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ROLE OF PLANT GROWTH REGULATORS IN BOOSTING CROP PRODUCTIVITY AND BUILDING STRESS RESILIENCE IN HORTICULTURAL CROPS: A REVIEW

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ABSTRACT

As the global population continues to grow, there is an increasing demand to boost the production and quality of agricultural and horticultural produce. In this context, plant growth regulators have become essential tools, offering a variety of applications that enhance the morphological, reproductive and physiological growth and development of horticultural crops. Plant growth regulators such as auxins stimulate root initiation, cytokinin promote cell division, gibberellin improve seed germination and stem elongation, abscisic acid provide tolerance to environmental stress and ethylene induce flowering, stimulate fruit set and improve fruit ripening along with modern plant growth regulators like brassinosteroids, salicylic acid, jasmonates, etc. which also plays an active role in promoting growth and development and act as signaling hormone against various stresses.
***Keywords*:** Plant growth regulators, phytohormones, ethylene, brassinosteroids, biosynthesis, biostimulants and jasmonates.

Introduction

The swift rise in the global population, along with shrinking natural resources, climate change, and worsening environmental issues, highlights the pressing need for innovative approaches to boost horticultural output. Conventional farming practices are proving insufficient to satisfy the increasing demand for food, making it essential to develop advanced methods that improve crops' structural, biological, physiological, and biochemical functions. One key method gaining prominence in modern horticulture is the use of plant growth regulators (PGRs).

Plant growth regulators are naturally occurring or synthetic compounds that, even at low concentrations, profoundly influence various aspects of plant growth and development (Pandey *et al.*, 2023). Unlike nutrients that supply vital elements necessary for plant survival, plant growth regulators (PGRs) act as chemical signals that influence key physiological activities such as cell division, elongation, and differentiation. They are essential throughout a plant's development, affecting stages like seed germination, root formation, vegetative growth, flowering, fruit production, and maturation. Through their regulatory actions, PGRs help control plant growth, encouraging favorable traits such as faster development, enhanced tolerance to environmental stress, and higher crop yields. Natural plant hormones are organic substances produced by the plants themselves, whereas plant growth retardants are synthetic compounds that do not naturally occur in plants. These retardants inhibit cell division and slow down the elongation of shoot tissues, although they do not entirely stop plant growth. Example: CCC, Alar, etc.

Plant growth regulators play a crucial role in boosting crops' resilience to environmental stress. Factors like drought, high salinity, and extreme temperatures can negatively impact plant development and productivity. Compounds such as abscisic acid (ABA) and salicylic acid (SA) help regulate how plants respond to these challenges by triggering defense responses and enhancing their ability to adapt to unfavorable conditions. For instance, ABA plays a vital role in plant responses to drought stress by inducing stomatal closure, thereby reducing water loss and enhancing drought tolerance (Mundiyara *et al*., 2020).

In precision agriculture, plant growth regulators (PGRs) serve as an eco-friendly alternative to conventional agrochemicals. They help decrease dependence on synthetic fertilizers and pesticides, promoting more sustainable farming methods. PGRs also boost water-use efficiency, enabling crops to perform better with limited water—particularly valuable in drought-prone areas. Additionally, they support better post-harvest outcomes by controlling fruit ripening, which can prolong shelf life and minimize losses after harvest.

Effectively understanding and utilizing PGRs is crucial for breeding crop varieties that are both resilient and high-yielding. As the agricultural sector strives to meet growing food demands while reducing environmental harm, incorporating PGRs into farming strategies offers a viable route to more sustainable and productive agricultural practices.

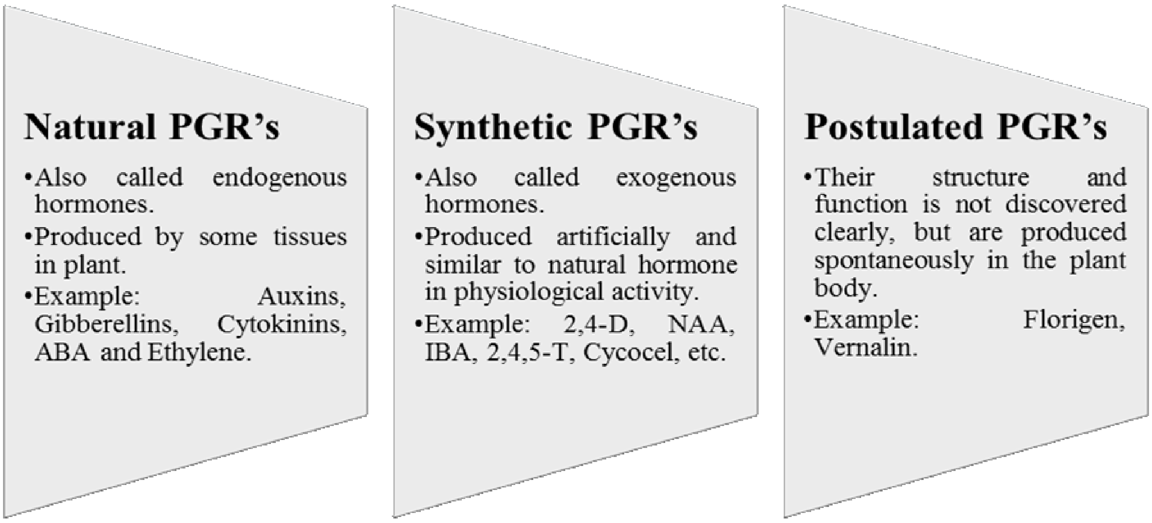

Fig. 1: Classification of plant growth regulators on the basis of origin

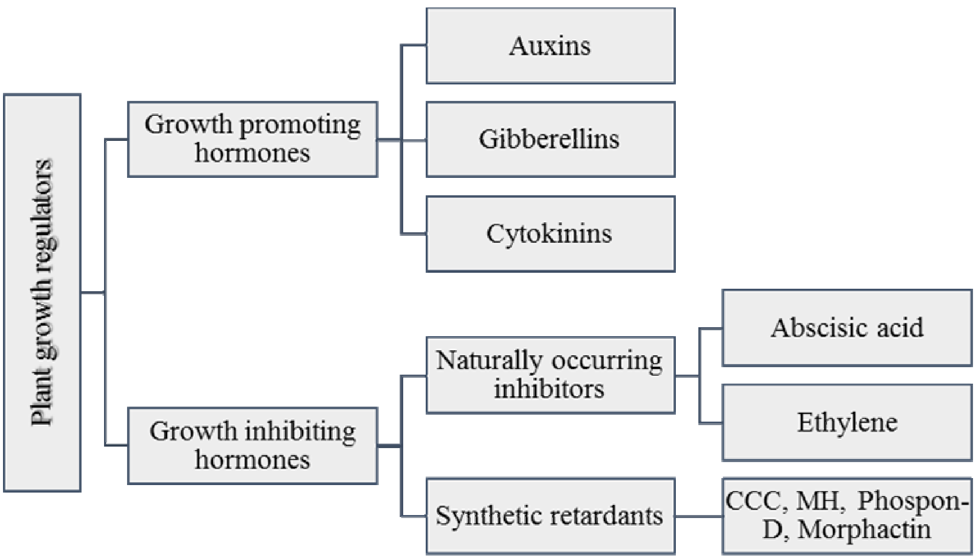

Fig. 2 : Classification of plant growth regulators on the basis of nature of function

Brief description and major functions of plant growth regulators

Auxins: Auxins were discovered by F. W. Went (1926), who isolated auxin from the Avena coleoptile tips by a method called Avena coleoptile or curvature test. These are first discovered plant hormone and derived from greek word auxein which means "to grow/increase." Auxins are a group of phytohormones produced in the shoot and root apices and they migrate from the apex to the zone of elongation. These are synthesized in apical meristem of stem and roots of plant, leaf primordia, young leaves and in developing seeds. These are transported in plants through basipetal in shoots and acropetal in roots having polar movement (Jain *et al*., 2023).

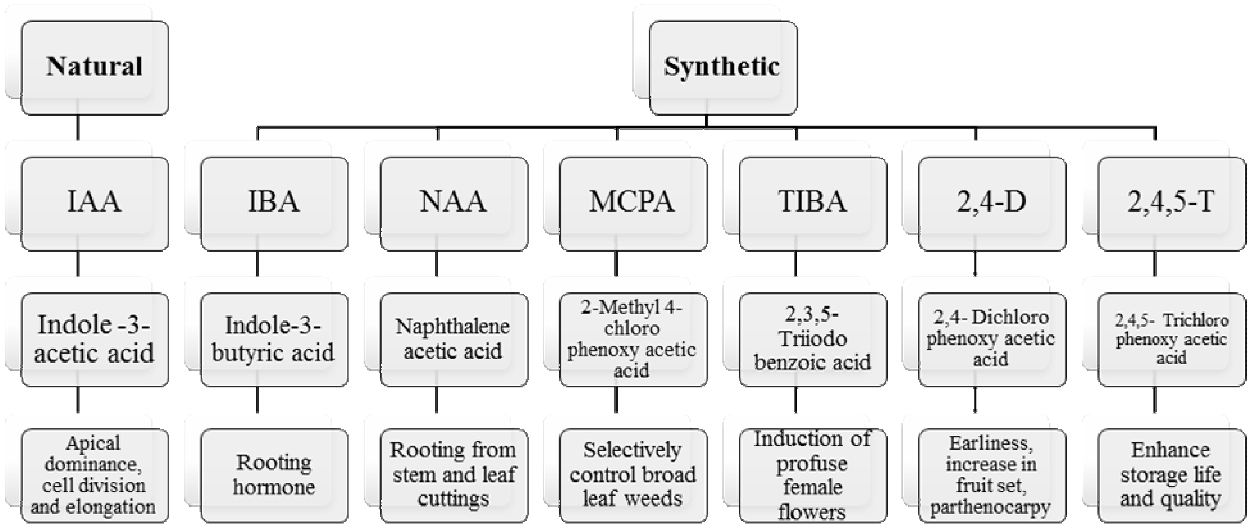

Fig. 3 : Major functions of plant growth regulators

Major functions of auxin include more growth of apical portion than lateral portion by suppressing the growth of lateral buds and domination of apical bud known as apical dominance. They stimulate cell elongation, prevent abscission, root initiation, callus formation, increase number and size of fruits, induce femaleness in plants and formation of seedless fruits without pollination and fertilization known as parthenocarpy. Bending of stem tips towards light (phototropism) is due to more auxin concentration on shaded side which leads to rapid elongation of cells on that side (Pal, 2019).

Gibberellin: A Japanese scientist Kurosawa first extracted gibberellin from the fungus *Gibberella fujikuroi* (*Fusarium moniliforme*), the causal organism of bakanae disease of rice or known as "foolish seedling of rice." GA_3 is the most common gibberellic acid. They are synthesized in young leaves (major site), shoot tip, root tip and immature seeds from mevalonic pathway or terpenoid pathway and geranyl geranyl di phosphate (GGPP) is precursor of GAs. Unlike auxins, the transport of gibberellins in plants is non-polar, in all directions and in all tissues including phloem and xylem (Meena *et al*., 2015).

Major functions of gibberellin include elongation of internodes, induction of flowering in long day plants, tolerance to chilling, induction of maleness in plants, delay in fruit maturity and senescence and enhancement of flower and fruit set. Major commercial use of gibberellin is in promotion of seed germination by stimulating the production of amylase, in the presence of water which breaks down starch to maltose, allowing for the formation of ATP (via glucose). The energy produced in the embryo is used to facilitate germination and break seed dormancy.

Cytokinins: Cytokinins were discovered by F. Skoog, C. Miller and co-workers during the 1950's as factors responsible for cellular division from a DNA preparation and found that when vascular tissues were placed in contact with them, cell division was resumed in pith tissue. Translocation of cytokinins is from roots to shoots through xylem and their mobility is polar and basipetal. Precursors of cytokinin is either Adenine or Adenosine. Cytokinins are found in abundance in young roots, leaves and young fruits and are synthesized in the meristematic regions of the plants mainly roots (Kaur *et al*., 2018). Naturally occurring cytokinins include zeatin, isopentenyl adenine (IPA), etc., while synthetic cytokinins are kinetin, N-N diphenyl urea, 6-Benzylaminoprine (BAP), etc.

Major functions of cytokinins include cell division and enlargement, stimulates lateral bud formation, induction of flowering in short day plants and delay leaf senescence and stimulates chlorophyll synthesis. The senescence of leaves usually accompanies with loss of chlorophyll and rapid breakdown of proteins. Senescence can be postponed to several days by kinetin treatment by improving RNA synthesis followed by protein synthesis (Richmand and Lang, 1957).

Abscisic Acid: It is a naturally occurring growth inhibitor in plants. Precursor of ABA are mevalonic acid or xanthophylls (violaxanthin). They are synthesized in leaves of wide variety of plants and is found in all parts of the seed namely the seed coat, embryonic axis, cotyledons and endosperm. Transport of ABA is through xylem in roots and phloem in leaves. It is responsible for closing stomata during drought conditions, hence acts as plant stress hormone. It is also known as dormins, which acts as anti-gibberellins.

Major functions of abscisic acid include inducing the dormancy of buds and seeds, promotes the abscission of leaves and flowers, accelerate the process of ageing and stimulates the closure of stomata.

Ethylene: Ethylene is a colorless gaseous hormone. In higher plants, most of the plant parts produce ethylene. Meristematic region and nodal regions are main site for ethylene biosynthesis. It is found in ripening fruits, flowers and leaves and nodes of stem. Precursor of ethylene is methionine. Synthesis of ethylene is inhibited by carbon dioxide and requires oxygen. Available forms are gaseous (ethephon) and liquid (ethrel).

Major functions of ethylene include induction of flowering and fruiting, fruit ripening, stimulates flower and leaf abscission and promotes female sex expression.

Brassinosteroids: Brassinolide was the first isolated brassinosteroid in 1979 from extracts of *Brassica napus* pollen. They are class of polyhydroxysteroids and are recognized as 6^{th} class of plant hormones. They are produced in almost all plant tissues, but especially in seeds, pollens, and young vegetative tissues. It stimulates stem elongation, cell division, tolerance to stresses and can reverse an ABA-induced seed dormancy while stimulating germination (Sourabh *et al.*, 2024). It stimulates stem elongation, cell division and vascular differentiation. They can reverse an ABA-induced seed dormancy while stimulating germination and provide tolerance to plants from drought and chilling stress.

Jasmonic acid (Jasmonates): Jasmonates trigger the production of stress-related proteins and are involved in processes such as seed germination and root development. They contribute to leaf aging, fruit ripening, the formation of tubers and bulbs, and the onset of dormancy. Additionally, jasmonates are key compounds in activating plant defense mechanisms against insect pests and pathogen infections.

Florigen: It is a systemic signal for the transition to flowering in plants. It is generated in leaves and transported to the shoot apical meristem to promote floral transition.

Polyamines: They are strongly basic protein-based substances of low molecular weight that exist either free or bound in all plant cells. They influence flowering and promote plant regeneration.

Salicylic acid: It is a phenolic plant hormone with roles in photosynthesis, transpiration, ion uptake and transport. Most widely known role of SA is signaling plant defense against pathogens.

α-Tocopherol (Vitamin E): It is an antioxidant, found in green parts of plants, thus protect the plant from oxygen toxicity.

Fusicoccin: Fusicoccin, like gibberellin, is a terpenoid, which affects a number of physiological and biochemical processes of any higher plant, such as breaking of seed-dormancy (antagonistic to abscisic acid) and cell growth, evokes root formation in cuttings (like auxin).

Plant Peptide Hormones (Systemin): Systemin (an 18 amino acid peptide) useful for jasmonic acid signaling. They travel in the phloem from leaves under insect attack to increase the content of jasmonic acid and proteinase inhibitors in distant leaves.

Nitric oxide: NO is one of the smallest diatomic molecules, has been implicated as a signaling hormone and defense responses (e.g. stomatal closure, root development, germination, cell death, stress response).

Chlormequat chloride (CCC or Cycocel): Induces retardation of shoot elongation and vegetative growth in most crops (Suman *et al.*, 2017).

Paclobutrazol: Cell elongation and internode extension inhibitor that retards plant growth by inhibition of gibberellins biosynthesis.

Aminoethoxy vinyl glycine (AVG): Inhibition of ethylene biosynthesis. They increase fruit-set, controls fruit-drop and maintains late-season fruit quality.

Application of plant growth regulators in horticultural crops:

In horticulture and agriculture, plant growth regulators are indispensable tools for enhancing crop yield, quality and stress tolerance. They are used for:

1. **Promotion of Growth and Development**

- Auxins such as IAA, IBA and NAA are used to stimulate root initiation in cuttings, promote apical dominance and prevent premature fruit drop.
- Gibberellic acid (GA) promotes stem elongation, seed germination, flowering and fruit size in horticultural crops (Swamy *et al.*, 2021).

- Cytokinins promote cell division and are used to delay senescence and for enhancing shoot growth in horticultural plants. The most important biological effect of kinetin on plants is to induce cell division especially in carrot root tissue, soybean cotyledon, pea callus etc. (Sosnowski *et al.*, 2023).
- Ethylene is involved in fruit ripening and senescence.
- PGRs are used to regulate lateral branching and canopy architecture, improving light penetration and air circulation within the plant canopy for better growth and development.
- Growth regulators are used to control plant height, compactness and flowering time in potted plants and bedding plants.
- Yadav *et al.* (2015) found that applying kinetin at a concentration of 200 ppm resulted in the greatest stem diameter, highest fresh flower weight, earlier seed ripening, and superior seed yield in marigold compared to other treatments. According to Chaudhary *et al.* (2016), treatment with GA_3 at 30 ppm led to the longest main creeper length at 60 and 90 days after sowing (201.78 cm and 309.23 cm), the highest number of sub-creepers (7.53 and 8.23), the most leaves per plant (244.10 and 412.68), and the maximum chlorophyll content at 45 and 60 days (31.38 and 36.85). This treatment also resulted in the highest number of male flowers (165.75). Application of TIBA at 20 ppm was most effective in inducing the first female flower at a lower node position (node 8.25), increasing the number of female flowers (19.35), decreasing the sex ratio (1:7.13), and improving both the number of fruits per plant (3.00) and fruit yield per plant (12.39 kg) and per hectare (619.50 q/ha), along with increasing fruit length (24.32 cm). The highest average fruit weight (4.27 kg) and fruit diameter (22.71 cm) were recorded with TIBA applied at 15 ppm in the watermelon variety Durgapura Lal.

2. Root Development and Nutrient Uptake

- IAA promotes cell division and elongation in the root meristem, leading to root growth. In horticulture, synthetic auxins like IBA and NAA are commonly used for rooting cuttings.
- Cytokinins promote lateral root formation and prevent premature senescence of roots. Benzyladenine (BA) is a well-known cytokinin used in tissue culture for root induction.
- Gibberellins primarily regulate stem elongation, but they also impact root growth by enhancing root elongation and branching. However, excessive GA levels may inhibit root growth.
- Ethylene promotes adventitious root formation in cuttings.
- PGRs interact with mycorrhizal fungi to improve nutrient acquisition, especially phosphorus and micronutrients.
- Kumar *et al.* (2023) reported that seed priming with 15 ppm GA_3 in the radish variety Pusa Chetki resulted in the highest values for several growth parameters, including days to 50% germination (5.33 days), plant height (35.95 cm), root length (24.40 cm), root diameter (3.73 cm), fresh root weight (133.51 g), dry root weight (18.41 g), root yield (24.38 t/ha), total soluble solids (5.53 °Brix), and antioxidant content (21.14 mg/100g).
- Similarly, Ullah *et al.* (2023) found a clear correlation between IBA concentration and rooting success in Carnation cuttings. While low IBA levels had little effect, moderate concentrations significantly enhanced root initiation and elongation. In contrast, very high concentrations inhibited rooting, indicating a possible hormetic effect. Optimal IBA levels promoted the development of robust root systems with greater length, number, and biomass.

3. Seed Germination and Dormancy

- It has been suggested that pre-sowing seed with growth regulators improves seed emergence.
- In tomato, pre-sowing seed treatment with 100 ppm IAA, IBA and NAA enhanced the seed germination. Seed germination in tomato is also enhanced by treatment with GA_3 @ 0.5 ppm or 2,4-D @ 0.5 ppm.
- Muskmelon, bottle gourd, squash melon and watermelon seeds benefited by soaking in ethephon at 480 mg/l for 24 hours when grown at low temperatures.
- Pre-sowing treatment of seed with GA_3 and KNO_3 @ 50 ppm enhanced the germination of endive and chicory, respectively. IAA and NAA @ 20 ppm enhances seed germination in okra.
- Madhavan *et al.*, 2023 observed that the dipping of Papaya (*Carica papaya*) var. Red lady seeds in GA_3 @ 200 ppm for 12 hrs recorded the maximum germination percentage of papaya seeds (88.28 %) followed by GA_3 300 ppm (83.56 %).

- **Seed dormancy** is main problem in vegetable crops like potato and lettuce. Before the end of the rest period, potato tubers are unable to sprout, substances such as GA, ethylene chlorohydrin and thiourea are said to disrupt the rest period.
- Chemicals which have been reported to break the rest period are GA_3, ethylene, jasmonates, brassinosteroids and thiourea. Another vegetable where seed dormancy brought on by high temperatures has been found to be broken by GA_3 treatment is lettuce.

Crops	PGR and dosage	Method	Effect
Potato	Ethylene chlorohydrin (50ml/q) + 1% thiourea (1 hour) + 1mg/l GA_3 (2 sec.)	Vapour treatment + dipping	Break dormancy
Tomato	GA_3 or 2,4-D @ 0.5 ppm	Seed soaking	Enhances germination
Tomato	NAA @ 25-30 ppm	Seed treatment	Enhances germination and seedling growth
Brinjal	GA_3 @ 10-40 ppm	Seed soaking	Improves germination

Use of various PGR and their dosage for breaking seed dormancy

4. Regulation of Flowering

- PGRs are extensively used to manipulate flowering time and ensure synchronized blooming for ornamental plants and crops. For instance, cytokinins can delay flowering, while gibberellins can induce flowering in specific conditions.
- Plants sprayed with 300 ppm GA_3 were earliest to flower and recorded highest number of fruits and yield per plant in tomato. NAA @ 50 ppm has been reported to induce early flowering in paprika.
- Application of GA_3 @ 50 ppm to young leaves of non-flowering varieties of potato, when floral buds had just formed, resulted in flower induction in all varieties.
- Okra blossoming was postponed by MH. Gibberellic acid has been reported to induce early flowering in lettuce.
- Foliar application of ethrel @ 200 ppm has increased number of flowers/panicles in off season mango cv. Alphonso.
- **Sex expression:** It has been discovered that the use of growth regulators alters the sex expression in cucurbits, okra and pepper.
- GA_3 (10-25 ppm), IAA (100 ppm) and NAA (100 ppm) when sprayed at 2-4 leaf stage in cucurbits, then they have been found to increase the number of female flowers, whereas, GA_3 (1500-2000 ppm), silver nitrate (300-400 ppm) and silver thiosulphate (300-400 ppm) sprayed at 2-4 leaf stage induces male flower production in cucurbits.
- Treating both *Cucurbita maxima* and *Cucurbita pepo* with ethephon at the two true leaf stage led to a reduction in the number of male flowers and an increase in female flowers, thereby improving the female-to-male flower ratio per plant.
- According to Singh *et al*. (2023), applying 250 ppm of GA_3 25 days after transplanting significantly enhanced several growth and floral traits in African marigold (*Tagetes erecta* L.) cv. Pusa Narangi Gainda, including plant height, canopy spread, number of flowers per branch and per plant, as well as the fresh and dry weight of individual flowers and total flowers per plant, resulting in a higher flower yield per hectare. Similarly, Maurya *et al*. (2023) reported that using 150 ppm of gibberellic acid in African marigold produced the highest values for plant height (44.11 cm), number of branches (43.53), stem thickness (1.61 cm), number of leaves (118.93), plant spread (37.17 cm²), bud length (0.93 cm), days to first flowering (66.07 days), flower size (8.77 cm), number of flowers per plant (34.10), and flower shelf life (8.67 days).

5. Fruit Set and Development

- Auxins and cytokinins play crucial roles in fruit set and development. They can enhance fruit size, induce fruit ripening, improve fruit quality and increase yield by influencing cell division and expansion processes.
- Poor fruit set is a significant issue for solanum crops. Applying 4-CPA, 2,4-D @ 2-5 ppm or PCPA @ 50-100 ppm to tomatoes can improve fruit set and ripeness.
- Fruit set in bottle gourd can be increased by spraying the plant twice at 2 and 4 true leaf stage with MH @ 400 ppm and TIBA @ 50 ppm.

6. Pokharel *et al*., 2023 observed that the foliar application of NAA 20 mg/l + ZnSO4 0.5% at fruit development stage of mango *cv*. Mallika resulted

in maximum fruit retention (9.81 %) and minimum fruit drop (90.18%). The maximum average fruit weight (282.18 g), average stone weight (34 g), average peel weight (39.67 g), average pulp weight (208.51 g) and TSS (11.4° Brix) were observed on NAA @ 20 mg/l + $ZnSO4$ @ 0.5% while maximum fruit yield per tree (9.36 kg per tree) was obtained in GA_3 @ 25 mg/l + Borax @ 0.2%. Sharma *et al.* (2024) reported that treating pea plants with 200 ppm GA_3 followed by a foliar spray of Cycocel at the same concentration notably enhanced yield components and total yield, indicating a promising strategy for boosting pea productivity. Similarly, Thakar *et al.* (2024) found that applying Ethrel at 150 ppm to the watermelon variety 'Sugar Baby' resulted in the highest values for number of fruits per vine (2.27), average fruit weight (2702.33 g), fruit yield per vine (4.02 kg), yield per plot (48.05 kg), and yield per hectare (266.96 q).

7. Improving Crop Yield and Quality

- **Fruit Thinning**: PGRs like auxins and cytokinins are used to thin fruits on trees, ensuring larger, higher-quality fruits by reducing competition among developing fruits and allowing more resources to the remaining fruits.

Crops	Plant growth regulator	Stage of treatment
Sweet pepper	0.05% NAA	Prior to anthesis
Watermelon	CPPU @ 0.5 ml/l	At the time of anthesis
Pumpkin	GA_3 @ 150 ppm	At the time of anthesis
Muskmelon	CPPU @ 10 mg/l and BA	At the time of anthesis
Bottle gourd	CPPU @ 10-100 mg/l	After or 2 days before anthesis
Pointed gourd	2,4-D @ 25 ppm, NAA @ 50 ppm and TIBA @ 200 ppm	At the time of anthesis

- **Parthenocarpy:** Plant growth regulators help to stimulate the fruit development without fertilization (Parthenocarpy). Cucumber and watermelon treated with auxin produced seedless fruits, tomato and brinjal treated with PCPA @ 50-100 ppm caused parthenocarpy.

Different plant growth regulators used for parthenocarpic fruit development

- Plant growth regulators are used to enhance fruit size, shape, and color development in fruits such as apples, grapes, and citrus. They improve fruit set, reduce fruit drop and increase market value by improving appearance and taste.
- They are applied to vegetables to increase yield, uniformity, and post-harvest shelf life. They regulate flowering and fruiting patterns, ensuring continuous production and quality throughout the growing season. Tomato fruit output has been observed to increase after seed soaking in NAA @ 25–50 mg/l, GA_3 @ 5–20 mg/l, CIPA @ 10–20 mg/l or 2,4-D @ 0.5 mg/l. In brinjal, it has been found that soaking seedling roots in NAA at 0.2 mg/l and ascorbic acid at 250 mg/l increases fruit output.
- Foliar application of GA_3 @ 25 ppm increased number of fruit, fruit weight, ascorbic acid, TSS and yield in Nagpur mandarin. Application of NAA @ 20 to 60 ppm in guava increased fruit weight, TSS and ascorbic acid content.
- Vyas and Mishra (2023) reported that soil drenching with GA_3 at 200 ppm in Papaya cv. Red Lady resulted in the best overall plant performance. This treatment led to the tallest plants (142.13 cm), highest number of functional leaves per plant (17.14), thickest stem diameter (54.37 mm), earliest flowering (95.42 days), most flowers (56.09) and fruits per plant (23.12), largest fruit weight (1263.38 g), and the highest fruit yield per plant (29.22 kg) and per hectare (129.85 t/ha). It also improved fruit quality traits, such as maximum total soluble solids (16.61 ºBrix), acidity (0.125%), non-reducing sugar (2.16 ºBrix), reducing sugar (7.83 ºBrix), and total sugar content (9.99 ºBrix). A slightly lower concentration of GA_3 at 150 ppm also performed well but to a lesser extent.
- Similarly, Patel *et al.* (2024) found that GA_3 at 50 ppm resulted in significantly better growth and yield attributes in cabbage. This included the tallest plants (18.85 cm), highest number of leaves (13.31), largest leaf area at harvest (1027 cm^2), and the heaviest average head weight (532.93 g). These plants also showed the highest yield per plot (25.51 kg) and per hectare (270.90 q/ha). Additionally, foliar spraying of NAA at 100 ppm produced results statistically similar to GA_3 at 50 ppm. They further observed that GA_3 at 50 ppm led to quicker head initiation and maturity.
- Kaur *et al.* (2024) also reported that applying GA_3 at 50 ppm yielded the best growth and production outcomes in capsicum.

Hybrid seed production

- Plant growth regulators can be utilised to produce F_1 hybrid seeds since they have gametocidal effects that render male sterility.
- PGRs have also been used for maintenance of gynoecious lines in cucurbits.
- Growth regulator like GA_3 (1500-2000 ppm) and chemical like silver nitrate (200-300 ppm) induces the male flowers on gynoecious cucumber.
- Exogenous application of silver thiosulphate (300-400 ppm) induces the male flower in gynoecious muskmelon.

Crops	PGR and dosage	Method
Tomato, Brinjal, Pepper	**MH @ 100-500 ppm**	Spray
Tomato, Brinjal, Okra	**TIBA, 2,4-D**	Seedling root dip
Pepper	**GA_3 @ 100 ppm**	Spray
Cucumber	**Silver nitrate @ 200-300 ppm**	Spray

Induction of pollen sterility (Gametocidal effect)

8. Enhancing Post-Harvest Life

- Compounds that inhibit ethylene action are applied post-harvest to extend the shelf life of fruits and vegetables, reducing spoilage and maintaining quality during storage and transport.
- Application of MH @ 2500 ppm 15 days before harvest suppresses onion sprouting in storage, thus prolonging post-harvest life.
- Khalil *et al.*, 2023 observed that minimum physiological loss in weight as well as berry shatter, highest total soluble solids (TSS), TSS/acid ratio and juice content after 5 and 10 days of ambient storage were recorded with application of GA_3 40ppm + BA 10ppm, thus enhanced the storability and postharvest quality of grape cv. Sahebi.

9. Abiotic Stress Management

Abscisic acid (ABA) plays a key role in how plants respond to environmental challenges like drought and high salinity. Applying ABA can boost a plant's ability to withstand these stresses, thereby improving its survival and productivity. During drought, ABA triggers stomatal closure, functioning as a stress hormone for plants.

Both abscisic acid (ABA) and cytokinins are used to increase plant resistance to drought and heat stress. They help control stomatal closure, optimize water use, and activate antioxidant defenses, reducing the negative effects of harsh environmental conditions on crop yield and quality.

- Roopa *et al.*, 2020 observed that the foliar sprays of SA (0.5 mM) and GA_3 (50 ppm) improved the morphological and yield attributes compared to water spray. Under stress condition, the exogenous application of gibberellic acid @ 50 ppm and salicylic acid @ 0.5 mM was effective in mitigating the deleterious effect of drought stress in muskmelon.

10. Tissue Culture and Micropropagation

- Callus formation begins when root explants are treated with an auxin-rich hormone medium (CIM). Following this, culturing the callus on various media directs the cells to develop into specific new organs. A high cytokinin-to-auxin ratio promotes shoot formation, while a high auxin-to-cytokinin ratio encourages root development.
- Plant growth regulators help eliminate viral infections during tissue culture by stimulating the growth of virus-free shoots from infected plant material.

Future Perspectives

- Synergistic effects between plant growth regulators and biostimulants (e.g., seaweed extracts, humic substances) can be explored to enhance plant growth, nutrient uptake efficiency and stress tolerance.
- Nanotechnology can be used for enhancing stability and targeted delivery of plant growth regulators, improving their efficiency and reducing environmental impact through controlled release formulations.
- Natural sources of plant growth regulators, such as seaweed extracts rich in auxins and cytokinins can be utilized by organic growers to meet organic certification standards while promoting sustainable crop production practices.
- Advances in biotechnology allow for the genetic modification of plants to produce or respond to specific plant growth regulators, enhancing traits such as yield potential, stress tolerance and disease resistance.

Conclusion

Plant growth regulators plays an important role in morphological, reproductive and physiological growth and development of plants by enhancing seed germination, rooting, flowering, fruiting, yield and quality of horticultural crops. They also help in earliness, flower synchronization, sex expression and provide tolerance to environmental stresses. But more research is needed to enhance efficacy and target delivery of plant growth regulators and improve utilization of modern plant growth regulators.

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