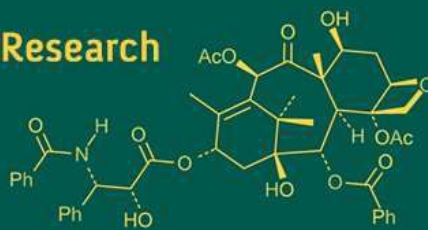
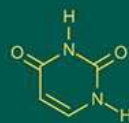


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## Review on role of plant growth regulators in vegetable crops

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### Abstract

Plant Growth Regulators (PGRs) are organic compounds, natural or synthetic, that profoundly influence plant physiological processes even at low concentrations. Their commercial use has become indispensable in vegetable production to enhance growth, yield, quality, and shelf life. PGRs effectively address key physiological limitations such as poor fruit set, delayed flowering, dormancy, and uneven ripening. This review discusses the commercial applications of PGRs in major vegetable crops, covering their role in fruit set, dormancy, flowering, sex expression, parthenocarpy, ripening, and hybrid seed production. Crop-wise details of effective PGRs, concentrations, and economic significance are presented, emphasizing their practical value in modern horticultural management.

**Keywords:** Plant growth regulators, gibberellic acid (GA<sub>3</sub>), Naphthalene Acetic Acid (NAA), INDOLE Acetic Acid (IAA), growth, yield, quality

### 1. Introduction

Vegetables have been an integral component of the human diet since ancient times and continue to serve as a vital source of nutrition worldwide. The diverse range of plant species and varying cultural practices across regions influence their economic potential and productivity. In recent years, the application of plant growth regulators (PGRs) has gained prominence as a promising approach to enhance germination, crop uniformity, ease of harvesting, and post-harvest storage quality in vegetable crops. By modulating physiological and biochemical processes, PGRs play a crucial role in improving vegetable growth, development, and yield.

Plant growth regulators are natural or synthetic compounds that influence one or more specific physiological and biochemical processes in plants, often through the regulation of gene expression and enzyme activities (Olaiya *et al.*, 2013) [10]. Unlike nutrients that provide essential elements for metabolism, PGRs act at very low concentrations to promote, inhibit, or modify plant growth and development. Although photosynthesis supplies carbon and respiration provides energy, plant growth and development are primarily governed by endogenous chemical messengers collectively known as phytohormones (Prajapati *et al.*, 2015) [18]. The term hormone, derived from the Greek word hormao meaning "to stimulate," was adapted by Thimann (1948) [6] to describe naturally occurring organic substances in plants termed phytohormones that are synthesized in one part of the plant and translocated to another, where they exert profound effects on growth and physiological functions. To distinguish them from animal hormones, these compounds are referred to as phytohormones. Plant growth regulators encompass both naturally occurring phytohormones and their synthetic analogs, often formulated as liquids, powders, or pastes. While all phytohormones are plant growth regulators, not all PGRs are phytohormones. Typically, active at extremely low concentrations (10<sup>-9</sup> to 10<sup>-5</sup> M), these compounds influence cell division, elongation, and differentiation, thereby orchestrating the overall plant developmental processes.

Growth and yield analysis in vegetable crops provide critical insights into the contribution of various physiological and morphological parameters. The use of PGRs, considered a new generation of agrochemicals, has emerged as an efficient, economical, and environmentally sustainable strategy to enhance productivity by manipulating the plant's intrinsic growth

regulation system. While traditional breeding techniques have significantly contributed to yield improvement, they are often time-consuming and resource-intensive. In contrast, the judicious application of PGRs offers a rapid and effective means of optimizing growth, enhancing nutrient utilization, and improving yield quality. Moreover, nutrients, as essential inorganic elements, complement the action of PGRs by facilitating enzymatic activities, oxidation-reduction reactions, and metabolic processes, thereby contributing to the overall biomass and productivity of vegetable crops.

## 2. Classification of plant growth regulators

Plant growth regulators (PGRs) are categorized into five major classes: auxins, gibberellins, cytokinins, abscisic acid, and ethylene (Singh, 2011) [16]. Among these, auxins, gibberellins, and cytokinins primarily act as growth-promoting hormones, while abscisic acid and ethylene generally function as growth-inhibiting hormones. Each category performs specific physiological and biochemical functions that collectively regulate the growth, development, and productivity of plants.

### 2.1 Auxins

The concept of auxins was first proposed by Charles Darwin (1880) [3], marking the discovery of the first class of plant growth regulators. The term auxin was later introduced by Kogl and Haagen-Smit (1931) [7] to describe plant hormones primarily responsible for cell elongation and shoot growth. Frits Went (1926, 1928) successfully isolated auxin from *Avena coleoptile* tips using the curvature test, concluding that growth cannot occur in the absence of auxin.

Auxins are distributed throughout the plant body but are most concentrated in actively growing regions, such as shoot and root tips and young leaves. These hormones promote cell enlargement, bud initiation, and root formation, and also interact synergistically with other hormones to regulate overall plant development. The major naturally occurring auxin is indole-3-acetic acid (IAA), whereas synthetic analogs include naphthaleneacetic acid (NAA), indole-3-butyric acid (IBA), and 2,4-dichlorophenoxyacetic acid (2,4-D).

- **Precursor:** Tryptophan
- **Site of Production:** Shoot and root apices, young expanding leaves, and developing seeds

### 2.2 Gibberellins

The discovery of gibberellins dates back to 1926, when Japanese scientist Eiichi Kurosawa observed a peculiar disease in rice plants, characterized by abnormal elongation, slender stems, and sterility later termed “Bakanae”, meaning

“foolish seedling”. The causal agent was identified as the fungus *Gibberella fujikuroi* (*Fusarium moniliforme*) (Sawada, 1912) [15]. The active growth-promoting compound was isolated and crystallized by (Yabuta and Hayashi 1935) [21], who named it gibberellin.

Gibberellins are widely recognized for their role in promoting stem elongation, seed germination, flowering, and fruit development.

- **Precursor:** Terpenoids
- **Site of Production:** Embryos, roots, and young leaves

### 2.3 Cytokinins

The term cytokinin was first introduced by Letham (1963) [9] to describe compounds that promote cell division (cytokinesis) and delay senescence. Early studies by Skoog and Miller (1955) [17] demonstrated that *Nicotiana tabacum* pith tissues required cytokinins for sustained cell division. The first naturally occurring cytokinin, zeatin, was isolated from developing maize kernels.

Cytokinins exist in two main categories:

1. Adenine-type cytokinins (e.g., kinetin, zeatin)-naturally occurring in plants.
  2. Phenylurea-type cytokinins (e.g., thidiazuron)-synthetic compounds not produced by plants.
- **Precursors:** Purine base
  - **Site of Production:** Root apices, developing fruits, seeds, and endosperm

### 2.4 Absciscic Acid (ABA)

Absciscic acid (ABA), initially termed abscisin or dormin, is a naturally occurring inhibitory plant hormone associated with growth suppression, dormancy, and stress tolerance. It regulates leaf abscission, seed dormancy, and stomatal closure, earning the title of “plant stress hormone.” ABA is widely distributed in higher plants and found in both young and mature tissues.

- **Precursor:** Mevalonic acid
- **Site of Production:** Mesophyll cells and other green tissues

### 2.5 Ethylene

Ethylene is a gaseous phytohormone ( $C_2H_4$ ) that plays a central role in fruit ripening, senescence, and abscission. It is produced in virtually all plant organs and acts as a signalling molecule during stress and developmental transitions. Ethylene synthesis is inhibited by carbon dioxide and requires oxygen for its formation.

- **Precursor:** Methionine
- **Site of Production:** Ripening fruits, senescing leaves, and stem nodes

## 2.6 Physiological Roles of Plant Growth Regulators

| PGR Type       | Major Functions                                                                                                                                           |
|----------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|
| Auxins         | Apical dominance, root initiation, inhibition of abscission, parthenocarpy, phototropism, geotropism, xylem differentiation, and regulation of flowering. |
| Gibberellins   | Stem elongation, seed germination, bolting, overcoming dwarfism, fruit development, induction of maleness in flowers, and delayed senescence.             |
| Cytokinin      | Cell division, nutrient mobilization, bud initiation, delay of senescence, chlorophyll retention, and prolonged post-harvest life.                        |
| Absciscic Acid | Induction of dormancy, stomatal closure, inhibition of seed germination, and mediation of stress responses.                                               |
| Ethylene       | Fruit ripening, leaf and flower senescence, abscission, and response to mechanical stress.                                                                |

### 3. Commercial utility of plant growth regulators in vegetable crops

#### 3.1 Functional Role of PGRs in Vegetable Crops

##### 3.1.1 Stimulation of Fruit Set

Poor fruit set, especially in solanaceous crops such as tomato and brinjal, is a major yield-limiting factor. Auxin-based PGRs like 4-CPA, 2,4-D (2-5 ppm), or PCPA (50-100 ppm) effectively promote fruit set and early fruit development by mimicking natural auxin activity enhancing pollen viability, ovary retention and subsequent fruit formation. In tomato, auxin sprays not only improve fruit set but also reduce blossom drop and enhance uniformity under stress conditions.

##### 3.2 Inhibition of Sprouting and Regulation of Dormancy

Sprouting during storage results in heavy post-harvest losses in bulb and tuber crops. Maleic hydrazide (MH) at 2500 ppm applied about 15 days before harvest effectively suppresses sprouting in onion bulbs during storage. In potatoes, soaking tubers in IAA (250-1000 ppm) prolongs dormancy whilst thiourea (1%) treatment effectively breaks dormancy and promotes uniform sprouting. Dormancy-breaking agents such as ethylene chlorhydrin, thiourea and GA<sub>3</sub> are also reported for potato and lettuce, facilitating off-season production and seed propagation.

##### 3.3 Flowering and Seed Germination

Gibberellins (especially GA<sub>3</sub>) are widely used to induce flowering in non-flowering varieties. For example, foliar GA<sub>3</sub> (50 mg/L) triggers flower buds even in non-flowering potato varieties. MH delays flowering in okra when vegetative growth is preferable. GA<sub>3</sub> also advances flowering in lettuce and spinach. Pre-sowing treatments with auxins (IAA, NAA @ 20 ppm) or GA<sub>3</sub> (@ 0.5 mg/L) enhance germination and seedling vigor in crops like okra and tomato. Soaking seeds in ethephon (480 mg/L for 24 h) improves germination under low temperature in cucurbits.

##### 3.4 Sex Expression

Manipulating sex expression through PGRs is crucial in cucurbits, okra and pepper. Low concentrations of GA<sub>3</sub> (10-25 ppm), IAA (100 ppm) and NAA (100 ppm) promote femaleness by enhancing ethylene production and modifying hormonal balance. Conversely, high GA<sub>3</sub> (1500-2000 ppm) or silver-based compounds (silver nitrate or silver thiosulphate at 300-400 ppm) suppress female flowers and induce maleness. Such hormonal manipulations are valuable for hybrid seed production by synchronizing male and female flowering.

##### 3.5 Parthenocarpy

Parthenocarpy the development of seedless fruits without fertilization is commercially desirable in tomato, cucumber and brinjal. Foliar application or lanolin paste containing 2,4-D or PCPA induces parthenocarpy, ensuring fruit set under unfavourable pollination conditions. This enhances fruit texture, shape and market acceptability.

##### 3.6 Gametocides and Hybrid Seed Production

PGRs are exploited as gametocides to induce male sterility in hybrid seed production. MH (100-500 mg/L), GA<sub>3</sub> and 2,3-dichloro-isobutyrate induce selective pollen abortion in crops like okra, pepper and onion. Ethephon sprays have been effective in producing female lines in cucurbits (e.g.,

butternut squash, cucumber). GA<sub>3</sub> or silver nitrate (500 mg/L) induce male flowers in gynoeceious cucumber lines, facilitating commercial hybrid seed production.

##### 3.7 Fruit Ripening

Ethephon a compound that releases ethylene is widely used for uniform and accelerated fruit ripening in tomato, chilli and pepper. Application of ethephon at 1000 mg/L during the turning stage increases early marketable yield by 30-35%. Post-harvest dipping in ethephon (500-2000 mg/L) induces uniform ripening in mature green tomatoes, improving colour development and marketability.

#### 4. Crop-wise Role of PGRs

##### 4.1 Solanaceous Crops

In tomato (*Solanum lycopersicum* L.), PGRs are widely used to enhance both vegetative growth and yield. For example, a field trial showed that foliar application of GA<sub>3</sub> at 50 ppm and NAA at 50 ppm significantly improved plant height, number of leaves and branches, shortened days to 50% flowering, and increased yield to 3.66 kg per plant (Jakhar *et al.*, 2018) <sup>[5]</sup>. Another study showed GA<sub>3</sub> at 50 ppm produced more flowers (61.00), largest fruit length (6.10 cm), and highest yield per hectare (1355.56 t/ha) (Prasad *et al.*, 2013) <sup>[11]</sup>. In brinjal (*Solanum melongena* L.), foliar application of GA<sub>3</sub> at 200 ppm along with salicylic acid at 75 ppm significantly enhanced vegetative growth, fruit yield, and showed a high benefit-cost ratio of 2.3 (Kumari *et al.*, 2022) <sup>[8]</sup>. Combined GA<sub>3</sub> and cycocel treatments improved number of fruits and seed yield. In chilli and capsicum (*Capsicum annum* L.), application of NAA at 50 ppm gave higher plant height (56.56 cm), fruit length (6.80 cm), fruit weight (2.54 g) and yield per plant (148.26 g). The combined use of IBA and GA<sub>3</sub> at 25 ppm each increased the number of fruits per plant, fruit weight, and overall tomato yield. Similarly, applying NAA at 20 ppm with GA<sub>3</sub> at 90 ppm improved total soluble solids, sugars, and fruit yield. These treatments show that plant growth regulators can enhance tomato yield and quality. (Poudel *et al.*, 2021) <sup>[12]</sup> This combination enhanced fruit quality and productivity under experimental conditions at Suresh Gyan Vihar University, Jaipur. These findings suggest that applying NAA and GA<sub>3</sub> together can effectively boost tomato growth and yield (Choudhary N *et al.*, 2024) <sup>[2]</sup>

##### 4.2 Malvaceous Crop-Okra (*Abelmoschus esculentus* L.)

In okra, NAA at 75 ppm yielded the highest fruit yield per hectare (13.21 t/ha), fruit weight (14.9 g) and marketable fruits per plant (25.7) (Kumai *et al.*, 2022). GA<sub>3</sub> at 75 ppm increased fruit length to 11.67 cm, and BAP and NAA treatments advanced fruiting and improved yield attributes. These PGR treatments contributed to earliest harvest (46.60 days after sowing) compared to control.

##### 4.3 Cucurbitaceous Crops

In cucumber, low doses of GA<sub>3</sub> (10-25 ppm), IAA (100 ppm) and NAA (100 ppm) when sprayed at 2-4 leaf stage increased female flower production, facilitating enhanced yield; conversely, GA<sub>3</sub> at 1500-2000 ppm and silver nitrate/thiosulphate at 300-400 ppm induced maleness in gynoeceious lines. In muskmelon and watermelon, soaking seeds in ethephon (480 mg/L for 24 h) improved germination under low temperature; GA<sub>3</sub> (50 ppm) increased fruit length and size.

#### 4.4 Cole Crops

In cabbage, foliar application of GA<sub>3</sub> at 120 ppm and NAA at 100 ppm significantly increased head diameter, fresh head weight and yield per hectare (407 q/ha) (Dev *et al.*, 2020) <sup>[14]</sup>. In broccoli, NAA at 120 ppm yielded the highest head diameter (22.77 cm), fresh head weight (~480 g) and total yield (237.25 q/ha) (Mandingbam *et al.*, 2020) <sup>[20]</sup>, while GA<sub>3</sub> at 60 ppm was next best. In cauliflower, GA<sub>3</sub> at 150 ppm accelerated curd initiation (44 days) and curd harvesting (67 days) while enhancing vegetative growth parameters (Chameli & Verma, 2021) <sup>[1]</sup>.

#### 4.5 Bulb Crops

In onion (*Allium cepa* L.), combined foliar application of NAA (150 mg/L) at the 3-leaf stage and GA<sub>3</sub> (150 mg/L) at the 7-leaf stage resulted in highest plant height (76.67 cm), number of leaves (11.33), bulb diameter (7.55 cm) and fresh weight (72.66 g) (Devi *et al.*, 2018) <sup>[4]</sup>. MH at 2500 ppm applied 15 days before harvest prevented sprouting during storage. In garlic (*Allium sativum* L.), thiourea at 100 ppm and GA<sub>3</sub> at 200 ppm produced maximum bulb weight (24 g), yield per plot (1.68 kg/2.1 m<sup>2</sup>) and projected yield (5.89 t/ha) with a benefit-cost ratio of 1:3.19 (Thapa *et al.*, 2021) <sup>[19]</sup>.

#### 4.6 Tuber Crops-Potato (*Solanum tuberosum* L.)

In potato, soaking tubers in IAA (250-1000 ppm) prolonged dormancy, while thiourea (1 %) or combined treatment with ethylene chlorhydrin and GA<sub>3</sub> (1 mg/L) broke dormancy, uniformised sprouting and facilitated off-season production. GA<sub>3</sub> at 50 mg/L promoted flowering in previously non-flowering varieties, assisting hybrid seed production. MH pre-harvest sprays also reduced post-harvest sprouting losses.

#### 4.7 Leafy Vegetables

In lettuce and spinach, GA<sub>3</sub> at 0.5 mg/L significantly improved seed germination, seedling vigor and early flowering under short-day conditions. Auxin pre-treatments enhanced leaf expansion, improved growth rates and quality, enabling more uniform harvesting and better marketability.

#### 4.8 Economic and Commercial Implications

The commercial application of PGRs in vegetable crops ensures higher productivity, improved quality, and uniform produce thereby enhancing market value, profitability and farm economics. By optimizing physiological processes such as flowering, fruit set, and ripening, PGRs contribute significantly to horticultural productivity. Integrating PGR use with nutrient and irrigation management further enhances crop performance, sustainability and resource-use efficiency.

#### 5. Conclusion

Plant Growth Regulators have revolutionised vegetable crop management by enabling growers to achieve higher yields, better quality and consistent produce. Crop- and stage-specific applications of GA<sub>3</sub>, NAA, IAA, 2,4-D, ethephon, and MH enhance physiological performance, control dormancy, and improve fruit quality. Future research should focus on bio-based and eco-friendly PGRs and integrate them into precision horticultural systems for sustainable production. Standardising crop-wise dose-recommendations

and timings will help farmers reap maximum benefits with minimal environmental impact.

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