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Nanotechnology Interventions in Fruit Production: Enhancing Production and Quality

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Nanotechnology has gained significant importance in enhancing fruit production and quality, offering novel solutions to challenges faced by traditional horticultural practices. The various applications of nanotechnology in fruit cultivation, focusing on Nano fertilizers, nanopesticides, nano-based fungicides, and post-harvest management technologies. Nanofertilizers have shown promise in improving nutrient uptake efficiency, stimulating vegetative and reproductive growth, enhancing yield, and reducing environmental impacts compared to conventional fertilizers. Similarly, nanopesticides and nanofungicides provide targeted pest and disease management, reducing the overuse of chemical inputs and minimizing their harmful effects on soil health. Post-harvest nanotechnologies, such as silver and zinc oxide nanoparticles, have been effective in extending the shelf life of fruits by preventing microbial decay and maintaining fruit firmness. Innovations in smart packaging, such as nanocomposite films and nano coatings, help slow down ripening and spoilage, significantly reducing post-harvest losses. Precision fruit cultivation techniques utilizing nanosensors and nano-based biosensors offer enhanced monitoring of soil conditions, nutrient levels, and early pathogen detection, improving overall fruit quality and sustainability. Despite these advancements, the widespread adoption of nanotechnology in fruit production is still limited by concerns related to public acceptance, potential environmental impacts, and regulatory challenges. Continued research is needed to address these issues and to explore the full potential of nanotechnology in fruit production.

Keywords: Nanoparticles; nano fertilizers; biosensor.

1. INTRODUCTION

Nanotechnology has gained significant traction in agriculture and horticulture, particularly with the use of nanofertilizers (NFs) in fruit crop production. Those NFs have shown promise in enhancing vegetative and reproductive growth, as well as promoting flowering, which ultimately boosts productivity, improves Product value, extends Storage life, as well as minimizes fruit residue (Babu et al., 2022). Fruit crops are vital sources of nutrition, vitamins, and minerals in human diets. On the other hand, their yield often faces challenges from environmental stressors, pests, and diseases, which can negatively impact crop yield and quality. Conventional methods for crop protection and enhancement, including the use of pesticides and fertilizers, pose environmental issues and can result in residual toxicity in fruit products (Kim et al., 2018).

Today, climate change, increasing population growth, and scarce natural resources such as water and soil pose major global challenges. The effects of climate change on fruit production worldwide are unprecedented, making the adoption of nanotechnology essential for boosting fruit yield and sustainability in this modern era. Richard P. Feynman first introduced the concept of nanotechnology in his 1960 lecture titled " In his 1960 essay, 'There's Plenty of Room at the Bottom,' Feynman suggested the potential for manipulating materials on a nanoscale level (Feynman, 1960). The term "nano" is derived from the Greek word meaning "dwarf," referring to particles that are one billionth of a meter in size (ranging from 1 to 100 nanometres).

Nanotechnology encompasses a wide array of precise instruments, including nano-based devices, machinery and automation that operate at the atomic level. The implementation of nanotechnology can reduce input losses and improve production efficiency through targeted delivery of resources. "Frequently utilized nanomaterials in fruit production encompass nano packaging, nano pesticides, nano fertilizers, nano fungicides, precision fruit cultivation methods, and strategies for crop enhancement.". Additionally, nanomaterial-based biosensors are utilized in advanced fruit production.

This review explores innovative applications of nanotechnology that could enhance fruit production and promote ecological sustainability. Despite the potential benefits, there has been a lack of focus on public acceptance of nano-based products among scientists, manufacturers, researchers, and authorities (Arnaldi and Muratorio, 2013). In the fruit production sector, there is a pressing requirement to implement advanced technologies to enhance the efficiency of nutrient and water use, facilitate the precise application of nutrients and pesticides, and minimize postharvest losses.. Currently, nanotechnology is acknowledged as a ground-breaking tool, with certain authors referring to it as the sixth technological revolution (Mustafa and Zaied, 2019). It represents an innovative approach to connecting fruit production with the increasing global demand for fruit. This review explores the diverse applications of advanced fruit production in today's context.

2. OVERVIEW OF THE CURRENT ROLE OF NANOTECHNOLOGY IN FRUIT PRODUCTION

Nanotechnology involves the utilization regarding nanomaterials with dimensions ranging from 1 to 100 nanometres. In the fruit industry, nanomaterials can be classified into three categories: organic (natural nanoparticles), inorganic (which includes metal and metal-oxide nanoparticles), and composite materials (such as clay). Among these, metal and silver nanoparticles are the most frequently utilized in fruit production and post-harvest management. Gold and titanium dioxide nanoparticles have distinct roles, functioning as sensors or detectors and disinfectants, respectively (He et al., 2019). Nanoparticles can be synthesized through several approaches, including physical methods (like nano-zeolite and nano-clay), chemical methods (such as vapor sedimentation, sol-gel processes, hydrothermal techniques, and micro emulsions), and biological methods (like nano-silver), as discussed by Mustafa and Zaied (2019).

In both advanced and advancing countries, fruit yield and the creation of fruit-based marketable products play a crucial role in driving the economy and meeting daily dietary needs. Horticulture is a burgeoning field, with cultivable land quickly increasing in developing countries. Improving fruit productivity involves cultivating superior and enhanced varieties, applying suitable cultural practices (such as training and pruning), adopting modern planting systems (like HDP and UHDP), and using fertilizers and irrigation methods, along with appropriate chemical applications. These practices significantly boost contemporary fruit production. However, the overuse of chemicals and fertilizers presents risks to both the environment and human health (Sharma and Singhvi, 2017).

Improvements in fruit production have come from enhancing the efficiency of input use and minimizing input losses. Nanomaterials enable precise and controlled delivery of fertilizers, pesticides, and herbicides, thus enhancing crop protection. It precise application maximizes the production of excellent fruits while minimizing input usage. Additionally, Micro-nano biosensors and nanotools are utilized in advanced fruit production technologies (Shang et al., 2019). This review discusses the commercial applications of nanotechnologies.

3. FRUIT PACKAGING AND POST-HARVEST PRACTICES

Many fruits are highly perishable and have a short shelf life. Tender tropical fruits like bananas, mangoes, and papayas are in high demand in export markets and are essential for the livelihoods of producers. Maintaining freshness is critical, as these fruits deteriorate rapidly and are prone to damage. It is estimated that up to 40% of produce in tropical countries is lost during post-harvest handling. Collaborative research involving partners from Canada, India, and Sri Lanka has uncovered a promising innovation: the use of nanotechnology with a natural plant extract called hexanal to slow down fruit ripening. Hexanal works by inhibiting an enzyme in plants that disrupts cell membranes during the ripening process.

Scientists in India and Sri Lanka are also working on 'smart packaging' systems utilizing materials like banana fiber, which gradually release hexanal to prolong the storage life of harvested fruits. Post-harvest spoilage from pathogens (including fungi and bacteria) further contributes to fruit decay. Stable silver nanoparticles (AgNPs) obtained from the peel of black grapes (*Vitis vinifera*) have been assessed for their effectiveness against a range of pathogens, including *Bacillus cereus*, *Staphylococcus aureus*, *Escherichia coli*, and Pseudomonas aeruginosa, demonstrating significant antibacterial activity. These AgNPs and AgPVA nanofibers have been found to prevent decay and enhance the shelf life of strawberries and lemons (Kowsalya et al., 2019).

Additionally, silver nanoparticles produced from various citrus peel extracts have shown antibacterial properties against *Pseudomonas aeruginosa*, Escherichia coli, and Salmonella typhimurium (Reenaa and Aathira, 2017). Kumar et al. (2019) described that using a fabricated agar-ZnO nanocomposite film improved the postharvest shelf life of green grapes. In studies involving Mazafati dates

(*Phoenix dactylifera* L.), polyethylene nanocomposite packaging containing 2% zinc oxide has been shown to improve fruit quality and life span when stored at 4 °C (Sadeghipour et al., 2019).

Silver nanoparticles (AgNPs) are commonly used for post-harvest treatments of fruits due to their antimicrobial and antibacterial traits. AgNPs produced via green synthesis using Citrus limon peel extract have been found to enhance the quality and shelf life of blackberries (Rodino et al., 2019). In mangoes, polylactic acid nanocomposite films that incorporate bergamot essential oil, TiO2 nanoparticles, and AgNPs have effectively minimized weight loss and maintained fruit firmness while extending shelf life by 15 days (Chi et al., 2019).

Nanocomposite edible layer made with glycerol and ZnO nanoparticles have also been found to enhance the excellence and storage stability of mangoes (Dubey et al., 2019). In the case of guava, edible fruit coatings made from alginate and chitosan have shown effectiveness, with the incorporation of nano ZnO into both coatings demonstrating effective antimicrobial action and extending shelf life by up to 20 days (Arroyo et al., 2019). These kinds of packaging likewise minimize ecological effect, as nano-ZnO has gained commercial importance due to its attractive physicochemical properties.

The shelf life of fresh-cut Fuji apples has been increased through nano protective cover using polyvinyl chloride (PVC) film combined with nano-ZnO powder, maintaining quality for 12 days at 4 °C (Li et al., 2011). Additionally, Nanomaterial-based stickers, such as Electrospun Nano-Fiber Matrix stickers, have been created to improve the post-harvest storage life of mangoes by regulating hexanal production (Shanmugapriya et al., 2016). Additionally, nano-based chitosan/nano-silica semi-permeable films have been shown to inhibit the increase of malondialdehyde and reduce the activity of the polyphenol oxidase enzyme. This action helps to minimize fruit weight loss and browning, ultimately enhancing the storage life of longan fruits (Shi et al., 2013).

4. PRECISION FRUIT PRODUCTION

Precision fruit production has become essential for effectively measuring and monitoring tree growth, soil conditions (such as moisture, nutrients, pH, and electrical conductivity), detecting diseases, assessing agrochemical penetration, and evaluating environmental impacts. By adopting precision fruit culture, we can improve fruit quality, preserve soil and plant health, and encourage sustainable fruit production, all while ensuring environmental safety (Chen et al., 2016).

Nano-engineering of materials plays a significant role In advanced fruit cultivation through providing a larger effective surface area, contributing to eco-friendly growth systems (Panpatte et al., 2016; He et al., 2018). Thus, the application of nanotechnology is considered an innovative approach in modern fruit farming. A key aspect of nano-fruit culture is its ability to produce high-quality fruits at reduced input costs while ensuring ecological sustainability. This modern approach incorporates nanosensors, nano-enhanced GPS, supercomputers, and remote sensing technologies

4.1 Nano Based Biosensors

Nanomaterial-based biosensors are extensively employed for the early detection and diagnosis of various pathogens (including fungal, bacterial, and viral) as well as food toxins (Chartuprayoon et al., 2010; Bansi et al., 2014; Wang et al., 2019). Recently, these biosensors have been utilized for the rapid identification of pathogens in plant tissues using DNA, antibodies, and biosensing receptors that detect volatile compounds. These techniques are economical, non-destructive, and facilitate early pathogen detection, making them minimally invasive, highly specific, and sensitive for on-field identification of plant pathogens (Kashyap et al., 2019).

Key types of nanotechnology-based biosensors utilized in the agricultural sector include (Kashyap et al., 2019):

1. Fluorescence Resonance Energy Transfer Nano sensor
2. Surface-Enhanced Raman Scattering Nano sensor
3. Electrochemical Nano sensors
4. Piezoelectric Nano sensor

Citrus greening, commonly referred to as yellow shoot disease or huanglongbing (HLB), poses a significant threat to citrus agriculture. Researchers have developed electrical sensor arrays capable of detecting volatile organic compounds, facilitating early identification of bacterial infections related to citrus greening

(Wang et al., 2019). Furthermore, ceria nanoparticles serve as microsensors that measure limonin levels, enabling the detection of yellow shoot disease via a platform for organic electrochemical transistors (Saraf et al., 2018).

Fernandez-Baldo et al. (2010) A carbon-based screen-printed electrode was developed using microfluidic principles to assess Botrytis cinerea infection levels in apples, pears, and grapefruits. Plum Pox Virus (PPV), commonly known as sharka, affects plums and other stone fruits, leading to significant economic losses. Regular monitoring and early pathogen detection are essential for effective disease management. Bioelectronic PPV biosensors, utilizing electrolyte-gated organic field-effect transistors (EGOFET), have been designed for the rapid identification of this virus in plant extracts (Berto et al., 2018).

Additionally, nano-based optical biosensors have been developed for the detection of Grapevine Virus A-type (GVA) proteins (GVA antigens) without the need for additional labels, achieving sensitivity levels ranging from 1 pg/ml to 10 ng/ml (Tereshchenko et al., 2017). Quantum dot-based biosensors are also utilized for viral disease detection (Hong and Lee, 2018). In Australia, sensor-based LiDAR systems have been developed that feature automatic image mask generation for single, double, and multi-view methodologies. These systems can detect, count, track, and locate specific fruits within trees, allowing for accurate yield estimations without the necessity for statistical calibration (Stein et al., 2016).

4.2 Nanotechnology-Based Products

4.2.1 Nanofertlizers

The widespread application of chemical fertilizers in fruit production has a significant effect on soil fertility, microbial activity, and mineral cycles. Overapplication and improper use of fertilizers can alter soil acidity, reduce nutrient use efficiency, and cause nutrient toxicity, leading to various deficiencies in fruit crops. In contrast, the application of nano fertilizers (NFs) can mitigate nutrient leaching, reduce emissions, and interact sustainably with soil microorganisms without causing environmental contamination. NFs have been extensively researched and developed in fruit cultivation, playing a crucial role in promoting vegetative and reproductive growth, flowering, and ultimately enhancing fruit productivity, quality, and postharvest longevity.

Typically used as growth stimulants, these nanocomposite fertilizers, including ZnFeMnB (zinc, iron, manganese, boron) and NPKMg (nitrogen, phosphorus, potassium, magnesium), along with macro- and micro-scale nano fertilizers such as zinc, boron, chitosan, and calcite, have been demonstrated to significantly enhance the vegetative and reproductive characteristics of several fruit trees, including coffee, date palm, strawberry, pomegranate, mango, and grape (Zahedi et al., 2019).

4.2.2 Nano fungicides

Nanoparticle-based bio-fungicides play a crucial role in managing specific fungal diseases in fruit cultivation. Effective plant protection is vital for optimizing fruit production; however, the extensive use of herbicides, insecticides, and fungicides can adversely affect soil fertility and environmental sustainability (Nuruzzaman et al., 2016). Consequently, targeted pest and disease management is essential in modern fruit culture to ensure improved protection against pathogens.

Nanoformulations or encapsulated fungicides consist of nano-sized particles integrated into the pesticides, and these engineered nanostructures possess pesticidal properties (Haq et al., 2019). The process of nanoencapsulation involves coating pesticides with active ingredients, where the core material serves as the insecticide or pesticide (the internal phase), while the nanomaterial constitutes the external phase (Nuruzzaman et al., 2016).

Nano-based derivatives of *Chaetomium cupreum*, such as nano-CCM, nano-CCE, and nano-CCH, have been shown to inhibit the growth of *Phytophthora* species, specifically targeting the mycelial growth and spore production responsible for root rot in durian (*Durio zibethinus* Murr.) (Thongkham et al., 2017). Additionally, Citrus trifoliata essential oil (CTEO) encapsulated in nano-cubosomes (self-assembled cubic liquid crystalline nanoparticles) has demonstrated efficacy against fungal diseases like *Fusarium oxysporum* and *Fusarium solani* (Abdel-Kawy et al., 2019).

Under in vitro conditions, zinc oxide nanoparticles (ZnO NPs) have exhibited strong antifungal activity when exposed to visible light.

Spraying ZnO NPs on sunny days has been found to reduce the incidence of *Botrytis* as well as improve fruit quality while minimizing decay losses in strawberries (Luksiene et al., 2019). Copper nanoparticles (Cu-NPs) have also shown effectiveness against *Botrytis* species (Malandrakis et al., 2019a).

4.2.3 Nano pesticides

These formulations resemble nano fungicides, created through the encapsulation of pesticides. Traditional pesticide use often leads to increased resistance in targeted pests while also harming beneficial organisms. However, these nano pesticides can help address these significant challenges (Dwivedi et al., 2016). Citrus trifoliata essential oil (CTEO) encapsulated in nano-cubosomes (self-assembled cubic liquid crystalline nanoparticles) has been shown to be effective against pests such as *Spodoptera littoralis* (Abdel-Kawy et al., 2019). Additionally, nanomaterial-based kaolin particle films act as a physical barrier to manage insect pests, including the Mediterranean fruit fly (*Ceratitis capitata*) (Diptera: Tephritidae) and the Southern green stink bug (*Nezara viridula*) (Heteroptera: Pentatomidae) (Salerno et al., 2019). Furthermore, nano gel-based low molecular mass gelators of methyl eugenol (ME) have been developed for the effective management of *Bactrocera dorsalis*, a major pest impacting various commercial fruit crops (Bhagat et al., 2013).

4.3 Nanoparticles in Horticulture Crops: Types and Potential Applications

Nanoparticles can be categorized into various forms based on their chemical, biological, morphological, size, and physical characteristics. Common classifications of nanoparticles include quantum dots, nanoballs, nanorods, nanosheets, nanotubes, nanofibers, and aerogels (Hasan, 2015; Nasrollahzadeh et al., 2019). Additionally, nanomaterials can be grouped according to their physical and chemical properties. Each shape and type of nanoparticle possesses distinct properties and applications across different fields, including electronics, medicine, agriculture, and fruit cultivation. Some of the primary categories of nanomaterials are:

4.4 Metal and Metal Oxide Nanoparticles

Such nanoparticles are composed of metals or metal oxides, including zinc oxide, silver, copper, and titanium dioxide. Metal nanoparticles exhibit antimicrobial properties, making them suitable for use as nanopesticides to combat plant diseases (Li et al., 2023). Additionally, they serve as nanofertilizers to improve nutrient uptake and boost crop yield (Qureshi et al., 2018). For instance, silver nanoparticles (AgNPs) are utilized in horticultural crops to control various fungal and bacterial diseases due to their broad-spectrum antimicrobial activity. Similarly, zinc oxide nanoparticles (ZnO NPs) function as nanofertilizers, Enhancing the absorption of potassium, phosphorus, and nitrogen in crops results in increased biomass and yield (Ahmed et al., 2023). Zinc oxide nanoparticles (ZnO NPs) can be utilized either as a foliar spray or integrated into the soil as a fertilizer.

Metal and metal-oxide nanoparticles inhibit aggregation, thereby enhancing transport and uptake by plants. The effectiveness of various coatings in different soil conditions is also taken into account, with zwitterionic coatings showing promise for maintaining stability in challenging environments. Additionally, incorporating natural organic matter and biopolymers could lead to cost-effective, non-agglomerating nanoparticles suitable for agricultural soil applications (Cartwright et al., 2020).

4.5 Carbon-Based Nanomaterials

“Carbon-based nanoparticles, such as graphene, carbon nanotubes, and fullerenes, exhibit unique thermal, mechanical, and electrical properties, rendering them ideal for use as nanosensors to detect toxins, pathogens, and other substances in plants and soil” (Berry et al., 2014; Husen and Siddiqi, 2014; Park et al., 2020). Research has also demonstrated that carbon-based nanomaterials promote growth in horticultural crops, enhancing parameters such as shoot and root length as well as overall living matter (Cañas et al., 2008). Additionally, Carbon-based materials that incorporate selenium are environmentally friendly and cost-effective, providing various applications in agriculture and environmental protection, thanks to the unique properties of selenium. To fully harness their potential and broaden their applications, interdisciplinary research and collaboration are essential (Xiao et al., 2021).

4.6 Polymer-Based Nanomaterials

Nanoparticles derived from polymers such as chitosan, cellulose, and polyethylene glycol act as effective nanocarriers (Dutta et al., 2022).

“These materials can enhance nutrient absorption and contribute to increased crop yields. For example, chitosan nanoparticles (CSNPs) have been extensively researched for their role as nanocarriers for nutrients, growth regulators, and pesticides in fruit crops. CSNPs can be loaded with various bioactive compounds and applied to crops as a foliar spray or incorporated into the soil as an amendment. Research has demonstrated that CSNPs can significantly improve crop yield and nutrient uptake across different crops, including strawberries” (Gao et al., 2020) (Guo et al., 2018; Ingle et al., 2022). In horticultural practices, the use of nanomaterials presents potential advantages, such as enhanced disease management and long-term improvements in soil health and ecosystem functionality (Dimkpa and Bindraban, 2017; Duhan et al., 2017). However, additional research is necessary to fully comprehend the risks and benefits associated with the use of nanomaterials in horticulture and to develop safe and effective applications.

4.7 Macro-Nanofertilizers

“Macro-nanofertilizers are becoming increasingly popular due to their nanoscale dimensions, which enable a reduction in the overall quantity of nutrients required for plant growth” (S. Kumar et al., 2021; Sidorowicz et al., 2019). “Essential macronutrients such as phosphorus, magnesium, sulfur, calcium, nitrogen, and potassium can be combined with nanomaterials to optimize nutrient delivery to plants while also reducing cultivation costs” (Ditta and Arshad, 2016). “The development of macro-nanofertilizers aims to address the limitations associated with traditional fertilizers. For instance, nitrogen fertilizers like urea face challenges related to rapid volatilization and leaching. To mitigate this issue, the Sri Lankan Institute of Nanotechnology has created a slow-release nitrogen nano-fertilizer by applying a coating of hydroxylapatite nanoparticles to urea” (Chhowalla, 2017).

Phosphorus fertilizers frequently face challenges related to low nutrient uptake efficiency and their contribution to global environmental problems like eutrophication (S. Sharma et al., 2021). However, nanotechnology presents opportunities to develop phosphorus fertilizers that improve nutrient uptake efficiency. For instance, fungal-mediated phosphorus nanoparticles have been created to enhance phosphorus availability, and Liu and Lal (2015a) introduced carboxymethyl cellulose-stabilized hydroxyapatite nanoparticles as a novel approach for phosphorus fertilization (Liu and Lal, 2015a).

“Many studies have demonstrated the positive impacts of macro-nanofertilizers on plant growth, fruit yield, quality, and pollination. These fertilizers can be utilized through various application methods, such as soil application, injection, or foliar spray, enhancing their adaptability” (S. Sharma et al., 2021). For instance, *Punica granatum* cv. Ardestani treated with nano-nitrogen via foliar application at concentrations ranging from 250 to 500 ppm exhibited a notable increase in fruit yield (17–44%) and the number of fruits per plant (15–38%). Additionally, improvements were observed in physicochemical properties, including total soluble solids, fruit size, titratable acidity, and aril juice content (Davarpanah et al., 2017).

Additionally, “*Vitis vinifera* treated with nanosized calcite products that contain calcium carbonate, silicon dioxide, and magnesium oxide showed enhancements in various growth parameters, including volume and length, berry weight, total soluble solids, cluster number, and cluster weight, along with a reduction in acidity” (Zahedi et al., 2020; M. Zhang, Liang, and Chu, 2017). “The development of macro-nanofertilizers offers promising solutions to the challenges posed by traditional fertilizers, such as their environmental impact and cost-effectiveness. By enabling targeted nutrient delivery, macro-nanofertilizers could transform the agricultural sector, optimizing plant growth while reducing environmental repercussions” (DeRosa et al., 2010; Liu and Lal, 2015b).

However, Further research is necessary to examine the long-term effects of these fertilizers on plant growth and the environment (DeRosa et al., 2010), as well as to evaluate their commercial viability on a larger scale.

4.8 Micronutrient Nanofertilizers

“Micronutrient nanofertilizers have shown considerable potential in promoting the growth and yield of horticultural crops. These nanofertilizers contain essential trace elements like zinc, iron, boron, and copper, which play vital roles in various metabolic and physiological processes within plants” (Ahmed et al., 2023; Rivera-Gutiérrez et al., 2021).

For example, in tomatoes, the application of zinc oxide nanoparticles at a concentration of 100 ppm led to significant increases in plant height, fruit yield, and weight compared to the control group (Ahmed et al., 2023). “Likewise, a study on sweet peppers found that the application of copper oxide nanoparticles at 100 ppm notably enhanced root dry weight, shoot fresh weight, and plant height in comparison to the control” (Abd-Alrahman and Aboud, 2021).

“Another study found that the application of iron oxide nanoparticles at 100 ppm through foliar spray on strawberries resulted in significant enhancements in plant height, leaf count, fruit yield, and vitamin C content” (U. J. Kumar et al., 2017). “Furthermore, the use of nanofertilizers has been shown to improve the quality of horticultural produce. For example, applying zinc oxide nanoparticles at 50 ppm to grapevines significantly boosted the antioxidant activity and total phenolic content in the fruits” (Abou El-Nasr et al., 2021). “In pomegranate, using boron nanoparticles at 34 ppm and zinc nanoparticles at 636 ppm resulted in a 30% increase in yield while also improving fruit quality” (Davarpanah et al., 2016).

4.9 Crop Improvement

“Nanotechnology offers practical applications in crop improvement through biotechnology. Nanomaterials can traverse phloem tissues and accumulate in plant storage organs like fruits, grains, and tubers. Notably, the translocation of these materials is not restricted to particular cell types, enabling lateral movement between xylem and phloem tissues” (Pate, 1975; Pérez-de-Luque, 2017).

“One of the primary uses of nanomaterials is to transport DNA and chemicals into plant cells with precise control. Additionally, they allow for controlled and simultaneous delivery of multiple genes, facilitating research on gene function within cells. For instance, chitosan nanoparticles have been developed as carriers for siRNA, demonstrating effective binding with RNA and the ability to penetrate cell membranes” (Zhang et al., 2010). Currently, nanoparticles are increasingly recognized for their significance in genetic modification techniques, particularly in genome editing in plants (Miller et al., 2017; Mout et al., 2017).

5. CONCLUSION

In horticulture, nanotechnology is becoming increasingly important for improving the quality of fruit production. Nanotechnology-based particles are applied in various areas, such as fruit packaging, post-harvest management, nano fertilizers, nano pesticides, nano herbicides, genetic engineering, and genome editing. Utilizing these nanoparticles helps safeguard the ecosystem from pollution and fosters sustainable production practices. Nanomaterials have the potential to enhance fruit yield by reducing agricultural risks. They are used for targeted and site-specific management of pests and diseases, as well as for efficient nutrient delivery. Moreover, nanotechnology enables pest and disease detection through biosensors and facilitates gene delivery in fruit crops. The adoption of nanoparticle applications is set to transform fruit production by improving productivity while minimizing input usage. Therefore, it is essential to integrate nanotechnology into fruit production systems across various fruit crops—be they tropical, subtropical, or temperate—and to investigate its applications under field conditions in developing countries.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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