



REVIEW ARTICLE

Enhancing cucurbit crop performance through plant growth regulator applications: A comprehensive review

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Abstract

Plant growth regulators (PGRs) serve as essential instruments for enhancing agricultural productivity in cucurbit vegetables, which account for roughly 5 % of vegetable cultivation in India. This review comprehensively examines how primary PGR categories including auxins, gibberellins, cytokinins, ethylene, abscisic acid, brassinosteroids and triacontanol influence the physiological processes and crop performance of economically significant cucurbit species. Evidence indicates that targeted PGR deployment effectively controls floral sex differentiation, with ethylene increasing female flower formation and gibberellins promoting male flower development, thus providing viable approaches for improving crop yields. Research demonstrates that auxins enhance root system development and facilitate seedless fruit formation, whereas cytokinins delay plant aging and optimise nutrient distribution within plants. Additionally, brassinosteroids and triacontanol exhibit potential for strengthening plant resilience under adverse conditions and boosting photosynthetic capacity. Detailed analysis of studies involving cucumber, watermelon, bottle gourd, muskmelon and bitter gourd indicates that PGR responses vary considerably based on application dosage, developmental stage during treatment and cultivar characteristics. This review synthesises optimal PGR utilisation protocols for major cucurbit crops while identifying research priorities for future studies. The findings offer scientifically validated guidance for producers and scientists aiming to enhance yield potential, produce quality and input efficiency in cucurbit vegetable cultivation.

Keywords: cucurbits; concentration; growth; plant growth regulators; yield

Introduction

The family Cucurbitaceae is widely distributed across the Indian subcontinent and other tropical and subtropical regions of the world. It is considered an economically and nutritionally important plant family due to the cultivation of several edible vegetable crops such as cucumber, pumpkin, bottle gourd, bitter gourd, ridge gourd and snake gourd, which contribute significantly to human

nutrition, traditional medicine and vegetable production systems. Prominent genera within this family include *Lagenaria*, *Momordica*, *Luffa*, *Cucurbita*, *Cucumis* and *Citrullus*, each contributing substantially to both agricultural and nutritional domains. This family holds considerable ethnopharmacological significance, as cucurbitaceous species have been extensively documented in traditional medicinal systems for their broad-spectrum biological activities, including anti-inflammatory and

antineoplastic properties, as well as their cardioprotective and immunomodulatory effects (1). In temperate climatic regions, certain cucurbitaceous species, including *Cucumis sativus* L. and *Sechium edule* (Jacq.) Sw., are cultivated under both greenhouse and open-field conditions. The fruits of this family serve diverse culinary purposes, consumed fresh as dessert fruits (*Citrullus lanatus* (Thunb.) Matsum. & Nakai, *Cucumis melo* L.), incorporated into salads, thermally processed (*Lagenaria siceraria* (Molina) Standl., *Momordica charantia* L., *Luffa* spp., *Cucurbita* spp), or preserved as pickles, conserves and confectionery products. Species possessing a sclerified pericarp, such as *L. siceraria*, are additionally utilised in the fabrication of domestic utensils, musical instruments and ornamental artifacts. Cucurbitaceae collectively contribute approximately 5 % of India's total vegetable production, encompassing both indigenous and exotic taxa. As the most taxonomically diverse vegetable family, cucurbits offer considerable potential for enhancing national vegetable productivity and addressing food security demands. Most species are annual, direct-seeded and monoecious, with the exception of *Trichosanthes dioica* Roxb. and *Coccinia grandis* (L.) Voigt, which exhibit dioecious reproductive biology. Propagation is predominantly through seeds. Since cucurbit species characteristically produce unisexual staminate and pistillate flowers on distinct plants, entomophilous pollinators play a critical role in pollination and fruit set.

Plant growth regulators (PGRs) are low-molecular-weight organic compounds that elicit significant physiological responses at remarkably low concentrations, typically below 10^{-7} M. Rather than directly participating in metabolic pathways, they function as modulators of plant metabolism and developmental processes. Translocation of these compounds occurs through vascular tissues, predominantly the phloem (sieve tubes), which facilitate assimilate transport from source to sink organs and the xylem, which conducts water and mineral solutes from the rhizosphere to aerial tissues. At the cellular level, PGRs function by activating or inhibiting specific enzymes or enzymatic systems, thereby regulating overall plant metabolism. Cucurbitaceous crops exhibit notable responsiveness to exogenously applied PGRs, which play a significant role in improving vegetative growth, flowering, fruit set, yield and fruit quality. For instance, gibberellic acid (GA_3) promotes vine elongation, early flowering and increased fruit yield; naphthalene acetic acid (NAA) enhances fruit set and reduces flower drop; while Ethephon stimulates femaleness and increases the number of pistillate flowers in cucurbit crops. Similarly, Cycocel (CCC) improves branching and flowering behaviour, leading to better yield performance and fruit quality. When applied in minute quantities, these chemical substances induce rapid phenotypic modifications and exert regulatory influence throughout the entire ontogenic continuum from seed germination to senescence, either by augmenting or stimulating the endogenous growth regulatory mechanisms. The PGRs modulate crop growth by altering the rate and pattern of plant responses to both endogenous and exogenous developmental stimuli. Furthermore, their regulatory influence extends beyond the growing season, significantly impacting postharvest physiological characteristics and commodity quality (2). Foliar application of plant growth regulators and nutrient chemicals such as micronutrients and flowering stimulants during the flowering stage can enhance physiological efficiency, improve flower retention and fruit set and

ultimately increase crop yield in cucurbitaceous crops (3). Plant growth regulating compounds are classified into five principal groups, namely auxins, gibberellins (GA), cytokinins, ethylene and abscisic acid (ABA). Each group encompasses both naturally occurring endogenous hormones and synthetically derived analogues; for example, indole-3-acetic acid (IAA) is a natural auxin, whereas NAA and 2,4-dichlorophenoxyacetic acid (2,4-D) are synthetic auxin analogues widely used in crop improvement practices. Applied concentrations of these bioactive compounds are quantified in parts per million (ppm) and, in certain instances, parts per billion (ppb). The most prevalent methods of exogenous application include foliar spraying and soil drenching at the plant base. The physiological effects induced by these compounds are generally transient in nature, necessitating periodic reapplication to sustain the desired agronomic response. Collectively, PGRs exert a profound and indispensable influence on the vegetative growth, reproductive development and overall productivity of cucurbitaceous crops.

Plant growth regulators

Based on their physiological roles in plants, the PGRs can be broadly categorised into two classes. One subset of PGRs is primarily responsible for mediating growth-promoting processes, encompassing cell division, cell elongation, pattern formation, tropic responses, floral induction, fruit development and seed development. These include auxin, gibberellin and cytokinin. They are also referred to as plant growth promoters. The second group of PGRs is primarily involved in plant responses to biotic and abiotic stresses and wound signalling. These regulators also play important roles in growth-inhibiting processes such as abscission, senescence and dormancy. This group includes PGR abscisic acid. Ethylene, the gaseous PGR, may be appropriate for either category, but it mostly inhibits growth activities. The diverse roles of plant growth regulators during different stages of cucurbit crop development are illustrated in Fig. 1. Even though PGRs have a great deal of potential to affect plant growth morphogenesis, the main obstacles to their applicability are species specificity, seasons, application stages and optimal concentrations. As such, it is crucial to carefully plan their application and make accurate assessments. Plant developmental stage is a critical factor influencing the efficacy of plant growth regulator applications due to variations in physiological sensitivity during different growth phases. Early blooming, harvesting and enhanced fruit setting are all greatly enhanced by the application of plant growth regulators during the 2-leaf and flower initiation stages.

Although PGRs provide substantial benefits in improving growth, flowering, fruit set and yield of cucurbit crops, their indiscriminate or excessive use may result in adverse effects. Application of PGRs at inappropriate concentrations or growth stages can induce phytotoxicity, hormonal imbalance, abnormal vegetative growth and malformed fruits. Excessive use of certain regulators may also negatively affect fruit quality, self-life and seed development. In addition, repeated application may raise concerns regarding chemical residues, environmental safety and production costs, particularly for small and marginal farmers. The effectiveness of PGRs is highly influenced by crop species, cultivar, environmental conditions, method of application and concentration used. Therefore, precise standardisation of dosage, timing and application methods is essential to maximise their beneficial effects while minimising potential risks and economic limitations.

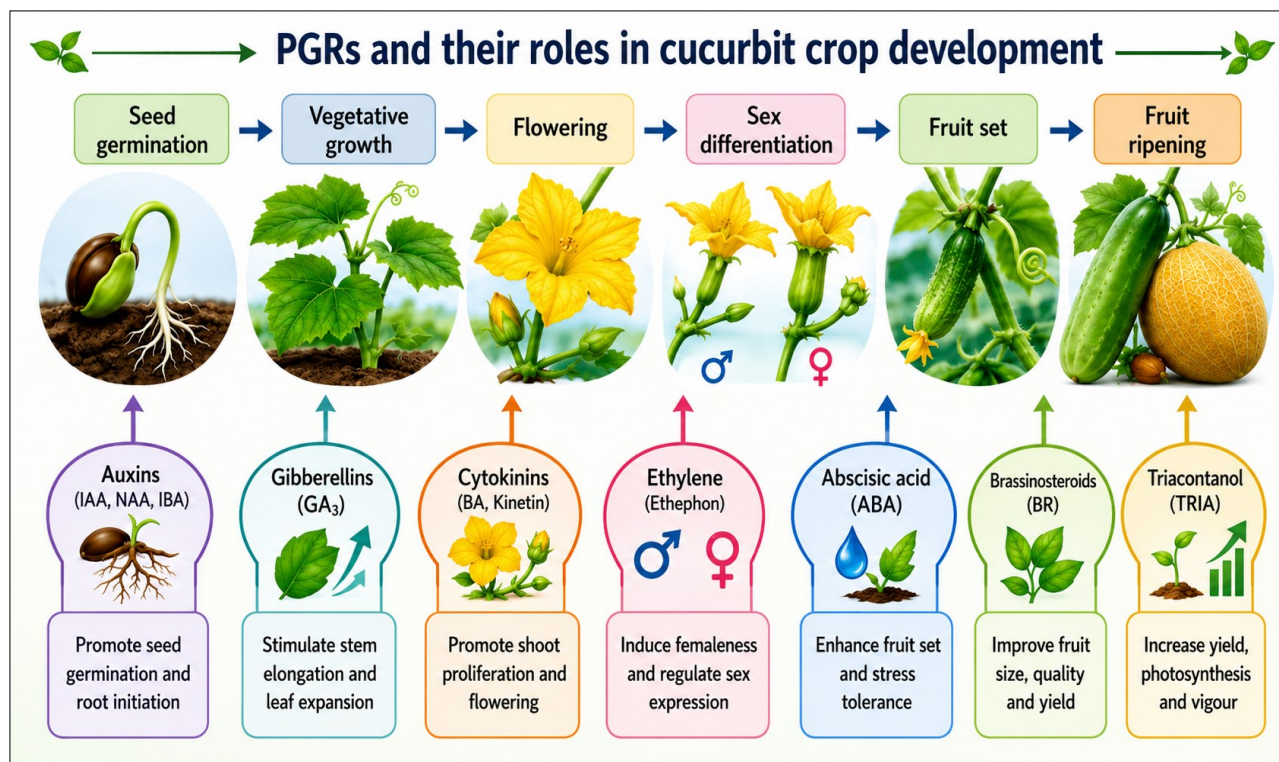


Fig. 1. Roles of plant growth regulators (PGRs) in cucurbit crop development.

Auxin

In cucurbit crops, auxins play a crucial role in regulating sex expression, fruit set and yield enhancement through their influence on floral differentiation and ethylene biosynthesis pathways. Application of auxins such as NAA and IAA has been reported to promote femaleness by increasing ethylene production, thereby enhancing the number of pistillate flowers in cucumber, bitter melon and bottle melon. Auxins also stimulate ovary enlargement, cell division and cell elongation during early fruit developmental stages, which contribute to improved fruit set and reduced premature flower and fruit drop. Furthermore, auxin-induced enhancement of assimilate translocation and sink strength facilitates better nutrient mobilisation towards developing fruits, ultimately increasing fruit retention and yield in cucurbitaceous vegetables. Auxins are also involved in parthenocarpic fruit development in certain cucurbits by activating physiological pathways associated with ovary growth in the absence of fertilisation. However, the effectiveness of auxin application depends on genotype, environmental conditions, concentration and stage of application.

Gibberellic acid

More than 100 gibberellins have been identified from a wide range of organisms, including fungi and higher plants. These compounds are systematically designated as GA₁, GA₂, GA₃ and so forth. Among these, Gibberellic acid (GA₃) represents one of the earliest discovered and most extensively investigated forms, originally extracted from the fungus *Gibberella fujikuroi*, the causal organism of the "bakanae disease" or "foolish seedling disease" of rice. Endogenous GAs are biosynthesised in actively dividing meristematic tissues, including root and shoot apical meristems, young leaves, developing fruits and maturing seeds, particularly the endosperm. The physiological functions of GA₃ are diverse and wide ranging. It stimulates seed germination, promotes floral development and enhances fruit growth and fruit set. The GA₃ also delays leaf senescence, promotes internodal elongation and

supports pollen germination and pollen tube growth. In addition, it can induce parthenocarp, influence sex expression and substitute for vernalisation requirements in certain crops. Additionally, GA₃ plays a significant role in improving nutrient translocation to the embryo during the germination process.

Cytokinin

Cytokinins, also referred to as phytochemicals, are purine derivatives that regulate cell division and various aspects of plant growth and development. Their discovery was prompted by the observation that isolated pith tissues of *Nicotiana tabacum* ceased cell division when separated from vascular tissues, whereas cell division resumed upon reestablishment of contact with the vascular tissues. Several synthetic cytokinins have since been identified, including 6-benzylaminopurine (BAP), kinetin, 6-(benzylamino)-9-(2-tetrahydropyran-2-yl)-9H-purine (PBA), 1,3-diphenylurea and thidiazuron (TDZ). Among adenine-type cytokinins, kinetin [N-(2-furylmethyl)-3H-purin-6-amine] and 6-benzyladenine are widely employed in tissue culture systems for the regeneration of transplants. Commonly recognised naturally occurring cytokinins include zeatin and other related naturally occurring cytokinins found in various plant tissues. Physiologically, cytokinins promote the development of adventitious shoots, stimulate lateral shoot proliferation, facilitate chloroplast differentiation in leaf tissues and induce new leaf formation. They are also effective in overcoming apical dominance. Furthermore, cytokinins actively encourage nutrient mobilisation within plant tissues, thereby contributing to the delay of senescence.

Abscissic acid

Abscissic acid is predominantly biosynthesised from carotenoid precursors and occurs naturally in plant tissues, exerting primarily inhibitory effects on plant growth and development. At the molecular level, ABA inhibits mRNA transcription and protein synthesis. Initially discovered for its regulatory role in abscission and dormancy induction, ABA has since been recognised for its wide range influence on plant growth and developmental

processes. It functions as a general inhibitor of plant growth and metabolism, suppressing seed germination and antagonising the promotive effects of (GA_3) under most physiological conditions. ABA plays a critical role in stimulating stomatal closure in the leaf epidermis, thereby enhancing plant tolerance to various abiotic stresses, which has earned it the designation of "stress hormone." Primary sites of ABA biosynthesis include mature leaves and root tissues, particularly in response to water deficit conditions, though synthesis may occur in all plant tissues under appropriate stimuli. The ABA is further implicated in the regulation of seed development, maturation and dormancy induction. By promoting dormancy, ABA confers upon seeds the capacity to withstand desiccation and other unfavourable environmental conditions that would otherwise impede normal growth and development.

Ethylene

Ethylene was identified as a physiologically active gaseous plant hormone that influences plant growth and development, marking the beginning of extensive research into its role in plant physiology. Conclusive evidence for the endogenous biosynthesis of ethylene in plants was subsequently provided by previous researchers (4). Ethylene is a simple gaseous plant growth regulator, biosynthesised in substantial quantities by senescing tissues and ripening fruits. The physiological influences of ethylene on plant growth and development are diverse, encompassing horizontal growth of seedlings, axial swelling and apical hook formation in dicotyledonous seedlings. It actively promotes senescence and abscission of plant organs, particularly leaves and floral structures. Ethylene is notably effective in accelerating fruit ripening, wherein it significantly enhances the respiration rate, a phenomenon collectively referred to as the respiratory climacteric. Furthermore, ethylene, depending on its concentration and plant species, can stimulate root hair formation and influence root growth, thereby increase the absorptive surface area of the root system and improving mineral nutrient and water uptake efficiency. In cucurbit crops, ethylene plays a central role in regulating sex expression, floral differentiation and fruit development through complex hormonal crosstalk and gene regulatory mechanisms. Ethylene promotes femaleness by stimulating the development of pistillate flowers, particularly in cucumber, melon and bitter melon. Recent studies have demonstrated that ethylene interacts synergistically with auxins to enhance the expression of genes associated with female flower formation, including *CsACS1G*, *ACS11* and *ACO2*, which are involved in ethylene biosynthesis pathways in cucumber. Transcriptomic analyses have further revealed that ethylene-mediated regulation of floral sex expression involves differential expression of transcription factors, hormone-responsive genes and signalling pathways associated with auxin, gibberellin and abscisic acid metabolism. Gibberellins generally promote maleness, whereas ethylene suppresses stamen development and enhances carpel formation, thereby influencing the male-to-female flower ratio in cucurbits. Ethylene also contributes to improved fruit set and ripening by regulating cell wall modification enzymes, respiration and sugar metabolism during fruit maturation. Moreover, recent molecular studies using RNA sequencing and gene expression profiling have provided deeper insights into hormone signalling networks governing sex determination, stress responses and yield enhancement in cucurbitaceous vegetables. However, the response of cucurbit crops to ethylene application varies with genotype, environmental conditions, concentration and developmental stage.

Brassinosteroids

Brassinosteroids (BRs) were initially identified in the pollen of *Brassica napus* L. based on their growth-promoting properties and were subsequently designated as "brassins." Brassinolide (BL), recognised as the most biologically active BR, was successfully isolated in 1979. The BRs have been detected in virtually all plant organs and tissues, including leaves, stems, roots, flowers, pollen, anthers and seeds. While universally distributed across all actively growing tissues of higher plants, significantly elevated concentrations have been recorded in seeds, pollen and fruits. Classified as steroidal hormones, BRs regulate a broad spectrum of developmental and physiological processes, encompassing cell expansion, cell division, stem cell maintenance, vascular tissue differentiation and floral transition. Their regulatory influence further extends to hypocotyl elongation, root and shoot growth, stomatal patterning, pollen tube growth, seed and pollen germination, tracheary element differentiation, xylem formation and differentiation, photomorphogenesis and plant reproduction and senescence. At the cellular level, BRs can activate the cell cycle during seed germination, regulating cell cycle progression and controlling leaf cell proliferation, while also inducing enhanced growth in hydroponically cultivated plants. Additionally, BRs play a significant regulatory role in mediating both abiotic and biotic stress responses as well as stomatal development (5).

Triacontanol

Triacontanol (TRIA) is a naturally occurring saturated primary alcohol, first identified in alfalfa hay (6), that affects many physio-biochemical processes in different crop plants. It is a well-known plant growth-promoting substance that enhances growth when applied exogenously at relatively low concentrations to most crops (7). Some major phytohormones that alleviate salinity stress in plants include ABA, GA_3 , BRs, ethylene (ET), jasmonic acid (JA) and nitric oxide (NO). Triacontanol naturally occurs in the epicuticular waxes of diverse plant species, including *Croton californicus* Müll.Arg., *Copernicia cerifera* (Arruda) Mart., *Medicago sativa* L., *Jatropha curcas* L., *Oryza sativa* L. and *Vaccinium virgatum* Aiton (syn. *Vaccinium ashei* Reade) (8). The major roles of TRIA in plants include increasing root and shoot length, enhancing photosynthetic pigments, improving gas exchange parameters, increasing mineral nutrient accumulation, enhancing antioxidant enzyme activities and improving yield attributes.

In cucurbitaceous crops, exogenous application of triacontanol has been reported to improve vegetative growth, flowering, fruit set, yield and stress tolerance through multiple physiological and biochemical mechanisms. The TRIA enhances photosynthetic efficiency by increasing chlorophyll synthesis, stomatal conductance, carbon dioxide assimilation and RuBisCO enzyme activity, thereby improving dry matter accumulation and biomass production. It also stimulates cell division, nutrient uptake and assimilate translocation, leading to increased vine growth, leaf area development and fruit productivity in cucurbit crops.

Under abiotic stress conditions such as salinity, drought and temperature stress, TRIA plays an important protective role by regulating antioxidant defence systems and osmotic balance. Application of TRIA enhances the activities of antioxidant enzymes such as superoxide dismutase, catalase and peroxidase, thereby reducing oxidative damage caused by reactive oxygen species. It also improves membrane stability, proline accumulation, water-

use efficiency and mineral nutrient uptake under stress conditions. In cucurbits grown under salinity stress, triacontanol has been shown to improve Na^+/K^+ balance, chlorophyll retention and overall plant vigour, contributing to enhanced stress tolerance and yield stability.

Recent studies suggest that triacontanol interacts with endogenous phytohormones including auxins, GA_3 , brassinosteroids and ethylene, thereby influencing hormonal crosstalk associated with flowering, fruit development and stress adaptation. At the molecular level, TRIA has been reported to activate genes related to photosynthesis, antioxidant metabolism and stress-responsive pathways, although detailed transcriptomic studies in cucurbit crops remain limited. Commercially, triacontanol-based formulations are increasingly utilised in vegetable production systems due to their eco-friendly nature, low application requirement and potential to improve productivity and fruit quality. However, the effectiveness of TRIA varies depending on crop species, genotype, environmental conditions, dosage and method of application, highlighting the need for further standardisation and molecular-level investigations in cucurbitaceous crops.

Cucumber

The response of cucumber to various plant growth regulators is summarised in Table 1. Ethrel application (150–600 ppm) consistently increased the number of female flowers, reduced male flowers and improved sex ratio, ultimately enhancing fruit yield. GA_3 treatments (40–200 ppm) significantly improved vegetative growth parameters such as vine length, number of leaves, branches and nodes, which resulted in higher fruit yield and total soluble solids (TSS) content. Combined application of GA_3 + NAA was effective in reducing days to first flowering and increasing fruit number per plant. Triacontanol also improved water use efficiency and salt stress tolerance in cucumber. Overall, Table 1 clearly indicates that ethrel is highly effective for modifying sex expression, while GA_3 enhances vegetative growth and yield parameters.

The physiological responses of cucurbit species to PGRs differ considerably due to variations in endogenous hormone balance, genetic makeup, floral biology and sensitivity of hormone signalling pathways. As indicated in Table 1, cucumber exhibits a strong response to ethylene-releasing compounds such as ethrel

Table 1. Effect of plant growth regulators on flowering and yield of cucumber

PGR	Concentration (in ppm)	Effects	Reference
Ethrel	400–500 ppm	Observed that foliar application increased the number of female flowers, enhanced maturity cycle and improved sex ratio by suppressing male flowers.	(2)
GA_3	200 ppm	Showed maximum effect on growth parameters by increasing vine length (132.44 cm), number of branches (6.81), nodes (22.67) and leaves (57.67).	(9)
GA_3	75 ppm	Recorded maximum vine length (271.76 cm), number of leaves (90.32), number of nodes on main stem (30.22), length of primary branches (153.25 cm) and leaf area (458.14 cm^2) whereas, the maximum number of primary branches (18.49) was recorded in ethrel at 300 ppm.	(10)
GA_3	40 ppm	Recorded highest fruit yield per vine at (1.87 kg) as well as the maximum fruit yield per plot (28.29 kg) and per hectare (251.50 q) by various factors, including enhanced fruit set percentage, increased fruit weight and improvements in the length and diameter of the fruits. Also showed a maximum (5.73 °Brix) Total Soluble Solid in fruit.	(11)
Ethrel	300 ppm	The maximum number of fruits per vine (14.13) was recorded from the application of 300 ppm ethrel. This may be because ethrel suppressed the number of male flowers and promoted number of female flower thereby, increased the number of fruits per vine.	(11)
NAA	100 ppm	The maximum number of pickings (8.59) was found with 100 ppm of NAA.	(11)
MH+ethephon	Each at 100 ppm	Proved best for increasing fruit yield and its contributing parameters. This treatment not only brought earliness, increased the sex ratio and reduced plant expansion (accommodation of more plants per unit area) but also gave the best economic result.	(12)
GA_3	200 ppm	Recorded the maximum yield per plant (3.89 Kg) and 180.69 q/ha. Also showed highest TSS (5.1 °brix) content.	(13)
GA_3	100 ppm	Fruit yield (218.33q/ha) and maximum average fruit weight (258g) were noted. TSS had a 4.15 °Brix value.	(14)
GA_3 + NAA	20 ppm + 100 ppm	It was found to be most effective in reducing number of days (34.85 days) required for appearance of first flower formation. The maximum number of fruits plant ⁻¹ (10.34) and highest tender green fruit yield (173.60 qha ⁻¹) were recorded.	(15)
Ethrel	300–400 ppm	Results showed that foliar spray of ethrel at 300–400 ppm retards the secondary development and increases femaleness in cucumber.	(16)
Ethrel	600 ppm	Recorded the highest yield per hectare (21223.28 kg) by enhancing number of fruits per vine (14.33) and maximum yield per vine (3.18 kg).	(17)
Ethrel	150 ppm	According to the study, the most effective way to increase the number of female flowers (29.58) per vine, induce female flowers at the lower node (3.67), decrease the male : female sex ratio (2.50), increase the number of fruits per vine (11.97) and increase yield per plot (23.08 kg) and per hectare (35.62 t) was to apply 150 ppm of ethrel.	(18)
Triacontanol	0.8 mgL^{-1} .	Enhancing WUE, chlorophyll content, enhancing the productivity of cucumber plants under salt stress. Foliar application of triacontanol decreased the adversities of salt stress and improved the number of fruits and their weight	(19)

PGR: plant growth regulator; GA_3 : gibberellic acid; NAA: α -naphthalene acetic acid; MH: maleic hydrazide; Ethrel: ethephon; ppm: parts per million; TSS: total soluble solids; WUE: water use efficiency.

because sex expression in cucumber is highly regulated by ethylene-mediated pathways that promote pistillate flower development. In contrast, watermelon generally shows comparatively lower sensitivity to ethylene, where GA₃ more strongly influence vine elongation, fruit growth and assimilate partitioning rather than floral sex modification. Bitter melon responds differently because of its naturally higher proportion of staminate flowers and distinct floral physiology, where auxins and ethylene-releasing compounds are more effective in shifting the sex ratio towards femaleness.

Differential responses among cucurbit crops are also associated with species-specific variations in source-sink relationships, photosynthetic efficiency, nutrient translocation and reproductive behaviour. Cucumber exhibits rapid physiological responses to PGRs due to its shorter growth cycle and high floral plasticity, whereas watermelon and pumpkin possess vigorous vegetative growth and comparatively longer crop duration, often requiring higher concentrations or combined hormone treatments for significant responses. Environmental conditions such as temperature, photoperiod and soil moisture further influence hormone sensitivity and physiological regulation in cucurbitaceous vegetables. Therefore, species-specific optimisation of plant growth regulator type, concentration and stage of application is essential for maximising growth, flowering, fruit set and yield enhancement in different cucurbit crops.

Watermelon

The influence of plant growth regulators on flowering and yield of watermelon is presented in Table 2. The GA₃ at different concentrations (20–150 ppm) significantly increased vine growth, fruit weight, yield per hectare and TSS content. Application of 2,3,5

-triiodobenzoic acid (TIBA) at 20 ppm was found to be effective in reducing the number of days to first female flower appearance and improving fruit yield. Maleic hydrazide (MH) at 200–625 ppm improved the sex ratio and increased fruit yield per plant. The findings summarised in Table 2 indicate that GA₃ and MH play crucial roles in improving both the growth and yield attributes of watermelon.

Bottle gourd

The effect of PGRs on bottle gourd is illustrated in Table 3. Ethrel (100–300 ppm) was highly effective in increasing female flower production, reducing male flowers and improving fruit yield per hectare. The NAA (80–100 ppm) enhanced vine length, leaf number and fruit diameter. Ethrel at 200 ppm significantly reduced days to first harvesting and increased fruit yield per plant. As shown in Table 3, ethrel is particularly effective for improving sex ratio and yield, whereas NAA promotes vegetative growth and fruit development.

Muskmelon

The results presented in Table 4 demonstrate that ethrel at 150–200 ppm significantly improved the sex ratio, increased the number of female flowers and enhanced TSS content. Gibberellic acid at 50 ppm mitigated the effects of drought stress and improved sex expression. The combined application of NAA and ethrel increased the number of fruits per vine, fruit diameter and yield per plant. Naphthalene acetic acid at 80 ppm also positively influenced vine length, fruit size and yield. Based on the findings presented in Table 4, ethrel and NAA are highly effective in improving flowering behaviour, fruit quality and yield in muskmelon.

Table 2. Effect of plant growth regulators on flowering and yield of watermelon

PGR	Concentration (in ppm)	Effects	Reference
GA ₃	25 ppm	Increased main axis, number of male flowers, number of fruits per plant, fruit weight (g), yield per hectare (q) and TSS content in cv. Sugar Baby.	(20)
GA ₃	20 ppm	Application of GA ₃ 20 ppm at 2 & 4 true leaf stage was found superior for most of the growth characters like length of main stem (291.10 cm), number of leaves plant ⁻¹ , number of primary branches plant ⁻¹ (9.73) and inter nodal distance.	(21)
TIBA	20 ppm	Took minimum days for first female flower appearance, produced first female flower at early node, the maximum number of fruits, average fruit weight (3.29 kg plant ⁻¹), fruit yield per plot (10.07 kg plant ⁻¹) and yield per hectare (503.38 q ha ⁻¹).	(22)
TIBA	20 ppm	Concluded that better growth, early flowering, minimum sex ratio, highest fruit yield and superior quality could be achieved by the spray of TIBA 20 ppm at 2-4 leaf stages in watermelon cv. 'Durgapura Lal (RW-177-3).	(23)
MH	200 ppm	MH 200 ppm was shown to have the shortest floral appearance times for the first male (44.33 days), female (47.00 days) and hermaphrodite (51.57 days). In MH 200 ppm treatment, the greatest female:male sex ratio of 1:2.03 was observed. The maximum productivity characteristics, including fruit yield (10.24 kg/plant and 34901.75 kg/ha) and number of fruits per plant (3.07), were seen in MH 200 ppm.	(24)
MH	625 ppm	Number of fruits per plant increased with the application of ethrel 625 ppm in cv. Sugar Baby	(25)
GA ₃	150 ppm	GA ₃ 150 ppm resulted in increased number of primary branches, length of main axis and minimum days to appearance first male flower in cv. Sugar Baby (Dadwadiya, 2002). Maximum plant weight and number of branches increased with ethrel 500 ppm.	(26)
GA ₃	40 ppm	The highest fruit yield plant ⁻¹ (17.51 kg) and fruit yield per hectare ⁻¹ (44.17 t) was recorded in treatment (GA ₃ at 40 ppm). The quality attributes such as Total Soluble Solid (TSS) (10.66 %) and total sugars (15.03 %) were noted highest in treatment (GA ₃ at 40 ppm).	(27)

PGR: plant growth regulator; GA₃: gibberellic acid; NAA: naphthalene acetic acid; Ethrel: ethephon; ppm: parts per million.

Table 3. Effect of plant growth regulators on flowering and yield of bottle gourd

PGR	Concentration (in ppm)	Effects	Reference
NAA	80 ppm	Showed the maximum vine length (8.20 m), number of leaves per plant (103.50) and took minimum days to first female flower initiation (53.33).	(26)
Ethrel	150 ppm	The results are revealed that foliar application of ethrel at 150 ppm at 2 and 4 true leaf stage increased number of female flowers and decreased number of male flowers per plant and showed the minimum sex ratio of 1 : 3.85 (female: male) and produced female flowers at the early nodes ultimately increased yield	(27)
Ethrel	100 ppm	Was found most effective in increasing fruit diameter (9.61 cm), number of fruits per vine (4.16), fruit weight (1282 g) and fruit yield per hectare (294 q).	(28)
Ethrel	200 ppm	significantly reduced days to first harvesting (54.00 days). Showed maximum fruit/vine (10.36) and the maximum fruit yield per plot was recorded in treatment (70.28 kg).	(29)
NAA	100 ppm	maximum fruit diameter (1.26 cm) was obtained from plant sprayed with NAA at 100 ppm applied at stage S1 (two true leaf stage)	(30)
Ethrel	300 ppm	it is concluded that foliar application of Ethrel at 300 ppm at 2–4 leaf stage was found best for getting higher yield (439.02 q/ha) with better quality and maximum net return of bottle gourd	(30)
Ethrel	200 ppm	Ethrel 200 ppm was found most effective in terms of days to first appearance of male (40.89 days) and female flower (45.44 days), node number to first male (8.11) and female flower (10.11), number of male (16.33) and female flowers (11.33) per vine, fruit diameter (8.67 cm), fruit length (39.84 cm), fruit weight (1064.28 g), number of fruits per plant (10.11), fruit yield per plant (8.72 kg), fruit yield per Hectare (29.01 t/ha)	(31)

PGR: plant growth regulator; GA₃: gibberellic acid; NAA: naphthalene acetic acid; Ethrel: ethephon; ppm: parts per million.

Table 4. Effect of plant growth regulators on flowering and yield of muskmelon

PGR	Concentration (in ppm)	Effects	Reference
Ethrel	150 ppm	Best in the following parameters sex ratio (M : F) - (7.89 : 1), TSS (11.75 °Brix), number of female flowers (16.53), average number of fruits per plant (3.90), days to emergence of 1st female (37.43), nodes at 1st female flower emergence (4.66), least number of male flowers (130.4).	(32)
Ethrel	200 ppm	Resulted in significantly reduced the time of appearance of first pistillate flower which was (8.70 days) earlier than staminate flowers appearance. The maximum TSS (11.30 ° Brix) and total sugar (11.35 %) were recorded in the application of ethrel 200 ppm	(33)
GA ₃	50 ppm	Exogenous application of gibberellic acid 50 ppm can effectively mitigate the deleterious effect of drought stress in muskmelon. GA ₃ at lower concentrations increased the female to male sex ratio.	(34)
NAA + Ethrel	NAA 150 ppm + Ethrel 250 ppm	The lowest number of male flowers (63.23), the highest number of female flowers (17.43), the number of fruits per vine (10.63) and fruit weight (0.679) were recorded. The yield characters such as fruit diameter (12.97) and yield per plant (7.01) were observed maximum	(35)
Ethrel	150 ppm	Resulted in maximum fruit yield per vine (3.78 kg) and increased fruit yield per plot (20.49 kg) and showed the highest TSS (11.34 °Brix) content while spraying of ethrel at 150 ppm at 2 and 4 leaf stage	(36)
NAA	80 ppm	Gave positive impact on growth, yield and quality parameters. i.e. Vine length (153.96 cm), number of days for 1 st male flower (33.6 Days), No. of days for 1 st female flower (38.83 Days), diameter of the fruit (22.53 cm), length of the fruit (13.4 cm), fruit yield per plant (1.4 kg), fruit yield per hectare (12.46 t) and total soluble solids (11.30 °Brix)	(37)

PGR: plant growth regulator; GA₃: gibberellic acid; NAA: naphthalene acetic acid; Ethrel: ethephon; ppm: parts per million.

Bitter gourd

The response of bitter gourd to different plant growth regulators is summarised in Table 5. Application of GA₃ at 20–50 ppm significantly increased fruit yield per plant and the number of female flowers, while reducing the male-to-female flower ratio. Ethrel (200 ppm) enhanced pistillate flower production and reduced male flower appearance. The NAA (200 ppm) improved vegetative growth, germination and benefit-cost ratio. The MH (400 ppm) increased number of pistillate flowers and fruits per vine. As indicated in Table 5, GA₃ and ethrel are the most promising PGRs for improving flowering and yield in bitter gourd.

Conclusion

The application of plant growth regulators (PGRs) exerts a significant influence on the growth, flowering, fruit development and yield of cucurbitaceous crops. The PGRs play a decisive role in regulating various physiological and developmental processes, including seed germination, shoot elongation, leaf expansion, floral induction, fruit

set, fruit growth, ripening and overall crop productivity. The use of suitable growth regulators can substantially improve both yield and fruit quality in cucurbit production systems. Growth-promoting hormones such as gibberellins, auxins and cytokinins enhance vegetative growth, flowering behaviour and fruit development, whereas certain inhibitory regulators are involved in controlling excessive growth, senescence and dormancy.

Among different PGRs, GA₃ has shown considerable effectiveness in promoting vegetative growth, internodal elongation and flowering behaviour in cucurbits. At appropriate concentrations, GA₃ significantly influences parameters such as vine growth, flowering pattern and appearance of male flowers. Auxins regulate plant growth by promoting cell elongation, apical dominance and vascular differentiation, while also influencing branching, leaf development and fruit set depending on crop species and concentration. Ethrel plays a crucial role in modifying sex expression by increasing the number of female flowers and suppressing male flowers, thereby improving fruit set and yield attributes in many cucurbit crops.

Table 5. Effect of plant growth regulators on flowering and yield of bitter gourd

PGR	Concentration (in ppm)	Effects	Reference
GA ₃	20 ppm	Fruit yield per plant and fruit yield per ha were significantly higher with foliar application of GA ₃ at 20 ppm.	(38)
GA ₃	20 ppm	Study revealed that the application of plant growth regulators significantly increased the biochemical and physiological characters in bitter gourd and foliar application of GA ₃ at 20 ppm was most effective in increasing the fruit yield and yield components such as several female flowers, number of fruits per plant.	(39)
Ethrel	200 ppm	It was found to be the most suitable PGR for increasing various flowering parameters viz., delayed days to first male flower, lowest node number to female flower appearance, lowest number of days taken to first female flower (35.42), lower male:female sex ratio and highest number of pistillate flowers (41.4)	(40)
NAA	200 ppm	The highest number of female flowers/vine (15.00) was recorded. but GA ₃ at 50 ppm sprayed twice at three leaf and tendril initiation stage was most effective for hybrid seed production of bitter gourd	(41)
MH	400 ppm	Showed maximum number of pistillate flowers and the minimum number of staminate flowers thereby registering the lowest sex ratio. Also recorded the maximum number of fruits (32.02/vine) followed by MH 300 ppm (30.41/vine).	(42)
NAA	200 ppm	Performed best in terms Germination as well as in vegetative growth, yield and quality of bitter gourd and the maximum survival % was also obtained from this treatment. The maximum benefit cost ratio was observed in NAA 200 ppm.	(43)
GA ₃	50 ppm	Spraying of GA ₃ at 50 ppm gave maximum vine length, number of branches per plant, narrow sex ratio and maximum yield (236.67 q/ha). The study also concluded that significant effect on all growth and yield attributes of bitter gourd crop was found with the application of GA ₃ 50 ppm.	(44)

PGR: plant growth regulator; GA₃: gibberellic acid; NAA: naphthalene acetic acid; Ethrel: ethephon; ppm: parts per million.

Recent advances in plant growth regulator research have also highlighted the importance of hormone crosstalk, molecular regulation of sex expression and stress-responsive signalling pathways in cucurbits. In addition, emerging technologies such as nano-formulated PGRs and precision hormone delivery systems are gaining increasing attention for improving application efficiency and sustainability. Nano-formulations can enhance controlled release, absorption efficiency and targeted delivery of growth regulators while minimising chemical wastage and environmental risks. Similarly, precision hormone delivery approaches may facilitate stage-specific and site-specific application for improved regulation of flowering, fruit set and stress tolerance. Therefore, future research should focus on integrating molecular biology, nanotechnology and precision agriculture approaches to optimise PGR use for sustainable and climate-resilient cucurbit production.

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Authors' contributions

BG, JM, KD, SP, TUM, SK, MM, WVR, NM and MM conceptualised the study. JM, CJ, MV, GV and PY performed the formal analysis. BG, KD and JM supervised and validated the work. MM, SP, CJ, MV, PY and GV carried out the language editing. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflicts of interest to declare.

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