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ADVANCES IN NANOTECHNOLOGY FOR FRUIT CROPPRODUCTION AND POST-HARVEST MANAGEMENT:A COMPREHENSIVE REVIEW

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ABSTRACT

Nanotechnology has emerged as a transformative field in modern agriculture, providing innovative solutions to enhance fruit crop productivity, improve post-harvest quality, and minimize environmental impacts. This review consolidates current advancements in the application of engineered nanoparticles (NPs), including metal, metal oxide, carbon-based, polymeric, lipid, and silica nanoparticles, across the entire fruit production value chain—from pre-sowing treatments and crop protection to intelligent packaging and quality monitoring.

The role of nano-fertilizers in improving the efficiency of macro- and micronutrient delivery is critically evaluated, along with the effectiveness of nano-pesticides and nano-fungicides in disease management. Significant progress in nano-coatings and nano-enabled packaging technologies for extending post-harvest shelf life is also highlighted. Furthermore, special emphasis is placed on nanosensor platforms for real-time detection of ethylene, mycotoxins, pathogens, and pesticide residues. This review also explores the underlying mechanisms of nanoparticle uptake, translocation, and phytotoxicity in plants, and discusses current regulatory frameworks governing the use of nanomaterials in food systems. Despite notable advancements, challenges such as scalability, cost-effectiveness, nano-ecotoxicological concerns, and consumer acceptance remain critical. Finally, key research gaps are identified, and a roadmap is proposed for the responsible and sustainable integration of nanotechnology in fruit production systems.

***Key words*:** nanotechnology; nanoparticles; fruit crops; post-harvest; nano-fertilizers; nano-pesticides; edible coatings; nanosensors; food safety; sustainable agriculture

Introduction

Fruit production worldwide is under immense pressure in the twenty-first century owing to issues such as the increasing global population that may exceed 10 billion individuals by 2050, the detrimental influence of climate change on crop phenology and water availability, the rising prevalence of new pests and phytopathogens, and consumers' and regulators' high expectations for pesticide-free, nutritive-quality fruits. At the same time, the tremendous economic loss caused by post-harvest fruit commodity wastage in developing countries (25-40%) represents an important challenge (Kah *et al.*, 2019).

The term "nanotechnology" refers to the fabrication, assembly, and utilization of particles, structures, devices, and systems with a size of 1-100 nm. Compared to their bulk analogs, nanomaterials exhibit unique physical and chemical properties due to their significantly higher surface area-to-volume ratio, quantum confinement effects, surface reactivity tuning, and reactivity enhancement (Nel *et al.*, 2006). Such material properties provide opportunities for agriculture, including enhanced nutrient delivery efficiency, increased antimicrobial efficacy at lower chemical doses, stimulus-responsive agrochemical delivery, and sensitive sensors for food quality assessment.

Nanotechnology in agriculture has an interesting yet short history. Early research in the mid-2000s concentrated mainly on carbon nanotubes and their ability to boost seed germination and growth (Khodakovskaya *et al.*, 2011). The years since have seen rapid advances in the development of nano-fertilizers (Dimkpa & Bindraban, 2017), nano-pesticides (Jampílek & Králová, 2017), nano-techniques for post-harvest coating (Dhall, 2013), and nano-biosensors (Vidic *et al.*, 2017). Currently, the field covers the range from basic research into cell and molecular mechanisms to pilot-scale commercial applications.

Fruits, which comprise a wide array of plants ranging from the economically important mango (Mangifera indica), apple (Malus domestica), various citrus crops (*Citrus* spp.), strawberry (Fragaria × ananassa), grape (Vitis vinifera), banana (*Musa* spp.), guava (Psidium guajava), and other tropical and sub-tropical crops, provide an excellent example of a class of plants that can benefit from the application of nanotechnology. Their significant economic importance, highly perishable nature, and sophisticated post-harvest logistics system mean that precision farming methods would be of considerable interest. Furthermore, fruits display a certain sensitivity to micronutrient deficiency disorders (for example, zinc, iron, or boron) which can be easily remedied by nano-micronutrients (Siddiqui *et al.*, 2015).

Purpose of the Review

This review seeks to present a critically integrative synthesis of the existing body of literature in relation to the application of nanotechnology throughout the entire agricultural chain from production to consumption in fruits. It is designed to systematically cover the following aspects:

(i) types of nanomaterials in agriculture and their physicochemical properties;

(ii) nano fertilizers for nutrients;

(iii) nano pesticides, fungicides, and herbicides for protecting plants;

(iv) nanoparticle-based stress tolerance;

(v) nanotechnologies after harvesting including food coatings, films, and extending shelf life;

(vi) nanosensors for monitoring quality and safety; and

(vii) risks and ecotoxicity.

Classification and Characterization of Nanomaterials Used in Fruit Horticulture

Overview of Nanomaterial Types:

The variety of nanomaterials used for the studies in fruit crop science is extremely wide and can be generally categorized into seven main groups according to their composition and structure (Table 1). Every group has some special characteristics making them suitable for certain agricultural uses. The selection of particular nanomaterial is crucially dependent on the purpose and crop being considered.

Synthesis and Characterization Methods:

Three general strategies to synthesize nanomaterials for agriculture purposes are:

(i) physical processes like ball milling, laser ablation, thermal evaporation;

(ii) chemical reactions such as sol-gel, coprecipitation, chemical vapor deposition and reduction of metal salts; and

(iii) biological or green synthesis by employing extracts from plants and microorganisms, or byproducts of agriculture as reducing and capping agents (Nasrollahzadeh *et al.*, 2018).

Biological synthesis of nanomaterials for agricultural uses has gained special attention due to low toxicity, non-utilization of hazardous chemicals and scalability using agricultural resources.

A proper characterization of the synthesized nanomaterials prior to their usage is crucial. The most important methods for the analyses are: dynamic light scattering (DLS) for determining the hydrodynamic diameter and distribution size of particles; transmission electron microscopy (TEM), scanning electron microscopy (SEM) for the morphology; X-ray diffraction (XRD) for the crystal structure and phases composition; Fourier transform infrared spectroscopy (FTIR) for functional groups; zeta potential for assessing the colloidal stability; and the Brunauer–Emmett–Teller (BET) method for estimating the specific surface area. All these physicochemical factors greatly affect the biological activity of the nanomaterials (Nel *et al.*, 2006; Nair *et al.*, 2010).

Table 1: Classification of Nanomaterials Used in Fruit Horticulture: Types, Examples, and Applications.

Nanoparticle Type	Examples	Agricultural Applications	Key References
Carbon-based NPs	Carbon nanotubes, Graphene, Fullerenes	Seed germination, plant growth, nutrient uptake enhancement	Khodakovskaya *et al.*, (2011); Lahiani *et al.*, (2015)
Metal NPs	Silver (AgNPs), Gold (AuNPs), Copper (CuNPs), Zinc (ZnNPs)	Antimicrobial activity, antifungal protection, post-harvest preservation	Shang *et al.*, (2019); Dimkpa *et al.*, (2019)
Metal Oxide NPs	ZnO, TiO_2, CeO_2, Fe_2O_3, MgO	Nutrient delivery, photocatalysis, stress tolerance, antimicrobial coatings	Raliya & Tarafdar (2013); Garcia-Gomez *et al.*, (2018)
Polymer NPs	Chitosan, PLGA, Alginate, Starch-based	Agrochemical encapsulation, slow-release fertilizers, edible coatings	Kashyap *et al.*, (2015); Abdel-Aziz *et al.*, (2016)
Lipid NPs	Solid lipid NPs, Nanostructured lipid carriers	Pesticide delivery, antifungal agents, edible film formation	Campos *et al.*, (2018); Rao & Bhattacharya (2019)
Silica NPs	Mesoporous silica, Silicon dioxide	Controlled-release agrochemicals, moisture retention, film coatings	Torney *et al.*, (2007); Fincheira *et al.*, (2020)
Quantum Dots	CdSe, ZnS, Carbon quantum dots	Biosensing, disease detection, fluorescent labeling	Liang *et al.*, (2019); Wang *et al.*, (2021)

Nano-Fertilizers for Fruit Crop Nutrition

Principles and Mechanisms of Nano-enabled Nutrient Delivery:

Typically, utilization efficiency of conventional fertilizers used in orchard agriculture is extremely poor — less than 30–40% for nitrogen and even lower, i.e., 5–15%, for phosphorus, due to their leaching, volatilization, runoff, and fixation processes (Liu & Lal, 2015). Nano-fertilizers, however, represent an entirely new approach: the fertilizer components are enclosed or surface-adsorbed on a carrier nanoparticle, thus altering release kinetics, reducing losses, and allowing for the unique ways of uptake via foliar or root routes inaccessible to regular ionic fertilizers.

Namely, the ways that make nano-fertilizers effective are:

(i) controlled release of the fertilizer component caused by variations in soil pH, temperature, water content, and microorganism activity;

(ii) foliar absorption through stomata and cuticle pores that excludes the effect of soil mineralization;

(iii) the ability to trigger the effect of rhizosphere that activates microorganism-based mobilization of immobile soil nutrients; and

(iv) intracellular transport due to nanometer size relative to the cell wall pores' size (Dimkpa & Bindraban, 2017; Liu *et al.*, 2006).

Macro-nutrient Nano-fertilizers:

Nano-fertilizers made from nitrogen using chitosan-encapsulated urea or ammonium nitrate have proved to reduce nitrogen loss in several studies on fruits by 20-30%. In a study by Corradini *et al.*, (2010), NPK fertilizers were loaded into chitosan nanoparticles with sustained delivery for more than 30 days in soil conditions. Zeolite nano-potassium has proved successful in apple and citrus orchards, whereby it increased the potassium availability index and reduced leaching loss by up to 40% compared to potassium chloride treatment (Trenkel, 2010).

There is no doubt that phosphorus nano-fertilizers offer the best prospects because of their large proportion in tropical and subtropical soils used for growing many fruits. Hydroxyapatite $[Ca10 (PO_4)6 (OH)_2]$ nanoparticles were proved to be superior to triple superphosphate in availability in mangoes and bananas by achieving yield increase of 12-28% in Indian field trials (Tarafdar *et al.*, 2014). Rock phosphate nano-fertilizers by mechanical milling to sub-100 nm size were found to show improved solubility and plant available P in citrus orchards (Rathore and Tarafdar, 2015).

Micronutrient Nano-fertilizers for Fruit Crops:

Deficiencies of micronutrients especially Zinc, Iron,

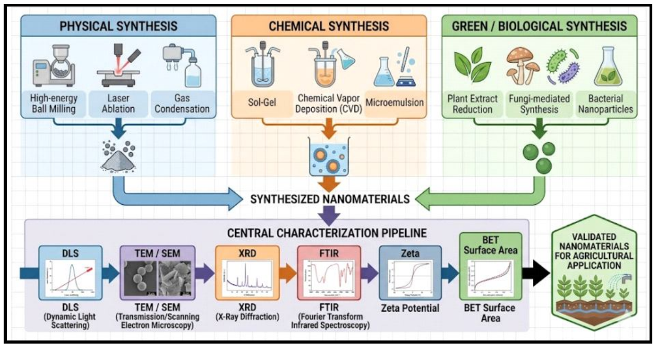

Fig. 1: Schematic Overview of Nanomaterial Synthesis Routes and Characterization Pipeline.

Table 2: Nano-fertilizer Applications in Fruit Crops: Formulation, Application Method, and Yield/Quality Effects.

Nano-fertilizer	Crop	Application Method & Dose	Effect on Yield/Quality	References
Nano-ZnO	Mango, Citrus	Foliar spray (0.5–2 g/L)	Improved fruit set, yield +18–35%	Siddiqui *et al*., (2015); Davarpanah *et al*., (2016)
Nano-Fe_2O_3	Strawberry, Apple	Soil application (10–50 mg/kg)	Enhanced chlorophyll, Fe uptake	Ghafari & Razmjoo (2013); Askary *et al*., (2017)
Nano-TiO_2	Tomato, Grape	Foliar (0.01–0.05%)	Photosynthesis boost, antioxidant activity	Jaberzadeh *et al*., (2013); Mohammadi *et al*., (2014)
Nano-Chitosan-N	Banana, Mango	Seed/foliar treatment	N-use efficiency +22%, growth promotion	Abdel-Aziz *et al*., (2016); Liu *et al*., (2019)
Nano-CeO_2	Tomato, Soybean	Soil/foliar (0.5–5 mg/L)	Oxidative stress mitigation	Rico *et al*., (2013); Cao *et al*., (2017)
Nano-Silica	Cucumber, Strawberry	Foliar (50–150 mg/L)	Enhanced water use efficiency	Fincheira *et al*., (2020); Kim *et al*., (2014)
Nano-K (zeolite)	Apple, Citrus	Soil incorporation	Improved K availability, fruit quality	Trenkel (2010); Mikkelsen (2018)

Boron, and Manganese are very common in fruit orchards that pose serious challenges for improving their quality and productivity. The application of nanofertilizers containing these micronutrients has shown impressive results in resolving such deficiencies. (Table 2).

Nano Zinc particles and nano-ZnO have received more attention than any other type of nanoparticle. Davarpanah *et al*., (2016) found that spraying nano-Zn at 0.5 g/L on pomegranate trees improved fruit weight, total soluble solids, and anthocyanins in comparison to zinc sulfate chelates at the same concentration. Raliya & Tarafdar (2013) showed that ZnO NPs produced by Aspergillus fumigatus promoted phosphate solubilization and indole acetic acid formation in the rhizosphere soil. The efficiency of nano iron fertilizers in strawberries (Askary *et al*., 2017) and apple plantations (Ghafari & Razmjoo, 2013) was evidenced by higher chlorophyll contents and SPAD readings than iron chelates at similar concentrations.

Nanotechnology in Fruit Crop Protection

Nano-pesticides and Nano-fungicides:

Fungal infections are estimated to cause 20-30% losses in fruit yield in both pre-harvesting and post-harvesting stages, and such serious diseases include anthracnose (*Colletotrichum* spp.), gray mold (Botrytis cinerea), blue mold (*Penicillium expansum*), crown rot (*Fusarium* spp.) and powdery mildew (*Podosphaera xanthii*). In addition, due to increasingly stringent regulations on conventional pesticides and the rise of resistance, there is a significant need for nano-based pesticides.

The antifungal activity of Nano fungicides operates by employing a number of different methods, including the production of reactive oxygen species, leading to oxidative stress on the fungal membranes; disruption of the membrane structure by physical interactions between the nanoparticles and the fungal cells; inhibition of the synthesis of cell wall chitin; disruption of enzyme activities within the fungus metabolic pathway; and finally physical penetration through hyphal cell walls by the nanoparticles. (Table 3).

The most widely investigated biological nano-fungicide is chitosan nanoparticles. The mode of action of this fungicide is based on the interaction of positively charged chitosan amino groups with negatively charged fungal phospholipids, resulting in cell membrane destruction and leakage of cytoplasmic material (Sathiyabama & Parthasarathy, 2016). Inhibitory effects of chitosan nanoparticles on *B. cinerea* in strawberry plants (Shao *et al*., 2018) and *C. gloeosporioides* in mango fruits (Meng *et al*., 2010) have been shown. Silver nanoparticles possess broad-spectrum antibacterial activity even in minimal doses (1-10 μg/mL minimum inhibitory concentrations), which is caused by Agz ions that generate ROS and induce protein denaturation (Hajipour *et al*., 2012; Prabhu & Poulose, 2012).

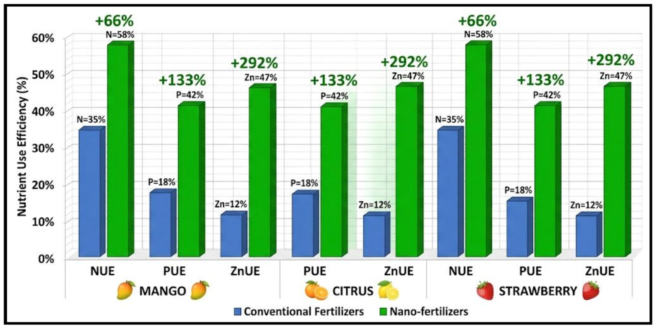

Fig. 2: Comparative Nutrient Use Efficiency: Conventional vs. Nano-fertilizer Delivery Systems in Fruit Crops.

Table 3: Nano-pesticides and Nano-fungicides for Fruit Crop Disease Management: Agents, Targets, and Mechanisms.

Nano-pesticide	Target Pathogen	Mechanism of Action	References
Chitosan NPs	*Botrytis cinerea, Fusarium spp.*	Direct antifungal activity; membrane disruption	Sathiyabama & Parthasarathy (2016); Liu *et al.*, (2018)
Ag NPs	*Colletotrichum gloeosporioides, Xanthomonas spp.*	ROS generation; protein denaturation in pathogens	Shang *et al.*, (2019); Prabhu & Poulose (2012)
ZnO NPs	*Penicillium expansum, Rhizopus stolonifer*	Cell wall disruption; photocatalytic antimicrobial action	He *et al.*, (2011); Garcia-Gomez *et al.*, (2018)
Thymol NPs (nanoemulsion)	Post-harvest fungal rots	Essential oil delivery; volatile antifungal	Meng *et al.*, (2018); Sharma & Bhattacharya (2017)
Nano-encapsulated azoxystrobin	Powdery mildew on grapes	Controlled release; reduced fungicide dose by 40%	Campos *et al.*, (2018); Grillo *et al.*, (2016)
Cu NPs	Bacterial canker, *Xanthomonas*	Bactericidal; disrupts enzyme activity	Giannousi *et al.*, (2013); Dimkpa *et al.*, (2019)
TiO_2 NPs (UV-activated)	Post-harvest molds	Photocatalytic oxidation of fungal cell membranes	Kim *et al.*, (2012); He *et al.*, (2016)

Nano-herbicides and Weed Management:

Herbicide application in orchards, especially the inter-row areas of newly planted orchards, is one of the important production costs. Nanocapsulation of herbicides provides the possibility of using smaller amounts of active substance without reducing the effectiveness of the action. According to Grillo *et al.*, (2012), poly(ε-caprolactone) nanocapsules containing atrazine had the same effectiveness of weed elimination with 75% reduction of the herbicide dose compared to commercial formulation without increasing soil leaching and promoting soil microflora. The technology of nanocapsules is also useful for creating effective mixtures of incompatible herbicides.

Nanoparticle-mediated Stress Tolerance:

There are numerous stresses such as drought, salinity, heat, and heavy metal toxicity that affect the productivity of fruits significantly in the scenario of changing climate conditions. Several methods have been suggested for improving stress resistance using nanotechnology. In addition to their effect on alleviating oxidative stress in grapevines and tomatoes under drought, TiO_2 nanoparticles increase the efficiency of the Calvin cycle through increasing the activity of antioxidant enzymes (superoxide dismutase, catalase, peroxidase) (Jaberzadeh *et al.*, 2013).

Nano-particles CeO_2, which act as superoxide dismutase-mimetic and catalase-mimetic nanoenzymes, provide remarkable protection against oxidative stress under different stresses for tomatoes and soybeans (Cao *et al.*, 2017; Rico *et al.*, 2011). The improvement of stress tolerance by silicon dioxide nanoparticles is mainly due to increasing cell wall stiffness and proline content in fruit plants, resulting in increased drought resistance in strawberries and cucumbers (Fincheira *et al.*, 2020). Nano-selenium at a concentration of 5–25 mg/L acts as an effective stress tolerancer inducer in multiple fruits (Singh *et al.*, 2018).

Post-Harvest Nanotechnology for Fruit Quality and Shelf-Life Extension

Nano-enabled Edible Coatings:

Losses of fruits after harvest are mainly due to water loss, physical damage, fungal growth, oxidation, and senescence due to ethylene buildup. The nano-based edible films help address all these challenges because of the dual benefits offered by their biopolymeric matrix and functional properties associated with nanoparticles (Table 4). Edible films need to comply with strict food safety requirements because the materials used must be GRAS or food-grade approved, and the film itself must neither induce any flavor changes nor change the nutritional content.

Nano-coatings based on chitosan stand out as the most commercialized form of nanoedible coatings because of their antifungal activity, film-forming ability, oxygen barrier nature, and biodegradability. Shao *et al.*, (2018) showed that nano-coatings based on chitosan

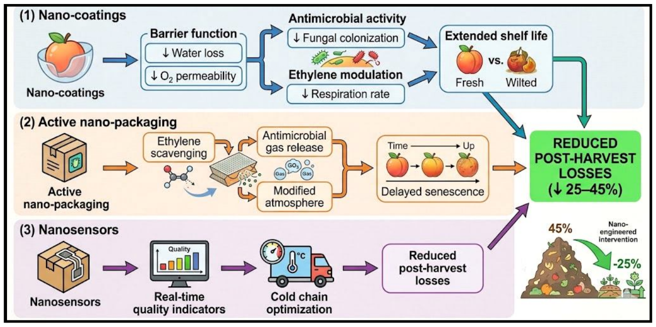

Fig. 3: Mechanisms of Action of Nano-enabled Post-Harvest Technologies.

Table 4: Nano-enabled Edible Coatings for Post-Harvest Fruit Preservation: Materials, Crops, and Outcomes.

Coating Material	Fruit Crop	Shelf-Life Extension	Mechanism/Benefit	References
Chitosan NPs	Strawberry, Mango, Citrus	3–7 days shelf-life extension	Reduced weight loss; antifungal activity	Shao *et al.*, (2018); Meng *et al.*, (2010)
ZnO NPs composite	Apple, Banana, Guava	4–6 days extension	Antimicrobial; ethylene barrier	He *et al.*, (2011); Li *et al.*, (2017)
Nano-silver coating	Papaya, Mango, Tomato	5–8 days extension	Reduced microbial load; delayed ripening	Nasrollahzadeh *et al.*, (2018); Hajipour *et al.*, (2012)
TiO, /SiO, nanocomposite	Grape, Cherry, Kiwi	6–10 days extension	UV protection; oxidation barrier	Khodakovskaya *et al.*, (2009); Fan *et al.*, (2019)
Nano-wax emulsion	Citrus, Plum, Peach	7–14 days extension	Glossy appearance; moisture barrier	Dhall (2013); Xing *et al.*, (2019)
Nano-$CaCO_3$/ Ca-chitosan	Litchi, Cherry, Blueberry	3–5 days extension	Firmness retention; Ca^{2}z signaling	Dong *et al.*, (2017); Wang *et al.*, (2019)
Carvacrol/Thymol nanoemulsion	Strawberry, Blueberry	5–9 days extension	Essential oil release; GRAS status	Meng *et al.*, (2018); Salvia-Trujillo *et al.*, (2015)

applied to strawberries had an extended shelf life of 5-7 days under refrigeration conditions compared to non-treated control strawberries. Nano-coatings formed by incorporating zinc oxide nanoparticles into chitosan matrices have been shown to provide broad antimicrobial activity and improved mechanical properties (Xing *et al*., 2019).

Nano-emulsions containing essential oils constitute a safe and effective method of combining the physical barrier role played by a coating with the strong antimicrobial properties of volatile components (carvacrol, thymol, cinnamaldehyde, eugenol). The small size of nanodroplets (20-200 nm) used in nano-emulsions significantly increases the uniformity of coating formation, reduces the amount of essential oil needed for coating (0.1-0.5%), and increases interaction between the active ingredient and the pathogen cell membrane (Meng *et al*., 2018; Salvia-Trujillo *et al*., 2015).

Nano-enabled Packaging Technologies:

Advanced packaging techniques utilizing nanotechnology involve a radical change in perspective from static to interactive packaging techniques that actively change the micro-environment around the fruits. Three main techniques in nanotechnology-based packaging of fruits include:

(i) nanocomposites using antimicrobial nanoparticles such as AgNPs, ZnO NPs, and TiO_2 NPs mixed in biopolymer matrices like polylactic acid, polyethylene, starch, and cellulose;

(ii) nano-clay strengthened films, enhancing gas and vapor-barrier properties; and

(iii) nano-technology based active packaging technique, which involves ethylene scavengers like nano-$KMnO_4$ and nano-ZnO to inhibit ripening (Chaudhry *et al*., 2008; Fan *et al*., 2019).

Reinforcement with nano-clay (montmorillonite, halloysite nanotubes) results in an enhanced barrier property of biopolymer films with extremely low permeability to oxygen and carbon dioxide gases due to the tortuous diffusion path formed by the exfoliation of the nano-clay platelets. The combination of the modified atmosphere concept employed in packaging and the antibacterial activity imparted by the metal oxide nanoparticles leads to increased shelf-life of climacteric fruits like mango, banana, and papaya by 7–14 days when compared to conventional packaging (Kim *et al*., 2018).

Ethylene Management with Nanotechnology:

Ethylene, which plays the most important role in climacteric fruits' ripening process, becomes an important molecule in relation to the potential post-harvest applications of nanotechnological methods. Various nano-based methods have been developed to regulate ethylene:

(i) Formulations involving nano-1-methylcyclopropene (1-MCP) which release 1-MCP more slowly than traditional sachets Smartfresh®;

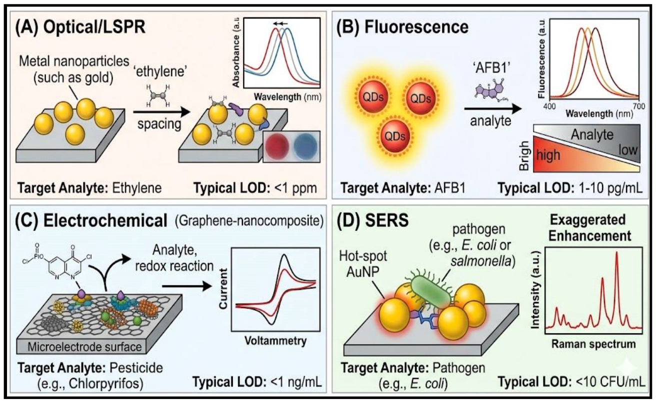

Fig. 4: Nanosensor Signal Transduction Mechanisms in Fruit Quality Monitoring.

(ii) methods using nano silver and nano-$AgNO_3$, which reduce the sensitivity to ethylene in receptors; and

(iii) ethylene scavengers such as ZnO nano-sachets, which act by catalytic oxidation of ethylene to carbon dioxide and water (Elmer & White, 2018; Dhall, 2013). In particular, nano-1-MCP microcapsules proved commercially successful, especially in China, where it increased 1-MCP retention rate 2–3 times compared to conventional gaseous 1-MCP in storage atmosphere.

Nanosensors for Fruit Quality Monitoring and Food Safety

Detection of Ripening Indicators:

To monitor fruit quality during the entire journey through the food chain, sensors with appropriate sensitivity, selectivity, and portability need to be developed, so that the monitoring can take place on location, not in laboratories, where they are subjected to complicated food systems. There have been many developments in the field of nanosensors, which utilize the distinctive physical properties of nanomaterials in order to carry out signal conversion. (Table 5).

Ethylene nanosensors, which use a network of carbon nanotubes functionalized with copper porphyrins, are able to detect ethylene in parts per billion levels, several orders of magnitude lower than the ripening level of most climacteric fruits, thus making in-transit monitoring possible (Esser *et al*., 2012; Wang *et al*., 2021; El-Argawy *et al*., 2017). They have quick response time (less than 30 seconds) and are completely reversible, making them ideal for in-transit monitoring. Ethylene sensor tags, which incorporate CNTs, have been used in trials involving the transportation of apples, triggering automatic notifications when a ripening level is reached.

Mycotoxin and Pathogen Detection:

Contamination of fruits by mycotoxins including aflatoxins (B1, B2, G1, G2), patulin, ochratoxin A and fumonisins constitutes an important food safety issue. The conventional approaches for the detection of such mycotoxins include HPLC-MS and ELISA and they involve lengthy procedures with the need for prior sample preparation, and are unsuitable for field testing and online monitoring. LFIA strips based on gold nanoparticles enable qualitative semi-quantitation of aflatoxin B1 with lower limits of detection of 0.001 μg/kg in less than 15 minutes and without any requirement of specialized equipment (Yang *et al.*, 2017). SERS biosensors based on aggregated AgNP or AuNP surfaces demonstrate attomolar sensitivity for the detection of patulin in apple juice without sample preconcentration step (Ye *et al.*, 2018).

For the identification of pathogens present on fruits, LSPR sensors based on Au nanoparticle array conjugated with antibodies against pathogens, i.e. Salmonella enterica and Listeria monocytogenes can detect the pathogens with limits of detection of 10-100 CFU/mL without cross reaction, which is 100 times better compared to the conventional plate count method (Vidic *et al*., 2017; Shao *et al.*, 2018).

Pesticide Residue Detection:

Increased consumer and governmental attention towards pesticide residues in fruit produce has led to the need for the development of efficient detection methods that are fast, inexpensive, and accurate. Silver nanoparticles have been used for the development of colorimetric sensors because of their ability to produce a spectral shift in their absorption band from 420 to >600 nm when organophosphorus or carbamate pesticides bind to them, leading to the appearance of visible colors and detection using the naked eye or even by smartphone-based colorimetry down to sub-ppb levels (Li *et al*., 2019; Ye *et al*., 2018). Electrochemical detection of chlorpyrifos, malathion, and methyl parathion was performed using graphene oxide/Au nanoparticle composite modified electrodes (Liang *et al*., 2019).

Mechanisms of Nanoparticle Uptake, Translocation, and Phytotoxicity in Fruit Crops

Uptake Pathways:

Understanding the modes of entry of nanoparticles into plant tissue is important in assessing biological action, determining toxicity risks to plant life, and implementing effective delivery techniques. The uptake of nanoparticles by fruit plants takes place in three ways:

(i) root uptake from soil and hydroponic media;

(ii) foliar uptake through stomatal openings, cuticle penetration or trichomes; and

(iii) translocation via phloem and xylem after uptake at either root or leaf levels (Nair *et al.*, 2010; Shang *et al*., 2019).

The process of root uptake includes the interaction of nanoparticles with soil (which may cause agglomeration, dissolution, and transformations), transport across the root epidermis by apoplastic and symplastic pathways, and possibly transport through the endodermis and the Casparian strips — which are known to pose a major barrier to larger particles. The smaller particles with sizes less than 20 nm can move through apoplastic

Table 5: Nanosensor Platforms for Fruit Quality and Safety Monitoring.

Sensor Type	Target Analyte	Performance	References
Carbon nanotube-based sensor	Ethylene detection	ppb-level; real-time ripening monitoring	Esser *et al.*, (2012); Liang *et al.*, (2019)
ZnO nanowire biosensor	Fungal metabolites (AFB1)	LOD: 0.001 ng/mL; high specificity	Wang *et al.*, (2021); Yang *et al.*, (2017)
Au NP-LSPR sensor	Salmonella, E. coli on fruit surfaces	Rapid detection < 30 min; no enrichment	Shao *et al.*, (2018); Vidic *et al.*, (2017)
Ag NP colorimetric sensor	Pesticide residues (organophosphates)	Visual color change; portable field use	Li *et al.*, (2019); Ye *et al.*, (2018)
Graphene oxide nanocomposite	Volatile organic compounds	Gas-phase freshness indicator	Kim *et al.*, (2018); Fan *et al.*, (2019)
Quantum dot fluorescent sensor	Heavy metals (Pb^{2}z , Cd^{2}z) in fruit	Highly sensitive; multiplexed detection	Liang *et al.*, (2019); Wang *et al.*, (2020)
Chitosan/TiO_2 nanosensor	H_2O_2 and oxidative stress indicators	In-package freshness monitoring	He *et al.*, (2016); Zhang *et al.*, (2017)

spaces, whereas larger particles might need other transport mechanisms such as endocytosis and transport across the membranes. Composition of root exudates, soil pH, organic carbon and ion contents in the soil solution greatly affect the dissolution, colloidal stability, and bioavailability of nanoparticles in the rhizosphere (Zhao *et al*., 2012; Stampoulis *et al*., 2009).

Phytotoxicity Considerations:

Whereas several research works have been carried out regarding the positive impacts of nanoparticles on the yield of fruits and their quality, phytotoxicity is another aspect that cannot be ignored in nanoagriculture studies. Phytotoxicity may occur in the following ways:

(i) oxidative stress due to overproduction of ROS resulting in oxidative damage;

(ii) genotoxicity leading to DNA strand breaks or chromosomal abnormalities;

(iii) damage to the cell membrane structure;

(iv) ion transporters interference due to ionic imbalances; and

(v) xylem obstruction from the aggregation of nanoparticles in the vessel walls (Barrena *et al*., 2009; Stampoulis *et al*., 2009).

The dose response relation in phytotoxicity shows that the dose of nanoparticles will affect plant growth either positively or negatively depending on its amount, and this relationship shows a hormetic effect. The threshold values for different nanoparticles and different crops are not constant; they vary depending on the type of nanoparticles used and the crop species. For instance, 10-50 mg/l zinc oxide nanoparticles enhance growth and increase antioxidant activities in tomatoes, while above 200 mg/l, they show negative impacts; silver nanoparticles become toxic in most crops above 50-100 mg/l (Garcia-Gomez *et al*., 2018; Nel *et al*., 2006).

Regulatory Frameworks, Food Safety, and Environmental Considerations

Regulatory Status of Nano-agrochemicals:

The regulatory control of nanomaterials in agriculture and food systems remains disjointed and quickly changing. In Europe, nanomaterials employed in food contact materials, food additives, pesticides, and fertilizers are regulated by specific nano provisions created via recent amendments to existing regulations (EU Novel Food Regulation 2015/2283; EU Fertilising Products Regulation 2019/1009; EU Cosmetics Regulation). The main regulatory approach in Europe is that nanomaterials need to undergo case-by-case risk assessment based on nano-specific data requirements, and nanoforms of registered chemicals are considered new chemicals that necessitate a novel registration (Kah *et al*., 2019; Kookana *et al*., 2014).

In the US, FDA, EPA, and USDA all have overlapping regulatory authority over nano-agrochemicals

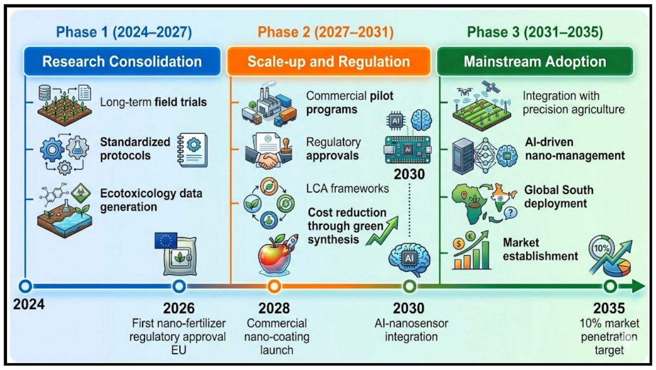

Fig. 5: Roadmap for Nanotechnology Integration in Fruit Crop Production: Current Status and Future Directions (2024–2035).

and food contact nanomaterials. The EPA regulates nanopesticides under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), and has developed guidelines in 2014 which have been revised to incorporate nano-specific information regarding fate, transport, and hazards. Pre-market notification is necessary in accordance with FDA guidelines on GRAS or food additive petition pathway for incorporation of nanomaterials in food products and food packages. Similarly, other national agencies like Australia's APVMA, Canada's PMRA, and India's DBT/GEAC have created their own nano-specific guideline frameworks but not without a lack of harmony (Chaudhry *et al.*, 2008; Scott & Chen, 2013).

Nano-ecotoxicology and Environmental Fate:

The fate of nano-agrochemicals in the environment and their ecotoxicological effects remain an important area of current research and regulation. While traditional agrochemicals undergo degradation through hydrolysis, photolysis, or biological processes like microbially mediated biodegradation, nanoparticles may remain in soil or water as modified, yet not totally mineralized compounds for long periods of time. Nano-agrochemicals containing metals (mainly ZnO, TiO_2 and AgNPs) tend to accumulate in the soil, undergo dissolution leading to release of toxic ions, participate in biological processes such as plants' uptake or even pollinator exposure (Nel *et al.*, 2006; Kookana *et al.*, 2014).

Several key principles in nano-ecotoxicology include:

(i) nano-toxicity to soil microorganisms is positively related to the degree of dissolution of metal ions, implying that very stable nanoparticles with low dissolution potential could be less environmentally hazardous;

(ii) organic compounds present in soil/water form a corona on the nanoparticle surfaces and affect their surface properties and toxicity;

(iii) biodegradable nano-carrier materials (e.g., chitosan, starch, PLGA, lipid NPs) have significantly shorter lifetimes compared to those of inorganic NPs; and

(iv) risk assessment should take into account the entire life cycle of the nanomaterials, from production to application and disposal. Prediction models for the environmental behavior of nanomaterials and large-scale ecotoxicological investigations in the field are highlighted as major areas for future research.

Consumer Acceptance and Nanotechnology Communication:

Public awareness and consumer acceptance of the role of nanotechnology in fruit production and food packaging form another socio-economic consideration in the utilization of nano-technological solutions for agriculture. Public attitude towards nanotechnology application in environmental purification and health care has been found to be largely positive while public perception towards the use of nanotechnology in food production is more hesitant, especially within the European Union (Chaudhry *et al.*, 2008). Factors that influence public attitude toward the application of nanotechnology include: perceptions regarding the 'naturalness' of the technology, clear product labeling and regulations, level of perceived risk, and the ratio of risks versus benefits. Communication on the scientific aspect and information dissemination regarding the nanomaterials used in food items have been identified as important considerations (Scott & Chen, 2013).

Current Challenges and Future Research Priorities

Technical and Scalability Challenges:

Despite all the significant breakthroughs highlighted in earlier parts of the discussion, some key technical issues must be addressed before the widespread implementation of nanotechnology in commercial fruit farming can occur. One key issue involves the mass production and economic efficiency of nanoparticle preparation; current laboratory methods for synthesis produce only gram- to kilogram-level amounts of nanoparticles at 10-100 times greater cost than that of traditional approaches, and scale up of the process to tonnage level while ensuring tight particle size control and surface homogeneity is technically difficult (Dimkpa & Bindraban, 2017; Kah *et al.*, 2019).

Another major technical obstacle concerns the long-term stability of the nano-formulations under realistic conditions of field application: nanoparticles tend to aggregate readily in solutions with high ionic strength (as would be found in typical formulations for agricultural sprays), and lipids or polymers used to formulate nano-carriers may degrade due to hydrolysis or oxidation during prolonged storage at room temperature. Formulation chemistry improvements are currently being investigated in attempts to overcome such stability limitations (Kashyap *et al.*, 2015; Rao & Geckeler, 2011).

Knowledge Gaps and Future Research Directions:

The following areas of knowledge need urgent focus:

(i) Field experiments conducted over time periods in varied agro-climatic conditions as well as commercial orchards compared to the currently abundant short-term controlled or greenhouse studies;

(ii) The behavior of nanoparticles in real soils versus simplified media such as hydroponic or agar;

(iii) Understanding the molecular mechanisms behind nanoparticle-plant interactions through genomic, transcriptomic, and proteomic analyses using advanced technologies;

(iv) Formulating standard procedures for the characterization of nanoparticles, their application processes, and ecotoxicological assessments to facilitate comparison among various studies; and

(v) Techno-economic assessment and LCA of nano-agriculture interventions vis-à-vis conventional methods (Worrall *et al*., 2018; Morales-Díaz *et al*., 2017).

Combination of nanotechnology with existing precision agriculture techniques, such as remote sensing technology, variable rate applicator, and artificially intelligent decision support system for crop management, could be especially useful in achieving maximum benefit from using nanotechnology-based agrochemicals while ensuring minimum exposure to the environment. Utilization of biosensors in precision irrigation and fertigation systems could make possible adaptive control over pests and nutrient supply and lead to the development of what is termed "smart nano-agriculture" (Kim *et al*., 2018; Fan *et al*., 2019).

Conclusions

Starting with the impressive increase in micronutrient utilization efficiency due to the use of nanotechnology-based zinc and iron fertilizers in mango and citrus trees, moving through the increased shelf-life of strawberries thanks to the chitosan-based nanoparticles that make berries stay fresh for one additional week, all the way up to the detection of the presence of aflatoxins via gold nanoparticles within minutes, the possibilities offered by nanotechnology in fruit horticulture are wide-ranging.

Overall, several key findings may be derived from this review:

(a) the efficacy of utilizing nanotechnology within fruit-growing has been proven; this is reflected in an evident improvement in fruit yield (generally speaking, ranging from 10% to 35%), fertilizer utilization rate (20% – 60%), shelf-life (3 days - 10 days), and, finally, increased detection sensitivity (10 to 1000 times).

(b) All those benefits can be achieved at low phytotoxicity rates as there were no major issues reported regarding ecological concerns.

(c) Biodegradable and bio-based nano-carriers (chitosan, lipid nanoparticles, plant-based NPs) offer a significantly better profile than inorganic nanoparticles.

Despite these positive findings, however, the journey from discovery in the lab to practical application in commerce is anything but short or easy. The absence of an internationally regulated framework results in uncertainty that does little to foster investment on the part of private enterprise. The absence of empirical findings based on extended field trials, especially within the variable agroclimatic environment of many fruit-growing countries in Asia, Africa, and Latin America, makes the extension of laboratory results into commercial guidelines difficult to achieve. In addition, the competitive advantage of nanoproducts compared to traditional ones, especially considering the limited resources available to small-scale farmers who provide the majority of the world's fruits, remains an issue to be addressed.

The future of nanotechnology within fruit horticulture will be decided based on how far along research goes along these lines, based on the further development of regulatory policies that allow for innovation while maintaining safety for the consumer and the environment, and through engagement with farmers, stakeholders, and consumers. In terms of the scientific basis, as shown throughout this review, there is much to commend it. However, it remains to see how this scientific knowledge will be used moving forward.

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