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G Narayana Swamy
Ph.D. Scholars, ICAR-Indian Institute of Horticultural Research Hesaraghatta, Bengaluru, Karnataka India

D Meghana
Ph.D. Scholars, ICAR-Indian Institute of Horticultural Research Hesaraghatta, Bengaluru, Karnataka India

Kowsalya K B
Ph.D. Scholars, ICAR-Indian Institute of Horticultural Research Hesaraghatta, Bengaluru, Karnataka India

K Sudeshna
ICAR-Indian Institute of Horticultural Research Hesaraghatta, Bengaluru, Karnataka India

K Anil Kumar Nair
PS (Agronomy), ICAR-Indian Institute of Horticultural Research Hesaraghatta, Bengaluru, Karnataka India

Corresponding Author:
G Narayana Swamy
Ph.D. Scholars, ICAR-Indian Institute of Horticultural Research Hesaraghatta, Bengaluru, Karnataka India.

History, mechanism and functions of plant growth regulators in vegetable crops

G Narayana Swamy, D Meghana, Kowsalya K B, K Sudeshna and K Anil Kumar Nair

Abstract
Plant growth regulators has quicker impact on vegetative as well as yield of the crops. As it has various advantages like less time consuming to treat the plant and environment friendly. Vegetables crops are rich sources of vitamins and minerals. Use of growth regulators in vegetable production must be specific their action and toxicologically and environmentally safe. The physiological activity of vegetable crops regulates and after the application of growth regulator finally enhance the vegetable production. Higher production with good quality is required in order to meet the food demand of our country. So, there is a need to use growth regulators in vegetable crop production.

Keywords: PGRS, History, Mechanism and Production.

Introduction
The Plant Hormones are natural with longer effect and Plant Growth Regulators are synthetic in nature with limited effect. Plant Bio-regulators are substances which enhance growth through modulation of signal mediated process (Thiourea, salicylic acid, polyamine). "Hormone" is Greek word derived from "*hormao*", which means to stimulate. Thimann in 1948 was coined the term „ Phytohormone‟‟ as organic substance that produce naturally in plants (Kaur *et al.*, 2018) [23] and which are produced naturally in plants, synthesized in one part and usually translocated to other part where in very small quantity affect the growth and other physiological function of the plants.

Classes of Plant Growth regulators and Retardants

Group	Examples
Auxins	IAA, NAA, IBA, 2,4-D, 4-CPA, 2,4,5-T
Gibberellins	GA_3 (Gibberellic acid)
Cytokinins	Kinetin, Zeatin , Benzyladenine, BAP
Ethylene	Ethephon (Ethrel)
Abscissic acid	Dormins, Phaseic Acid
Flowering hormones	Florigen, Anthesin, Vernalin
Growth inhibitors (Antiauxins)	Clofibric acid, 2,3,5-TIBA
Ethylene inhibitors	Aviglycine (AVG), 1-methylcyclopropene
Growth retardants	Paclobutrazol, chlormequat, uniconazole
Growth stimulators	Brassinolide

Difference between Growth inhibitor and Growth Retardant

Sl. No.	Growth Inhibitor	Growth Retardant
1	Growth inhibitors inhibit the transport of auxins	Growth retardants inhibit the biosynthesis of gibberellins
2	These are also called as anti-auxins or auxin-antagonists	These are also calles as anti-gibberellins or gibberellins-antagonists.
3	Growth inhibitors inhibit all growth processes permanently and promote abscission and senescence in plant.	Growth retardants inhibit only some growth and physiological processes temporarily and its effect is overcome after sometime.
4	NPA (Naphthylphthalamic acid), 2,3,5-Triiodobenzoic acid **(**TIBA**),** Morphactin, 2,4—dichloro-anisol and MH (Maleic hydrazide) are widely known auxins antagonists.	Growth retardants includes: Chlormeequat chloride or Chlorocholine Chloride (CCC), Paclobutrazol, Daminozide or succinic acid-2.2-dimethylhydrazide (SADH) and Mepiquat Chloride (DPC).
5	They may be synthetic as well as natural	They are synthetic only

Source: (Meena, 2015)

Plant Hormones Vs Plant Growth Regulators	
Definition	
Chemicals produced naturally by the plants	Chemicals either produced naturally by the plants or synthesized artificially by humans
Synthesis	
Synthesized as result of plant metabolic processes	Formulated by humans
Origin	
These are Endogenous	These are Exogenous
Effect	
These are long – lived chemicals. Hence, the effect is long lasting	These are short lived chemicals. Hence, the effects are temporary and reapplication is required.
Examples	
Auxin, Gibberellin, Cytokinin, Ethylene and Abscisic Acid	NAA, IBA, Ethephon, etc

History of Plant Growth Regulators

Auxins

The word Auxin is from Greek word i.e. *Auxem* (to growth). Most of knowledge about auxins comes from the work on oat (Avena sativa) coleoptile. The very existence of growth substances was proposed by Charles Darwin (1880) [9] in his book The Power of Movements in Plants. The first higher plant from which auxin could be extracted was maize kernels. It was identified as IAA. Indole Acetic Acid (IAA) is the principal naturally occurring auxin of all higher plants.

Gibberellins

Gibberellin was first known by a Japanese farmer Konishi in 1898 (Meena, 2015) but Kurosawa working in Farmosa discovered GA in 1926. It was first extracted from the ascomycetous fungus *Gibberella fujikuroi* (*Fusarium moniliforme*), the causal organism of "foolish seedling of rice" or commonly called bakanae disease of rice. The infected plants were usually taller, seedless and pale in colour. He applied the fungal extracts to intact healthy plants and observed enhanced growth. Later, Yabuta and Sumuki (1938) [40] named the active principle as 'gibberellin'. Further it was purified, crystallized and named as 'gibberellic acid' by Cross and Curtis in 1954. Now gibberellins are designated as GA_1, GA_2 and so on. The common gibberellic acid is GA_3. At present 112 types of gibberellins are known (Meena, 2015).

Cytokinins

Cytokinins were discovered by F. Skoog, C. Miller and co-workers during the 1950s as factors that promote cell division (cytokinesis). If vascular tissues were placed in contact with them, pith tissue resumed cell division. This observation proved instrumental in the discovery of cytokinins. Millar, Skoog, Saltza and Strong (1955 a) isolated a substance from herring sperm-DNA and named it kinetin. This liquid endosperm of coconut (coconut milk) is also found to be rich in cell division causing factors. Letham (1963) extracted, purified and crystallized cytokinin from immature kernel of maize and named it as zeatin. Functional activity of cytokinins occurs in the presence of auxins.

Abscissic Acid (ABA)

ABA is one of the wide spread and naturally occurring inhibitor found in plants this growth inhibitor was isolated in buds of Acer pseudoplatanus by Philip Wareing in 1963, and named dormin (Eagles and Wareing 1963) [18]. Addicot and his colleagues (1963) isolated this abscission causing compound from cotton bolls and named it as abscisin I and abscisin II but in 1967, a common name abscissic acid was given to both. ABA is known as dormancy inducing and abscission accelerating substance. ABA has been reported to inhibit mRNA and protein synthesis. ABA is found in all parts of the seed namely the seed coat, embryonic axis, cotyledons and endosperm.

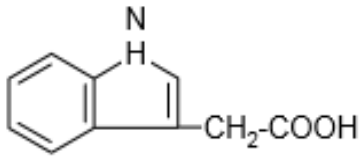
Ethylene (The Ripening Hormone)

Neljubow a Russian plant physiologist was the first to show the importance of ethylene present in the illuminating gas as a growth regulator of plants in 1901 (Meena, 2015). He observed that dark grown pea seed lings growing in the laboratory (illuminated with coal gas) exhibited symptoms that were later termed as triple response: reduced stem elongation, increased lateral growth, and abnormal horizontal growth. Denny reported that ethylene is highly effective in inducing fruit ripening in 1924 (Meena, 2015). Ultimately Gane established that ethylene is actually a natural product of ripening fruits in 1934 (Meena, 2015). It acts upon DNA, RNA and protein biosynthesis, induction and modification of endospermic reticulum. Auxins increased ethylene level in plants and many of auxin actions are attributed through ethylene such as increased percentage of female flowers, apical bud dominance and leaf epinasty.

Biosynthesis of Plant Growth regulators:

Auxins

- Precursor: tryptophan/ indole
- Synthesis: leaf primordia, young leaves & in developing seeds.
- Transport: root (phloem)

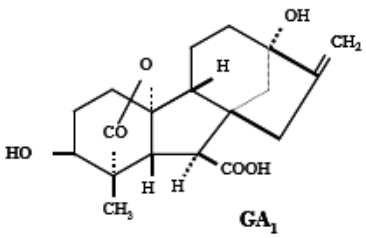


The auxin precursor in plants is tryptophan or substances derived from its degradation. It is formed by following three steps involving three enzymes: transaminase, which catalyzes the conversion of tryptophan into tryptamine, de carboxylase-from tryptamine to indole pyruvic acid, which transforms into β- indole acetaldehyde and aldehyde dehydrogenase, which catalyzes the formation of β-indole acetic acid. All the parts of the plant body produce auxin. However, the major sites of auxin production are the shoot tips, developing seeds and buds.

Gibberellins

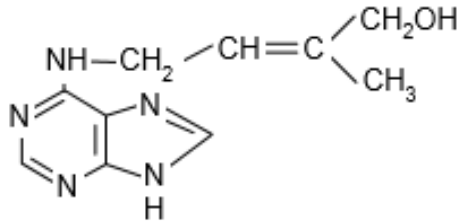
- Kurosava discovered gibberellins in 1926 from *Gibberella fujikuroi (Fusarium moniliformae)* of foolish disease infected rice.
- Composed of *ent*-gibberellane structure
- Precursor: mevalonic acid
- Synthesis: the young leaves (major site), shoot tip, root tip and immature seeds (embryo).
- Transport: through xylem & phloem

Gibberellin predecessor is kaurene. In the chemical structure of both of them there is a common backbone-gibban, to which certain side groups are attached that determines their specificity. Thus each plant species has its own set of gibberellins (Meena, 2015) [17].



Cytokinins (anti-senescence hormone):

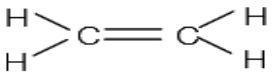
- Derived from cytokinesis (cell division)
- Natural cytokinin: zeatin
- Adenine derivatives
- Precursor: adenosine monophosphate
- Synthesis: root tips, developing seeds and cambial tissues
- Transport: roots to shoots (xylem)



Zeatin is synthesized from mevalonic acid and adenine. Usually Zeatin is the most abundant naturally occurring free cytokinin. It was found that cytokinins are the result of degradation of nucleic acids and therefore, could serve as an indicator of the rate of DNA replication. In plants cytokinins exist in free and bound form. Bound cytokinins are synthesized in the cytoplasm and chloroplasts. It is assumed that they may be synthesized also in mitochondria based on their own DNA. This confirms the endosymbiotic theory organelle genesis. Root tip is an important site of cytokinin synthesis.

Ethylene

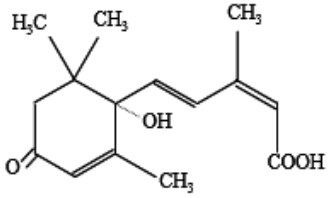
- Gaseous plant hormone / ripening hormone
- Precursor: methionine
- Synthesis: tissues (senescence or ripening)
- Transport: diffusion



In higher plants, all most the parts of the plant body produce ethylene. In general meristematic region and nodal regions are most active in ethylene biosynthesis. However, ethylene production also increases during leaf abscission and flower senescence, as well as during fruit ripening. This is otherwise called as phyto gerontological hormone. Very little is known about its synthesis inside the plants but it appears that methionine (an amino acid) may be an immediate precursor of ethylene. ACC (amino cyclo propane carboxylic acid) is the penultimate precursor of ethylene.

Ethylene Antogonists

Check ethylene activity either by blocking cellular receptor of ethylene (Sodium thiosulphate) or its synthesis (Amino-ethoxy vinyl glycine) or competeting with ethylene (CO_2).



Abscisic Acid

- Precursor: mevalonic acid
- Synthesis: roots, mature leaves, seeds
- Transport: roots (xylem) & leaves (phloem)

ABA biosynthesis occurs via two pathways.

- From mevalonic acid → isopentenyl pyrophosphate → heranylpirophosphate;
- By carotenoid and violaxanthine decomposition → xanthoxin → abscisic acid.

It was found that induction of ABA synthesis occurs during genome reprogramming and synthesis of increased amounts of ABA-inducing polypeptides, of which lectins are more significant.

Associated functions of Different PGR

Auxin	(I) It Causes Cell Elongation By Loosening Of The Cell Wall, (Ii) Promotes Secondary Growth Of Stem Through Cambium Activity, (Iii) Promotes Callus And Root Formation In Cutting, (Iv) Restores Apical Dominance, (V) Induction Of Flowering, (Vi) Increases Fruit Setting And Size, (Vii) Delays Leaf Abscission, (Viii) Prevention Of Premature Drop Of Fruits, (Ix) Develops Parthenocarpic Fruits, (Xi) Acts As Herbicide At Higher Concentration, (Xii) Inhibition Of Prolonged Dormancy, And (Xiii) Inhibiting Aging Processes In Tissues.
Gibberellin	(I) It Induces Maleness, (Ii) Promotes Growth Of Dwarf Plants, (Iii) Possesses Pollenicide Effect, (Iv) Replaces Chilling And Light Requirements Of Plants, (V) Promotes Seed Germination, (Vi) Used For Breaking Of Dormancy, (Vii) Delays Senescence Of Fruits, (Viii) Enhances Seedless Fruits, (Ix) For Stem Elongation, (X) Accelerates Flowering In Long Day Plants, And (Xi) Intensifies Transpiration, Photosynthesis And Respiration.
Cytokinin	(I) It Promotes Seed Germination And Radical Growth By Breaking Dormancy, (Ii) It Helps In Cotyledon Expansion In Immature Seedling Of Dicots, (Iii) It Stimulates Chlorophyll Synthesis, (Iv) It Induces Cell Division And Shoots Development, (V) It Delayed Senescence Of Leaves, (Vi) Nucleic Acid Metabolism, (Vii) Protein Synthesis, And (Viii) It Incorporation In RNA.
Ethylene	(I) It Cause Stomatal Closure In Response To Water Stress, (Ii) It Inhibits Cell Wall Loosening, (Iii) It Inhibits Viviparous Germination Of The Developing Embryo, (Iv) It Enhances Tuberization, (V) It Accelerated Senescence Of Leaves And Fruits, (Vi) Accumulates Sucrose In Seeds, Sweet Fruits, Reserve Tissues Of The Roots, And (Vii) Has Anti-Gibberellin, Anti-Auxin, Anti-Quinine Action.
Abscisic Acid	(I) Ethylene Acts As Soil Fungistasis, (Ii) It Hastens Abscission Of Plants, (Iii) It Encourages Root Formation, (Iv) It Acts As A Fruit Ripening Hormone, (V) It Enhances Seed Germination, (Vi) It Induces Production Of Female Flowers, (Vii) It Induces Male Sterility, And (Viii) It Inhibits Vegetative Growth And Triggers Reproductive Growth
Salicylates	Plant Pathogen Resistance
Jasmonates	Plant Defense
Polyamines	Influence Flowering & Promote Plant Regeneration
Brassinolides	Resistance, Tissue Culture, Increases Natural Preservation Value, Reduces Fruit Drop & Flowering
Nitrobenzene	Increase Flowering & Prevent Flower Shedding

Other Plant Growth Regulators

Brassinolides (Syn. Brassinosteroids or Terpenoids) Brassinolides are a plant steroid discovered in pollen of member of the mustard family (Steven D. Clouse 2011). The have been studied in Arabadopsis. Brassinolides represent a new sixth class of plant hormones with wide occurrences in the plant kingdom in addition to auxins, gibberellins, cytokinins, abscisic acid and ethylene. The substances from various pollen sources named 'brassins' a steroidal lactone, termed brssinolide, was first time isolated from pollen of Brassica napus by Grove and his associates in 1979. The first brassinosteroids-biosynthesis inhibitor named brassinazole, was first time reported by Asami and Yoshida (1999). Generally, pollen and immature seeds are rich source of brassinolide (with ranges of 1-100 ng g-1 fresh weight), while the concentrations in vegetative tissues are very low compared to those of other plant hormones. The functions of brassinosteroids analogous to that caused nyauxins and gibberellins such as stem elongation and plant morphogenesis. Therefore, it is difficult to study the brassinolides because their effects overlap those of auxins and gibberellins. Brassinosteroids activate signal transduction pathway that promote cell elongation and cell division. Brassinosteroids control a broad range of responses in plant, including seed germination, stem and root elongation, vascular differentiation, leaf expansion and apical dominance. Interestingly, each of these responses is also controlled by auxins, suggesting there might be considerable interplay between these two hormones in the control of development. In addition to their role in plant development, brassinosteroids have the ability to protect plants from various environmental stresses, including drought, extreme temperatures, heavy metals, herbicidal injury and salinity.

Jasmonates (Jasmonic Acid)

Jasmonates are a group of fatty acid derivatives. They appear to have a role in seed germination, root growth and the storage of protein (especially in seeds). In 1990, airborne jasmonic acid methyl ester (JAME) was shown to induce proteinase inhibitors in tomato, thereby attributing to an 'immunization' against herbivore attack. Jasmonic acid and JAME are lipid-derived signals. Jasmonic acid and its related compounds are short-chain alkylcyclopentanone or alkylcyclopentane carboxylic acids and their derivatives. It is recognized as a new type of plant growth regulator. It widely occurs in the plant kingdom together with abscisic acid like physiological activities at low concentrations.

Growth Inhibitors

These are substances which suppress the growth of plants.

Phenolic Inhibitors: Benzoic acid, salicylic acid, cinnamic acid, caffeic acid, ferulic acid, coumarin, juglone, scopoletin, naringenin, chologenic acid.

Synthetic Inhibitors: Maleic hydrazide, TIBA.

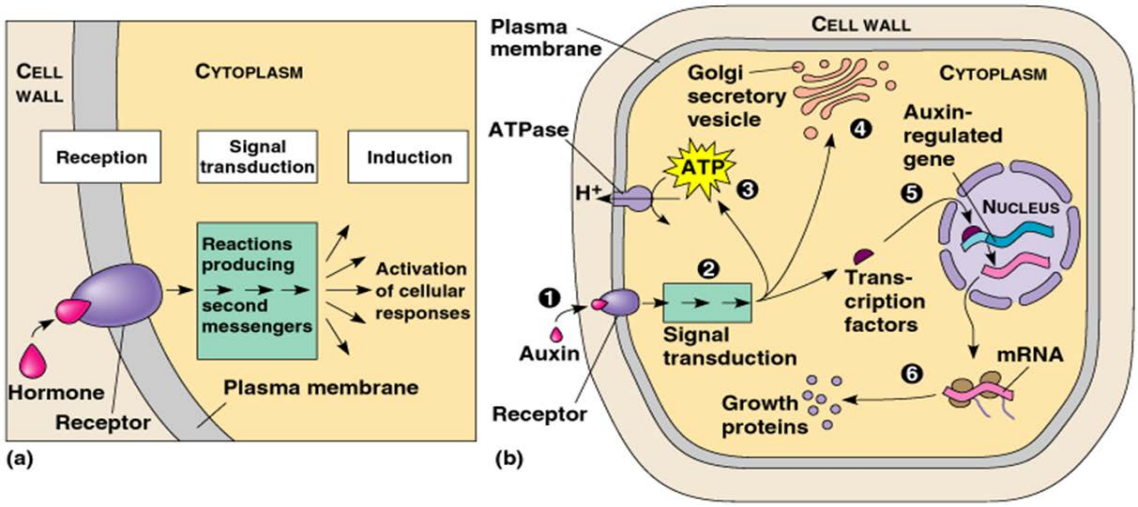
Functions: (i) it accelerates degreening, (ii) it induces abscission, (iii) it suppresses the vegetative growth and induce flowering, (iv) it induces sterility, and (v) it increases diseases resistance, salt tolerance and resistance to low temperature.

Growth Retardants

These are diverse groups of chemical having common physiological effect of reducing stem growth by inhibiting cell division of the sub-apical meristem. The formation of leaves, flowers and fruits remain unaffected. Growth retardation is primarily induced by inhibition of gibberellin biosynthesis between ent-kaurene and ent-kaurenoic acid. The important growth retardants are uniconazole, paclobutrazole (P333, Cultar), triapenthenol, flurpirimidol, inabefide, AMO-1618, CCC, Phosphon-D, C-111, B9, B2, 4-DNC.

Functions: (i) it retards stem elongation, (ii) it prevents cell division, (iii) it accelerates flower initiation, (iv) it inhibits root development, (v) it increases IAA oxidase activity, (vi) it inhibits staminate flower production, (vii) it block the synthesis of gibberellins, and (viii) it increases resistance to salt tolerance, drought resistance and pest resistance.

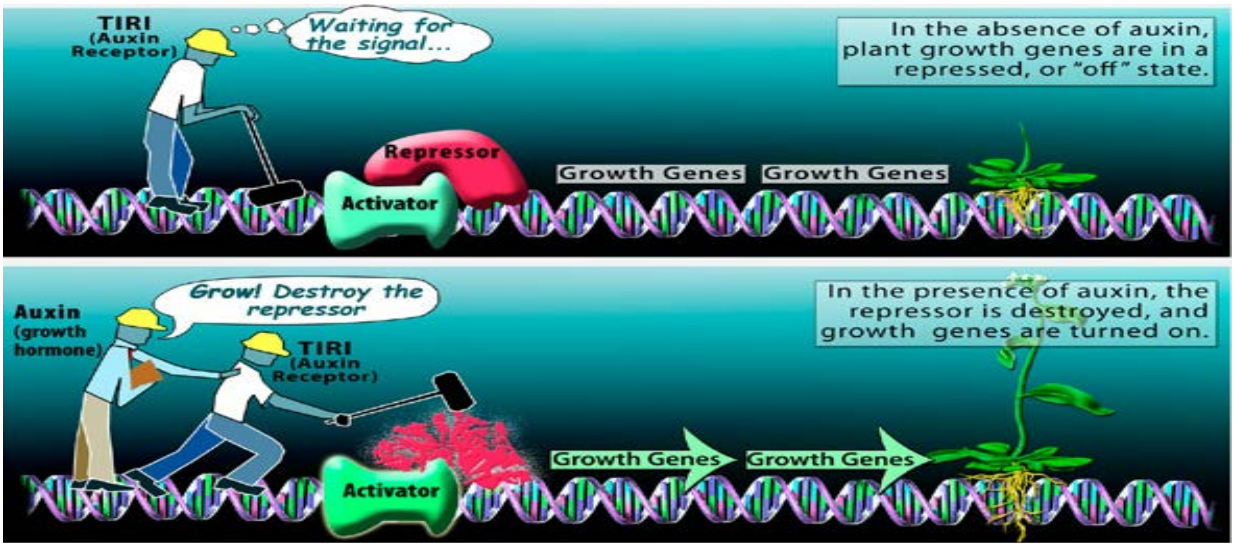
Mechanism for Auxin



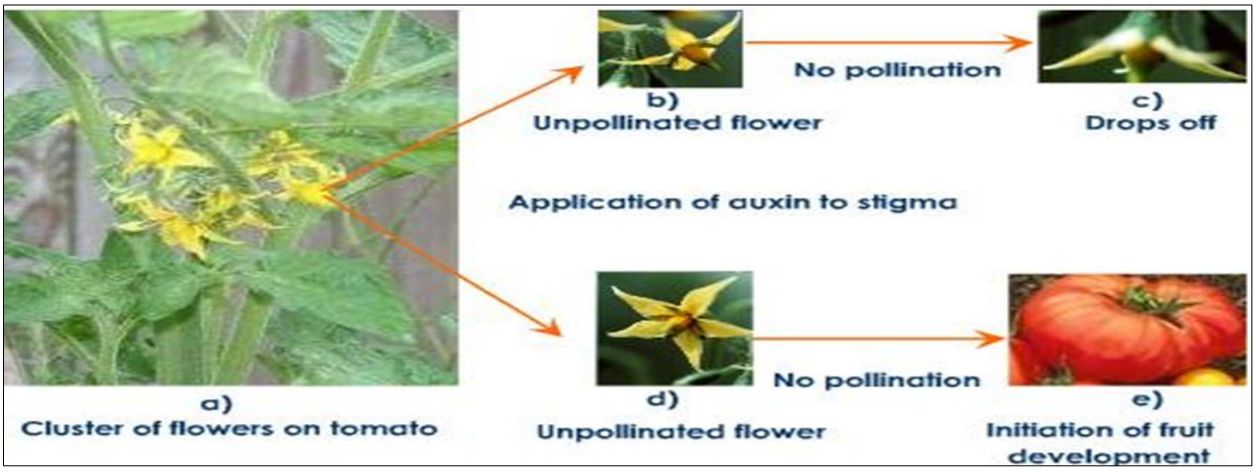
(a) Hormone binds to specific protein receptor which causes change in proteins conformation. This leads to production of secondary messengers which triggers or activates various cellular responses.

(b) Auxin binds to receptor which in turn through singaling causes proton pump, regulation of auxin genes, production of transcriptional factors. This leads to mRNA synthesis which in turn produces growth proteins thereby growth is enhanced.

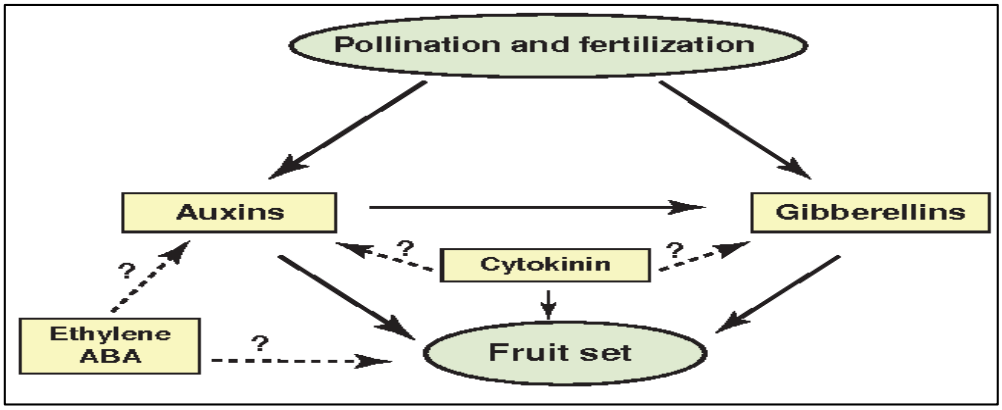
Signal Mechanism of Auxin:



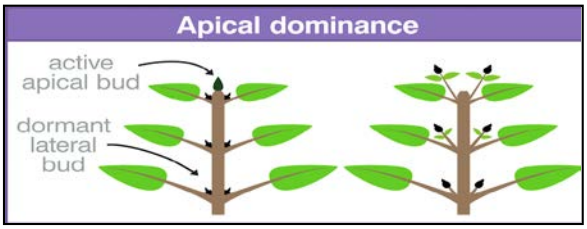
Parthenocarpy:



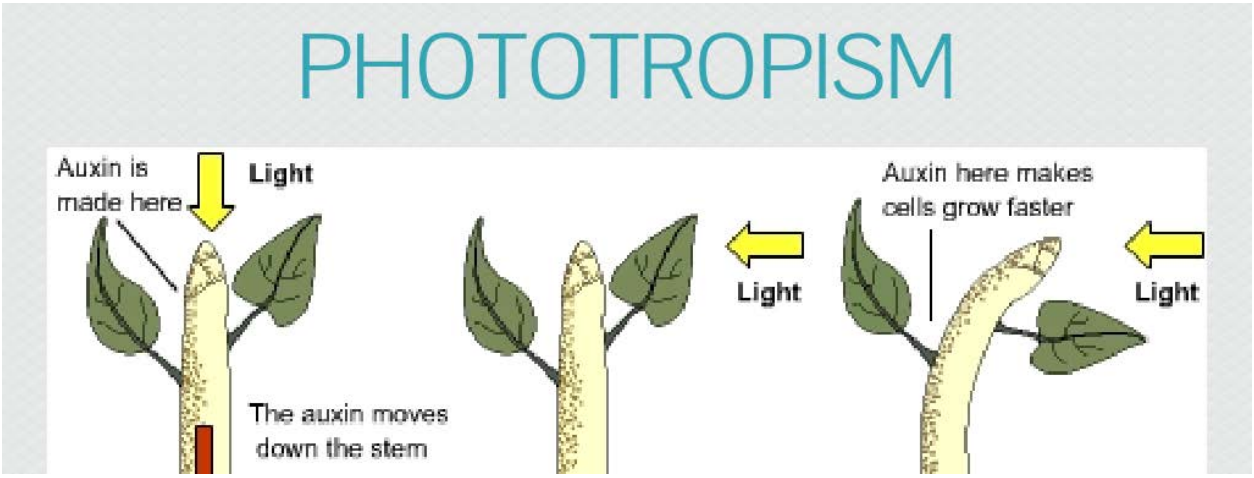
Fruit development:



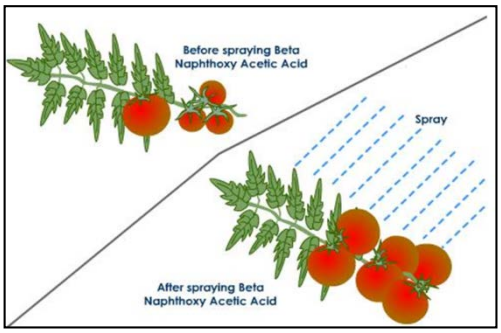
Pollination triggers the activation of auxin, which down regulates ethylene biosynthesis. This in turn reduces the suppressive effects of ethylene on GA synthesis, thereby promoting cell expansion. Pollination also activate cytokinin metabolism and suppresses ABA action thereby influence fruit set with growth. GA levels are also increased after pollination and lead to cell division and expansion.



If apical portion removed, then there is no auxin production and transport hence lateral buds are activated and developed.

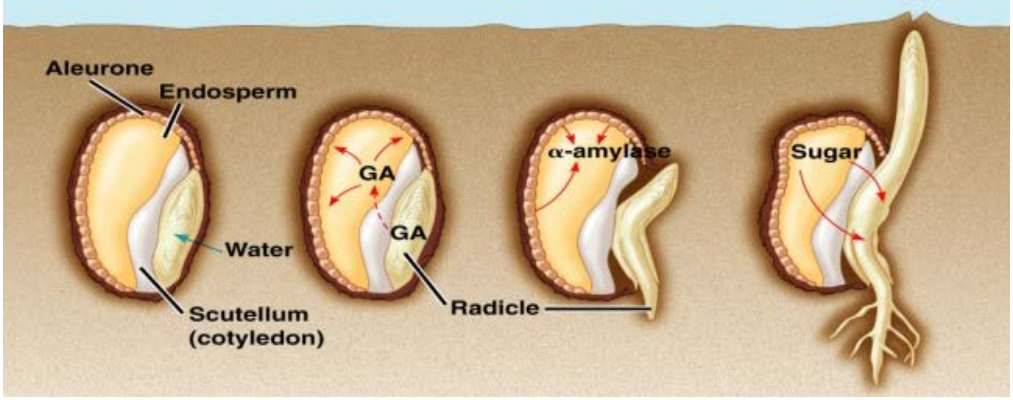


When NAA applied, auxin level is increased which causes nutrients mobilization and retention of fruits. So improved fruit set and yield.



When cuttings are treated with auxin, mobilization of reserved carbohydrates and nitrogen fractions takes place at wounded portion. Hence root initiation occurs.

GA activates the amylase which in turn converts starch to simple carbohydrate. This gives energy required for embryo activation hence germination takes place.



Stem elongation caused by GA is due to increased parenchymatous and mesophyll cells in tissue.

Cyto Kinin delays leaf senescence by preventing chlorophyll degradation and its synthesis.

Commercial Utility of PGRs in vegetable crops (Sunil Prajapati *et al.* 2015) [38]

Stimulation of fruit set: Poor fruit set is a major problem in solanum crops. In tomato apply 4-CPA, or 2,4-D@2-5ppm or PCPA 50-100ppm enhance the fruit set, and earliness.

Inhibition of sprouting: Application of MH @ 2500 ppm 15 days before harvesting prevents sprouting of onion in storage. Soaking potato tuber in IAA @ 250 to 1000 ppm solution or prolongs dormancy and thiourea @ 1% breaking the tuber dormancy.

Flowering: Application of GA at 50 mg/l to young leaves of non- flowering varieties of potato, when floral buds had just formed, resulted in flower induction in all varieties. MH delayed flowering in okra. GA has been reported to induce early flowering in lettuce.

Seed Germination: Pre-showing treatment of seed with growth regulators has been reported to enhance seed emergence. Okra IAA, NAA @ 20ppm enhances seed germination, In tomato, higher germination with GA_3 at 0.5 mg/l, and 2,4-D at 0.5 mg/l is reported. Soaking of seeds in ethephon at 480 mg/l for 24 h improved germination in muskmelon, bottle gourd, squash melon and watermelon at low temperature.

Seed Dormancy: Potato tubers fail to sprout before the termination of rest period; chemicals reported to break the rest period are GA, ethylene chlorhydrin and thiourea. For breaking of dormancy in potato comprise the vapour treatment with ethylene chlorhydrin (1 liter per 20 q) followed by dipping in thiourea (1%) for 1hr. finally in GA (1 mg/l) for 2 seconds. Lettuce is another vegetable in which treatment with GA has been reported to break seed dormancy induced by high temperatures.

Sex expression: Sex expression the treatment with growth regulators has been found to change 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.

Parthenocarpy: Auxin produced seedless fruits in cucumbers and watermelon, PCPA 50-100 ppm induced parthenocarpy in tomato and brinjal, application of 2,4-D at 0.25% in lanolin paste to cut end of styles or foliar sprays to freshly opened flower cluster has been reported to induced parthenocarpy.

Gametocides: Plants growth regulators possess gametocidal actions to produce male sterility this can be used for F1 hybrid seed production. MH at 100 to 500 mg/l in okra, okra, peppers and tomato, GA_3 in onion, 2,3- dichloro-isobutyrate (0.2 to 0.8%) in okra, muskmelon, okra, onion, root crops, spinach and tomato and TIBA in cucumber, okras, onion, and tomato. GA at 100 mg/l can also be used for inducing male sterility in pepper.

Hybrid seed production: Ethephon has been used for producing female lines in some cucurbits. Successful F1 hybrid in butter-nut squash has been made by using female line produced with ten weekly sprays of ethephon. Plant growth regulators have also been used for maintenance of gynoecious lines. In cucumber, GA_3 sprays have been made to induce staminate flowers in gynoecious lines. Silver nitrate at 500 mg/l has been reported to be as effective as GA_3 in inducing male flowers on gynoecious lines of cucumber. However, in muskmelon foliar sprays of Silver thiosulphate at 400 mg/ l was found best for induction of male flower on gynoecious lines.

Fruit ripening: Ethephon, an ethylene releasing compound, has been reported to induce ripening in tomato and pepper. Application of ethephon at 1000 mg/l at turning stage of earliest fruits induced early ripening of fruits thus increasing the early fruit yield by 30-35%. Postharvest dip treatment with ethephon at 500-2000 mg/l has also been reported to induce ripening in mature green tomatoes.

Fruit yield enhancer: Soaking of seed in NOA at 25-50 mg/l, GA at 5-20 mg/l and CIPA at 10-20 mg/l, 2,4-D, 0.5 mg/l or thiourea at 10-1 M have been reported to improve fruit yield in tomato. In brinjal soaking of seedlings roots in NAA at 0.2 mg/l and ascorbic acid at 250 mg/l has been reported to produce higher fruit yield.

Case studies of Role of Plant Growth Regulators in Vegetable Production:

Tomato:

Role of plant growth regulators are beneficial for growth parameters and yield of tomato. The different concentrations of NAA at 25, 50, 75 and 100 ppm and GA_3 20, 40, 60 and 80 ppm were sprayed on the plants of tomato and it was reported

that maximum plant height i.e., 85.3 cm and 82.3 cm was observed by using NAA at 100 ppm and GA_3 at 80 ppm and yield was also increased 483.6 q/ha and 472.2 q/ha with the use of NAA at 100 ppm and GA_3 at 80 ppm (Prasad *et al.*, 2013) [21].

In BARI Hybrid Tomato-8, 4- CPA (4- Chlorophenoxy acetic acid) + GA_3 applied together after 75 days of transplanting and observed that the tallest plant (79.35 cm), number of flowers (38.11) and fruits and (19.04) per plant, height (87.90 cm), number of flowers (49.04) and fruits (21.9) per plant, individual fruit weight (61.16 g), and fruit yield (27.28 tha-1) individual weight (58.44 g) and fruit yield (22.75 t ha-1) were found to be maximum (Rahman *et al*., 2015) [22].

The application of CCC (Cycocel) @ 500 ppm gave increased in height of plant, number of fruits per plant, fruit diameter and per plant seed yield after 45 days of transplanting of tomato seedlings as compared to NAA @ 50 ppm and GA3@ 50 ppm (Chauhan *et al*., 2017) [10].

Chilli

The treatments 2,4-D @ 2 ppm, triacontanol @ 5 ppm, NAA 40 ppm and GA_3@ 10 ppm produced 28.75%, 25.70%, 13.61% and 2.30% maximum fruit yield over control. It was recorded that maximum net profit and B: C ratio was found in case of 2 ppm 2,4-D. The use of GA_3 as foliar spray was not economical (Chaudhary *et al*., 2006) [9].

Different concentrations of growth regulators such as NAA (25, 50 and 75 ppm), GA_3 (20, 40 and 60 ppm), 2, 4-D (5, 7.5 and 10 ppm) and ethrel (300, 400 and 500 ppm) were used in chilli and applied after 30 and 60 days after transplanting. It was recorded that NAA @ 75 ppm gave maximum yield per plant (182.31g) and yield per hectare (6.37t). On the other hand, GA_3 @ 20 and 60 ppm treated plants gave maximum plant height (60.67 cm), maximum dry weight of 20 fruit (9.39g). The plant spread in (N-S) (36.97 cm) and maximum number of seeds per fruit (60.47) were recorded in 2,4-D @ 7.5 ppm treated plants.

Capsicum

In capsicum, NAA @ 60 ppm gave maximum plant height (120.59 cm), number of branches (16.05), days to first flowering (32.51), per plant number of flowers (11.83), weight of fruit (169.66g), per plant number of fruits (9.87), per fruit number of seeds (110.78), per plant yield (1.67kg) and per plot yield of fruit (15.07kg), yield per hectare (69.76t) were recorded (Singh *et al*., 2017).

Brinjal

Netam and Sharma (2014) [22] studied that GA_3 @ 10 ppm and NAA @ 20 ppm gave maximum number of branches, number of fruits, fresh fruit weight, total soluble solid.

Dhakar and Singh (2015) [16] observes that GA3@ 150 ppm gave heighest plant height, per plant number of leaves, length of leaf, per plant number of branches and stem diameter as compared to GA_3 @ 100 ppm and 200 ppm and minimum recorded in control.

Cauliflower

The performance of GA_3 and NAA at different levels as dipping of roots and by foliar spray on “SNOWBALL- 16” variety of Cauliflower. It was reported that foliar spray of GA3 at 50 mg/l in cauliflower gave better results for diameter of curd (17.78 cm), length of stalk (5.22 cm), net weight of curd (3.53 kg/plant), curd yield (12.5 kg/plot) and required minimum days to 50 % marketable curd (88.80 days) was reported by Sitapara *et al*., (2011).

Highest plant height (63.10 cm), number of leaves per plant (23.66), leaf length (59.05 cm), leaf breadth (18.98 cm) at the time of harvest, diameter of curd (22.39 cm), marketable yield per hectare (29.88 t/ha) were recorded by using IAA 10ppm + GA3 70 ppm than control. Also studied that the highest plant height (65.96 cm), number of leaves per plant (26.42), leaf length (63.64 cm), leaf breadth (20.92 cm) at the time of harvest, curd diameter (25.75 cm), marketable yield per hectare (31.03 t ha-1) were recorded from planting on 15 November and IAA 10 ppm with GA_3 70 ppm (Rahman *et al*., 2016) [22].

Cabbage

Islam *et al*., 2017 [21] used different concentrations of GA_3 on cabbage. They took four different levels of GA3 such as 0, 90, 120 and 150 ppm. They reported that GA_3 at 120 ppm gave highest marketable yield (65.5 t/ha) while minimum yield was recorded in GA 0 ppm (41.2 t/ha). Heighest plant height, maximum number of loose leaves per plant and diameter of head was recorded by using GA_3 at 120 ppm while minimum in GA 0 ppm. On the other hand, minimum days were recorded for formation of head in GA 120 ppm and maximum days was recorded in GA 0 ppm. So, they found that GA3 at 120 ppm was more effective.

Chaurasiy *et al*., (2014) used different concentrations of NAA (40, 80 and 120 ppm) and GA3 (30, 60 and 90 ppm) and applied as foliar spray on plants of cabbage at 30 and 45 days after transplanting. They reported that NAA 80 ppm and GA3 60 ppm gave heighest plant height, number of leaves per plant, plant spreading, diameter of stem, weight of plant, weight of head, and head yield as compared to all the other treatments and control.

Okra

Dhage *et al*., 2011 [12] revealed that IAA @ 100 ppm gave maximum plant height (107.74 cm), intermodal length (3.1 cm). However, by the application of GA3 @ 150 ppm, minimum days are required for first flowering (39.67 days) and minimum days were required for first harvesting (44.67 days). Ravat *et al*.,2015 recorded that GA3@ 50 ppm gave best seed quality characters like average pod weight (g), 100 seed weight (g). While GA3 gave maximum plant height, number of leaves, per plant number of nodes and thiourea @500 ppm gave maximum no. of pods per plant, length of pod (cm), number of seed per pod, per plant seed yield (g) and seed yield per hectare(q).

Onion and garlic

Patel *et al*., 2010 recorded that root dipping treatment of NAA @ 100 ppm significantly reduced physiological loss of weight, reduced loss in spoilage. Anbukkarasi *et al*., 2013 recorded that CCC, ethylene and and fungicides play an important role in delay in sprouting and extant shelf life in onion. Bannu Priya *et al*., 2014 reviewed the work done onpre and post-harvest treatments in onion to extend shelf life.

Cucurbits

Hidayatullah *et al*., 2012 [20] revealed that GA3 @ 30 ppm increased in production of pistillate flowers, maximum no. of fruits and fruit weight as compared to control in bottle gourd. Dalai *et al*., 2015 [11] reported that GA_3 @ 20 ppm + NAA @ 100 ppm gave heighest wine length/plant (cm), no. of leaves/ plant. On the other hand, GA_3 @ 20 ppm + NAA @ 100 ppm

gave maximum yield in cucumber.
Sandra *et al*., 2015 resulted that NAA @ 200 ppm, GA_3@ 50 ppm and etheral @ 50 ppm were very effective for enhancement in vegetative growth, fruit and seed yield and modification in sex expressions and GA_3 @ 50 ppm was effective in production of hybrid seed in bitter gourd.

Potato
Foliar application of ethrel at 250 ppm was effective in changing phenotype of plant, increased in plant height, diameter of shoot, per plant number of tubers and total yield of tuber as compared to control (Awati *et al*., 2016) [33].

Application of GA_3 at 60 days after transplanting had increased in height of plant but number of tubers, weight and content of dry matter were not affected. Late application of GA_3 leads for induction of high percentage of sprouted tubers prior to harvest and also lead to increase physiological age of tubers (Alexios *et al*., 2006) [1].

Pea
Singh *et al*., 2016 reported that GA3 at 200 ppm gave significantly increased in height of plant, number of leaves, total number of branches, number of pods, length of pod and 100 seed weight.

Effect of Plant growth regulators in quality of Vegetable crops.

Growth Regulator	Concent ration (Ppm)	Method of Application	Crop	Effect on Quality
GA_3	15	Foliar spray	Muskmelon	Improve rind thickness
GA_3	5-15	Foliar spray	Cauliflower, cabbage	Increases head or curd size
GA_3	50	Foliar spray	Lettuce and Chinese Cabbage	Increases dry matter, protein and ascorbic acid content
PCPA	50	Foliar spray	Tomato	Increased dry matter, sugar and vitamin-C, but reduces acidity
Ethephon	250	Foliar spray	Tomato	Increases TSS
NAA	50-70	Seed treatment	Chilli	Increases amino acid and vitamin-C content in fruits
Mixtallol	1-2	Foliar spray	Potato	Increases starch, reducing sugars, non-reducing sugars, total sugars, and protein
CCC	250	Foliar spray	Potato	Increases TSS and vitamin-Ccontent in tuber
MENA (vapour) + CIPA	5000	Post-harvest dip	Potato	Reduces sprouting and rooting of tuber in storage
2, 4, 5-T	75-125	Pre-harvest spray	Potato	Reduces sprouting and rooting of tuber in Storage
MH	2500	Pre-harvest spray	Potato	Reduces sprouting and rooting of tuber in storage
Cytozyme	1%	Foliar spray	Garden pea	Increases vitamin-C, reducing sugars and total sugars

(**Source:** Bahadur and Singh, 2014).

Role of plant growth regulators in Plant Tissue Culture

Class	Name	Comments
Auxins	Indole-3-acetic acid (IAA)	Use for callus induction at 10-30 µM. concentration of 1-10 µM can stimulate organogenesis. It is inactivated by light and readily oxidized by plant cells.
	Indole-3-butyric acid (IBA)	Use for rooting shoots regenerated via organogenesis. Either maintains at a low concentration (1-50 µM) throughout the rooting process, or expose to a high concentration (100-250 µM) for 2-10 days and then transfer to hormone free medium.
	2, 4 dichlorophenoxy-acetic acid (2, 4-D)	Most commonly used synthetic auxin for inducing callus and maintaining callus and suspension cells in de-differentiated states. Usually used as sole auxin source (1-50 µM), or in combination with NAA
	Para-chlorophenoxy acetic acid (PCPA) and α- Naphthaleneacetic acid (NAA)	Its use is similar to 2, 4-D. Commonly used either as sole auxin source (2-20 mM for callus induction and growth of callus and suspension cultures; 0.2-2 µM for root induction) or in combination with 2, 4-D
Cytokinin	6-Furfurylaminopurine (kinetin)	Often induced in culture media for callus induction, growth of callus and cell suspensions, and induction of morphogenesis (1-20 µM). Higher concentration (20-25 µM) can be used to induce the rapid multiplication of shoots, axillary/adventitious buds or meristem.
	6-Benzylaminopurine (BAP, BA)	Induced in culture media for callus induction, growth of callus and cell suspensions (0.5-5.0 µM), and for induction of morphogenesis (1-10 µM). More commonly used than kinetin for inducing the rapid multiplication of shoots, bud, or meristem at concentration of 5-50 µM.
	N-Isopentenyl amino-purine (2iP)	Less commonly used than kinetin or BAP. For callus induction and growth (2-10 µM), induction of morphogenesis (10-15 µM), or multiplication of shoot, bud, or meristem (30-50 µM) is used.
	Zeatin (Zea)	Seldom used in callus or suspension media. Can be used for induction of morphogenesis (0.05-10 µM). Zea is thermolabile and must not be autoclaved.
Gibberellin	Gibberellic acid (GA_3)	Rarely used in callus or suspension medium (one exception being potato). Can promote shoot growth when added to shoot induction medium at 0.03-14 µM. Also used to enhance development in embryo/ ovule cultures (0.3-48 µM). GA_3 is thermolabile and must not be autoclaved.
Abscisic acid	Abscisic acid (ABA)	Used at concentrations of 0.4-10 µM to prevent precocious germination, and promote normal development of somatic embryos.

(**Source:** Bahadur and Singh, 2014).

ROLE: Germination and Growth

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

Hardening and Seedling establishment

Crop	PGR and dosage (ppm)	Method	Effect
Tomato	CCC (500-1000)	Spray	Inducing hardening, reduces leaf curl infestation
	NAA (0.1-0.2)	Seedling root dip	Reduce transplanting shock & improves seedling growth
Brinjal	NAA (0.1-0.2)	Seedling root dip	Reduce transplanting shock & improves seedling growth

Flowering

Crop	PGR and dosage (ppm)	Method	Effect
Tomato	GA_3 (ppm)	Spray	Induction of exerted stigma, maintenance of antherless mutant

Induction of pollen sterility (Gametocidal effect)

Crop	PGR and dosage (ppm)	Method	Effect
Tomato, Brinjal, Pepper	MH (100-500)	Spray	Inducing MS
Tomato, Brinjal	FW-450, TIBA, 2,4-D	Seedling root dip	Inducing MS
Pepper	GA (100)	Spray	Induces MS

Fruit set:

Crop	PGR and dosage (ppm)	Method	Effect
Tomato	MH (20) & NAA/PCPA (50-100)	Foliar spray	Increases fruit set, earliness
	4-CPA or 2,4-D (2-5), kinetin (5) & GA_3 (10)	Foliar spray	Increases fruit set
	PCPA (50-100)	Spray	Induces parthenocarpy
Brinjal	IAA (100)	Foliar spray	Increases fruit set
	2,4-D (2.5) or PCPA (50-100)	Lanolin paste	Induces parthenocarpy
Chilli	Triacontanol (1) NAA (10-20)	Foliar spray	Reduces flower drop & increases fruit set

Fruit ripening

Crop	PGR and dosage (ppm)	Method	Effect
Tomato Chilli	Ethephon (1000) & (500-2000)	Spray & post-harvest dip	Early and uniform ripening

Yield

Crop	PGR and dosage (ppm)	Method	Effect
Chilli	Planofix (10) or GA_3 (50)	Spray	Increases fruit set & yield
	Triacontanol (2)	Spray	Check fruit drop and improves yield
Tomato	Ethephon (250) or PCPA (50)	Spray	Increases fruit set & yield
	NOA (25-50) or GA_3 (5-20) or 2,4-D (0.5) or CIPA (10-20)	Spray	
Brinjal	Mixtallol (4)	Spray	Increases fruit yield
	IAA (50) or GA_3 (40) or ascorbic acid (250) or NAA (0.2)	Seed soaking & seedling dip	

Biotic & Abiotic Resistance

Crop	PGR and dosage (ppm)	Method	Effect
Tomato	2,4-D, NAA, TIBA, IAA	Spray	Reduce Fusarium wilt, TLCV, TMV
	Ethephon or cycocel (500) & GA_3 (25) CCC (0.4-0.5%)	Spray	Frost tolerance Cold hardiness
	Ethephon or MH (5000), IAA, ABA, cytokinins	Root drenching	Drought tolerance
	Cycocel (5-12 mg a.i./plant) or (0.1-0.3%) or 1%	Soil application Foliar spray, dipping	Salinity tolerance
	PCPA (50) or NAA (10)	Spray	High temperature
Potato	Daminozide	Spray	Reduces common scab
	CCC (0.74 kg/ha), GA_3	Spray	Frost tolerance

Application Method

- Seed treatment
- Seedling treatment
- Foliar application
- Post-harvest dipping
- Root feeding method
- Aerosol method
- Lanolin paste

- Injection of solution into internal tissues

Calculation

The rate of growth regulator is calculated using this formula,

$$\text{Formulation required (lb)} = \frac{\text{(Desired ppm)}}{1{,}000{,}000} \times \frac{\text{(gallons of water) x 8.345}}{\text{(\% active ingredient)}}$$

To convert pounds to kg/g, multiply the result by 0.454/454

Precautions

- Sprayed in afternoon
- Avoid in windy hours
- Uniform spray
- Add surfactant or adhesive materials - Teepol & Tween-20 (0.5-1 ml/l)
- Use at proper growth stage
- Completely dissolved before use
- Use fresh solution
- Use distilled water
- Clean sprayer after each spray
- If chemical lost, repeat spray within 8 hours

Constraints

- The difference in sensitivity of each plant species or even cultivars to a given chemical treatment prevent easy predication of the biological effects.
- The cost of developing new plants growth regulator is very high, due to which they are very much costly.
- Screening for plant growth regulatory activities entails high costs and is very much difficult.
- Lack of basic knowledge of toxicity and mechanism of action.
- Inadequate market potential.
- Lack of support from agricultural researchers in public and private sectors.
- Difficulty in identification of proper stage of crop at which the growth regulators should be applied.

Future thrust

- Most of the biological processes associated are polygenic, so gene transfer may be difficult and hence the use of PGR's may be beneficial for short imperatives.
- PGR's provide an immediate impact on crop improvement programmers and are less time consuming.
- Applications of PGR's must lead to quantifiable advantages for the user.
- Industries involved in development of PGR's should be well informed about the latest scientific development in production of PGR's.
- PGR's must be specific in their action and toxicologically and environmentally safe.
- Plant growth regulators should be recognized as more than academic curiosities. They are not only interesting but profitable to use to grower, distributor and manufacturer.
- More research is needed to develop simple, economic and technical viable production systems of PGR's.

Conclusion

Plant growth regulators has an immense potential in vegetable production to increase the yield, quality, synchronization in flowering, earliness, cold and high temperature fruit setting, sex modification, increase post-harvest life and resistance to biotic and abiotic stresses of vegetables to better meet the requirements of food supply in general. But more research is needed to develop simple, economical and technical viable production system of bio-regulator. Bioregulators must be toxicologically and environmentally safe

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