

## Review Article

### Role of Plant Growth Regulators in Improving Vegetable Crop Productivity: A Review

#### Abstract

Vegetable crops are one of the most critical sources of world nutrition and food security. However, optimal productivity can be challenging to achieve often due to biotic as well as abiotic factors. Plant growth regulators (PGRs) have evolved as effective tools for improving the growth and development of vegetables and stress resilience. This review discusses the major categories of PGRs, including auxins, gibberellins, cytokinins, ethylene, abscisic acid, brassinosteroids, jasmonates, and salicylic acid. Key physiological mechanisms, such as growth modulation, stress tolerance, and nutrient uptake, are discussed. The review also highlights challenges, practical applications, and future research directions to maximize the benefits of PGRs in sustainable vegetable production.

**Keywords:** - Plant growth regulators, vegetable crops, stress tolerance, crop productivity.

#### Introduction

Vegetable crops are integral crops in the global agriculture network, and they are quite important to human nutrition, economic balance, and food security (Ebert, 2020). Because of the high content of nutritional vitamins, minerals, and dietary fibers, these crops play crucial roles in combating malnutrition and enhancing health. (Singh, 2008) Their productivity, however, is often constrained by a myriad of factors, including environmental stressors such as drought, salinity, and temperature extremes, nutrient deficiencies, and suboptimal agronomic practices (Saimbhi MS 1993).

Plant growth regulators have thus become one of the essential tools in modern agriculture for combating these challenges (Olaiya *et al.*, 2013). PGRs encompass naturally occurring endogenous compounds as well as synthetic analogues externally applied, which play a major role in plant physiology through influencing the key biochemical and molecular processes (Steward, F. C. 2012). They act at several growth and developmental stages such as seed germination, root and shoot growth, flowering, fruit development, and stress tolerance (Zahid *et al.*, 2013).

This review provides a comprehensive examination of the types, mechanisms, and multifaceted roles of major plant growth regulators. This should highlight their potential in improving vegetable crop productivity and quality while offering sustainable solutions to meet the rising global demand for food amid growing environmental pressures.

#### Types and Roles of Plant Growth Regulators

Plant growth regulators play a significant role in various physiological and biochemical processes affecting plant growth and development (Sabagh *et al.*, 2021). Their use in vegetable crops has contributed to increased productivity and stress tolerance and improved general crop quality. Below are the main PGRs, their functions, and applications in vegetable crop management.

## **Auxins**

Auxins are important for promoting cell elongation as they loosen the cell wall, allowing turgor-driven expansion (Majda & Robert 2018). They maintain apical dominance by suppressing lateral bud growth, channeling energy toward vertical growth, and induce root initiation in cuttings through the stimulation of adventitious roots (Jansen *et al.*, 2013). Auxins control the differentiation of vascular tissues, thus ensuring that these tissues transport water and nutrients. They are also implicated in tropic responses such as phototropism - response to light - and gravitropism - response to gravity (Vandenbrink *et al.*, 2014). The use of auxins has promoted root induction in vegetative propagation, such as cuttings of sweet potatoes (Pan *et al.*, 2020). Auxin sprays improve fruit set in tomatoes as they prevent fruit drop from adverse conditions (Pramanik *et al.*, 2017). Auxins are used for the regulation of flowering in cucurbits to ensure equal fruiting and for thinning and shaping fruits such as cucumbers and melons to achieve maximum size and quality (Pathak *et al.*, 2023).

## **Gibberellins**

In 1926, the Japanese scientist Kurosawa made the discovery of gibberellins. Gibberellins (GAs) promote stem elongation by inducing cell division and elongation within internodes, break seed dormancy by mobilizing reserve food during germination, induce flowering in long-day and biennial plants, and enhance fruit enlargement at the expense of malformation (Bagale *et al.*, 2022). They are used to induce seed germination in crops like potatoes and carrots, thus bringing uniform sprouting and better plantation efficiency. Gibberellins increase the size of cucumbers, zucchinis, etc. by promoting cell enlargement and division during the initial fruit development (Bagale *et al.*, 2022). They also induce flowering in leafy crops such as spinach under short-day conditions, supporting off-season production and applied in hydroponic systems to enhance biomass and maximize growth cycles in crops such as lettuce and kale.

## **Cytokinins**

In 1995, Skoog conducted an experiment demonstrating that when the pith tissues of *Nicotiana tabacum* were isolated from the vascular tissues, they grew without undergoing cell division (Thakur, O. 2022). Cytokinins are involved in cell division and differentiation; they promote growth in meristematic tissues (Kaur *et al.*, 2018). They retard leaf senescence through chlorophyll retention and photosynthesis activity and improve nutrient mobilization by channeling assimilates to actively growing tissues. Cytokinins in foliage sprays in crops such as lettuce and spinach stimulate biomass, marketable yield, but above all, they keep fresh produce longer by resisting yellowing (YADAV *et al.*, 2024). Cytokinin application in tissue culture for shoot regeneration and subsequent multiplication can increase fruit quality in fruits of solanaceous crop tomatoes (Bagale *et al.*, 2022), through better nutrient partitioning while the same can apply for shoots of crops like broccoli and cauliflower.

## **Ethylene**

Ethylene acts as a key regulator of fruit ripening, facilitating changes in color, texture, and flavor (Panigrahi, & Joshi, 2016). It triggers leaf abscission and senescence in response to stress or developmental cues and plays a role in stress signaling, helping plants adapt to mechanical injury or pathogen attack. Controlled application of ethylene inhibitors like silver thiosulfate delays senescence

in broccoli and cauliflower, reducing postharvest losses (Rademacher, 2015). Ethylene treatments are applied to synchronize fruit ripening in climacteric fruits like tomatoes and peppers, thereby ensuring uniform harvesting (Watkins, 2002). It manages flowering and fruit thinning in cucurbits by promoting selective abscission under crowded conditions and is applied to de-green citrus fruits, enhancing their visual appeal for the market.

### **Abscisic Acid**

Abscisic Acid (ABA) mediates stomatal closure in drought conditions, thereby reducing transpiration loss of water and increasing drought tolerance by regulating osmotic adjustments in plant tissues (Swamy *et al.*, 2021). It is also very important in seed maturation and dormancy by modulating storage protein synthesis. ABA treatments enhance the water-use efficiency of leafy vegetables such as spinach and lettuce, especially in areas with water scarcity, and is used to increase the stress tolerance of tomatoes and cucumbers cultivated at high temperatures (Waśkiewicz *et al.*, 2016). ABA promotes seed maturation uniformly for crops like carrots to attain higher germination rates, and enhances the postharvest quality of leafy greens by reducing water loss and maintaining freshness (Jain *et al.*, 2023 and El-Ramady *et al.*, 2015).

### **Brassinosteroids**

Brassinosteroids promote cell elongation and division, leading to strong plant growth (Nolan *et al.*, 2020). They enhance photosynthetic efficiency by increasing chlorophyll content and activity and improve resistance to abiotic stresses such as heat, drought, and salinity. Brassinosteroids reduce heat and drought stress in peppers, tomatoes, and cucumbers through enhanced antioxidant activity (Halaji *et al.*, 2024). They are used in promoting seedling vigor and uniform growth in vegetable nurseries; they help in reducing transplant shock. Foliar application in leafy vegetables, such as kale and lettuce, promotes higher photosynthesis rates and yields (Velavan, 2023). Brassinosteroids enhance the quality and shelf life of fruits in solanaceous crops by mitigating oxidative damage (Zhou *et al.*, 2023).

### **Jasmonates**

Jasmonates (JAs) enhance resistance against pests and pathogens by activating defense-related genes, regulate stress signaling pathways, and influence the biosynthesis of secondary metabolites, thereby improving flavor and nutritional quality (Kumar *et al.*, 2023). These substances have been applied for the pest management of leafy vegetables such as spinach and lettuce, thereby reducing reliance on chemical pesticides (Ofuya *et al.*, 2023). Jasmonates improve stress resilience in cucurbits that include pumpkins and melons, partly through the repair of oxidative damage (Sun *et al.*, 2024), and enhance bioactive compound production by herbs and spices, to raise their therapeutic potential. They induce resistance in crops such as tomatoes and peppers against fungal diseases (Bozbuga, *et al.*, 2022).

### **Salicylic acid**

Salicylic acid plays its role in systemic acquired resistance (SAR) of enhancing plant immune responses, decreasing the oxidative stress from such sources as high temperatures or salt, and influencing flowering and seed set under stressful situations (Song *et al.*, 2024). Salicylic acid, at higher concentrations, can reduce crop losses due to bacterial as well as fungal pathogens that cause diseases in tomatoes and peppers (Jabnoun-Khiareddine *et al.*, 2015). It also improves the fruit quality of

cucumbers and zucchinis, enhancing antioxidant activity, applied to improve salinity tolerance and heat stress in leafy vegetables such as spinach (Laxman *et al.*, 2024). It also promotes uniform flowering in crops like beans and peas, which improves the consistency of yields (Anjum *et al.*, 2020). PGRs regulate the division, elongation, and differentiation of cells for optimal vegetative and reproductive development (Durner, E. F. 2013). This is achieved through the modulation of hormonal signaling pathways that control growth in particular plant tissues to ensure balanced and coordinated development. PGRs are critical in improving plant resistance to abiotic stresses such as drought, salinity, and temperature extremes (Dempsey *et al.*, 1999). They activate antioxidant enzyme systems such as superoxide dismutase and catalase, which neutralize ROS (Agarwal *et al.*, 2005). In addition, PGRs induce the accumulation of osmolytes such as proline and soluble sugars, which help maintain cellular osmotic balance and protect cellular structures under stress conditions (Ashraf, *et al.*, 2010). The PGRs can modify the root architecture, enhance its elongation and the activity of the lateral roots, thus increasing root hair (Bhatla *et al.*, 2018). They improve water and nutrient uptake. This means improved resource uptake and better utilization, thus providing better nutrient use efficiency as well (Ikiz, *et al.*, 2024).

**Table-1: different plant growth regulators and their classes**

Plant Growth Regulators	Classes
<b>Auxins</b>	Indole-3-acetic acid (IAA), 1-Naphthaleneacetic acid (NAA), Indole-3-butyric acid (IBA), 2,4-Dichlorophenoxyacetic acid (2,4-D), 4-Chlorophenoxyacetic acid (4-CPA)
<b>Gibberellins</b>	Gibberellic acid (GA3)
<b>Cytokinins</b>	Kinetin, Zeatin
<b>Ethylene</b>	Ethereal
<b>Abscisic Acid</b>	Dormins, Phaseic Acid

Source: (Kaur *et al.*, 2014) and (Meena, 2015)

**Table-2: Different growth regulators and their function**

Name of Plant Growth Regulators	Functions
<b>Auxin</b>	(a) Apical dominance (b) Cell division and enlargement (c) Shoot and root growth (d) Plant growth movement (e) Parthenocarpy (f) Abscission
<b>Gibberellin</b>	(a) Prevents genetic dwarfism (b) Regulates bolting and flowering (c) Promotes production of parthenocarpic fruit (d) Aids in germination
<b>Cytokinins</b>	(a) Stimulates cell and organ enlargement (b) Promotes seed germination (c) Supports bud development and shoot growth
<b>Ethylene</b>	(a) Promotes fruit ripening (b) Aids in seedling growth and emergence (c) Induces leaf abscission
<b>Abscisic Acid</b>	(a) Promotes abscission (b) Induces dormancy (c) Inhibits seed development and germination (d) Causes stomatal closure (e) Assists during water stress
<b>Salicylates</b>	Plant Pathogen Resistance
<b>Jasmonates</b>	Plant Defense

<b>Brassinolides</b>	Resistance, Tissue Culture, Increases Natural Preservation Value, Reduces Fruit Drop & Flowering
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Source: (Kaur *et al.*, 2014), P. Hazra and M.G. Som, (2006) and (Swamy *et al.*, 2021)

### Applications in Vegetable Crop Productivity

The overall applications of auxins and cytokinins help induce fruit setting in tomatoes (Mariotti, *et al.*, 2011). Such applications are most suitable in suboptimal pollination conditions that arise from high temperatures or insufficient pollinator activity. Brassinosteroids enhance plant vigor, enhance resistance to heat stress, and ensure constant yields under extreme weather conditions (Sahni *et al.*, 2016).

**Table-3- Use of different growth regulators with concentration in different vegetables**

Growth Regulator	Concentration (PPM)	Method of Application	Crop	Effect on Quality
GA <sub>3</sub>	15	Foliar spray	Muskmelon	Improve rind thickness
GA <sub>3</sub>	5-15	Foliar spray	Cauliflower, cabbage	Increases head or curd size
GA <sub>3</sub>	50	Foliar spray	Lettuce and Chinese, Cabbage	Increases dry matter, protein and ascorbic acid content
PCPA	50	Foliar spray	Tomato	Increased dry matter, sugar and vitamin-C, but reduces acidity
Ethephon	250	Foliar spray	Tomato	Increases TSS
NAA	50-70	Seed treatment	Chilli	Increases amino acid and vitamin-C content in fruits
CCC	250	Foliar spray	Potato	Increases TSS and vitamin-C content in tuber
2, 4, 5-T	75-125	Pre-harvest spray	Potato	Reduces sprouting and rooting of tuber in Storage
MH	2500	Pre-harvest spray	Potato	Reduces sprouting and rooting of tuber in storage

(Source: Bahadur and Singh, 2014).

**Tomatos:** Plant growth regulators positively impact growth parameters and yield in tomatoes. Foliar sprays of tomato plants were done with NAA (25, 50, 75, and 100 ppm) and GA<sub>3</sub> (20, 40, 60, and 80 ppm). As mentioned by (Prasad *et al.* 2013), the highest plant height of 85.3 cm and 82.3 cm was achieved by the application of 100 ppm NAA and 80 ppm GA<sub>3</sub>, respectively. Yields were greatly enhanced to 483.6 q/ha and 472.2 q/ha by the treatment of 100 ppm NAA and 80 ppm GA<sub>3</sub>, respectively (Prasad *et al.*, 2013).

**Cucurbits:** Ethylene inhibitors, such as 1-methylcyclopropene (1-MCP), are applied to extend shelf life for cucumbers, melons, and squashes through delay of ripening and minimizing postharvest losses (Lurie, & Paliyath, 2008). Brassinosteroids enhance fruit quality through increased photosynthetic efficiency and minimized stress-induced deformities (Kumar *et al.*, 2023). Jasmonates are applied to

enhance resistance against powdery mildew and other fungal pathogens and protect crop health and productivity (Rohwer *et al.*, 2008).

**Potatoes:** Gibberellins are required for breaking dormancy in seed tubers and ensure uniform and synchronized sprouting (Kumari *et al.*, 2024). This is particularly relevant in commercial potato production where uniform growth and development is vital to maximize yield (Sheikh *et al.*, 2022). Abscisic acid treatments are utilized to enhance drought tolerance of potato crops grown under drought conditions (Zhang *et al.*, 2020).

**Leafy Vegetables:** Cytokinins delay leaf senescence in crops like spinach, lettuce, and kale, maintaining chlorophyll content and extending marketability (Koukounaras, A. 2009). Foliar sprays of brassinosteroids enhance photosynthetic activity, resulting in higher biomass and improved tolerance to heat and salinity stress (Castañeda-Murillo *et al.*, 2022). Ethylene inhibitors are used during postharvest handling to reduce yellowing and preserve freshness, improving the shelf life of leafy greens (Ebrahimi *et al.*, 2022).

**Capsicum (Bell Peppers and Chili Peppers):** Jasmonates are used to stimulate pest resistance by inducing expression of defense-related genes, which reduces the dependency on chemical pesticides (Zhang, *et al.*, 2015). Brassinosteroids enhance drought tolerance in capsicum by increasing antioxidant activity and strengthening the plant's mechanisms of stress response (Kaya *et al.*, 2019). Additionally, auxins and cytokinins stimulate uniform fruit setting and development, hence better quality produce (Hajam *et al.*, 2018).

**Carrots:** Gibberellins are applied to stimulate uniform germination and early seedling vigour in carrots, that ensures better stand establishment (Muhie *et al.*, 2024). Cytokinins application enhances nutrient mobilization, leading to increase root biomass and quality improvement (Pretorius, & Engelbrecht, 2009). Abscisic acid applied treatments enhance the drought hardness of carrots grown in areas with arid or semi-arid conditions (Yan, & Gong, 2020).

**Cabbage and Cauliflower:** Ethylene inhibitors such as silver thiosulfate are applied to delay postharvest senescence and thereby delay yellowing and keep the crop visually appealing (Sharma *et al.*, 2021) and (Martínez-Romero, 2007). Cytokinins applied at early growth stages enhance head formation and marketable yield (El-Hady *et al.*, 2023). Brassinosteroids are applied to counteract heat stress so that heads can develop uniformly during hot periods (Singh *et al.*, 2023).

**Onions and Garlic:** Gibberellins induce bulb enlargement and decrease malformation during development, leading to a higher marketable yield. Cytokinins enhance leaf growth and delay senescence, increase photosynthetic activity, and improve bulb quality (Hönig *et al.*, 2018). Ethylene inhibitors are used to decrease sprouting during storage, thereby prolonging shelf life (Chope, G. A., & Terry, L. A. 2008).

**Peas and Beans:** Salicylic acid treatments improve flowering consistency and enhance disease resistance, reducing losses from bacterial and fungal infections (Raskin, I. 1992). Brassinosteroids and jasmonates improve drought and pest tolerance, respectively, ensuring stable production even under adverse conditions (Yahia *et al.*, 2019).

**Eggplant (Brinjal):** Auxins are used to increase fruit set and decrease fruit drop especially under stress conditions (Khan and Nabi 2023). Brassinosteroids enhance heat tolerance and thus allow for better yield in warm climates, and jasmonates help in the management of pests, mainly aphids and whiteflies.

**Herbs and Spices:** Jasmonates and salicylic acid induce the production of secondary metabolites in herbs such as basil, mint, and coriander, enhancing flavor, aroma, and medicinal values (Rahimi *et al.*, 2013). The regulators also help increase resistance to fungal pathogens, thereby ensuring healthy crops of higher market value.

**Zucchini and Pumpkins:** Ethylene treatments are applied to synchronize fruit ripening, thus allowing uniform harvest (Grierson, D. 2013). Brassinosteroids increase fruit size and quality, and jasmonates offer resistance to pest infestation and increase heat stress tolerance (Hussain *et al.*, 2020).

**Broccoli and Cauliflower:** Cytokinins and gibberellins aid in curd and head development to make the same more uniform in growth and have a greater yield that is marketable (Cung, T. 2015). Ethylene inhibitors delay the yellowing during storage thereby enhancing the appearance and the shelf life of these vegetables (Martínez-Romero *et al.*, 2007).

Integrating PGRs into agronomical practices will significantly increase the productivity of vegetable crops ensuring better yield, quality, and stress resilience through a wide range of conditions.

**Table-4. Use of different growth regulators for different purpose in vegetable.**

<b>Dormancy Break</b>			
<b>Crop</b>	<b>PGR and Dosage (ppm)</b>	<b>Method</b>	<b>Effect</b>
Potato	Ethylene chlorohydrin (50ml/q) + thiourea (1% -hour) + GA <sub>3</sub> (1-2 seconds)	Vapour treatment + dipping	Break dormancy
<b>Germination</b>			
Tomato	GA <sub>3</sub> or 2,4-D (0.5)	Seed soaking	Enhances germination
Tomato	NAA (25-30)	Seed treatment	Enhances germination & seedling growth
Brinjal	GA <sub>3</sub> (10-40)	Seed soaking	Improves germination
<b>Hardening and Seedling Establishment</b>			
Tomato	CCC (500-1000)	Spray	Induces hardening, reduces leaf curl infestation
Tomato	NAA (0.1-0.2)	Seedling root dip	Reduces transplanting shock & improves seedling growth
Brinjal	NAA (0.1-0.2)	Seedling root dip	Reduces transplanting shock & improves seedling growth
<b>Flowering</b>			
Tomato	GA <sub>3</sub> (varied ppm)	Spray	Induces exerted stigma, maintains antherless mutant, induces pollen sterility

<b>Induction of Male Sterility (MS)</b>			
Tomato, Brinjal, Pepper	MH (100-500)	Spray	Induces MS
Tomato, Brinjal	FW-450, TIBA, 2,4-D	Seedling root dip	Induces MS
Pepper	GA (100)	Spray	Induces MS
<b>Fruit Set</b>			
Tomato	MH (20) & NAA/PCPA (50-100)	Foliar spray	Increases fruit set, earliness
Tomato	4-CPA or 2,4-D (2-5), kinetin (5), GA <sub>3</sub> (10)	Foliar spray	Increases fruit set
Tomato	PCPA (50-100)	Spray	Induces parthenocarpy
Brinjal	IAA (100)	Foliar spray	Increases fruit set
Brinjal	2,4-D (2.5) or PCPA (50-100)	Lanolin paste	Induces parthenocarpy
Chilli	Triaccontanol (1), NAA (10-20)	Foliar spray	Reduces flower drop & increases fruit set
<b>Fruit Ripening</b>			
Tomato, Chilli	Ethephon (1000) & (500-2000)	Spray & post-harvest dip	Early and uniform ripening
<b>Yield</b>			
Chilli	Planofix (10) or GA <sub>3</sub> (50)	Spray	Increases fruit set & yield
Chilli	Triaccontanol (2)	Spray	Checks fruit drop, improves yield
Tomato	Ethephon (250) or PCPA (50)	Spray	Increases fruit set & yield
Tomato	NOA (25-50), GA <sub>3</sub> (5-20), 2,4-D (0.5), CIPA (10-20)	Spray	Improves yield
Brinjal	Mixtallol (4)	Spray	Increases fruit yield
Brinjal	IAA (50), GA <sub>3</sub> (40), ascorbic acid (250), NAA (0.2)	Seed soaking, seedling dip	Improves yield
<b>Biotic &amp; Abiotic Resistance</b>			
Tomato	2,4-D, NAA, TIBA, IAA	Spray	Reduces Fusarium wilt, TLCV, TMV
Tomato	Ethephon, CCC (500), GA <sub>3</sub> (25), CCC (0.4-0.5%)	Spray	Frost tolerance, cold hardiness
Tomato	Ethephon, MH (5000), IAA, ABA, cytokinins	Root drenching	Drought tolerance
Tomato	Cycocel (5-12 mg a.i./plant) or (0.1-0.3%)	Soil application, foliar spray	Salinity tolerance
Tomato	PCPA (50), NAA (10)	Spray	High temperature tolerance
Potato	Daminozide	Spray	Reduces common scab
Potato	CCC (0.74 kg/ha), GA <sub>3</sub>	Spray	Frost tolerance



(Source: Swamy *et al.*, 2021)

**Table-5: Different growth regulators with their concentration in different vegetable**

Growth Regulator	Concentration (mg/l)	Method of Application	Crops	Attributes Affected
Cycocel (CCC)	250-500	Foliar spray	Cucurbits, tomato, okra	Flowering, sex expression, fruit yield
Para-Chloro Phenoxy Acetic Acid (PCPA)	50	Foliar spray	Tomato	Fruit set and yield
Ethephon (CEPA)	100-500	Foliar spray	Cucurbits, okra, tomato	Flowering, fruiting, sex expression, yield
	2000	Post-harvest	Tomato, chillies	Fruit ripening
Gibberellic Acid (GA)	10	Foliar spray	Watermelon, tomato	Sex expression, fruiting, yield
Indole-3-Acetic Acid (IAA)	10-15	Foliar spray	Okra, tomato, brinjal	Seed germination, fruit set, yield
Naphthalene Acetic Acid (NAA)	0.2	Seedling roots	Tomato, brinjal, onion	Growth and yield
	10-20	Foliar sprays	Chillies, tomato	Flower drop, fruit set, yield
	25-30	Seed/foliar	Okra, tomato, brinjal, onion, cucurbits	Seed germination, growth, yield
Naphthoxy-Acetic Acid (NOA)	25-100	Seed/foliar	Tomato, okra	Germination, growth, yield
Silver Nitrate	500	Foliar spray	Cucumber	Induction of male flower in gynocious lines
Silver Thiosulphate	400	-	Musk melon	Induction of male flower in gynocious lines
2,3,5-Tri-Iodobenzoic Acid (TIBA)	25-50	Foliar sprays	Cucurbits	Flowering, sex expression, yield
Tricentanol	2	Foliar sprays	Chilli, peas	Fruit set and yield

(Source: Thakur, O. 2022).

**Table-6- Regulators (PGR) with different concentration in various vegetable crops**

Crops	PGR	Effects	Remarks
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<b>Tomato</b>	Tomatotone or Tomatolan (4-CPA), 2,4-D @ 2-5 ppm, PCPA @ 50-100 ppm	Enhance fruit set at high temperatures (34/20°C), increase earliness and parthenocarp, fruit set under high and low temperatures	Apply at flower clusters, seed treatment to improve fruit set and early yield
<b>Brinjal</b>	2,4-D @ 2 ppm	Enhances flower and fruit set	Spray at first flower appearance
<b>Chilli</b>	NAA @ 40 ppm, GA <sub>3</sub> @ 10-100 ppm	Enhances flower and fruit set	Spray at first flower appearance
<b>Okra</b>	IAA @ 20 ppm, NAA @ 20 ppm	Enhances seed germination	
<b>Bottle Gourd</b>	MH @ 50-150 ppm	Induction of female flowers	
<b>Ridge Gourd</b>	IAA @ 20-200 ppm, NAA @ 25-100 ppm	Induction of female flowers	
<b>Sponge Gourd</b>	IAA @ 20-200 ppm, NAA @ 25-100 ppm	Induction of female flowers	
<b>Watermelon</b>	TIBA @ 25-250 ppm	Induction of female flowers	Apply at 2 & 4 true leaf stage
<b>Musk Melon</b>	Ethrel @ 250 ppm	Increase female flower production	Apply at 2 & 4 true leaf stage
<b>Musk Melon (Gynoecious lines)</b>	Silver thiosulphate (STS) @ 300-400 ppm	Induces male flowers	Apply at 2 & 4 true leaf stage
<b>Musk Melon (Gynoecious lines)</b>	Amino ethoxyvinyl glycine (AVG) @ 50-100 ppm	Induces male flowers	Apply at 2 & 4 true leaf stage
<b>Musk Melon (Gynoecious lines)</b>	GA <sub>3</sub> @ 1500-2000 ppm	Induction of male flowers	Apply at 2 & 4 true leaf stage
<b>Cucumber</b>	Ethrel @ 150-200 ppm	Increase female flower production	Apply at 2 & 4 true leaf stage
<b>Cucumber (Gynoecious lines)</b>	Silver nitrate (AgNO <sub>3</sub> ) @ 200-300 ppm	Induction of male and morphologically functional bisexual flowers	Apply at 2 & 4 true leaf stage
<b>Bitter Gourd</b>	CCC @ 100-500 ppm, MH @ 150-200 ppm	Increase the female to male ratio, increase female flowers	
<b>Bitter Gourd (Gynoecious lines)</b>	Silver nitrate (AgNO <sub>3</sub> ) @ 200-300 ppm	Induces male flowers (commercially used)	
<b>Summer Squash</b>	Ethephon @ 250 ppm	Temporarily suppresses male flowers	Apply at 1 true leaf stage, repeated spray for 2-3 weeks

<b>Summer Squash</b>	Ethephon @ 600 ppm	Complete suppression of male flowers (for hybrid seed production)	Apply at 2 & 4 true leaf stage, repeated spray for 2-3 weeks
<b>Pumpkin</b>	Ethephon @ 250 ppm	High female flower production	
<b>Garden Pea</b>	CCC @ 50 ppm	Increases yield and drought tolerance	
<b>Onion</b>	GA <sub>3</sub> @ 50 ppm	Increases yield	Application before harvest
<b>Onion</b>	Maleic Hydrazide (MH) @ 1500-2000 ppm	Sprout suppressant	
<b>Potato</b>	GA <sub>3</sub> @ 10-15 ppm	Breaks tuber dormancy, enhances sprouting	Duration: 10-20 minutes
<b>Potato</b>	Thiourea @ 1%	Breaks tuber dormancy	
<b>Potato</b>	Maleic Hydrazide (MH)	Sprout inhibitor	Suitable for storage, applied after curing of tubers
<b>Potato</b>	Chloropropham (CIPC) @ 25 mg/tonne of tubers	Sprout inhibitor (for storage)	

**Source – Glaustas Horticulture**

### Challenges and Limitations

Despite the considerable advantages presented by plant growth regulators, their widespread acceptance is prevented by several challenges and limitations. One key challenge lies in the variability in plant response, as PGR effectiveness can vary highly between different plant species and varieties as well as different environmental conditions. Soil type, climate, and the physiological stage of the crop can make a tremendous difference in the outcome of PGR application (Fahad *et al.*, 2021). For example, the same concentration of a PGR can produce desirable effects in one crop and toxicity or ineffectiveness in another.

Another challenge is that the application should be precise. With PGRs, to achieve optimal results, dosage, timing, and method of delivery should be controlled. Over application will result in phytotoxicity, reduced growth, or effects on neighboring crops (Vlahoviček-Kahlina, *et al.*, 2021), whereas under application may not provide the desired results, which leads to waste in resources.

Yet high costs stand as one other massive hindrance to the diffusion of PGRs in vast numbers among developing countries. Synthetic PGRs could be highly priced, coupled with the need for special and equipment like a sprayer for a certain formulation. Such adds additional costs for poor, smaller-scale farmers (Samal *et al.*, 2024).

The use of synthetic PGRs is also limited by environmental concerns. Overuse or misapplication of these regulators can lead to chemical residues in the soil and water, disrupting the soil microbiota, harming non-target organisms, and contributing to environmental pollution.

Little work has been done on long-term effects of PGR use on soil health, biodiversity, and sustainability of agroecosystems as a whole (Wu *et al.*, 2024). Some synthetic PGRs may create resistance in pests and pathogens and decrease soil fertility upon long-term application.

Strict regulatory frameworks surrounding the production, sale, and application of PGRs may limit their availability in regions (Ahmad *et al.*, 2015). Safety concerns over chemicals applied on edible parts of crops tend to hamper consumer acceptance.

The lack of awareness and training of farmers in the effective use of PGRs is another major limitation. Without proper education, farmers may misuse these chemicals, leading to suboptimal results or even environmental harm.

### **Future Perspectives**

Despite all these, advancements in science and technology present exciting possibilities to overcome the deficiencies of PGRs and upgrade their importance in sustainable agriculture. Advances in biotechnology, for example, have made it possible to engineer plants to produce optimal amounts of endogenous PGRs within themselves (Gupta *et al.*, 2024). This means the exogenous applications of PGRs will not be necessary. Crop plants could be engineered to overexpress genes that confer tolerance to abiotic stresses or increase uptake of nutrients.

Another key to the future of PGRs is the development of eco-friendly alternatives. Research into natural, biodegradable options, such as plant, algae, or microbial-based biostimulants, can provide environmentally safe and cost-effective alternatives (Malik *et al.*, 2020). Natural PGRs can mimic or even enhance the effects of synthetic ones, thereby minimizing environmental risks.

With PGRs in precision agriculture systems, their better usage will soon be an exciting reality. With these technologies, drones, satellite imagery, and soil sensors provide instant data to optimize PGR usage, with exact dose and timing. Further, AI and ML models can predict crop response, thus recommending site-specific application for utmost efficiency.

Advances in formulation science also open opportunities for tailoring PGR products to specific crops, environmental conditions, or growth stages. For instance, controlled-release formulations or encapsulated PGRs can deliver active ingredients in a sustained manner, thus ensuring the desired effect with minimal waste.

The long-term effects of PGRs on soil health and biodiversity should be researched upon (Small, et al., 2024). How PGRs interact with the soil microbial community will thus be used as a basis for the development of formulations that enhance soil fertility rather than degrade it.

PGRs should be integrated, not used as standalone solutions, to holistic crop management strategies. When all these sustainable practices are undertaken together, including crop rotation (Ali *et al.*, 2024), organic farming, and integrated pest management, it maximizes the benefits while maintaining environmental balance.

Widespread adoption of PGRs will also require investment in farmer education and capacity building. Training programs should focus on the proper use, benefits, and safety of PGRs (Engels *et al.*, 2001). Demonstration plots and success stories can help build farmer confidence and encourage adoption of these tools.

Governments and agricultural organizations can provide incentives and policies to support PGR adoption. For instance, subsidies for eco-friendly PGRs, research funding, and streamlined regulatory procedures could make these technologies more available to farmers.

The increased impact of climate change on agriculture will increasingly make PGRs essential in crop adaptation to extreme weather events, such as heatwaves, droughts, and floods (Paroda *et al.*, 2024). Research on PGR formulations that improve resilience to these stresses will be vital in maintaining food security under global environmental challenges.

With the right challenges and future prospects, plant growth regulators can be more vital in achieving sustainable production of vegetable crops with high productivity under environmentally friendly conditions.

## **Conclusion**

Plant growth regulators (PGRs) are a revolutionary and critical means of improving the productivity of vegetable crops. They provide a wide spectrum of benefits that are urgently needed to meet the requirements of modern agriculture. Such versatile compounds can modulate key physiological and biochemical processes in plants, making them invaluable tools for optimizing growth, improving stress resilience, and enhancing nutrient use efficiency. With global agricultural systems under increasing pressure from climate change, soil degradation, and the demand for increased yields, PGRs have become essential elements in sustainable crop management strategies.

The primary advantage of PGRs is their influence on plant growth at various stages, including seed germination and fruit ripening. PGRs facilitate optimal cell division, elongation, and differentiation, which enable crops to achieve their maximum growth potential. This modulation of growth improves not only the size and quality of the harvest but also in the efficient utilization of available resources, including water and nutrients. For example, auxins and cytokinins can improve root development and nutrient mobilization, whereas gibberellins can enhance stem elongation and fruit enlargement. These effects are very important in vegetable crops, which are sensitive to environmental changes and require very accurate management to obtain good quality yields.

PGRs also have a critical role in enhancing plant tolerance to abiotic stresses such as drought, heat, and salinity. Through the activation of stress-response pathways, PGRs help plants cope with challenging growing conditions, thereby ensuring crops continue to thrive even under adverse circumstances. For instance, abscisic acid (ABA) plays a role in controlling stomatal closure under drought stress, while brassinosteroids (BRs) enhance heat and drought tolerance. As climate change is expected to intensify extreme weather conditions, the role of PGRs in stress resilience will be even more important to ensure food security and sustainability in agriculture.

PGRs also optimize nutrient utilization in crops, thereby enabling them to absorb and mobilize necessary minerals and organic compounds. This is important, especially when one considers the

decreased environmental footprint of agriculture through the improved uptake of nutrients by plants, which lessens the requirement for extra fertilizers that can ultimately degrade the soil and also cause water pollution. With regard to improved nutrient allocation within the plant, PGRs ensure enhanced crop yield and quality in the production of more nutritious and marketable produce.

But for the full exploitation of PGRs, techniques for their application need to be refined and integrated with developing technologies. Precision agriculture tools such as drones, soil sensors, and AI-driven decision support systems will become a great opportunity for using PGRs optimally—to apply them at the right time, in the right amount, and to the right crops. With such technologies, a farmer can monitor response at the plant level. Real-time monitoring will guide such farmers to alter practices as needed and avoid high-risk over application or ineffectiveness.

In addition, future research and innovation in biotechnology will continue to provide more targeted and eco-friendly PGR formulations. These include bio-based, biodegradable, and environmentally friendly alternatives to synthetic PGRs. Focusing on natural sources and minimizing the environmental impact of PGR use will ensure that future formulations can offer sustainable solutions for crop production without compromising ecological balance.

In conclusion, plant growth regulators hold immense promise in transforming vegetable crop production systems. By enhancing growth, improving stress tolerance, and optimizing nutrient use, they contribute significantly to achieving sustainable agricultural practices. As research continues to uncover new applications and refine existing methods, PGRs will play an even more crucial role in feeding a growing global population while preserving the health of our ecosystems. The integration of PGRs with advanced technologies will unlock all their potentialities, leading to a resilient future for agriculture, provided such understanding is accompanied by improvement in their practices.

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