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. They have different (PGRs) helpful under drought condition (ABA), and many of (PGRs) helpful for molecular aspect (genome editing tool CRISPR/Cas9**)** such as gibberellins. 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.

In cucumber used different dose of GA_3 at 75 ppm, 150 ppm and 250 ppm, Ethrel at 100 ppm, 200 ppm and 300 ppm, Salicylic acid at 75 ppm, 150 ppm and 250 ppm and control (water spray) in 3 replications. Reported that highest fruit yield was obtained from GA3 at 250 ppm, which is 165.17 t/ha. The quality parameters showed that the highest total soluble solids (5.88° Brix) was found in GA3 at 150 ppm, and the lowest physiological weight loss after harvest (1 DAH, 5 DAH, and 10 DAH) was found in GA3 at 250 ppm reported by Dinesh *et al.,* 2024.

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).

Bassinosteroids

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).

PGRs such as abscisic acid (ABA) help in enhancing the drought tolerance of a plant by influencing physiological and molecular processes in the plant. These include closure of stomata by stomatal closure regulator, induction of root growth by growth promoters, enhancement of production of osmolytes, such as proline and sugars, which helps the cell in maintaining turgor and osmotic balance during water deficit, activation of stress-related genes such as Heat shock proteins, and also the senescence and abscission of older leaves (Sabagh *et al.,* 2021).

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).

Jasmonates (JAs), which include jasmonic acid and its derivatives, are plant hormones involved centrally in defense mechanisms against herbivorous pests. They participate in the regulation of complex signaling pathways that activate plant defenses (Wang *et al.,* 2019). Jasmonates trigger the production of protease inhibitors, which disrupt the digestive enzymes of herbivorous insects, reducing their ability to utilize plant nutrients (Wang *et al.,* 2021). Jasmonates induce secondary metabolism and, hence, promote alkaloids, terpenoids, and phenolic, which either repel the herbivore or are toxic to them.

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**

Auxins	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)
Gibberellins	Gibberellic acid (GA3)
Cytokinins	Kinetin, Zeatin
Ethylene	Ethereal
Abscisic Acid	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**
Auxin	(a) Apical dominance (b) Cell division and enlargement (c) Shoot and root growth (d) Plant growth movement (e) Parthenocarpy (f) Abscission
Gibberellin	(a) Prevents genetic dwarfism (b) Regulates bolting and flowering (c) Promotes production of parthenocarpic fruit (d) Aids in germination
Cytokinins	(a) Stimulates cell and organ enlargement (b) Promotes seed germination (c) Supports bud development and shoot growth
Ethylene	(a) Promotes fruit ripening (b) Aids in seedling growth and emergence (c) Induces leaf abscission
Abscisic Acid	(a) Promotes abscission (b) Induces dormancy (c) Inhibits seed development and germination (d) Causes stomatal closure (e) Assists during water stress
Salicylates	Plant Pathogen Resistance
Jasmonates	Plant Defense
Brassinolides	Resistance, Tissue Culture, Increases Natural Preservation Value, Reduces Fruit Drop & Flowering

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_3	15	Foliar spray	Muskmelon	Improve rind thickness
GA_3	5-15	Foliar spray	Cauliflower, cabbage	Increases head or curd size
GA_3	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 GA3 (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 GA3, 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 GA3, 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.

<table>
<tr><th colspan="4">Dormancy Break</th></tr>
<tr><th>Crop</th><th>PGR and Dosage (ppm)</th><th>Method</th><th>Effect</th></tr>
<tr><td>Potato</td><td>Ethylene chlorohydrin (50ml/q) + thiourea (1% -hour) + GA_3 (1-2 seconds)</td><td>Vapour treatment + dipping</td><td>Break dormancy</td></tr>
<tr><th colspan="4">Germination</th></tr>
<tr><td>Tomato</td><td>GA_3 or 2,4-D (0.5)</td><td>Seed soaking</td><td>Enhances germination</td></tr>
<tr><td>Tomato</td><td>NAA (25-30)</td><td>Seed treatment</td><td>Enhances germination & seedling growth</td></tr>
<tr><td>Brinjal</td><td>GA_3 (10-40)</td><td>Seed soaking</td><td>Improves germination</td></tr>
<tr><th colspan="4">Hardening and Seedling Establishment</th></tr>
<tr><td>Tomato</td><td>CCC (500-1000)</td><td>Spray</td><td>Induces hardening, reduces leaf curl infestation</td></tr>
<tr><td>Tomato</td><td>NAA (0.1-0.2)</td><td>Seedling root dip</td><td>Reduces transplanting shock & improves seedling growth</td></tr>
<tr><td>Brinjal</td><td>NAA (0.1-0.2)</td><td>Seedling root dip</td><td>Reduces transplanting shock & improves seedling growth</td></tr>
<tr><th colspan="4">Flowering</th></tr>
<tr><td>Tomato</td><td>GA_3 (varied ppm)</td><td>Spray</td><td>Induces exerted stigma, maintains antherless mutant, induces pollen sterility</td></tr>
<tr><th colspan="4">Induction of Male Sterility (MS)</th></tr>
<tr><td>Tomato, Brinjal, Pepper</td><td>MH (100-500)</td><td>Spray</td><td>Induces MS</td></tr>
<tr><td>Tomato, Brinjal</td><td>FW-450, TIBA, 2,4-D</td><td>Seedling root dip</td><td>Induces MS</td></tr>
<tr><td>Pepper</td><td>GA (100)</td><td>Spray</td><td>Induces MS</td></tr>
<tr><th colspan="4">Fruit Set</th></tr>
<tr><td>Tomato</td><td>MH (20) & NAA/PCPA (50-100)</td><td>Foliar spray</td><td>Increases fruit set, earliness</td></tr>
<tr><td>Tomato</td><td>4-CPA or 2,4-D (2-5), kinetin (5), GA_3 (10)</td><td>Foliar spray</td><td>Increases fruit set</td></tr>
<tr><td>Tomato</td><td>PCPA (50-100)</td><td>Spray</td><td>Induces parthenocarpy</td></tr>
<tr><td>Brinjal</td><td>IAA (100)</td><td>Foliar spray</td><td>Increases fruit set</td></tr>
<tr><td>Brinjal</td><td>2,4-D (2.5) or PCPA (50-100)</td><td>Lanolin paste</td><td>Induces parthenocarpy</td></tr>
<tr><td>Chilli</td><td>Triacontanol (1), NAA (10-20)</td><td>Foliar spray</td><td>Reduces flower drop & increases fruit set</td></tr>
<tr><th colspan="4">Fruit Ripening</th></tr>
<tr><td>Tomato, Chilli</td><td>Ethephon (1000) & (500-2000)</td><td>Spray & post-harvest dip</td><td>Early and uniform ripening</td></tr>
</table>

Yield			
Chilli	Planofix (10) or GA$_3$ (50)	Spray	Increases fruit set & yield
Chilli	Triacontanol (2)	Spray	Checks fruit drop, improves yield
Tomato	Ethephon (250) or PCPA (50)	Spray	Increases fruit set & yield
Tomato	NOA (25-50), GA$_3$ (5-20), 2,4-D (0.5), CIPA (10-20)	Spray	Improves yield
Brinjal	Mixtallol (4)	Spray	Increases fruit yield
Brinjal	IAA (50), GA$_3$ (40), ascorbic acid (250), NAA (0.2)	Seed soaking, seedling dip	Improves yield
Biotic & Abiotic Resistance			
Tomato	2,4-D, NAA, TIBA, IAA	Spray	Reduces Fusarium wilt, TLCV, TMV
Tomato	Ethephon, CCC (500), GA$_3$ (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$_3$	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 gynoecious lines
Silver Thiosulphate	400	-	Musk melon	Induction of male flower in gynoecious lines
2,3-5, Tri-Iodobenzoic Acid (TIBA)	25-50	Foliar sprays	Cucurbits	Flowering, sex expression, yield
Tricontanol	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**
Tomato	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 parthenocarpy, fruit set under high and low temperatures	Apply at flower clusters, seed treatment to improve fruit set and early yield
Brinjal	2,4-D @ 2 ppm	Enhances flower and fruit set	Spray at first flower appearance
Chilli	NAA @ 40 ppm, GA_3 @ 10-100 ppm	Enhances flower and fruit set	Spray at first flower appearance
Okra	IAA @ 20 ppm, NAA @ 20 ppm	Enhances seed germination	
Bottle Gourd	MH @ 50-150 ppm	Induction of female flowers	
Ridge Gourd	IAA @ 20-200 ppm, NAA @ 25-100 ppm	Induction of female flowers	
Sponge Gourd	IAA @ 20-200 ppm, NAA @ 25-100 ppm	Induction of female flowers	
Watermelon	TIBA @ 25-250 ppm	Induction of female flowers	Apply at 2 & 4 true leaf stage

Musk Melon	Ethrel @ 250 ppm	Increase female flower production	Apply at 2 & 4 true leaf stage
Musk Melon (Gynoecious lines)	Silver thiosulphate (STS) @ 300-400 ppm	Induces male flowers	Apply at 2 & 4 true leaf stage
Musk Melon (Gynoecious lines)	Amino ethoxyvinyl glycine (AVG) @ 50-100 ppm	Induces male flowers	Apply at 2 & 4 true leaf stage
Musk Melon (Gynoecious lines)	GA_3 @ 1500-2000 ppm	Induction of male flowers	Apply at 2 & 4 true leaf stage
Cucumber	Ethrel @ 150-200 ppm	Increase female flower production	Apply at 2 & 4 true leaf stage
Cucumber (Gynoecious lines)	Silver nitrate ($AgNO_3$) @ 200-300 ppm	Induction of male and morphologically functional bisexual flowers	Apply at 2 & 4 true leaf stage
Bitter Gourd	CCC @ 100-500 ppm, MH @ 150-200 ppm	Increase the female to male ratio, increase female flowers	
Bitter Gourd (Gynoecious lines)	Silver nitrate ($AgNO_3$) @ 200-300 ppm	Induces male flowers (commercially used)	
Summer Squash	Ethephon @ 250 ppm	Temporarily suppresses male flowers	Apply at 1 true leaf stage, repeated spray for 2-3 weeks
Summer Squash	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
Pumpkin	Ethephon @ 250 ppm	High female flower production	
Garden Pea	CCC @ 50 ppm	Increases yield and drought tolerance	
Onion	GA_3 @ 50 ppm	Increases yield	Application before harvest
Onion	Maleic Hydrazide (MH) @ 1500-2000 ppm	Sprout suppressant	
Potato	GA_3 @ 10-15 ppm	Breaks tuber dormancy, enhances sprouting	Duration: 10-20 minutes
Potato	Thiourea @ 1%	Breaks tuber dormancy	
Potato	Maleic Hydrazide (MH)	Sprout inhibitor	Suitable for storage, applied after curing of tubers
Potato	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.

Genetic engineering approaches, including CRISPR/Cas9 and other genome-editing technologies, can be used to optimize PGR biosynthetic pathways (Sims, 2022), or enhance receptor activity in the plant to improve the response of the plant towards stress. Omics approaches, which include transcriptomics, proteomics, and metabolomics, can give insights on how PGRs interact with the signaling networks in plants. Synthetic biology allows for opportunities for the design of synthetic analogs or innovative delivery systems for PGRs to enhance their stability, bioavailability, and targeted action. Also, through systems biology, predictive models could be developed for optimization of PGR activity across varied environmental conditions.

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 crucial for improving vegetable crop productivity and addressing climate change, soil degradation, and increased yield demands. These versatile compounds can modulate physiological and biochemical processes, enhancing growth, stress resilience, and nutrient use efficiency. They play a significant role in enhancing plant tolerance to abiotic stresses like drought, heat, and salinity, ensuring crop survival even under adverse conditions. PGRs also optimize nutrient utilization, reducing the environmental footprint of agriculture by allowing plants to absorb and mobilize necessary minerals and organic compounds. However, to fully exploit PGRs, techniques for their application need to be refined and integrated with developing technologies. Precision agriculture tools like drones, soil sensors, and AI-driven decision support systems can help farmers apply PGRs optimally, allowing for real-time monitoring and avoiding high-risk practices. Future research in biotechnology will provide more targeted and eco-friendly PGR formulations, focusing on natural sources and minimizing environmental impact. In conclusion, PGRs hold immense promise in transforming vegetable crop production systems, contributing significantly to sustainable agricultural practices.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Option 2:

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology

Details of the AI usage are given below:

1. used chatgpt for some correction

2.

3.

References

1. Agarwal, S., Sairam, R. K., Srivastava, G. C., & Meena, R. C. (2005). Changes in antioxidant enzymes activity and oxidative stress by abscisic acid and salicylic acid in wheat genotypes. *Biologia plantarum*, *49*, 541-550.
2. Ahmad, N., Fatima, N., Ahmad, I., & Anis, M. (2015). Effect of PGRs in adventitious root culture in vitro: present scenario and future prospects. *Rendiconti Lincei*, *26*, 307-321.
3. Ali, A., Niu, G., Masabni, J., Ferrante, A., & Cocetta, G. (2024). Integrated Nutrient Management of Fruits, Vegetables, and Crops through the Use of Biostimulants, Soilless Cultivation, and Traditional and Modern Approaches—A Mini Review. *Agriculture*, *14*(8), 1330.
4. Anjum, Q. S., Amjad, M., Ziaf, K., & Habib, A. (2020). Seed treatment with salicylic acid improves growth, biochemical attributes and quality seed production of pea.
5. Ashraf, M., Akram, N. A., Arteca, R. N., & Foolad, M. R. (2010). The physiological, biochemical and molecular roles of brassinosteroids and salicylic acid in plant processes and salt tolerance. *Critical Reviews in Plant Sciences*, *29*(3), 162-190.
6. Bagale, P., Pandey, S., Regmi, P., & Bhusal, S. (2022). Role of plant growth regulator “Gibberellins” in vegetable production: An overview. *International journal of horticultural science and technology*, *9*(3), 291-299.
7. Bahadur A, Singh NK. Plant Growth Substances in Vegetable Production. In: Singh, K.P. and Bahadur, A. (eds.). Olericulture: Fundamentals of Vegetable Production. Kalyani Publishers, Noida, Utter Pradesh, India 2014;I:178-196.
8. Bhatla, S. C., A. Lal, M., & Bhatla, S. C. (2018). Recently discovered plant growth regulators. *Plant physiology, development and metabolism*, 681-728.
9. Bozbuga, R., Ates, S. Y., Guler, P. G., Yildiz, H. N., Kara, P. A., Arpaci, B. B., & Imren, M. (2022). Host-Pathogen and Pest Interactions: Virus, Nematode, Viroid, Bacteria, and Pests in Tomato Cultivation. In *Tomato-From Cultivation to Processing Technology*. IntechOpen.
10. Castañeda-Murillo, C. C., Rojas-Ortiz, J. G., Sánchez-Reinoso, A. D., Chávez-Arias, C. C., & Restrepo-Díaz, H. (2022). Foliar brassinosteroid analogue (DI-31) sprays increase drought tolerance by improving plant growth and photosynthetic efficiency in lulo plants. *Heliyon*, *8*(2).
11. Chope, G. A., & Terry, L. A. (2008). The role of abscisic acid and ethylene in onion bulb dormancy and sprout suppression. *Stewart Postharvest Review*, *4*(2).
12. Cung, T. (2015). Effects of Gibberellic Acid and Benzyl Adenine on Growth and Yield of Broccoli *(Brassica oleracea* var. *italica)* (Doctoral dissertation, MERAL Portal).
13. Debbarma, S., & Singh, A. K. Chapter-5 Plant Growth Regulators in Vegetable Production. *ADVANCES IN HORTICULTURE*, 85.
14. Dempsey, D. M. A., Shah, J., & Klessig, D. F. (1999). Salicylic acid and disease resistance in plants. *Critical reviews in plant sciences*, *18*(4), 547-575.
15. Durner, E. F. (2013). *Principles of horticultural physiology*. CABI.
16. Dinesh, A., Prasanth, P., Lakshminarayana, D., Nagaraju, K., & Gouthami, P. (2024). Efficacy of Plant Growth Regulators on Quality and Yield of Cucumber cv. Malini under Shade Net Conditions. *Asian Journal of Soil Science and Plant Nutrition*, *10*(3), 121-125.
17. Ebert, A. W. (2020). The role of vegetable genetic resources in nutrition security and vegetable breeding. *Plants*, *9*(6), 736.

18. Ebrahimi, A., Zabihzadeh Khajavi, M., Ahmadi, S., Mortazavian, A. M., Abdolshahi, A., Rafiee, S., & Farhoodi, M. (2022). Novel strategies to control ethylene in fruit and vegetables for extending their shelf life: A review. *International Journal of Environmental Science and Technology*, *19*(5), 4599-4610.
19. El-Hady, A., Ahmed, M., & Doklega, S. M. (2023). Effect of spraying some microelements and bio-stimulants on yield, quality and storage ability of red cabbage heads. *Egyptian Journal of Horticulture*, *50*(1), 109-122.
20. El-Ramady, H. R., Domokos-Szabolcsy, É., Abdalla, N. A., Taha, H. S., & Fári, M. (2015). Postharvest management of fruits and vegetables storage. *Sustainable Agriculture Reviews: Volume 15*, 65-152.
21. Engels, J. M. M., Withers, L., Raymond, R., & Fassil, H. (2001). The importance of PGR and strong national programmes. *Towards Sustainable National Plant Genetic Resources Programmes: Policy, Planning and Coordination Issues*, *1*, 2001.
22. Fahad, S., Sonmez, O., Saud, S., Wang, D., Wu, C., Adnan, M., & Turan, V. (Eds.). (2021). *Plant growth regulators for climate-smart agriculture*. CRC Press.
23. Grierson, D. (2013). Ethylene and the control of fruit ripening. *The molecular biology and biochemistry of fruit ripening*, 43-73.
24. Gupta, D., Saini, A., van der Vyver, C., & Panda, S. K. (2024). Gene Editing: Paving the Way for Enhancing Plant Tolerance to Abiotic Stresses-Mechanisms, Breakthroughs, and Future Prospects. *Journal of Plant Growth Regulation*, 1-17.
25. Hajam, M. A., Hassan, G. I., Parray, E. A., Wani, M. A., Shabir, A., Khan, I. F., ... & Masoodi, L. (2018). Transforming fruit production by plant growth regulators. *Journal of Pharmacognosy and Phytochemistry*, *7*(1), 1613-1617.
26. Halaji, B., Haghighi, M., Kovács, G. P., Mirmazloum, I., & Szegő, A. (2024). The Role of Brassinosteroids and Nano-Encapsulated Brassinosteroids in Capsicum Pepper Growth and Physiological Adaptations to High-Temperature Stress. *Horticulturae*, *10*(10), 1062.
27. Hönig, M., Plíhalová, L., Husičková, A., Nisler, J., & Doležal, K. (2018). Role of cytokinins in senescence, antioxidant defence and photosynthesis. *International journal of molecular sciences*, *19*(12), 4045.
28. Hussain, M. A., Fahad, S., Sharif, R., Jan, M. F., Mujtaba, M., Ali, Q., ... & Hou, J. (2020). Multifunctional role of brassinosteroid and its analogues in plants. *Plant Growth Regulation*, *92*, 141-156.
29. Ikiz, B., Dasgan, H. Y., & Gruda, N. S. (2024). Utilizing the power of plant growth promoting rhizobacteria on reducing mineral fertilizer, improved yield, and nutritional quality of Batavia lettuce in a floating culture. *Scientific Reports*, *14*(1), 1616.
30. Jabnoun-Khiareddine, H., El-Mohamedy, R. S. R., Abdel-Kareem, F., Abdallah, R. A. B., Gueddes-Chahed, M., & Daami-Remadi, M. (2015). Variation in chitosan and salicylic acid efficacy towards soil-borne and air-borne fungi and their suppressive effect of tomato wilt severity. *J. Plant Pathol. Microbiol*, *6*(11), 325-335.
31. Jain, S., Nidhi, N., Kale, S., Rathod, M., Dhurve, L., Mehara, H., & Baidya, B. K. (2023). A Comprehensive Review on Role of Bio-Regulators in the Growth and Development of Fruit and Vegetable Crops. *International Journal of Environment and Climate Change*, *13*(11), 2879-2892.

32. Jansen, L., Demeulenaere, M., & Beeckman, T. (2013). Lateral root development. *Plant Roots: The Hidden Half*, 6-1.
33. Kaur, P., Mal, D., Sheokand, A., Singh, L., & Datta, D. (2018). Role of plant growth regulators in vegetable production: A review. *International Journal of Current Microbiology and Applied Sciences*, *7*(6), 2177-2183.
34. Kaya, C., Ashraf, M., Wijaya, L., & Ahmad, P. (2019). The putative role of endogenous nitric oxide in brassinosteroid-induced antioxidant defence system in pepper (Capsicum annuum L.) plants under water stress. *Plant Physiology and Biochemistry*, *143*, 119-128.
35. Khan, M. N., & Nabi, G. (2023). Role of Auxin in vegetative growth, flowering, yield and fruit quality of Horticultural crops-A review. *Pure and Applied Biology*, *12*(2), 1234-1241.
36. Koukounaras, A. (2009). Senescence and quality of green leafy vegetables. *Stewart Postharvest Review*, *5*(2), 1-5.
37. Kumar, A., Prakash, S., Pandey, V., Prakash, O., Meena, N. K., Kumar, R., ... & Shukla, K. K. (2023). Biosynthesis, Mechanism and Potential Application of Hormones for Mitigating Stress, Conserving Bioactive Constituents in Fruits. *International Journal of Plant & Soil Science*, *35*(19), 1467-1480.
38. Kumari, N., Kumari Manhas, S., Jose-Santhi, J., Kalia, D., Sheikh, F. R., & Singh, R. K. (2024). Emerging into the world: regulation and control of dormancy and sprouting in geophytes. *Journal of Experimental Botany*, *75*(19), 6125-6141.
39. Kurosawa E (1926) Experimental studies on the nature of the substance excreted by the 'bakanae' fungus. Trans Nat Hist Soc Formos 16:213–227
40. Laxman, R. H., Kumar, R., Ramesh, K. V., Saini, D. R., Sreekanth, D., Verma, R. K., & Behera, T. K. (2024). Impact of Climate Change on Vegetable Production and Management Strategies. *Vegetable Science*, *51*, 11-21.
41. Lurie, S., & Paliyath, G. (2008). Enhancing postharvest shelf life and quality in horticultural commodities using 1-MCP technology. *Postharvest Biology and Technology of Fruits, Vegetables, and Flowers*, 139.
42. Majda, M., & Robert, S. (2018). The role of auxin in cell wall expansion. *International journal of molecular sciences*, *19*(4), 951.
43. Malik, A., Mor, V. S., Tokas, J., Punia, H., Malik, S., Malik, K., ... & Karwasra, A. (2020). Biostimulant-treated seedlings under sustainable agriculture: A global perspective facing climate change. *Agronomy*, *11*(1), 14.
44. Mariotti, L., Picciarelli, P., Lombardi, L., & Ceccarelli, N. (2011). Fruit-set and early fruit growth in tomato are associated with increases in indoleacetic acid, cytokinin, and bioactive gibberellin contents. *Journal of Plant Growth Regulation*, *30*, 405-415.
45. Martínez-Romero, D., Bailén, G., Serrano, M., Guillén, F., Valverde, J. M., Zapata, P., ... & Valero, D. (2007). Tools to maintain postharvest fruit and vegetable quality through the inhibition of ethylene action: a review. *Critical reviews in food science and nutrition*, *47*(6), 543-560.
46. Meena, O. P. (2015). A review: role of plant growth regulators in vegetable production.
47. Muhie, S. H., Akele, F., & Yeshiwas, T. (2024). Phenological and yield response of primed carrot (*Daucus carota* L) seeds under deficit irrigation. *Advances in Horticultural Science*, *38*(2), 119-127.

48. Nolan, T. M., Vukašinović, N., Liu, D., Russinova, E., & Yin, Y. (2020). Brassinosteroids: multidimensional regulators of plant growth, development, and stress responses. *The Plant Cell*, *32*(2), 295-318.
49. Ofuya, T. I., Okunlola, A. I., & Mbata, G. N. (2023). A review of insect pest management in vegetable crop production in Nigeria. *Insects*, *14*(2), 111.
50. Olaiya, C. O., Gbadegesin, M. A., & Nwauzoma, A. B. (2013). Bioregulators as tools for plant growth, development, defence and improvement. *African Journal of Biotechnology*, *12*(32), 4987-4999.
51. Pan, R., Liu, Y., Buitrago, S., Jiang, W., Gao, H., Han, H., ... & Yang, X. (2020). Adventitious root formation is dynamically regulated by various hormones in leaf-vegetable sweetpotato cuttings. *Journal of Plant Physiology*, *253*, 153267.
52. Panigrahi, T. K., & Joshi, B. (2016). Plant growth regulators in vegetable crops: A review. *Indian Horticulture Journal*, *6*(2), 155-159.
53. Paroda, R., Agrawal, A., & Tripathi, K. (2024). Plant Genetic Resources for Adaptation to Climate Change in Drylands. In *Climate Change and Sustainable Agro-ecology in Global Drylands* (pp. 77-101). GB: CABI.
54. Pathak, S., Johar, V., Angaria, A., & Vishal, A. (2023). Alteration in Flowering and Fruiting of Commercial Vegetable Crops under Protected Condition: A Review. *International Journal of Environment and Climate Change*, *13*(12), 139-151.
55. Pramanik, K., & Mohapatra, P. P. (2017). Role of auxin on growth, yield and quality of tomato- A review. *Int. J. Curr. Microbiol. Appl. Sci*, *6*(11), 1624-1636.
56. Prasad, R. N., Singh, S. K., Yadava, R. B., and Chaurasia, S. N. S. (2013). Effect of GA_3 and NAA on growth and yield of tomato. *Vegetable Science*, 40(2), 195-197.
57. Pretorius, J. C., & Engelbrecht, G. (2009). *Growth, yield and physiological response of carrot (Daucus carota L.) to different fertilizer levels and bio-stimulants* (Doctoral dissertation, University of the Free State).
58. Rademacher, W. (2015). Plant growth regulators: backgrounds and uses in plant production. *Journal of plant growth regulation*, *34*, 845-872.
59. Rahimi, A. R., Rokhzadi, A., Amini, S., & Karami, E. (2013). Effect of salicylic acid and methyl jasmonate on growth and secondary metabolites in *Cuminum cyminum* L. *Journal of Biodiversity and Environmental sciences*, *3*(12), 140-149.
60. Raskin, I. (1992). Role of salicylic acid in plants. *Annual review of plant biology*, *43*(1), 439-463.
61. Rohwer, C. L., & Erwin, J. E. (2008). Horticultural applications of jasmonates. *The Journal of Horticultural Science and Biotechnology*, *83*(3), 283-304.
62. Sabagh, A. E., Mbarki, S., Hossain, A., Iqbal, M. A., Islam M. S., Raza, A., ... & Farooq, M. (2021). Potential role of plant growth regulators in administering crucial processes against abiotic stresses. *Frontiers in Agronomy*, *3*, 648694.
63. Sahni, S., Prasad, B. D., Liu, Q., Grbic, V., Sharpe, A., Singh, S. P., & Krishna, P. (2016). Overexpression of the brassinosteroid biosynthetic gene DWF4 in Brassica napus simultaneously increases seed yield and stress tolerance. *Scientific Reports*, *6*(1), 28298.
64. Saimbhi, M. S. (1993). Growth regulators on vegetable crops. *Advances in horticulture*, *6*(1), 619-642.

65. Salaria AS, Salaria BS. Horticulture at a Glance, (Vegetables, Spices and Condiments). Jain Brothers, New Delhi, India 2008, II
66. Samal, I., Bhoi, T. K., Mahanta, D. K., Komal, J., & Pradhan, A. K. (2024). Sustainable Plant Protection Measures in Regenerative Farming. In *Regenerative Agriculture for Sustainable Food Systems* (pp. 387-421). Singapore: Springer Nature Singapore.
67. Sharma, R. R., Raghavendra, H. R., & Sethi, S. (2021). Postharvest Treatments for Horticultural Produce. In *Postharvest Handling and Diseases of Horticultural Produce* (pp. 43-56). CRC Press.
68. Sheikh, F. R., Jose-Santhi, J., Kalia, D., Singh, K., & Singh, R. K. (2022). Sugars as the regulators of dormancy and sprouting in geophytes. *Industrial Crops and Products*, *189*, 115817.
69. Selvakumar, R and Mathur, P. (2018). Glaustas Horticulture, New Vishal publication, Paperback
70. Singh, A. K., Shikha, K., & Shahi, J. P. (2021). Hybrids and abiotic stress tolerance in horticultural crops. In *Stress tolerance in horticultural crops* (pp. 33-50). Woodhead Publishing.
71. Small, C. C., & Degenhardt, D. (2018). Plant growth regulators for enhancing revegetation success in reclamation: A review. *Ecological engineering*, *118*, 43-51.
72. Song, W., Shao, H., Zheng, A., Zhao, L., & Xu, Y. (2023). Advances in roles of salicylic acid in plant tolerance responses to biotic and abiotic stresses. *Plants*, *12*(19), 3475.
73. Steward, F. C. (2012). *Plant, chemicals and growth*. Elsevier.
74. Sun, W., Shahrajabian, M. H., Kuang, Y., & Wang, N. (2024). Amino acids biostimulants and protein hydrolysates in agricultural sciences. *Plants*, *13*(2), 210.
75. Swamy, G. N., Meghana, D., Kowsalya, K. B., Sudeshna, K., & Nair, K. A. K. (2021). History: Mechanism and functions of plant growth regulators in vegetable crops. *J. Pharm. Innov*, *10*, 556-567.
76. Sims, K. (2022). Genetic transformation and regeneration in the Galena hop variety, towards CRISPR/Cas9 modification of shoot elongation.
77. Sabagh, A. E., Hossain, A., Islam, M. S., Iqbal, M. A., Amanet, K., Mubeen, M., ... & Erman, M. (2021). Prospective role of plant growth regulators for tolerance to abiotic stresses. *Plant growth regulators: signalling under stress conditions*, 1-38.
78. Thakur, O. (2022). Recent advances of plant growth regulators in vegetable production: A review. *The Pharma Innovation Journal*, *11*(3), 1726-1731.
79. Vandenbrink, J. P., Kiss, J. Z., Herranz, R., & Medina, F. J. (2014). Light and gravity signals synergize in modulating plant development. *Frontiers in plant science*, *5*, 563.
80. Velavan, M. Response and defense mechanism of vegetables. Advances in horticulture and allied sciences ISBN: 9-789395-423724 First Edition; 2023 Chapter – 23, Page: 259 – 293
81. Vlahoviček-Kahlina, K., Jurić, S., Marijan, M., Mutaliyeva, B., Khalus, S. V., Prosyanik, A. V., & Vinceković, M. (2021). Synthesis, characterization, and encapsulation of novel plant growth regulators (PGRs) in biopolymer matrices. *International journal of molecular sciences*, *22*(4), 1847.
82. Waśkiewicz, A., Gładysz, O., Beszterda, M., & Goliński, P. (2016). Water stress and vegetable crops. *Water Stress and Crop Plants: A Sustainable Approach*, *2*, 393-411.

83. Watkins, C. B. (2002). Ethylene synthesis, mode of action, consequences and control. *Fruit quality and its biological basis*, 180-224.
84. Wu, X., Gong, D., Zhao, K., Chen, D., Dong, Y., Gao, Y., ... & Hao, G. F. (2024). Research and development trends in plant growth regulators. *Advanced Agrochem*, *3*(1), 99-106.
85. Wang, Y., Mostafa, S., Zeng, W., & Jin, B. (2021). Function and mechanism of jasmonic acid in plant responses to abiotic and biotic stresses. *International Journal of Molecular Sciences*, *22*(16), 8568.
86. Wang, J., Wu, D., Wang, Y., & Xie, D. (2019). Jasmonate action in plant defense against insects. *Journal of Experimental Botany*, *70*(13), 3391-3400.
87. YADAV, K., TIWARI, J., & KASWAN, H. (2024). An Overview: Role of plant growth regulator in vegetable production. *Annals of Plant and Soil Research*, *26*(2), 434-441.
88. Yahia, E. M., Gardea-Béjar, A., de Jesús Ornelas-Paz, J., Maya-Meraz, I. O., Rodríguez-Roque, M. J., Rios-Velasco, C., ... & Salas-Marina, M. A. (2019). Preharvest factors affecting postharvest quality. In *Postharvest technology of perishable horticultural commodities* (pp. 99-128). Woodhead Publishing.
89. Yan, Y., Shi, Q., & Gong, B. (2020). Review of melatonin in horticultural crops. In *Melatonin-the hormone of darkness and its therapeutic potential and perspectives*. IntechOpen.
90. Zahid, G., Iftikhar, S., Shimira, F., Ahmad, H. M., & Kaçar, Y. A. (2023). An overview and recent progress of plant growth regulators (PGRs) in the mitigation of abiotic stresses in fruits: A review. *Scientia Horticulturae*, *309*, 111621.
91. Zhang, H., Duan, W., Xie, B., Wang, B., Hou, F., Li, A., ... & Zhang, L. (2020). Root yield, antioxidant capacities, and hormone contents in different drought-tolerant sweet potato cultivars treated with ABA under early drought stress. *Acta Physiologiae Plantarum*, *42*, 1-15.
92. Zhang, Y. T., Zhang, Y. L., Chen, S. X., Yin, G. H., Yang, Z. Z., Lee, S., ... & Yang, F. S. (2015). Proteomics of methyl jasmonate induced defense response in maize leaves against Asian corn borer. *BMC genomics*, *16*, 1-16.
93. Zhou, H., Cheng, L., & Wang, Z. (2023). Current understanding of unlocking the power of melatonin and other phytohormones to boost abiotic stress tolerance in solanaceous vegetable crops. *Scientia Horticulturae*, *321*, 112313.