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Integration of plant growth regulators and fertigation: A sustainable approach to enhance fruit yield and quality

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Abstract
PGRs with fertigation, an advanced, novel and ecofriendly technique may have the potential to contribute to fruit yield and quality enhancement in modern horticulture. Fertigation is the application of water-soluble fertilizers through irrigation, which contributes to an efficient nutrient delivery and to an enhanced plant nutrient-use efficiency. Meanwhile, PGRs are able to control plant physiological and biochemical activities including cell division, flowering, fruit set and ripening, as well as tolerance to stress. In concert, these systems result in synergistic improvements in nutrient uptake, hormone balance, and metabolic function. Several reports on fruit crops (mango, banana, citrus and grapes), have shown a positive feedback of PGRs (paclobutrazol, NAA, GA_3, and cytokinins) application with fertigation with respect to canopy structure, uniform flowering, fruit set, size of the fruit and quality parameters such as total soluble solids, sugars and storage life. Overall, the synergistic approaches lead to enhanced process efficiency and sustainability by reducing nutrient losses, chemical input, and enhancing soil-water health. Prospective studies need to be directed toward designing crop- and region-specific fertigation-PGR protocols and integrate smart-tools such as IoT and precision fertigation for climate-resilient fruit production.

Keywords: Plant growth regulators, fertigation, fruit crops, sustainable agriculture, nutrient-use efficiency, fruit quality, productivity

1. Introduction
Fruits are very important staple foods for human health and economic gains as they serve as a source of vitamins, minerals and dietary fiber. But their production and quality are facing an unprecedented threat from the degradation of soil fertility, water shortage and climate change (Yang *et al*., 2024; Seijger *et al*., 2025) [47, 34], and thus innovative measures are urgently needed for the sustainable production.

Sustainable horticultural intensification is the enhancement of yield in horticulture with minimum environmental degradation. Fertigation and plant growth regulators (PGRs) play an important role by enhancing efficiency of nutrient utilization, and by controlling plant growth, development and responses to stress (Contreras *et al*., 2020; Ali *et al*., 2024) [10, 1].

Fertigation, the introduction of water soluble fertilizers in irrigation water through the irrigation systems, has the advantages of precise delivery of fertilizer to the plant root zone, which minimizing losses and increasing fertilizer uptake. In fruit crops, compared with traditional application methods, fertigation can save 30-50% of nutrients (Ashrafi *et al*., 2020; Contreras *et al*., 2020) [5, 10], and under drip irrigation, the efficacy of nutrients and water can be further improved.

Plant growth regulators have an impact on germination, flowering, fruit set, and stress response (Anim *et al*., 2025) [3]. Cytokinins have been found to stimulate cell division and nitrogen assimilation, whereas auxins increase nutrient and water uptake by regulating root architecture. Application of PGR can enhance fruit set, uniform ripening, and tolerance to environmental stressors including drought and salinity (Ali *et al*., 2024) [1].

The combination of fertigation and PGRs offers comprehensive management: matching nutrient supply with crop demand, increasing fruit yield and quality, and reducing

Environmental pollution (Anim *et al*., 2025) [3]. This synergy supports the aims of sustainable intensification, increasing output with decreasing inputs while preserving environmental.

2. Concept and Mechanism of Fertigation
Definition and Development

Fertigation: The term fertigation is originated from the words "fertilization" and "irrigation". The practice has had early origins in 1960's in Israel with the evolution of micro-irrigation systems in arid regions. Computer control of these systems allowed for the timing, amounts, and targets of nutrients to be more refined, thus increasing the efficiency of both water and fertilizer.

Evolutionary Milestones of Fertigation	Key Developments
1930s	Early subsurface irrigation trials using canvas tubes
1960s	Introduction of drip irrigation in Israel and integration with nutrient application
1970-1990s	Advancements in pressurized and micro-irrigation systems for uniform fertigation
2000s onward	Automated and sensor-controlled fertigation for precision farming

Source- Kafkafi, 2005

Concept and Operation
The fertigation system starts with soluble fertilizers combined in a nutrient tank. An injector system introduces this nutrient solution into the line of irrigation water, and is operated via valves and sensors to manage dosage and timing. This nutrient-packed solution is pumped through drip or sprinkler lines to the root zone where it facilitates nutrient uptake.

Mechanistic Steps Involved
1. **Preparation of Fertilizer Stock Solutions:** The water-soluble fertilizers are mixed and dissolved in a mixing tank to form a nutrient-rich solution. For fertigation, solutions of fertilizer can be made on the farm as stock solutions from the number of water-soluble solid fertilizers (Hagin *et al*., 2002) [17].
2. **Injection into Irrigation Lines:** Nutrients are added to the irrigation water using injectors (venturi, pump, etc.) that are calibrated to manage flow rate and concentration of the fertilizer solution.
3. **Regulation of pH, Electrical Conductivity (EC) and Flow:** The automated sensors continuously measure pH and the EC of the nutrient solution, and the system automatically compensates to maintain proper levels for plant uptake. Flow meters provide a stable delivery rate. Fertilizers must be dissolved in solution or in a series of solutions concentratedThese nutrient (or stock) solutions are injected into the irrigation system through one of several available systems of fertigation.
4. **Homogenous application through micro-irrigation emitters:** The solution is applied to the root zone uniformly by drip or through a sprinkler system so the plants have the same access of nutrients.
5. **Water and Nutrients-Upkeep of Synchronized Growth:** At the pace of growing plant, nutrients makes available together with water. And accordingly they have balanced and efficient growth during the entire growing season.

Advantages over Conventional Fertilization
Fertigation offers multiple agronomic and environmental benefits

- **Nutrient efficiency:** Fertigation enhances nutrient-use efficiency by synchronizing nutrient availability to water uptake by plants, which induces both higher uptake and reduced losses. Fertigation systems are frequently composed of automated controls, leading to a decrease in labor time.For instance, the benefit-to-cost ratio of sugarcane production was found to increase when using fertigation, partly because of reduced labor time (Bao *et al*., 2023) [7].
- **Reduced leaching and runoff:** Sequential release allows a controlled delivery that reduces leaching, runoff and volatilization, thus contributes to the protection of water quality. Fertigation has been proven not only to decrease fertilizer use but also to decrease nutrient leaching (Bao *et al*., 2023) [7].
- **Water and labor savings:** When integrated with an automated irrigation system, it minimizes labour, optimizes water use, and helps conserve the resources.Agitation-Free Fertigation systems don't require you to apply fertilizer manually, they save time and reduce labor costs (Lakhiar *et al*., 2024) [25].
- **Environmental sustainability:** Reduced volatilization and runoff protect the ecosystems and contribute to the reduction of the carbon footprint related to the use of fertilizers.Timing was not considered in this study, although risk of nutrient loss can be reduced by reducing temporal mismatch between nutrient application and crop uptake This chapter outlines the basic principles of fertigation, which guarantees delivery of right amount of nutrients at the right time to the right place by applying them through irrigation water (Tyagi *et al*., 2022) [44].

Interaction between Fertigation and Soil-Plant Systems
How fertilization through irrigation (fertigation) affects soil-plant interactions

- A notable benefit of fertigation is the delivery of nutrients to the root zone with irrigation/ water, resulting in the nutrient availability being localized in the rhizosphere (soil zone around the roots) rather than a field application. This enhances the spatial synchrony of plant nutrient and nutrient supply. For instance, one extension bulletin reads

  Differences in nutrient availability - Since nutrients are provided during the entire growing season in small amounts using fertigation, nutrients are more concentrated in the root zone compared to traditional, dry granule fertilization treatments (Meng *et al*., 2023) [27].
- The proximity of the nutrients to the roots enhances the chances of nutrient uptake by plants and reduces the risk of loss by leaching or runoff.
- Fertigation also commonly involves micro-irrigation systems (drip, micro-sprinkler), which allow precision delivery of water and nutrients, as well as improved monitoring of soil moisture levels, root zone

conditions, and nutrient mobility.In a study on drip irrigation and fertigation:

Fertigation applies fertilizer to the crops within the root zone at the right time and concentration.Together, these also contribute to labor saving, improving soil-air-water relations for enhanced productivity (Singh *et al*., 2023) [37].

Impact on Soil Micro-Environment, Structure & Microbial Activity

- Fertigation has an impact on nutrients availability and on soil physical, chemical and biological status:
- The Soil moisture regime is more stable and localized; improved moisture management encourages desirable root growth and microorganism living (Singh *et al*., 2023) [37].
- The root-zone soil nutrient concentrations are more stable, preventing large swings that could stress the roots or microbes. For example, studies on N-fertigation frequency observed shifts in soil N distribution around roots (Dan 2023).

On microbial activity: Numerous reports indicate that irrigation regimes and nutrient applications influence the size, diversity and community composition of microbes in the soil. For example: Irrigation, but not N fertilization, had a strong effect on the bacterial alpha diversity index. The effect of irrigation (IR) on the abundance, diversity and composition of soil bacteria was much stronger than that of N fertilization (NF) (Li *et al*., 2021) [26].
Although fertigation can contribute to the improvement of nutrient use efficiency, the effect on soil health, especially on the availability of nutrients, microbial community and enzyme activities, is still poorly known in tropical environment (Sneha *et al*., 2025) [38].
A report on the integration of drip-fertigation with organic residue management (straw mulching and straw incorporation) reported a beneficial impact on soil microbial diversity and activity: Drip fertigation in combination with straw addition enhances soil microbial diversity and stability (Hu *et al*., 2023) [18]. These results are consistent with the notion that fertigation may improve soil microbial habitat (due to favourable moisture and nutrient status, and root exudates), thereby enhancing nutrient cycling, and root health, and consequently plant growth.

Effect on Root Distribution, Nutrient Uptake and Plant Growth

As the nutrient and water are supplied to the root zone at the same time, roots may "chase" the nutrient-rich patches, leading to optimized root architecture and distribution. For example: Tailoring fertigation strategies to root distribution.Fertigation schemes influenced soil nutrient dynamics, root uptake and crop yield (Meng *et al*., 2023) [27].
With the positive soil moisture and nutrient gradients, root expansion is facilitated, roots may sample a greater soil volume, and nutrients (N, P, K, micro nutrients) are more accessible when the plant demands them. The combined effect of improved root access and more strategic nutrient placement leads to increased nutrient uptake efficiency.
Better absorption, and better root access, then translate to more robust growth, development, and yield above ground. As the extension article points out: since nutrients are concentrated in the area of the root and applied more often in smaller quantities, fertigation "maximizes the potential for nutrient uptake by the plant.

Tailoring to Different Fruit Crops and Optimisation of Fertigation Schedules

- A key advantage of fertigating is the flexibility in the rate, time and placement of nutrients that can be closely synchronized with crop growth stages (vegetative, flowering, fruiting) and patterns of root development. For example, an extension source states
  Matching fertigation to major crop uptake periods will help maximize nutrient efficiency and increase crop yields and quality (Quinones *et al*., 2012) [31].
- This was shown by a modelling study: in various soil types (silty clay, loam, sandy loam) for a micro-irrigation system, adjusting the fertigation schedule resulted in an increase in plant N uptake and a decrease in nitrate leaching (Azad *et al*., 2020) [6].

This customization is particularly pertinent for fruit crops (which typically have different nutrient requirements during flowering, fruit set, enlargement and maturation) providing the correct nutrient combinations at the right time, adjusting for root zone water status, and minimizing losses is made possible by the fertigation system.

3. Role and Mechanisms of Plant Growth Regulators (PGRs)

Overview of Different Classes

- Plant growth regulators (PGRs) are either naturally occurring or synthetic substances that influence certain processes of plant growth and development. The main classes include.
- **Auxins:** These hormones control cell elongation, induce root formation and are important in fruit set. Auxins modify cell division and cell expansion, and thereby plant architecture and fruit formation.
- **Gibberellins:** Gibberellins stimulate stem elongation, flowering, and fruit growth. They also promote seed dormancy breaking as well as induce enzyme production in fruits.
- **Cytokinins:** Cytokinins retard leaf senescence by enhancing chlorophyll retention and also stimulate cell division. They also affect nutrient mobilization and they can potentially influence fruit size through enhancement of cell proliferation.
- **Ethylene:** Ethylene is a hormone, released as a gas, that regulates fruit ripening and abscission (shedding of leaves, flowers, or fruits). It controls the soft tissue destruction, color transformation and aroma formation in fruit.
- **Abscisic Acid (ABA):** ABA is the main regulator of stress responses such as drought tolerance by closing stomata, thereby reducing water loss. It also influences seed dormancy and fruit ripening.
- **Brassinosteroids:** These steroidal hormones increase stress tolerance, enhance photosynthetic capacity, and facilitate plant growth and development.

These classes of PGRs work in a complex network affecting plant physiology and morphogenesis (Ghosh *et al.*, 2022) [14].

Physiological Roles in Fruit Development

PGRs effect several phases of fruit development, including

- **Flowering and pollination:** The use of auxins, gibberellins, and cytokinins in flower initiation, flower development and successful pollination, all of which are required for fruit set.
- **Fruit Set and Growth:** Auxins and gibberellins stimulate fruit set formation by promoting cell division and cell expansion and preventing uneven fruit growth and fruit size.
- **Ripening and Quality:** Ethylene orchestrates the ripening process, affecting important quality traits such as flavor, texture, color, and shelf life (Bisht *et al*., 2018) [8].

Mechanisms by Which PGRs Influence Yield and Fruit Quality

PGRs modulate yield and quality through several physiological mechanisms

- **Carbohydrate Partitioning:** PGRs affect the distribution of carbohydrates, directing energy and assimilates towards developing fruits to support growth (Kumari *et al*., 2018) [24].
- **Nutrient Uptake:** Auxins and cytokinins enhance root activity, improving nutrient absorption and availability to the fruit (Tiwari *et al*., 2023) [42].
- **Stress Tolerance:** Abscisic acid and brassinosteroids improve resilience against drought, salinity, and other abiotic stresses, protecting yield and fruit quality under adverse conditions (Zhang *et al*., 2023; Singh and Roychoudhury, 2023) [49, 36].

Understanding the roles and interactions of PGRs is crucial for optimizing fruit crop management, improving yield, and enhancing post-harvest quality.

4. Integration of Plant Growth Regulators (PGRs) and Fertigation: Concept and Rationale

Synergistic Effects of PGRs and Fertigation

The co-delivery of Plant Growth Regulators (PGRs) with nutrients through fertigation is an advanced technique of crop management in which the nutrient and hormonal regimes are synchronized to achieve best plant performance. This common approach leads to multi-fold benefits

- **Enhanced Nutrient Use Efficiency:** Fertigation provides a precise and timely application of nutrients directly to the soil root zone and PGRs control physiological processes that lead to an enhanced nutrient absorption and assimilation. Combined, they allow maximum absorption and exploitation of essential nutrients, reducing losses and enhancing fertilizer use efficiency.
- **Improved Hormonal Balance:** PGRs applied using fertigation or as a foliar spray allow for a balanced hormonal milieu required for growth regulation. The coordination of nutrient supply and hormonal signaling is important for key events such as flowering, fruit set, and enlargement.
- **Better Stress Management:** PGRs, such as abscisic acid and brassinosteroids, increase plant tolerance to abiotic stresses, and fertigation ensures good soil moisture and nutrients balance. This dual dependent modulation of ABA signaling enhances the ability of plants to tolerate drought, salinity, and temperature stress and thereby protects the potential for high yield and fruit quality under stress conditions.

Examples from Fruit Crops

- **Mango:** The foliar application of paclobutrazol (a growth retardant PGR) along with potassium nitrate (KNO_3) through fertigation was found to be effective in enhancing the magnitude of flowering and uniformity of fruit set. This is conducive to better source-sink relationship and hormonal manipulation during reproduction stages (Swain *et al*., 2023) [40].
- **Banana:** Application of gibberellic acid (GA_3) in combination with balanced NPK fertigation increases the size of the fruit, the bunch weight, and the total fruit quality.The hormonal control promotes cell elongation and cell division and the optimal supply of nutrients fulfills thehigher metabolic needs in the growing fruit during fruit enlargement (Khodair and Radwan, 2018; Gawade *et al*., 2021) [22, 12].
- **Citrus:** Use of synthetic auxins like 2,4-dichlorophenoxyacetic acid (2,4-D) along with balanced fertigation schedules results in uniform fruit set and better peel quality. This concerted action on fruit abscission, resulting in reduced fruit drop, stabilizes yield (Stander *et al*., 2014) [39].

5. Effects on Vegetative Growth and Flowering

Influence on shoot growth and canopy development

The combined use of plant growth regulators (PGRs) with fertigation has frequently resulted in a more balanced vegetative response than when applied separately. Growth retardants such as paclobutrazol (PBZ) reduce unacceptable excessive vegetative elongation (shorter internodes and denser canopy) allowing the production of a more compact, manageable canopy that intercepts light more uniformly, and combined with the supply of nutrients in a targeted way through fertigation, plants take up the right quantities of N, K and micro elements necessary for the development of the leaves without favoring this excessive extension of the shoots. This equilibrium (less excessive elongation + sufficient nutrition) generally results in more uniform canopy expansion and an improved canopy organization for light interception and spray penetration (Upreti *et al*., 2013) [45].

Improved Leaf Chlorophyll Content and Photosynthetic Capacity

Fertigation which is achieved through keeping the soil moisture content at a desired level and by providing nutrients in small amounts at high frequencies promotes steady availability of nitrogen in the root zone that is closely associated with leaf chlorophyll concentration and photosynthetic behavior. Investigations and up-to-date reviews describe improvements in leaf chlorophyll and photosynthetic parameters upon optimized fertigation regimens and PGRs can also indirectly promote chlorophyll conservation by curbing excessive vegetative growth and by mitigating plant water stress. Collectively, these phenomena enhance canopy photosynthetic capacity and resource-use efficiency (Mian *et al*., 2024) [28].

Role in Synchronization of Flowering

Some PGRs are widely used to alter flowering phenology and synchrony. PBZ, a gibberellin biosynthesis inhibitor, is widely used to promote or advance flowering of fruit trees (including mango) by altering the plant's hormonal status from vegetative growth to reproductive growth. When applied at the correct stages/rates panicle/flower emergence and deformed panicles can be reduced and this may contribute to a more synchronous and better quality bloom.Along with fertigation (where nutrient supply meets reproductive demand), these hormonal products tend to produce a narrower, more synchronous flowering window and better fruit set (Husen *et al*., 2012) [19].

6. Effects on Yield Attributes- Integrated PGR + Fertigation

Impact on Fruit Number and Size

Integrated management using Plant Growth Regulators (PGRs) together with optimized fertigation commonly results in

- **Increased fruit number:** PGRs (auxins, gibberellins, cytokinins) enhance retention of flowers and fruit set and fertigation provides nutrients at critical stages of growth during necessary fruit development (Wagle *et al*., 2022) [46].
- **Fruit with bigger size:** Plant growth regulators application (such as auxins and gibberellins) proliferate cell expansion and thus fruit growth; fertigation provide for a constant supply of nutrients (N, K and micronutrients) during the period of fruit enlargement which favor higher individual fruit mass (Moradinezhad *et al*., 2024) [29].

Mechanisms (How Integration Produces These Effects)

1. **Enhanced photosynthetic efficiency and assimilate supply**

- Certain PGRs (such as brassinosteroids and gibberellins) enhance photosynthetic activity, promote source-sink alterations that may result in increased availability of carbohydrates for fruit development, or delay senescence. These hormonal influences along with continuous nutrient supply via fertigation contribute to the maintenance of carbohydrate formation and movement to fruit (Trejo *et al*., 2023) [43].

2. **Better nutrient uptake and utilization (NUE)**

- Fertigation is the application of nutrients over time at a certain frequency and locally in the rhizosphere where the roots are active in Canada infinitely more efficient. This temporal and spatial synchrony of nutrient supply and demand minimizes nutrient losses and maximizes plant- available nutrient supply during critical fruit-development stages, enhancing nutrient uptake efficiency and fruit growth (Alva, 2005) [2].

3. **Hormonal control of fruit retention and growth**

- The abscission-suppressing effect of auxins (including synthetic auxins) and gibberellins can extend the phase of cell expansion in fruits; under non-limiting nutrient conditions, the hormonal stimulation of retention and growth directly results in increased fruit number and size (Sabir *et al*., 2021) [33].

Experimental Evidence

- Fertigation enhances yield and fruit quality in citrus as well as in other fruit crops. Long-term and comparative experiments indicate that fertigation (mainly through drip) promotes nutrient use-efficiency and frequently increases yield and fruit size as compared to traditional soil application of fertilizers in a broadcast manner.For instance, a multi-season trial revealed greater mean fruit yield with fertigation in citrus orchards in comparison with granular soil application (Alva, 2005) [2].
- PGRs also suppress fruit drop and increase fruit size in citrus. Several citrus investigations have shown that auxin type PGRs (and auxin + gibberellin mixtures) inhibit's preharvest fruit drop and may increase fruit size or growth rate (or delay abscission). Field observations and small scale studies as well as industry trials (including most recent grower trials) indeed indicate decreased drop following 2, 4-D or tank mixes (GA + 2, 4-D) applications at suitable timings.Example reports and trials: Sylvertsen (2015) [41] on single 2, 4-D application reducing preharvest drop; industry CRDF trials reporting GA + 2, 4-D mixes reducing drop percentages (Sylvertsen *et al*., 2015) [41].

7. Effects on Fruit-Quality Attributes

Influence on TSS, acidity, and sugar-acid ratio

Integrated nutrient and PGR management (fertigation combined with targeted application of PGR) based on fruit growth and ripening stages is nowadays recognized as a standard practice for enhancing fruit quality through modification of carbohydrate accumulation and organic-acid metabolism in developing and ripening fruit. Low-level but frequent nutrient application (fertigation) provides N, K and other nutrients in accordance with the requirements of the crop and has been demonstrated to increase fruit soluble solids (TSS) and reduce titratable acidity in several fruit species, thereby changing the sugar-acid balance, which is the major factor regulating flavor and the first attribute considered in marketability.

Plant growth regulators exert an additional influence on these biochemicals by modifying sink-source relations and the rate at which ripening processes are delayed or accelerated. For example, gibberellins and auxins are known to influence sugar accumulation and acid metabolism in berries and other fruits whereas some of the newer PGR formulations and application strategies have been linked to increased TSS and improved fruit compositional characteristics. The combination of well-timed PGR application with balanced fertigation, therefore, potentially results in fruits with elevated TSS, manipulated acidity and superior sugar-acid ratios (Kumar *et al*., 2024) [23].

Role in Delaying Senescence and Maintaining Photosynthetic Source Strength

Cytokinins (either natural or applied) have been shown to delay leaf senescence, maintain the chlorophyll content and photosynthetic activity in source leaves. Source leaves were active physiologically for longer during fruit fill, and this was thought to be responsible for the enhanced supply of assimilates to the developing fruits under the influence of cytokinins (and treatments that raise cytokinin activity) resulting in a greater accumulation of sugars and other quality factors. Genetic and exogenous-application studies reveal a role for cytokinin in delaying senescence and maintaining photosynthetic capacity, which leads to superior fruit quality in many situations (Glanz-Idan *et al*., 2022) [15].

Nutrient-Interaction Effects and Balanced Fertilization

Balanced fertilization - supplying macro and micronutrients in ratios close to crop demand - is essential to obtain good fruit quality. Imbalances or excesses (e.g., in the N: K balance) may lead to reductions in TSS and to increased vegetative growth rather than fruit filling and to modifications in acidity and, possibly, in mineral related flavor attributes. Comparisons of fertilization treatments and fertigation schedules indicate that balanced nutrient ratios and dose timing improve TSS, juice yield and other quality attributes, and prevent deleterious effects, such as excessive vegetative vigor or unbalanced flavor profiles, of these.

8. Integration for Stress Mitigation

Targeted fertigation in conjunction with application or modulation of plant-growth regulators (PGRs) is a powerful means for increasing crop tolerance to abiotic stress.The integration of enhanced water and nutrient management (through fertigation) with hormonal control of stress responses (through PGRs) results in a synergism beneficial in drought, heat and salinity tolerance, which is also manifested in the coordinated strategy (Yang *et al*., 2024) [47].

Abiotic Stress Tolerance

Resilience to Drought: Enhanced Water Use Efficiency (WUE)

Precision fertigation (particularly drip/micro-irrigation with scheduled nutrients application) enhances WUE and relieves water stress in plants, as water and soluble nutrients are applied to the root zone, and irrigation can be scheduled to couple crop demand.Meta-analyses and research in the field indicate significant improvements in WUE and nutrient use efficiency when water and fertilizer are managed together (Yang *et al*., 2024) [47].

Heat Tolerance: Thermotolerance Enhancement Mechanisms

PGRs, for example, brassinosteroids (BRs) and other regulators, regulate the antioxidant systems, the expression of heat-shock proteins, and the stability of membranes, and these processes contribute to plant tolerance to high temperatures. BRs, have been demonstrated multiple times to upregulate physiological as well as molecular responses to heat stress, thereby leading to increased survival and yield during heat events (Chaudhuri *et al*., 2022) [9].

Salinity Tolerance: improved Osmotic Adjustment and Ionic Homeostasis

Salinity stress impairs water uptake by plants due to its negative effect on soil water potential. Efficient fertigation may contribute to sustaining a favorable soil moisture condition and to delivering required ions and osmoprotectants whereas PGRs (and hormonal changes such as ABA signalling) promote osmotic adjustment and ionic homeostasis in plant tissues.Reviews on salt stress highlight the ability of enhanced irrigation management in conjunction with biochemical/hormonal treatments to alleviate ionic toxicity and preserve turgor through osmolyte accumulation (Shahid *et al*., 2020) [35].

Role of PGRs

Abscisic Acid (ABA)

ABA is a key hormone in osmotic-stress signal transduction. ABA accumulation in response to drought or salinity leads to stomatal closure (thereby reducing transpiration), activation of stress-responsive gene networks, and modulation of root architecture to enhance the water foraging. Consequently, altering the levels of endogenous ABA or applying ABA-analogues can be used as a strategy to enhance drought and salinity tolerance in crops (Muhammad *et al*., 2022) [30].

Brassinosteroids (BRs)

BRS are also powerful regulators of stress tolerance through control of gene expression, activity of antioxidant enzymes, membrane integrity and cross-talk with other hormones (among them ABA).Application of exogenous BR or the selection of BR responsive genotypes has been found to improve the tolerance to drought, salinity and heat in a number of crop species (Chaudhuri *et al*., 2022) [9].

Fertigation's Role in Stress Mitigation

Osmotic Balance and Constant Nutrient and Water Supply

Fertigation provides water and soluble nutrients in multiple small doses to the root zone, resulting in a more constant soil water potential and nutrient availability than that observed in single events of high rates of fertilizer or irrigation applications. This more stable root-zone environment helps to sustain osmotic homeostasis, diminishes transient stress events, and enable plants to continue growth and metabolism during stress.Several reviews and field evaluations have demonstrated that fertigation enhances WUE, decreases nitrate leaching and maintains yields under water-stressed and marginal saline environment (Yang *et al*., 2024) [47].

9. Crop-Specific Case Studies

Mango (*Mangifera indica*)

Application of paclobutrazol (PBZ) to the soil or foliage and use of auxins like NAA have been reported extensively to control luxuriant vegetative growth, promote and synchronize flowering and enhance fruit set in mango; the addition of potassium-based fertigation (like KNO_3) to PBZ/NAA treatments also leads to enhanced flowering intensity, fruit set, and yield attributes, according to many fruit growers (Gollagi *et al*., 2019; Rebolledo-Martinez *et al*., 2008) [16, 32].

Banana (*Musa spp*.)

Use of gibberellic acid (GA3) usually as foliar applications to developing bunches is related to larger bunch/fruit size, delayed ripening and improved some quality traits; application of the GA treatments in combination with balanced NPK fertilization (including application in high input systems by the fertigation route) the cumulative effect is usually larger fruit and improved marketable quality of the fiber (Ghimire *et al*., 2021; Khodair and Radwan, 2018) [13, 22].

Grapes (*Vitis vinifera*)

In grape production, cytokinins are used to regulate berry growth, cluster compactness and senescence delay; when cytokinins are combined with a relatively low number of applications of microelements via targeted fertigation (B, Ca, Zn, etc. several trials confirm enhancement in berry growth, firmness and postharvest quality - most of all in table-grape production where appearance and shelf life have a major relevance (Aremu *et al*., 2020) [4].

Citrus (*Citrus spp*.)

2,4-D synthetic auxin (that is often tank mixed with other PGRs like GA in some province/regional programs) is employed to decrease pre-harvest fruit drop and to affect fruit retention and fruit size; extension/research reports also indicate that coordinated nutrient programs (balanced fertigation) lead to improved fruit development and quality.Integrated PGR application (2,4-D ± GA) has also resulted in reducing the % fruit drop in a number of studies, while distinct research demonstrates that balanced fertigation contributes to greater fruit size, peel and internal quality again indicating that a synergistic PGR + fertigation regime increases yield stability and fruit development (Khan *et al*., 2016) [21].

10. Conclusion

The integration of fertigation and plant growth regulators (PGRs) offers a sustainable and efficient strategy to enhance fruit yield, quality, and resource-use efficiency in modern horticulture. Fertigation ensures precise and continuous nutrient supply synchronized with crop needs, while PGRs regulate key physiological processes such as growth, flowering, fruit set, and stress tolerance. Together, they create a synergistic system that improves productivity, fruit quality, and overall plant performance. This integrated approach has shown remarkable potential in fruit crops like mango, banana, grape, and citrus, leading to uniform growth, higher yields, and superior physico-chemical traits. Moreover, it promotes water conservation, minimizes nutrient losses, and supports environmentally sustainable production systems.

Future emphasis should be placed on developing crop- and region-specific fertigation-PGR schedules and integrating advanced technologies such as sensors, automation, and biostimulants to enhance precision and sustainability. Interdisciplinary collaboration will be vital to optimize these practices under diverse agro-climatic conditions. In essence, the fertigation-PGR integration aligns with the concept of sustainable intensification producing more with fewer resources while preserving environmental balance. Its adoption can transform fruit production into a more resilient, efficient, and climate-smart system capable of meeting future nutritional and economic demands.

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