Mini-Review

Plant Growth Regulators (PGRs) for Enhanced Plant Abiotic Stress Tolerance: Mini-Review

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Abstract | Abiotic stresses (salt, drought, oxidative, and ionic imbalance) severely reduce global food security and sustainable agriculture by disrupting cellular function, water balance, germination, and generating oxidative damage. The exogenous application of plant growth regulators (PGRs) offers a rapid, eco-friendly, time-saving, cost-effective strategy for enhancing stress resilience. This review demonstrates how key PGRs, including abscisic acid, salicylic acid, jasmonic acid, melatonin, polyamines, auxins, gibberellins, and cytokinins, orchestrate defense responses through profound physiological adjustments, antioxidant enhancement, compatible solutes, and membrane stabilization. We systematically explore PGR-mediated improvements in vegetative growth, germination, reproduction, photosynthesis, secondary metabolite accumulation, and post-harvest quality. Hormonal crosstalk mechanisms and integrated strategies are analyzed. Future recommendations, including nano-delivery systems and CRISPR-based approaches, are discussed.

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Introduction

The global agricultural sector faces an unprecedented challenge in ensuring food security for a rapidly growing population against the backdrop of intensifying climate change (Seppelt *et al.*, 2022). Plants, being sessile organisms are constantly subjected to various abiotic stresses, such as waterlogging, drought, salinity, temperature extremes, freezing, and heavy metal toxicity (Zhang *et al.*, 2022). These abiotic stresses are the primary cause of crop yield losses worldwide, disrupting cellular homeostasis, generating reactive oxygen species (ROS), and impairing fundamental physiological and

metabolic processes from germination to reproduction. Developing robust strategies to fortify plant resilience is, therefore, not just an academic pursuit but a critical imperative for sustainable agriculture (Yang *et al.*, 2025).

Among the various biotechnological and breeding approaches, the exogenous application of plant growth regulators (PGRs) has emerged as a powerful, rapid, eco-friendly, and cost-effective tool to engineer stress tolerance in crops/plants (Hossain *et al.*, 2022). PGRs are naturally occurring or synthetic signaling molecules that orchestrate a plant's life cycle, acting as primary messengers in the stress perception and response network at minuscule concentrations. They are not merely growth promoters; under stress, they function as key mediators of adaptive responses. By fine-tuning the endogenous balance of classic phytohormones like abscisic acid (the central "stress hormone" governing stomatal closure), salicylic acid, jasmonic acid, melatonin, ethylene, polyamines, and 5-Aminolevulinic acid, plants can initiate defense cascades. Furthermore, other regulators such as auxins, gibberellins, and cytokinins are reprogrammed to modulate root architecture and delay senescence, enhancing resource capture and utilization under duress (Samanta and Roychoudhury, 2025).

The mechanistic basis of PGR-mediated tolerance lies in a multi-pronged defense strategy. Thisncludes the enhancement of the antioxidant defense system to scavenge toxic ROS, the accumulation of compatible solutes (osmolytes) like proline for osmotic adjustment, and the stabilization of cellular membranes, enzymes, and proteins (Cao *et al.*, 2022). By deciphering the intricate signaling crosstalk and downstream gene regulation controlled by these molecular agents, researchers can develop targeted seed priming and foliar spray formulations. This introduction explores the pivotal role of key PGRs in transforming a susceptible plant phenotype into a tolerant one, effectively providing a chemical blueprint for safeguarding crop productivity in an era of climatic volatility (He *et al.*, 2025). In this review, we reported the effect of plant growth regulators (PGRs) on different attributes of stress resistance and their management strategies to cope with abiotic stressors on different physiological and biochemical characteristics.

Effect of plant growth regulators on enhanced attributes of plants

Enhancement of vegetative growth attributes: The vegetative phase constitutes the foundational stage of plant development, where the establishment of a robust morphological framework determines the plant's subsequent reproductive potential. Plant growth regulators exert profound influences on vegetative attributes, fundamentally altering roots, leaves, and shoot architecture to optimize resource acquisition and utilization (Zhang *et al.*, 2024b).

Shoot growth, branching, and canopy architecture

The aerial architecture of plants encompassing stem elongation, branching patterns, and leaf orientation is highly plastic and subject to hormonal regulation (Pacifici *et al.*, 2015). Gibberellins (GAs) are the quintessential promoters of shoot elongation, functioning by stimulating both cell division and cell expansion (Greenboim-Wainberg *et al.*, 2005). Their mechanism of action involves the degradation of DELLA repressor proteins, which normally restrain growth by inhibiting transcription factors (TFs) (Wang *et al.*, 2016). When GAs bind to the GID1 receptor, the resulting complex targets DELLA proteins for ubiquitination and proteasomal degradation, thereby releasing the transcriptional machinery that drives elongation. Commercial application of gibberellic acid (GA3) at concentrations of 50-200 ppm results in dramatic increases in internode length and plant height in crops such as sugarcane, where it can increase stalk length by 25-40%, and celery, where improved petiole length directly enhances marketable yield. Similarly, GA treatment of turfgrasses produces the aesthetically desirable, uniformly elongated blades characteristic of high-quality lawns and golf courses (Zhang *et al.*, 2024a). Cytokinins play an equally important but functionally distinct role in shaping shoot architecture by overcoming root gravitropism and apical dominance (Aloni *et al.*, 2006). Produced primarily in root tips and transported acropetally through the xylem, cytokinins promote the outgrowth of lateral buds that would otherwise remain suppressed by apically derived auxin. This counteraction forms the physiological basis for producing bushy, well-branched ornamental plants (Rounkova, 1984). Commercial formulations such as 6-benzyladenine (6-BA) applied as foliar sprays at 100-300 ppm effectively stimulate axillary bud break in species including roses, poinsettias, and various potted foliage plants. The increased branch number not only enhances aesthetic appeal but also expands the photosynthetic canopy area, potentially increasing whole-plant carbon gain (Zhang *et al.*, 2023). Additionally, cytokinin application delays the

onset of apical senescence, maintaining meristematic activity and extending the productive vegetative phase in Arabidopsis thaliana (Werner *et al*., 2025) (Figure 1).

Root system architecture and development

The root system serves as the primary interface between the plant and the soil environment, governing water uptake, nutrient acquisition, and anchorage (Fageria, 2012). Auxins, particularly indole-3-acetic acid (IAA) and indole-3-butyric acid (IBA), are the principal regulators of root system architecture (Dilfuza, 2011). Their exogenous application has demonstrated remarkable efficacy in promoting adventitious root formation in stem cuttings, a practice indispensable to horticultural propagation. At the cellular level, auxins stimulate the dedifferentiation of parenchyma cells into root primordia, activating cell cycle progression and lateral root emergence (Roychoudhry and Kepinski, 2022). Research has consistently shown that IBA treatment at concentrations between 1000 and 3000 ppm dramatically increases rooting percentage, root number, and total root length in difficult-to-root species such as Apples, Ficus, Citrus, and various ornamental shrubs (Alvarez *et al*., 1989). Furthermore, auxins regulate lateral root spacing along the primary axis through an oscillating gene expression module involving the PIN-formed (PIN) family of auxin efflux carriers, creating a precisely patterned root architecture optimized for soil exploration (Xu *et al*., 2025). The synergistic interaction between auxins and other phytohormones further refines root development. Cytokinins, which generally act antagonistically to auxins in root meristem maintenance, must be carefully balanced (Boivin *et al*., 2016). While elevated cytokinin levels suppress lateral root initiation by downregulating PIN gene expression at primordia founder cell sites,

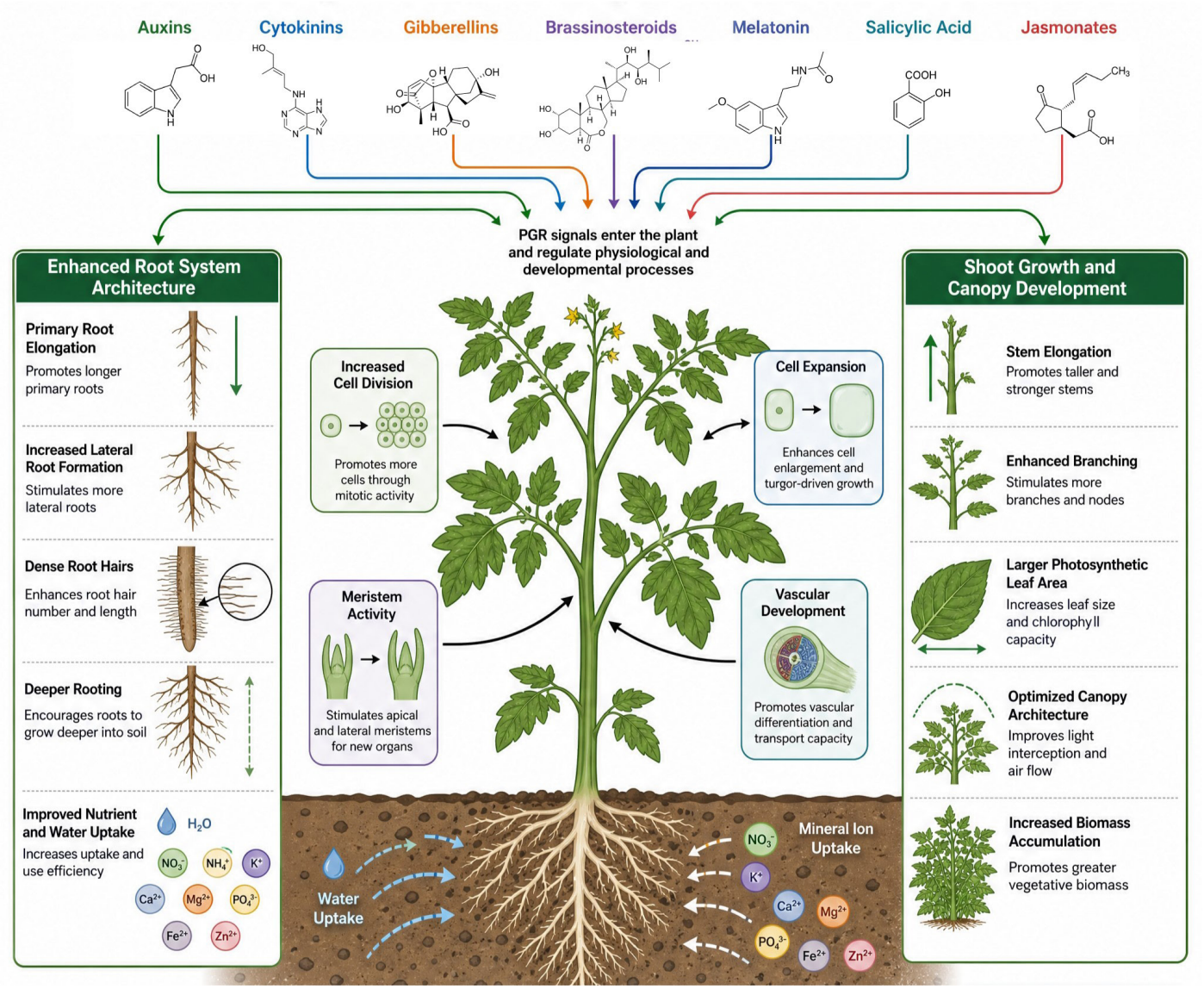

Figure 1: *Plant growth regulators enhance vegetative growth and plant architecture.*

low concentrations applied exogenously can promote root hair elongation and enhance the absorptive surface area (Sosnowski *et al.*, 2023). Gibberellins, too, modulate root growth; moderate GA application promotes primary root elongation by stimulating cell division in the meristematic zone and cell expansion in the elongation zone, whereas excessive concentrations can inhibit lateral root formation through Aspartic acid (D), Glutamic acid (E), Leucine (L), Leucine (L), Alanine (A), collectively termed as DELLA protein-mediated mechanisms (Islam *et al.*, 2025). This intricate hormonal crosstalk allows for the fine-tuning of root architecture, deep, extensive taproot systems for drought-prone environments versus shallow, highly branched fibrous systems for surface nutrient capture (Aloo *et al.*, 2023) (Figure 1).

Enhancement of reproductive attributes

The transition from vegetative to reproductive development represents a critical developmental switch, and the quantitative and qualitative attributes of flowers, fruits, and seeds directly determine agricultural productivity. PGRs provide powerful tools for manipulating every stage of the reproductive process (Zhang *et al.*, 2009).

Flowering induction, synchronization, and sex expression

The control of flowering time and intensity is of paramount importance in agriculture, where synchronized blooming facilitates efficient pollination and uniform harvest (Maple *et al.*, 2024). Gibberellins (GAs) exhibit a dual role in flowering regulation that is dependent on the plant's photoperiodic requirements (Chu *et al.*, 2024). In long-day plants and cold-requiring biennials, GA application can substitute for photoperiod and vernalization requirements, respectively. For example, GA3 treatment of carrot and cabbage at the rosette stage induces premature bolting and flowering without exposure to winter chilling, a technique utilized in seed production programs (Wang *et al.*, 2015). Conversely, in many woody perennials and short-day plants, GAs may inhibit flowering, while inhibitors of GA biosynthesis, such as paclobutrazol, promote floral induction by diverting resources from vegetative growth (Yuan *et al.*, 2024). Auxins and ethylene play critical roles in the floral initiation of pineapple and other bromeliads, a commercially significant application discovered serendipitously (Wang *et al.*, 2025). Application of naphthaleneacetic acid (NAA) or ethephon (an ethylene-releasing compound) at low concentrations (10-25 ppm) induces synchronous flowering across entire fields, enabling the coordinated harvest essential for large-scale production (Cronje, 2023). Ethylene is also instrumental in altering sex expression in cucurbitaceous crops (Boualem *et al.*, 2022). Application of ethephon at 100-300 ppm to monoecious cucumber and squash plants promotes femaleness, increasing the ratio of pistillate to staminate flowers and thereby enhancing fruit-bearing potential (Khan *et al.*, 2008). Gibberellins, by contrast, promote maleness in these species, providing breeders with tools to manipulate sex ratios for hybrid seed production (Woo *et al.*, 2023). Cytokinins further enhance flower quality by promoting floret size, petal pigmentation, and longevity in cut flowers, with 6-BA applications extending vase life significantly (Srivastava and Pandey, 2023) (Figure 2).

Fruit set, development, and parthenocarpy

Fruit set, the transition from flower to developing fruit, represents a critical yield-determining step vulnerable to environmental disruption (Tang *et al.*, 2023). Auxins, synthesized in developing seeds following successful pollination, are essential for stimulating the cell division and enlargement that characterize early fruit growth (Zhao, 2018). Exogenous auxin applications can circumvent the pollination requirement entirely, inducing parthenocarpic (seedless) fruit development in species where seed presence is commercially undesirable. Synthetic auxins such as 2,4-dichlorophenoxyacetic acid (2,4-D) and 4-chlorophenoxyacetic acid (4-CPA) applied to tomato, eggplant, and cucumber at flowering induce seedless fruit development with quality comparable to or exceeding that of pollinated fruits (Luitel *et al.*, 2015). Gibberellins are equally effective parthenocarpy-inducing agents in different species, with GA3 and GA4+7 formulations producing seedless grapes with elongated, loosely clustered berries when applied at bloom and fruit set stages at concentrations of 10-50 ppm. This technology, pioneered in the 'Delaware' grape cultivar, has transformed table grape production worldwide, allowing for the production of the now-consumer-preferred seedless varieties (Li *et al.*, 2024). Beyond parthenocarpy, PGRs enhance fruit size, shape, and quality through their effects on cell division and expansion (Watanabe *et al.*, 2008). The application of cytokinins during the cell division phase of fruit development increases the number of pericarp cells, establishing a greater potential for final fruit size (Sosnowski *et al.*, 2023). Gibberellins applied

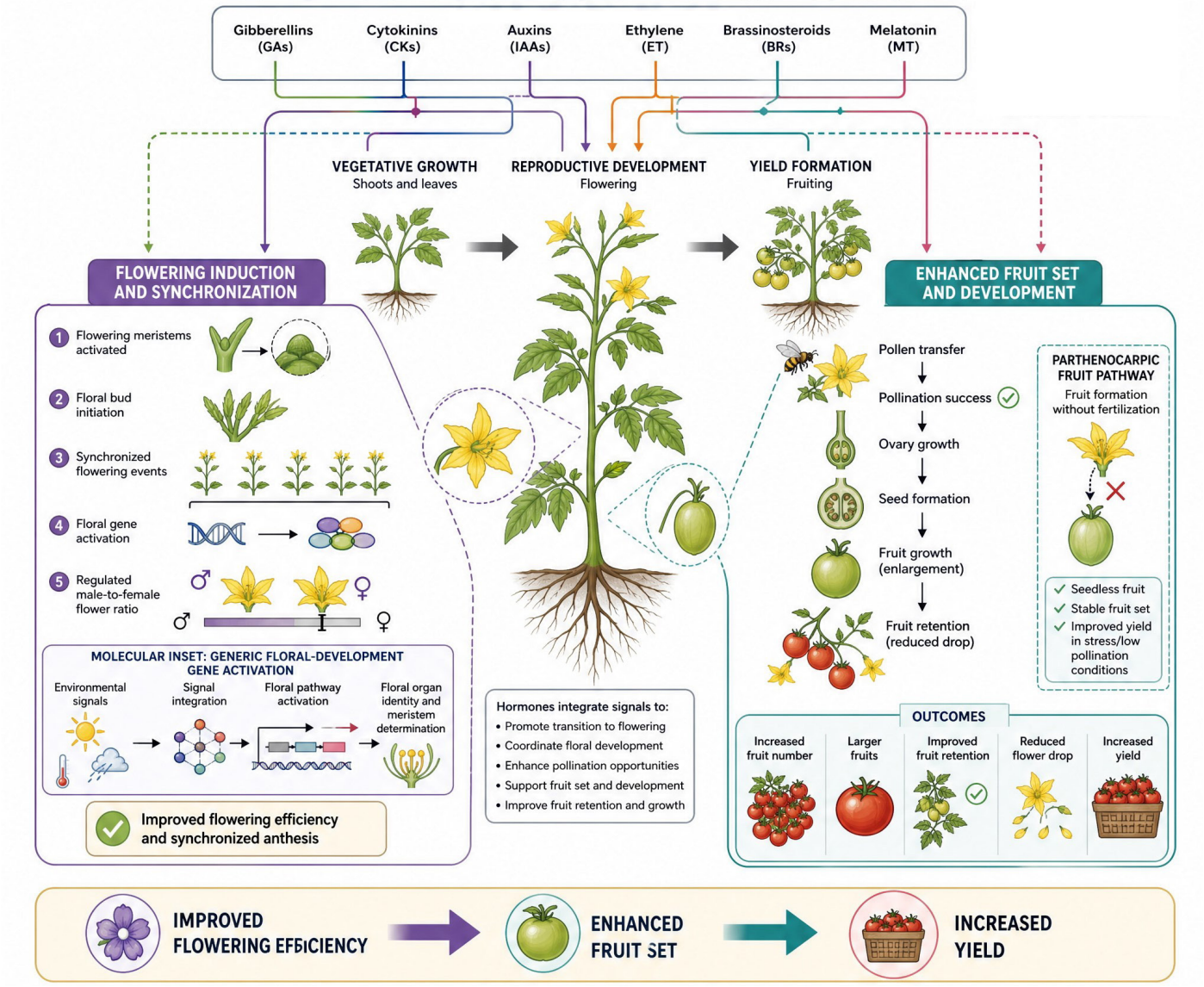

Figure 2: *Plant growth regulators improve reproductive development and yield formation.*

during the cell expansion phase further amplify fruit dimensions (Shah *et al.*, 2023). This sequential application protocol, combining synthetic cytokinins like forchlorfenuron (CPPU) with GA3, has proven remarkably effective in kiwifruit, watermelon, mango, apple, and cherry production, where it increases fruit weight by 30-60% without compromising eating quality (Li *et al.*, 2025). Moreover, auxins regulate fruit abscission, and their synthetic forms, such as 1-Naphthaleneacetic Acid (NAA), are used as chemical thinners in apples and citrus at moderate concentrations (5-20 ppm) to reduce excessive fruit load and improve the size and quality of remaining fruits, preventing biennial bearing patterns (Hakeem *et al.*, 2025b) (Figure 2).

Enhancement of physiological and biochemical attributes

While morphological attributes define the physical structure of plants, physiological and biochemical attributes determine the efficiency of internal processes and the composition of harvested products. PGRs profoundly modulate photosynthesis, senescence, and the accumulation of valuable secondary metabolites (Ihsan *et al.*, 2024).

Photosynthetic efficiency and chlorophyll dynamics

The photosynthetic apparatus is highly responsive to hormonal status, with cytokinins emerging as the principal positive regulators of chloroplast development and function. Cytokinins stimulate chlorophyll biosynthesis by upregulating the expression of genes encoding key enzymes in the tetrapyrrole pathway, including magnesium chelatase and protochlorophyllide oxidoreductase. Foliar application of kinetin or 6-BA at 10-50 ppm to soybean, wheat, and various vegetable crops significantly increases total chlorophyll content, enhances the chlorophyll a/b ratio in favor of

reaction center pigments, and delays the senescence-associated decline in photosynthetic capacity. The maintenance of a functional photosynthetic apparatus for an extended duration, a phenomenon termed the "stay-green" trait, directly translates to prolonged assimilate production and higher grain fill duration in cereals (Aremu *et al.*, 2020). Gibberellins and auxins also influence photosynthetic characteristics, leaf chlorophyll fluorescence, and total chlorophyll content (Tanimoto, 2005). GA application increases leaf area index and alters leaf angle, optimizing light interception across the canopy. The resulting architectural changes can increase whole-plant carbon assimilation by up to 25% in widely spaced horticultural crops (Hu *et al.*, 2026). Auxins modulate stomatal aperture dynamics, with low concentrations promoting stomatal opening and thereby facilitating CO_2 diffusion into the mesophyll. The combined application of PGRs that synergistically enhance both the biochemical and biophysical components of photosynthesis represents a promising strategy for maximizing radiation use efficiency in crop systems (Khan *et al.*, 2020) (Figure 3).

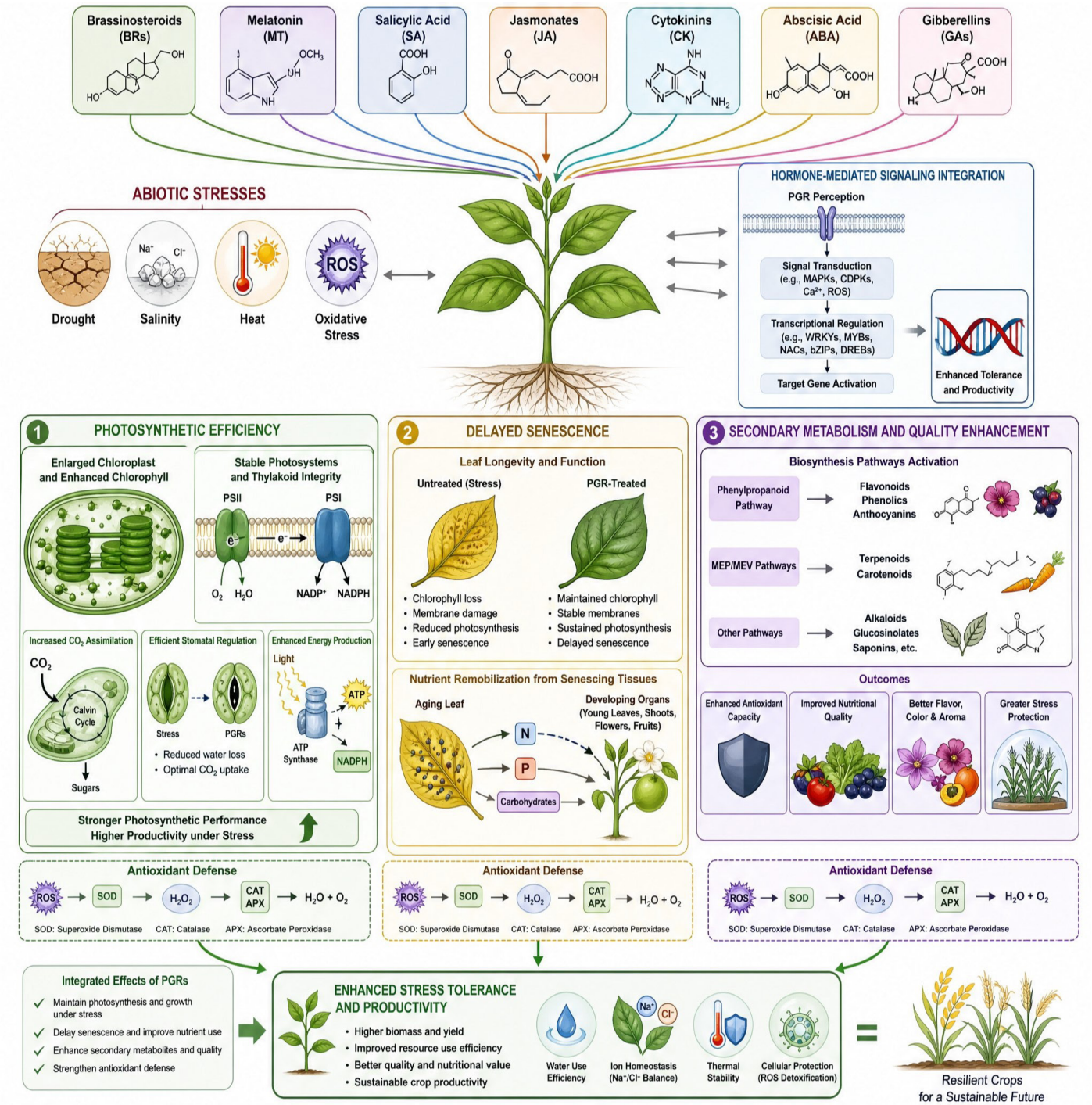

Figure 3: *Physiological and biochemical enhancement by plant growth regulators under abiotic stress.*

Senescence retardation and nutrient remobilization

Senescence, the genetically programmed degradation of cellular constituents culminating in organ death, imposes a ceiling on yield potential by terminating the grain-filling or fruit-maturation period (Bhat *et al.*, 2019). Cytokinins are the most potent natural antagonists of senescence, and their declining root-derived supply during reproductive development is a key signal initiating the senescence program (Prasad, 2022). Exogenous cytokinin application, whether through root drench or foliar spray, dramatically delays chlorophyll degradation, stabilizes thylakoid membrane protein complexes, and suppresses the expression of senescence-associated genes (SAGs) encoding catabolic enzymes (Hu *et al.*, 2021). In crops like rice and wheat, post-anthesis cytokinin treatment extends flag leaf photosynthetic duration by 7-14 days, directly increasing the grain-filling period and final kernel weight (Nisler *et al.*, 2024). The mechanism of cytokinin-mediated senescence delay involves both direct antioxidant effects and antagonism of senescence-promoting hormones (Wei *et al.*, 2023). Cytokinins upregulate the activity of antioxidant enzymes, including superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), glutathione reductase (GR), glutathione peroxidase (GPX), and ascorbate peroxidase (APX), mitigating the oxidative stress that enhances cellular deterioration (de Moura *et al.*, 2017). Simultaneously, cytokinins antagonize ethylene biosynthesis and signaling, interrupting the autocatalytic ethylene production that accompanies ripening and senescence (Lubovská *et al.*, 2014). Gibberellins contribute to senescence delay in specific contexts, particularly in delaying the degreening of citrus fruits through inhibition of chlorophyllase activity (Liu *et al.*, 2023). The application of GA3 to mature citrus before harvest maintains rind chlorophyll content, allowing for extended on-tree storage and marketing flexibility (Hakeem *et al.*, 2025a) (Figure 3).

Secondary metabolite accumulation and quality enhancement

The concentrations of secondary metabolites, including phenolic compounds, alkaloids, flavonoids, terpenoids, and essential oils, are decisive determinants of crop quality attributes such as flavor, aroma, color, nutritional value, and medicinal potency (Li *et al.*, 2020). Jasmonic acid (JA) and its methyl ester (MeJA) are master regulators of secondary metabolite biosynthesis, activating the expression of genes encoding phenylalanine ammonia-lyase (PAL), chalcone synthase (CHS), and different terpene synthases through a signal transduction cascade involving the SCF-COI1 receptor complex and MYC2 TFs (Creelman *et al.*, 1992). Exogenous MeJA application at concentrations of 10-100 μM elicits dramatic increases in phenolic content, anthocyanin pigmentation, and volatile aroma compounds in crops including grapevines (*Vitis vinifera*), strawberries (*Fragaria* × *ananassa*), sunflowers (*Helianthus annuus*), corns (*Zea mays*), and various medicinal herbs. In grapevine cell cultures and field-grown berries, MeJA treatment increases resveratrol (a health-promoting stilbene) content by three to five-fold, significantly enhancing the nutraceutical value of the product (Kazemi *et al.*, 2024). Salicylic acid (SA) similarly functions as an elicitor of secondary metabolism, particularly of the phenylpropanoid pathway leading to flavonoids, tannins, and lignin. Post-harvest SA treatment of fruits and vegetables not only induces disease resistance through systemic acquired resistance (SAR) mechanisms but also enhances the accumulation of antioxidant compounds beneficial to human health (Fang *et al.*, 2025). Abscisic acid (ABA), conventionally associated with stress responses and growth inhibition, plays a critical role in fruit ripening-associated anthocyanin accumulation. Exogenous ABA application to table grapes at veraison dramatically intensifies skin coloration, a quality attribute of primary commercial importance, by upregulating the *MYBA1* and *UFGT* genes encoding the transcriptional regulators and enzymes of anthocyanin biosynthesis (Safari *et al.*, 2024) (Figure 3).

Enhancement of post-harvest attributes

The post-harvest phase represents the period of greatest economic vulnerability in horticultural supply chains, with losses ranging from 25-40% in developing countries due to inadequate storage and handling infrastructure. PGRs offer effective interventions for maintaining quality and extending marketable life (Mwelase *et al.*, 2024).

Ripening control and shelf-life extension

Ethylene, the gaseous ripening hormone, governs the coordinate expression of genes responsible for chlorophyll degradation, cell wall softening, starch-to-sugar conversion, and aroma volatile production in climacteric fruits (Zhang *et al.*, 2017). The strategic manipulation of ethylene biology forms the

cornerstone of post-harvest technology. For fruits destined for distant markets, pre-harvest application of aminoethoxyvinylglycine (AVG) or aminooxyacetic acid (AOA), inhibitors of the ethylene biosynthetic enzyme ACC synthase, effectively retards the onset of the climacteric respiratory rise. Post-harvest application of 1-methylcyclopropene (1-MCP), an irreversible inhibitor of ethylene receptors, at concentrations as low as 0.5-1.0 µL/L, extends the storage life of plums, apples, pears, kiwifruit, and avocado by weeks to months, preserving firmness, acidity, and eating quality (Valero *et al.*, 2003). Conversely, for fruits requiring uniform ripening at destination, ethylene gas application at 100-150 ppm for 24 hours provides synchronized ripening in banana (*Musa*), mango (*Mangifera indica*), and tomato (*Solanum lycopersicum*), transforming them from unripe, unmarketable commodities to ready-to-eat consumer products (Huang *et al.*, 2024). Gibberellins contribute to post-harvest quality retention through a distinct mechanism. For instance, the suppression of peel senescence. GA3 treatment of citrus fruits delays chlorophyll breakdown in the flavedo, maintaining green coloration in limes and delaying the development of senescence-related disorders (Chen *et al.*, 2025). Additionally, the GA application reduces the incidence of various physiological disorders, including superficial scalds in apples (*Malus domestica*) and chilling injury in tropical commodities, by preserving membrane integrity and antioxidant capacity under cold storage conditions (Zhu *et al.*, 2016) (Figure 4).

Quality attribute preservation

Beyond ripening control, PGRs influence the retention of texture, color, aroma, and nutritional quality during storage. Cytokinins delay the senescence of leafy vegetables and fresh herbs, maintaining turgor pressure, green color, and ascorbic acid content. Pre-harvest cytokinin spray or post-harvest dip treatment extends the shelf life of spinach, lettuce, and broccoli florets by preserving membrane phospholipid integrity and reducing electrolyte leakage. Polyamines, including putrescine, spermidine, and spermine, constitute an additional class of naturally occurring regulators with potent anti-senescence activity. Their polycationic nature allows them to stabilize membrane surfaces, bind to nucleic acids, protecting them from

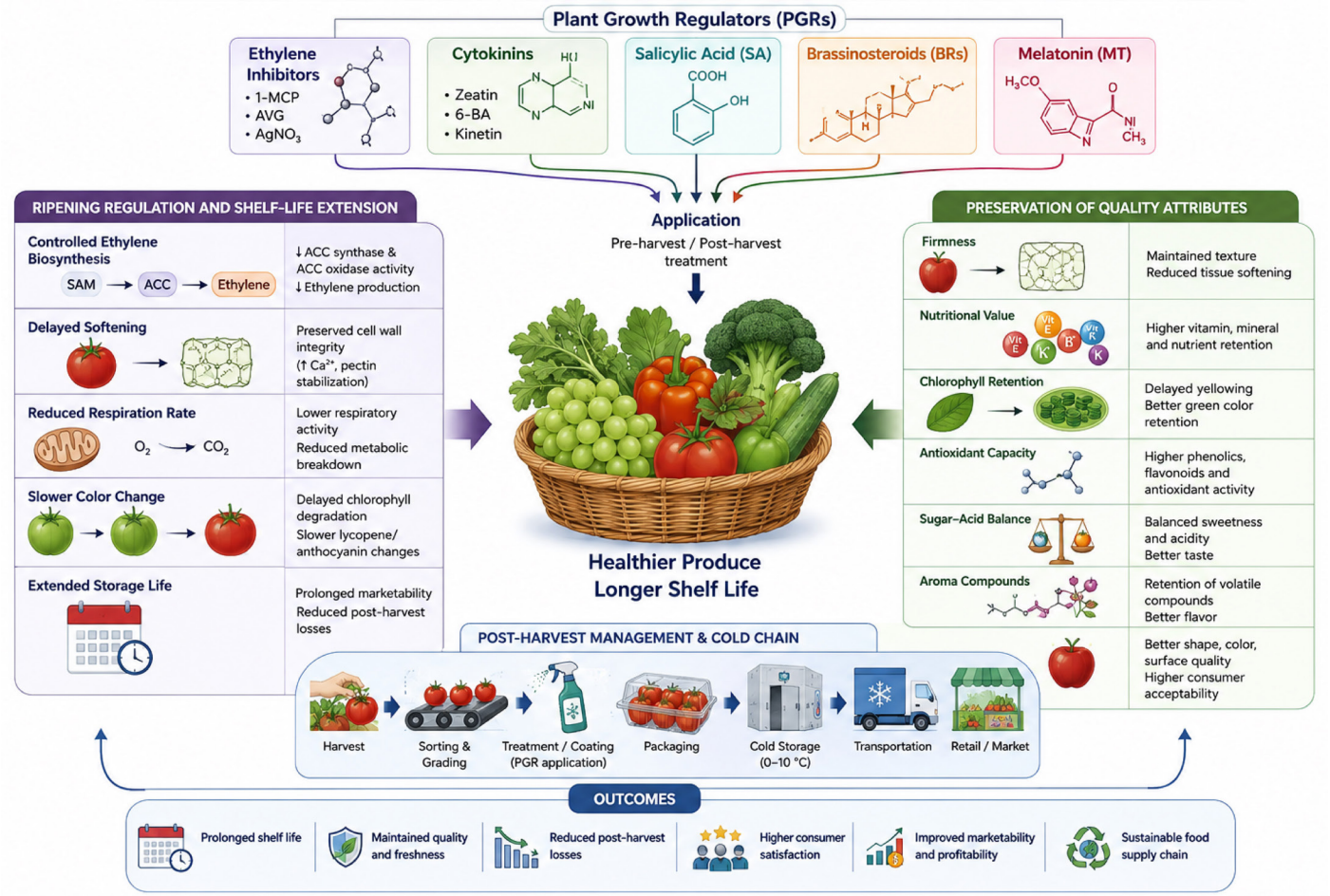

Figure 4: *Plant growth regulators improve post-harvest quality and shelf life.*

degradation, and scavenge free radicals. Post-harvest polyamine infiltration at millimolar concentrations effectively extends shelf life and maintains firmness in stone fruits, strawberries, and various vegetables, often outperforming conventional cold storage alone (Mampholo *et al.*, 2016) (Figure 4).

Synergistic interactions and integrated PGR strategies The enhancement of plant attributes through PGR application is rarely achieved through a single compound in isolation. The extensive crosstalk between hormonal signaling pathways necessitates a systems-level approach, where combinations of PGRs are applied sequentially or simultaneously to achieve specific objectives (Verma *et al.*, 2024). The auxin-cytokinin ratio, famously demonstrated in tissue culture systems where high auxin-to-cytokinin ratios promote rooting, low ratios promote shooting, and balanced ratios promote callus proliferation, exemplifies the principle that developmental outcomes are determined by hormonal balance rather than absolute concentration. This principle extends to whole-plant applications, where the strategic combination of auxins for root enhancement, cytokinins for branching, and gibberellins for elongation can sculpt plant architecture with remarkable precision (Zhang *et al.*, 2024c). The integration of PGR applications with optimal cultural practices, including balanced mineral nutrition, appropriate irrigation scheduling, and integrated pest management, is essential for realizing the full potential of hormonal manipulation. A plant experiencing nutrient deficiency or water stress cannot mount the full biosynthetic response to exogenous hormonal signals, as substrate limitations constrain the synthesis of proteins, membranes, and metabolites required for growth enhancement (Pidlisnyuk *et al.*, 2022). The future of PGR technology lies in precision agriculture approaches, where real-time sensor data on plant water status, nutrient content, and developmental stage inform site-specific, variable-rate PGR applications that maximize attribute enhancement while minimizing environmental impact and input costs. Emerging tools, including nanotechnology based delivery systems for controlled PGR release and CRISPR-based editing of endogenous hormonal pathways, promise to further revolutionize our ability to program plant form and function for specific production environments and market requirements (Chen *et al.*, 2019).

Conclusions and Recommendations

This review highlighted the exogenous plant growth regulators (PGRs) are vital tools for enhancing plant resilience against diverse abiotic stresses. PGRs orchestrate a multi-pronged defense strategy by enhancing antioxidant capacity, metabolite-encoding players, stomatal regulation, osmotic adjustment, and membrane stabilization through extensive hormonal crosstalk. Key regulators such as abscisic acid, salicylic acid, jasmonic acid, melatonin, and polyamines mediate stress-oriented responses, while auxins, gibberellins, cytokinins, and other hormones reprogram root and shoot architecture to optimize resource capture under drought, salinity, temperature extremes, flood, and heavy metal toxicity. Critical future priorities include developing species- and stress-specific dose-optimization protocols, elucidating molecular crosstalk mechanisms via omics approaches, and engineering nanotechnology-based smart delivery systems for controlled PGR release. Integrating PGR priming with beneficial microorganisms and translating insights into CRISPR-edited crops with optimized hormonal pathways holds transformative potential. Bridging the gap between laboratory findings and large-scale field validation under real-world, multi-stress scenarios remain the most urgent challenge requiring interdisciplinary collaboration.

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Novelty Statement

The current review provides a comprehensive, unified mechanistic framework for a diverse array of plant growth regulators (PGRs) from abscisic acid to melatonin against concurrent abiotic stressors. It systematically integrates the 'defense-response' paradigm with critical productivity metrics, including post-harvest quality, and it critically advances the field by synergistically coupling classical PGRs physiology with cutting edge nano-delivery and CRISPR technologies, thereby shifting the discussion from basic stress tolerance to actionable, sustainable yield-security strategies.

Author's Contribution

AH: The idea for the review, conceptualization, data curation, writing original draft, writing review and editing. EE: Conceptualization, data curation, resources, and writing review and editing. BE: Data curation, writing review and editing. GM and TMMS: Supervision, writing review and editing.

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Data availability

No data was used for the research described in the article.

Generative AI and AI assisted technology statement

The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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