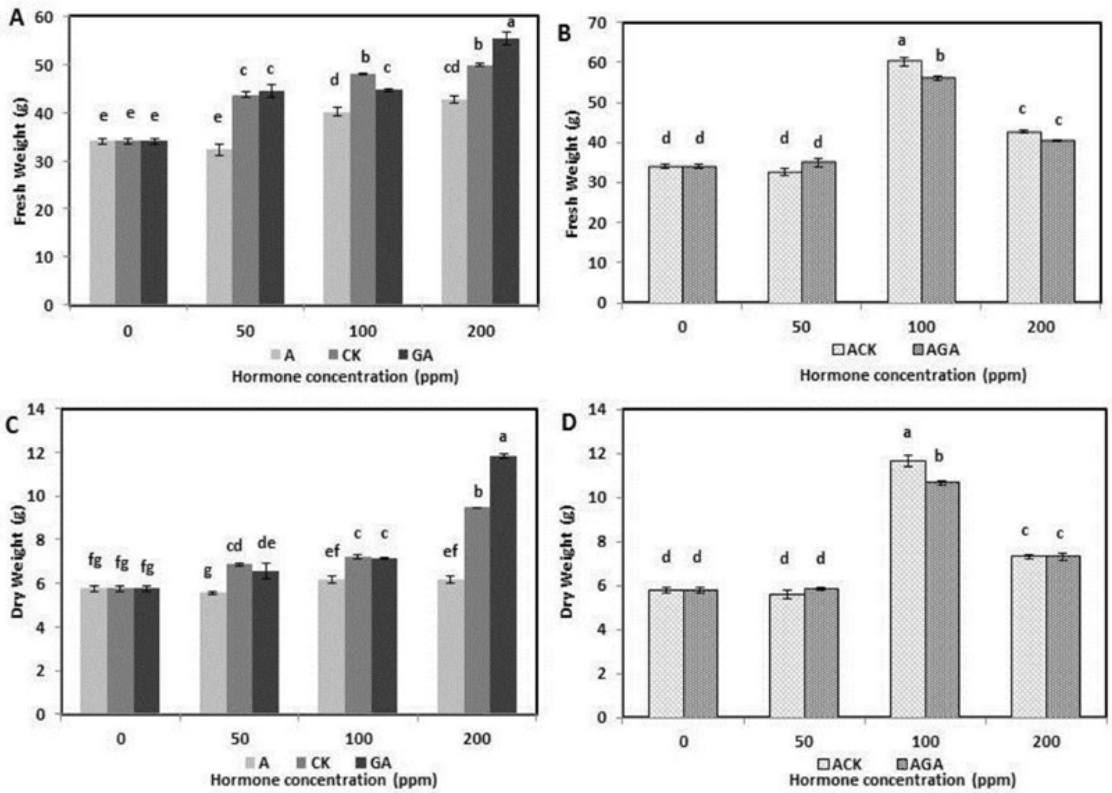

Fig. 4: Effect of hormone treatments on fresh and dry weight of plants. (A, B) Fresh weight and (C, D) dry weight. Error bars (mean ± S.E.) with different lowercase letters indicate significant difference with DMRT post-hoc test at significance level of 5% (p <0.05)

Fig. 5: Flower and fruit setting. (A) Flower initiation from CK100-treated plants and (B, C) flowering and early fruit setting from AGA100 treatment. Figure B also depicts trichomes on the tomato stem

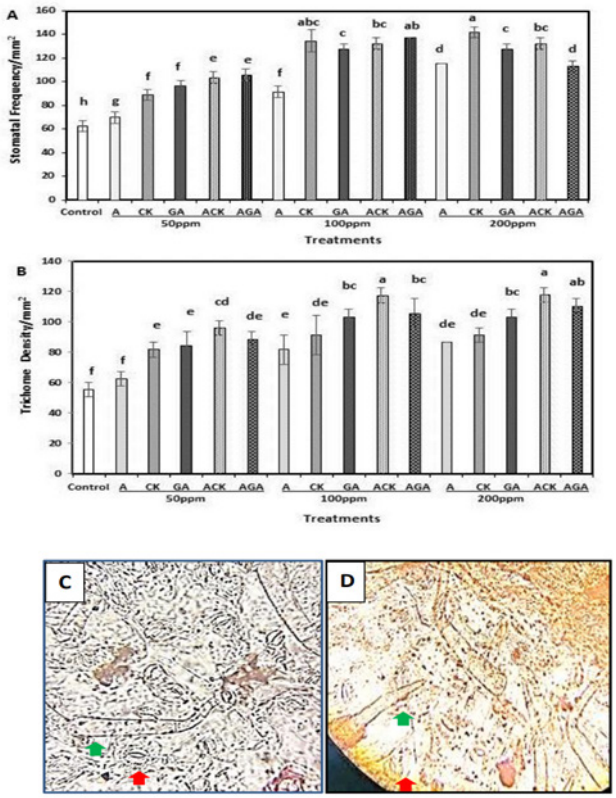

Fig. 6: (A, B) Effect of hormone treatments on physiological parameters. (A) Stomatal Frequency, (B) Trichome Density. Error bars (mean ± S.E.) with different lowercase letters indicate significant difference with DMRT post-hoc test at significance level of 5% (p <0.05). (C, D) Photograph of tomato leaf peel showing stomata (Red Arrow) and trichomes (Green Arrow), as seen under light microscope, (C) CK200 and (D) ACK200 (magnification, 400x)

frequency was observed for CK at 200 ppm, followed by the hormone combination AGA100. Minimum stomatal frequency was recorded for the control without any hormone application as depicted in Fig. 6A and C.

Trichome density

Maximum trichome density was observed for the hormone combination ACK200 followed by ACK100 as depicted in Fig. 6 B and D. However, no significant difference was observed among the two treatments. Similarly, auxin at 50 ppm was not statistically different from the control.

Relative water content

Maximum relative water content was recorded from the hormone combination of auxin + cytokinin at 100 ppm, followed by auxin treatment at 200 ppm. This increase in relative water content was found to be significantly different as shown in Table 2.

Chlorophyll and carotenoid content

Effect of hormone treatment was also observed on chlorophyll and carotenoid analysis. An increase in assimilatory pigments- chl a, chl b, total chlorophyll and carotenoids content was recorded for the hormone combination ACK100 (Table 2).

Discussion

The research study on amelioration of vegetative growth parameters of tomato plants with exogenous application of hormones and their combinations has shown interesting results. Vegetative growth parameters analysed for plant height, branch number, number of leaves per branch, length of shoot and root showed an increase with GA at 100 to 200 ppm. This was closely followed by cytokinin at a lower concentration of 100 ppm. At 200 ppm, cytokinin did not show increase in these parameters except a little increase shoot length. This may be because at higher concentration the endogenously synthesized hormones maintain a balance which modulates the plant growth (Kaur *et al*., 2018). Cary *et al*., (1995) and Rupp *et al*., (1999) observed that exogenous application of cytokinin at higher concentration may lead to inhibition of root growth. Furthermore, the cross talk between endogenous and exogenous hormones may regulate the effect of foliar application complicating the results. It is also not clear if the effects of exogenous hormones on growth are direct or whether the regulation has been with the endogenous hormones (Szalai *et al*., 2011). Similar studies on mung bean have shown that hormones either in combination or alone have enhanced effect on parameters of growth (Naeem *et al*., 2004). The legume (mung bean) shows an increased growth with auxin at 100 ppm (Parveen *et al*., 2023). Amelioration in growth of tiller buds has been recorded in wheat (Cai *et al*., 2018; Hanaa and Safaa, 2019). Similar work has been done by Yolcu *et al*., (2024). Cytokinin and/or auxin are known to have a positive regulation in faba beans on chlorophyll a, b and carotenoids, total carbohydrates, polysaccharides, free amino acids, proline and total phenols (Sadak *et al*., 2013). Gibberellins at a higher concentration of 200 and 300 ppm resulted in moderately improved photosynthetic pigments and yield in mung bean, *Vigna radiata* (El Karamany *et al*., 2019; Islam *et al*., 2021), wheat (Pazuki *et al*., 2013) and cotton (da Costa, 2017). The present study supports the idea that amelioration of developmental traits such as plant height and leaf area can lead to improved crop performance (Meyer and Purugganan, 2013).

In the present study on tomato, the auxin at lowest concentration of 50 ppm did not ameliorate growth with respect to all the parameters under study. Auxin, however recorded increased root parameters even at low concentration of 50 ppm in a grafted cucumber (Balliu and Sallaku, 2017). In a combination with cytokinin or gibberellin, auxin in tomato has ameliorated plant height, though to a limited extent as compared to control but has resulted in significant increase in root length. These combinations in present study also resulted in increase in fresh and dry weight of tomato plants. Similar observations have been made in blueberry plants (Zang *et al*., 2016). The increased weight may be due to improved tissue anatomy as shown in studies on carrot (Khadr *et al*., 2020). The study further showed an increase in lignin deposition in vessels and hence the root parameters improved with exogenous application of IBA. In a study on carrot Wang *et al*., (2015) found Gibberellins to establish a cross talk with other hormones to regulate plant growth.

The combination of hormones in present study have worked significantly for parameters such as stomatal frequency, trichome density, relative water content and photosynthetic pigments especially auxin and cytokinin in combination at 100

Table 2: Relative water content, chlorophyll a, chlorophyll b, total chlorophyll and carotenoids content in response to hormone treatments

Treatments	*Relative Water Content (%)*	*Chlorophyll a (mg/g FW)*	*Chlorophyll b (mg/g FW)*	*Total Chlorophyll (mg/g FW)*	*Carotenoids (mg/g FW)*
Control	66.19 ± 0.17i	6.482 ± 0.00k	2.088 ± 0.01k	8.557 ± 0.02l	2.844 ± 0.01n
A50	68.55 ± 0.40h	6.289 ± 0.01k	2.247 ± 0.01i	8.523 ± 0.02l	2.865 ± 0.01m
CK50	72.04 ± 0.10f	7.328 ± 0.18cd	2.168 ± 0.01j	9.311 ± 0.02g	3.248 ± 0.01g
GA50	69.78 ± 0.21g	6.793 ± 0.02fg	2.090 ± 0.01k	8.870 ± 0.02j	2.893 ± 0.01l
ACK50	74.25 ± 0.31d	7.273 ± 0.01d	2.943 ± 0.01c	10.201 ± 0.02c	3.880 ± 0.01c
AGA50	65.53 ± 0.34ij	6.879 ± 0.01ef	2.366 ± 0.01g	9.230 ± 0.02h	2.991 ± 0.01i
A100	73.17 ± 0.08e	6.323 ± 0.01k	2.373 ± 0.01g	8.683 ± 0.02k	2.917 ± 0.01k
CK100	77.26 ± 0.16c	7.384 ± 0.01cd	2.376 ± 0.01g	9.745 ± 0.02e	3.367 ± 0.01f
GA100	73.52 ± 0.06e	6.382 ± 0.01jk	2.629 ± 0.01e	8.998 ± 0.02i	2.937 ± 0.01j
ACK100	81.41 ± 0.28a	10.120 ± 0.01a	3.595 ± 0.01a	13.695 ± 0.02a	4.360 ± 0.01a
AGA100	65.11 ± 0.08j	6.589 ± 0.01i	2.932 ± 0.01c	9.508 ± 0.02f	3.118 ± 0.01h
A200	78.04 ± 0.09b	6.609 ± 0.00hi	3.495 ± 0.01b	10.089 ± 0.02d	4.019 ± 0.01b
CK200	76.66 ± 0.33c	7.608 ± 0.01b	2.812 ± 0.01d	10.404 ± 0.02b	3.493 ± 0.01d
GA200	69.77 ± 0.11g	6.987 ± 0.01e	2.304 ± 0.01h	9.277 ± 0.02g	3.262 ± 0.01g
ACK200	63.71 ± 0.26i	6.732 ± 0.00gh	2.507 ± 0.01f	9.226 ± 0.02h	3.106 ± 0.01c
AGA200	65.98 ± 0.17i	7.426 ± 0.01c	2.639 ± 0.01e	10.049 ± 0.02d	3.456 ± 0.01e

Values (mean ± S.E.) with different lowercase letters indicate significant difference with DMRT post-hoc test at significance level of 5% ($p<0.05$).

ppm. Auxin at 50 ppm alone for these parameters has continued with lowest values. The tomato plants reached early flowering with cytokinin at 100 ppm and at a combination of auxin and gibberellin at 100 ppm while the latter also set the first fruit. The rest of the treatments did not enter early flowering in the present study. Similar results have been obtained in other plants (Bangerth, 2009; Wood, 2011). Serrani *et al*., (2008) observed that fruit setting in tomato crop was ameliorated through exogenous application of auxin and also of gibberellin (alone). They suggested that probably auxin leads to biosynthesis of gibberellins which results in fruit set.

The present study is a comprehensive follow-up of hormone application to tomato seedlings from transplantation till the appearance of first fruit in the plants. Most of the studies have so far documented the effect of hormone application near flowering stage (Davenport *et al*., 2000; Aliyu *et al*., 2011). The amelioration of onset of flowering with application of hormones (auxin, cytokinin and gibberellin) bears a correlation on seed and fruit development (Cho *et al*., 2002). However, the reproductive development of a plant depends on its vegetative growth (Taiz *et al*., 2015). The allocation of resources from vegetative parts of the plant affects reproductive fitness of the plant (Koelewijn, 2004). Ameliorating vegetative growth of plant hastens flowering and therefore increases quality and quantity of fruits. Legumes because of their economic importance have been extensively investigated to increase productivity through hormonal formulations. The nodulation, pod set, and seed yield of legume plants has been enhanced by hormone application (Hosni *et al*., 2023; Chen *et al*., 2023). A few studies have focussed on cereals and tissue culture raised plants (Bima *et al*., 1995; Wang *et al*., 2020; Yaroshko *et al*., 2023). It is therefore important that the studies are extended to the improvement of other crop plants and vegetables which would help to meet the food quality and productivity.

The potential role of auxins also needs to be investigated more because it has resulted in increased growth in most of the legumes but did not show a promotive effect in tomato as evidenced by present investigation. This may be due to the interaction between exogenous and endogenous hormones of the plant. The performance of foliar application is also dependent on the soil and climatic conditions as any abiotic effect might be mitigated under suboptimal conditions of growth (Sabagh *et al*., 2022). However, the auxins in tomato have enhanced flowering in combination with cytokinin and gibberellin (Present study).

More on-field research on exogenous application of hormones in crop species is required. Such studies on ameliorating vegetative growth of plants would have a long-term benefit as healthy foliage translates into a healthy stand at maturity. It is further emphasized that application in drench form works well for enhancing growth and is a better formulation than foliar spray. The foliar spray is affected by transpiration and is therefore applied during the day when transpiration is minimum (Bouranis and Chorianopoulou, 2023). The study provides a simple technology that can be adopted for raising kitchen gardens and backyard farming. The prospects of such studies can be extended to plants raised on marginal soils, which are nutrient-poor but can be brought under cultivation without the use of synthetic fertilizers.

Conclusion

The data obtained through hormone treatment of auxin, cytokinin, gibberellin alone or combination of auxin with cytokinin and gibberellin resulted in enhanced morphological growth and flowering of tomato plants. In the present investigation, application of gibberellin and cytokinin alone and a combination of auxin with cytokinin at 100 ppm through the soil drench method resulted in better growth of tomato plants. Root growth was enhanced with a combination of auxin with cytokinin. Thus, cross-talk between hormones, if investigated at the molecular level, will help in understanding the nutrient uptake and combating of abiotic stresses. Besides vegetative growth, early floral initiation and fruit setting were also observed through the application of hormones. Further exogenous application of hormones through the drench method is safe for the environment and could be a beneficial and sustainable approach for the cultivation of horticultural crops.

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Author's Contributions

The authors Inderdeep Kaur (IDK), Preeti Kaur (PK) and Harmeet Kaur (HK) conceptualized the experiment work. Rayees Ahmad Bhat and Tamanna Sharma carried out experiments and collected the data. Preeti Kaur (PK) analyzed the results and did statistical analysis. The authors IDK, PK and HK contributed in drafting and subsequently finalized the manuscript.

Conflict of Interest

The authors have no conflict of interest.

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