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Synergistic Effects of Nanoparticles and Plant Growth Regulators in Enhancing Fruit Quality and Yield: Mechanisms and Future Perspectives: A review

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Abstract: Integrating nanomaterials with phytohormonal regulators represents an increasingly compelling strategy for elevating both the yield and the commercial quality of fruit-bearing horticultural species. The present review synthesizes and critically evaluates current evidence on the physiological, biochemical, and molecular consequences of nanoparticles (NPs) and plant growth regulators (PGRs) deployed either independently or in conjunction. Metal- and metalloid-based nanomaterials, notably zinc oxide (ZnO), silicon dioxide (SiO_2), and titanium dioxide (TiO_2), have been shown to facilitate mineral acquisition, strengthen photosynthetic performance, and stimulate the enzymatic antioxidant machinery. Phytohormones such as auxins, cytokinins, and gibberellins, by contrast, govern key developmental events spanning fruit set, enlargement, and ripening. When co-applied, these two classes of agents act synergistically, yielding larger fruit, richer biochemical composition, fewer physiological disorders, and extended postharvest longevity, effects attributable to the coordinated modulation of hormonal signaling networks, antioxidant defenses, and transcriptional regulation. Several molecular pathways underpinning this synergy are delineated herein. Nevertheless, the precise nature of NP–PGR interactions at the molecular level remains insufficiently resolved, and species-specific, environment-tailored application protocols have yet to be established, underscoring the need for targeted future investigation.

Keywords: Nanoparticles, Plant Growth Regulators, Fruit Quality, Yield, Synergistic Interaction, Horticulture

Introduction

Amongst the major crops of horticulture, fruits are one of the most important commodities and they play a significant role in the world agricultural economy. However, their production is still continuously hampered by many physiological and environmental constraints, including nutrient deficiency, physiological disorders and unfavorable growing conditions [1]. Such constraints have been exacerbated by a changing climate and human-induced abiotic stresses, which reduce the productivity and quality of the produce [2]. Thus, there is an urgent need to develop new strategies that can improve fruit production and quality without adding further environmental pressures.

One approach receiving increasing attention is the combined use of nanoparticles (NPs) and plant growth regulators (PGRs). It has been reported that engineered nanomaterials such as zinc oxide (ZnO), silicon dioxide (SiO_2) and titanium dioxide (TiO_2) enhance nutrient assimilation, strengthen photosynthetic capacity and upregulate antioxidant enzymes [3]. At the same time, phytohormones, especially auxins, cytokinins and gibberellins, regulate the developmental processes, such as fruit setting, growth and ripening [4]. There is some evidence that these two classes of agents are synergist, hence yield and fruit quality is improved [5]. Accordingly, this review brings together the existing literature on NP–PGR co-application and highlights its physiological, biochemical and molecular implications for the selected fruit species.

Nanoparticles in Horticulture

Nanoparticles are generally defined as materials with dimensions of 1–100 nm and distinctive physicochemical properties. These unique properties make them useful in various fields, such as medicine, electronics and agricultural science [6].

NPs can be classified according to their source and their chemical and physical properties, and are generally divided into inorganic, organic and carbon-based NPs. In agriculture, inorganic NPs such as ZnO, SiO_2 and TiO_2 have been the most widely studied [7]. These particles can enter the plant through the roots, leaves or seeds and accumulate in various tissues and organs, while their uptake and translocation are regulated by factors such as particle size, surface charge and applied dose [8].

Physiologically, NP treatment can improve chlorophyll levels, improve photosynthesis and boost the activity of antioxidant enzymes. For instance, it has been reported that ZnO NPs support the uptake of minerals and the antioxidant defense in various plants species [9]. But, under high concentrations, phytotoxic effects can appear that affect growth and development [10].

At the molecular level, NPs can modulate hormonal signal transduction pathways, gene transcription and metabolic processes, resulting in a wide range of physiological and biochemical responses [11].

Table 1. Representative studies on NP–PGR interactions in horticultural crops

Crop	Nanoparticle	PGR	Major Response
Tomato	ZnO-NPs	NAA	Increased fruit set and yield
Strawberry	SiO2-NPs	GA3	Improved firmness and shelf life
Citrus	ZnO-NPs	Auxins	Reduced fruit drop
Grapevine	TiO2-NPs	Cytokinins	Enhanced photosynthesis

Crop	Nanoparticle	PGR	Major Response
Pomegranate	Se-NPs	Salicylic acid	Improved antioxidant activity

Plant Growth Regulators in Fruit Crops

Plant growth regulators (PGRs) are naturally occurring or synthetic compounds that influence a broad range of plant physiological processes. Among these, auxins play a major role in cell proliferation, fruit set and abscission, and both indole-3-acetic acid (IAA) and naphthalene acetic acid (NAA) have been reported to enhance fruit retention and delay abscission in several horticultural crops [12].

Cytokinins are useful for improving fruit size and quality because they can stimulate cytokinesis and slow the senescence process [13]. Gibberellins (GAs) are also involved in fruit development and could be utilized to improve fruit size and yield [14].

On the other hand, abscisic acid (ABA) and ethylene play important roles in ripening and senescence. Ethylene, in particular, regulates the loss of firmness and pigment changes associated with ripening; inhibiting its action is a practical way to extend postharvest storage life [15].

The regulatory role of PGRs is complex and depends on hormonal crosstalk; for example, auxins, cytokinins and GAs interact closely in regulating fruit set and final yield [16]. These effects are mediated by the ability of PGRs to modulate gene transcription, thus modifying physiological and biochemical functions [17].

Synergistic Interaction Between NPs and PGRs

Synergism occurs when the combined effect of two or more agents is greater than the sum of their individual effects. Such interactions between NPs and PGRs have been reported in various aspects of plant physiology and biochemistry.

Nanoparticles can modulate hormonal signal transduction pathways and thus strengthen downstream physiological and biochemical responses; for example, ZnO NPs have been shown to enhance auxin transport, while SiO_2 NPs stimulate cytokinin production [18]. Consequently, the NP–PGR combination can enhance photosynthetic activity, mineral uptake and antioxidant enzyme capacity [19].

This synergistic effect also improves fruit set and reduces physiological disorders**, such as** fruit drop. For example, NAA has been shown to reduce fruit drop by regulating the abscission process [20], and when combined with NPs, it has resulted in further fruit set and yield improvements. Mechanistically, the NP–PGR interaction upregulates genes involved in cell proliferation and fruit maturation. Similarly, the combined application of ZnO NPs and NAA has been shown to produce significantly more and larger fruits compared with their individual application [21].

Table 2. Physiological and biochemical effects of nanoparticles in fruit crops

Nanoparticle	Main Physiological Effect	Biochemical Response	Potential Risk
ZnO-NPs	Enhanced nutrient uptake	Increased SOD and CAT activity	Oxidative stress at high doses
TiO2-NPs	Improved photosynthesis	Higher chlorophyll synthesis	Leaf toxicity under excess exposure

Nanoparticle	Main Physiological Effect	Biochemical Response	Potential Risk
SiO2-NPs	Improved water relations	Enhanced antioxidant capacity	Potential accumulation in tissues
Se-NPs	Stress tolerance improvement	Activation of antioxidant enzymes	Phytotoxicity at elevated concentrations

Effects on Yield and Quality

Quality of fruits is one of the important parameters of their marketability and is determined by various physiological, biochemical and molecular factors. NPs have been demonstrated to improve a range of quality parameters such as fruit size and flavour when used in combination with PGRs. For example, the use of ZnO NPs along with auxins can increase fruit size because of cell division and expansion [9]. Likewise, it has been found that the combination of SiO2 NPs and GA3 helps to improve fruit firmness and shelf life [22].

The NP-PGR interaction can also enhance various biochemical attributes, including total soluble solids (TSS) and color development. TSS content is the key factor to assess fruit quality and is related to photosynthesis and carbohydrate metabolism. NPs can be combined with PGRs to increase the TSS content due to increased photosynthesis [23]. Further, NP-PGR interaction also can stimulate carotenoid and anthocyanin production, which further enhances the colour of fruits [24].

The NP-PGR interaction can also enhance various physiological processes, including fruit set, growth, and maturation. For instance, auxins play a crucial role in fruit set by promoting cell division and inhibiting abscission. Consequently, the application of auxins can enhance fruit set and reduce physiological disorders such as fruit drop [12]. The combination of auxins and NPs can further enhance fruit growth by improving nutrient uptake and photosynthesis [25].

Table 3. Major research gaps and future research directions

Current Limitation	Scientific Impact	Future Recommendation
Limited field validation	Uncertain commercial scalability	Conduct long-term field trials
Insufficient omics studies	Weak molecular understanding	Integrate transcriptomics and proteomics
Environmental toxicity concerns	Potential ecological risks	Develop biodegradable nano formulations
Lack of standardized protocols	Poor reproducibility	Establish international guidelines
Genotype-specific variability	Inconsistent crop responses	Perform cultivar-based optimization

Limitations and Research Gaps

The current literature on the combined application of NPs and PGRs indicates that the interaction has beneficial effects on various physiological, biochemical, and molecular processes in plants. However, there are several limitations and research

gaps that need to be addressed. First, most of the studies on NP-PGR interactions have been conducted under controlled experimental conditions, and little is known about their efficacy under field conditions [26]. Second, the molecular mechanisms by which NPs and PGRs interact to influence plant processes are not well understood [27].

Moreover, NPs can accumulate in the soil and plant tissues, posing potential environmental and health risks [28]. Therefore, further research is needed to evaluate the long-term effects of NP-PGR application on the environment and human health.

Effects of NP-PGR Integration on Fruit Yield and Growth

The current study found that the combination of NPs and PGRs led to significant improvements in fruit yield and growth compared to the individual application of NPs or PGRs. The combined treatment of ZnO NPs and auxins was found to be most effective in terms of fruit yield and growth improvement.

Mechanistically, the beneficial effects of NP-PGR interaction on fruit yield can be attributed to the synergistic effects of improved nutrient uptake due to NPs and enhanced cellular processes caused by PGRs. NPs such as ZnO, SiO2, and TiO2 can improve root absorption and translocation of nutrients, thus strengthening the source. At the same time, PGRs such as auxins and cytokinins can enhance the sink strength by promoting fruit growth. Together, the enhanced source-sink relationship can lead to improved yield [29].

Critical Comparison

While most studies found that the combined application of NPs and PGRs led to enhanced yield and growth, the magnitude of the effects varied among studies. For instance, while Sharma et al. [21] reported that ZnO NP in combination with NAA significantly enhanced fruit size and yield, Tripathi et al. [30] found no significant effect on growth and yield. This suggests that the effects of NP-PGR interactions on yield are context-dependent.

Influence on Fruit Biochemical Quality and Metabolic Traits

Besides growth and productivity, joint NP–PGR applications have been reported to induce significant changes in biochemical composition of fruits including the accumulation of soluble solids, pigmentation and activity of antioxidant enzymes. This increase in TSS associated with such treatments has been related to an increase in the photosynthetic carbon fixation and in the carbohydrate metabolism activity [23]. Pigment benefits appear to be linked with increased biosynthesis and accumulation of carotenoids and anthocyanins, and accumulation of polyphenols and flavonoids (phenolic antioxidants) are also promoted under the combined treatment [24].

Critical Comparison

Despite this, the current evidence suggests that there is a positive effect of the NP – PGR combinations on fruit biochemistry; however, there are studies that show no detectable effects. Wang et al. [24] reported significant increase in carotenoid and anthocyanin production, while Singh et al. [31] reported only minor changes in most biochemical parameters studied. This type of divergence suggests that biochemical consequences depend on the species' physiology and on the context to which the environment belongs.

Reduction of Physiological Disorders and Postharvest Improvements

Fruit cracking and premature drop are among the main physiological constraints to orchard productivity and integrated NP–PGR strategies have been shown to be effective in reducing their incidence. Auxin-type regulators like NAA block the abscission process and thus fruit holding [12] while silica nanoparticles strengthen the integrity of the cell wall and prevent the fruit from cracking [31]. In addition, the increase of antioxidant enzymatic defenses in the combined treatment also delays the senescence, maintaining fruit quality during storage [19].

Critical Comparison

Most reports suggest that physiological disorders have been reduced as a result of NP–PGR application, but this is not always the case. Ali et al. [32] showed significant reduction in cracking and fruit drop, while Singh et al. [31] indicated that the treatment was not much effective in reducing the disorders evaluated.

Molecular and Physiological Mechanisms Underlying Synergistic Effects

The synergy of NP–PGR co-application is manifested at interconnected physiological and molecular levels. Physiologically, it is reflected in an increased photosynthetic capacity, strengthening of the antioxidant enzymatic systems and more efficient acquisition of nutrients; molecularly, it is reflected in the reprogramming of hormonal signaling networks, transcriptional activity and metabolic fluxes. Remarkably, nanoparticles also generate ROS that could trigger oxidative stress; however, PGRs added simultaneously with nanoparticles have an opposite effect, as they increase ROS scavenging enzymes, thus protecting cell structures [33]. It has also been demonstrated that combined treatments can affect the expression of genes coding for important enzymes and hormones that finally result in enhanced physiological and biochemical performance [21].

Critical Comparison

Although previous research has confirmed that NP–PGR treatments have effect on various physiological and molecular processes, the exact modes of action are so far, not fully understood. It has been largely focused on physiological endpoints and the molecular regulation is relatively under-studied.

Limitations, Variability, and Research Gaps

Although there is growing evidence of the physiological, biochemical and molecular advantages of NP–PGR treatments, there are still some restrictions that limit their use. The most significant of these is the use of the experiments in the controlled environment, meaning that efficacy and safety of these treatments under open field is largely uncharacterized [26]. The marked variance in the outcomes of treatment also limits practical application and this variability can be attributed to differences in nanoparticles, type of regulators, and environmental conditions [34]. Besides, long term effects of these applications on ecosystems and human health have not been properly investigated [28].

Critical Insight

Overall, the evidence available indicates a wide range of positive impacts of NP–PGR treatment on the physiological, biochemical, and molecular activities of plants. However, this conclusion is based primarily on experiments conducted under a controlled environment, which do not reflect field level performance and safety. The molecular regulatory mechanism underlying these effects is not well understood and the variability in the response continues to be a major concern that requires extensive investigation in the future, as do the uncertain environmental and health risks.

Synthesis and Implications for Sustainable Horticulture

The findings presented in this synthesis confirm that NP–PGR co-application is a potential tool for improving the several aspects of fruit crop production. To bring this potential to fruition in practice, however, will require more in-depth mechanistic understanding and more elaborate application protocols.

Conclusion

The co-application of nanoparticles with plant growth regulators strengthens the various physiological, biochemical and molecular events in plants. While nanoparticles mainly increase the photosynthetic efficiency and nutrient assimilation, growth regulators control the fundamental developmental and growth processes, thus, their combination results in better fruit yield and quality. Molecular mechanisms by which these combined treatments regulate plant function remain to be explained.

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