Use of nanotechnology in management of fruit crops and their associated products (#104031)

First revision

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- Introduction adequately introduces the subject and makes audience and motivation clear.

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- Article content is within the Aims and Scope of the journal.
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- Methods described with sufficient detail & information to replicate.
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- Is the review organized logically into coherent paragraphs/subsections?

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- **Impact and novelty is not assessed.** Meaningful replication encouraged where rationale & benefit to literature is clearly stated.
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Use of nanotechnology in management of fruit crops and their associated products

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Fresh fruits, rich in essential nutrients and bioactive compounds, contribute positively to human health. However, the perishable nature of the fruit crops and their limited post-harvest lifespan results in substantial losses on a global scale. Ensuring quality and reducing wastage remains a key challenge in fruit crop production. Thus, many advancements have been developed, including nanotechnology, which has the potential to increase fruit production and enhance food security. Nano-science is rapidly advancing as one of the key areas of applied research, offering diverse applications in crop sciences such as nano-fertilizers, nano-pesticides, nano-coatings, post-harvest treatments, and packaging. It also contributes to increasing water use efficiency and defense measures in fruit crops. Such applications are adapted to boost the development, reproductive growth, blossoming, product quality and reduce fruit waste. Nanoparticles have distinct chemical and physical features that promote the growth of plants and resilience to stress, making them beneficial for improving fruit crops. It also has the potential to boost productivity, extend shelf life, reduce post-harvest damage, and enhance the quality of crops. Nano-particles are also used for targeted site-specific pest and disease management, smart nutrient supply, and delivery via biosensor(s) in horticulture, specifically in fruit crops. Moreover, they are synthesized efficiently, functioning rapidly in cost effective and environmentally sustainable manner. This review comprehensively highlights substantial insights into using nanoparticles as a promising technique for increasing fruit crop resilience and ensuring food security in the context of environmental changes, as well as the recent application of nanotechnology at various stages of fruit production.

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Short Title: Nanotechnology and Fruit Crop

Abstract

Fresh fruits, rich in essential nutrients and bioactive compounds, contribute positively to human health. However, the perishable nature of the fruit crops and their limited post-harvest lifespan results in substantial losses on a global scale. Ensuring quality and reducing wastage remains a key challenge in fruit crop production. Thus, many advancements have been developed, including nanotechnology, which has the potential to increase fruit production and enhance food security. Nano-science is rapidly advancing as one of the key areas of applied research, offering diverse applications in crop sciences such as nano-fertilizers, nano-pesticides, nano-coatings, post-harvest treatments, and packaging. It also contributes to increasing water use efficiency and defense measures in fruit crops. Such applications are adapted to boost the development, reproductive growth, blossoming, product quality and reduce fruit waste. Nanoparticles have distinct chemical and physical features that promote the growth of plants and resilience to stress, making them beneficial for improving fruit crops. It also has the potential to boost productivity, extend shelf life, reduce post-harvest damage, and enhance the quality of crops. Nano-particles are also used for targeted site-specific pest and disease management, smart nutrient supply, and delivery via biosensor(s) in horticulture, specifically in fruit crops. Moreover, they are synthesized efficiently, functioning rapidly in cost effective and environmentally sustainable manner. This review comprehensively highlights substantial insights into using nanoparticles as a promising technique for increasing fruit crop resilience and ensuring food security in the context of environmental changes, as well as the recent application of nanotechnology at various stages of fruit production.

Keywords:

Horticulture; Fruit crops; Nanofertilizers; Nanopesticides; Nanocoatings; Nanopackaging; Precision farming

Introduction

Fruit crops play a crucial role in the global economy, contributing to agricultural trade, employment, and rural development. As consumer demand for fresh and processed fruits continues to rise, countries with favorable climates and production capabilities benefit from high export revenues (Gergerich *et al.,* 2015). The fruit industry supports farmers and supply chain workers and drives logistics, food processing, and biotechnology advancements. Beyond economic significance, fruits are essential to human nutrition due to their rich composition of vitamins, minerals, fiber, and antioxidants (Abobatta, 2021). The growing awareness of health benefits has increased the preference for organic and minimally processed fruits, further shaping global agricultural practices and trade policies. Despite their importance, the global fruit industry faces numerous challenges, such as climate change, weather patterns, pest infestations, post-harvest losses, and market fluctuations, threatening fruit production and profitability (Bhattacharjee *et al*., 2022). Additionally, the overuse of chemical pesticides and fertilizers has raised environmental concerns (Sah *et al*., 2024), leading to stricter regulations and consumer demand for sustainable farming practices (Beyuo *et al*., 2024). To address these challenges, conventional management strategies include integrated pest management, efficient post-harvest handling, and storage technologies, which help to reduce losses and maintain fruit quality. In recent years, frontier technologies such as nanotechnology have arisen innovative solutions for mitigating these hazards (Manzoor *et al*., 2024). Nanotechnology is an emerging strategy for increasing fruit productivity with limited inputs in contemporary fruit cultivation(Kamatyanatti *et al.*, 2019). Nanoscience is the study of materials at the nanoscale (10^9 meters) from 1-100 nanometers (Singh, 2017). Nanomaterials have unique physical and chemical properties that differ from those of conventional materials larger than 100 nanometers (Kumar *et al*., 2024). Nanoparticles have unique chemical and physical qualities that promote plant growth, development, and stress tolerance (Figure 1), making them helpful in improving fruit crops (Manzoor *et al*., 2023). Nanomaterial seed coatings have attracted significant interest in fruit crops due to their ability to enhance plant growth, increase crop yields, and improve resource efficiency. Nanomaterial coatings help seeds adhere better to the soil, reduce wastage during planting, and boost planting efficiency (Mehta, 2023). Recently, nanoparticles have improved plant tolerance against biotic and abiotic stresses. Nanoparticles play a crucial role in enhancing plant yield characteristics under stress conditions. It has significant effects on various physiological processes, including stress response mechanisms, hormone metabolism, osmolyte biosynthesis, ethylene production, and signaling pathways (Rasheed et al., 2022).

Nanomaterials provide numerous beneficial functions in biological systems; nevertheless, their toxicity can also be demonstrated to be detrimental (Jena *et al*., 2022; Paital *et al*., 2019; Yadav *et al*., 2023). Therefore, green synthesis of nano-particles and nano-herbals is now being used to open a new horizon in all fields, including horticulture, either to protect the crops or to use their products as neutraceuticals, crop protectors, herbicides, pesticides, etc. (Patel et al., 2023; Mishra et al., 2024; Paital, 2020; Raja et al., 2020; Subaramaniyam et al., 2024; Ilango et al., 2022). So, organizing information and their critical evaluation of the role of nanomaterials on organisms is essential.

Pests, such as insects, mites, nematodes, and diseases, significantly impact crop profitability (Reddy &Reddy, 2015; Kroumova*et al*., 2013; Sahoo *et al*., 2017; Sahoo *et al*., 2021; Yoon*et al*., 2018). Using pesticides frequently has led to insect and disease resistance, accumulating residues in produce, and environmental damage (Van *et al*., 2016). As a result, alternative pest and pathogen control strategies are required. Nanotechnology has the potential to effectively manage insects and pathogens through targeted pesticide delivery and early detection systems (Rana *et al*., 2024). The most frequent nanomaterials in fruit production include packaging, nano insecticides, nano fertilizers, nano fungicides, and precision fruit culture (Figure 2) (Rana *et al.*, 2021). Nanoparticles are highly stable and biodegradable, making them suitable for producing nanocapsules to carry insecticides, fertilizers, and other agrochemicals. Nanoparticle's slower release of functional molecules limits their use in many applications (Al-Hchami&Alrawi, 2020). Nanoparticles perform differently than bulk particles due to their smaller size, higher charge, larger surface area, and increased stability and solubility (Shrestha *et al*., 2020). Recently, focus has been given heavily to producing bio-based edible coverings to improve the post-harvest processing longevity of fruits. Added to that, nanotechnology has been recognized as an excellent approach (Travičić&Ćetković, 2023) for increasing coating qualities, a better moisture barrier, and superior mechanical, optical, and microstructural capabilities, as well as the progressive and controlled discharge of bioactive substances. Some nanotechnology-based plant extracts are frequently used to extend the post-harvest shelf life of fruits.

Fruits coated with edible nanocoating have an extended shelf life as they effectively retain moisture and preserve their freshness. This is due to the coating's protective layering, which keeps gases and water vapour from entering or exiting the fruit and preserves its texture, colour, and firmness(Sharma *et al*., 2023). These coatings improve barrier qualities on the outer covering of fruits, creating a favorable microenvironment by optimizing the concentration and impeding the ripening process. A diverse spectrum of nano-based precision and tiny equipment, which includes nano-sensors (Mishra *et al*., 2017), nano-based gadgets, machines, and robotics are used in modern fruit production. These nanomaterial-based biosensors are also used in high-tech fruit production. Nano-biosensors play a vital role in transforming farming by developing diagnostic tools. These sensors are accurate, reliable, and economical in dealing with various agricultural, food, and environmental concerns (Dar &Pirzadah, 2020). Some agricultural sensor uses include identifying heavy metal ions, contaminants, microbial load, and pathogens and monitoring temperature, traceability, and humidity. Consequently, nanotechnology has enhanced most fruit crops' quality and packaging aesthetic. With the current context of the improved crop growth and yield using nano-fertilizers, nano-pesticides, nano-biosensors for soil health, the targeted pest and disease management using nanoparticle-based biocides and nano-carriers for bio-pesticides, for post-harvest preservation and shelf-life extension of fruits using nano-coatings, antimicrobial packaging, ethylene control methods, for quality enhancement of the processed fruit and their products using nano-emulsions for flavor and nutrient enhancement, improved texture and stability, for the detection of contaminants and quality monitoring using nanosensors, etc., nano-science can lead to the reduced chemical usage and with less environmental impacts in one hand and increase in precision and efficiency with improved product quality and safety on the other hand. So, the use of nano-technology in the challenges and considerations, including safety and toxicity in fruits and fruiting crops, reduced cost and scalability, regulatory approval, etc, need to be reviewed on a priority basis. Therefore, it is suggested that nanotechnology holds transformative potential for managing fruiting crops, pre and post-harvest quality handling of fruits, and their derived products specifically for extending shelf life. This review article thoroughly highlights significant insights into the application of nanoparticles as a promising method for enhancing fruit crop resilience and ensuring food security amid environmental changes, along with the recent use of nanotechnology at different stages of fruit production.

Methods of literature review

Major online databases such as PubMed, Science Direct, Web of Science, Scopus, Agricola, and Google Scholar were searched with relevant terminologies (Doshi et al., 2024; Oza et al., 2024). Terms or phrases such as "fruit crops and nanotechnology" were added with additional terms such as challenges, harvest, post-harvest, shelf life, texture, packaging, quality, scalability, safety, environmental impacts, regulatory, transport, fertilizer, pesticide and soil health were searched on the above webpages. Articles merely containing the search words but out of the scope of the topic were rejected. Articles in English that fall under the topic were screened and > 100 articles were selected for the review in an unbiased method. Articles were selected irrespective of specific laboratory, person, or country of publication.

Nanomaterial – Seed Coatings

The application of nanomaterials in seed priming is an emerging research area aimed at enhancing seed germination and seedling growth. Nanomaterials influence germination, yield, and stress tolerance by modulating gene expression, optimizing plant metabolism, and improving nutrient uptake, thereby promoting better plant development (Seyed *et al*., 2020). Nanoscale coatings offer a range of benefits by forming a protective layer around seeds, they ensure secure germination and early development. One of the primary advantages of using nanomaterial seed coatings is their capacity to protect seeds from environmental stressors such as pests, diseases, and harsh weather (Zhao *et al*., 2024). Acting as a barrier, these materials safeguard seeds during their most vulnerable stages, leading to higher germination rates and the development of healthier, more resilient plants. Moreover, nanomaterials can be used to encapsulate essential nutrients, growth-promoting agents, or beneficial microorganisms, enabling their precise and controlled release to seedlings. This targeted delivery ensures that plants obtain the necessary resources for vigorous growth and robust development. By enhancing nutrient absorption and promoting beneficial microbial interactions, these coatings contribute to improving crop vitality and yield (Mahra *et al*., 2024). In addition, nanomaterial coatings help seeds adhere better to the soil, reducing wastage during planting and boosting planting efficiency—a critical factor in horticulture where optimal seed spacing and placement are essential for successful crop development. While the potential benefits of nanomaterial seed coatings are substantial, it is crucial to use them responsibly, considering both safety and regulatory guidelines (Zaim *et al*., 2023). When applied appropriately and within regulatory frameworks, nanomaterial seed coatings could transform the practices by improving crop quality, increasing yields, and promoting sustainable, efficient cultivation methods.

Nanofertilizers –Salutary role in fruit crops

Nanofertilizers, an emerging innovation in the field of agriculture, offer a proper solution to improve nutrient efficiency, productivity, and sustainability in fruit crops. Nano fertilizers have several advantages over conventional fertilizers as these substances are harmless and less harmful to the natural world and humans (Sharma *et al*., 2021). Nano-fertilizers can be derived from various plant parts using physical, chemical, mechanical, or biological techniques, or they can be synthesized from modified forms of traditional fertilizers (Gade *et al*., 2023) to improve soil fertility, productivity, crop quality standards, and lower expenses while raising profits (Figure 2). Nano-fertilizers can prepare one or more plant nutrients to boost growth and production while performing better (Al-Juthery *et al*., 2021), using less fertilizer and releasing nutrients more slowly than conventional fertilizers (Table 1).

Nanoparticles improved nutrient efficiency and quality of the fruits (Zahedi *et al*., 2020) Additionally, it has been put forth that balanced fertilization of the agricultural produce can be accomplished by nanotechnology. Nanoparticles boost plant development by resisting infectious diseases and plant solidity by preventing bending and causing deeper rooting of crops (Singh *et al*., 2017); this technology has enabled the exploitation of small nanomaterial particles carried on the fertilizer to build the so-called smart fertilizer, which enhances the efficiency of nutrient use and reduces the costs of protecting the environment by intelligently controlling the speed of nutrient release (Tarafdar*et al*., 2015) to match the absorption pattern of crops and improving the solubility of insoluble nutrients in the soil, it reduces its adsorption and stability, and increases its availability.

Nanoparticles – Their role in mitigating abiotic stress of fruit crops

Abiotic stress has globally imposed environmental issues, which have a significant impact that leads to a reduction in the production and productivity of fruits (Dilnawaz *et al*., 2023). Nanotechnology plays a substantial role in mitigating abiotic stress in fruit crops as nanoparticles have shown positive effects on plants under abiotic stress conditions as they can be used to assist plants in coping with abiotic stress management (Khalid *et al*., 2022). Nanoparticles infiltrate plants through their roots and leaves, causing biochemical, morphological, molecular, and physiological changes in crops during stress. Nanoparticles have significant effects on various physiological processes, including stress response mechanisms, hormone metabolism, osmolyte biosynthesis, ethylene production, and signaling pathways involving nitric oxide, abscisic acid (ABA), and calcium. They also regulate signal transduction pathways during drought and salinity stress, activating stress-responsive genes to enhance plant survival (Rasheed et al., 2022). Nanoparticles play a crucial role in improving plant yield under drought and salinity conditions. They help mitigate water loss by maintaining water balance, ultimately improving abiotic stress tolerance (Rasheed et al., 2022). Nanoparticles also regulate stomatal conductance and transpiration rates by influencing leaf anatomy and promoting stomatal closure (Acosta-Motos et al., 2017). Additionally, Nanoparticles protect photosynthetic machinery, enhance photosynthesis, and activate antioxidant systems to repair damage caused by reactive oxygen species (ROS) in chloroplasts and photosystems. Furthermore, they stimulate the electron transport chain and increase chlorophyll content in plant cells (Forni et al., 2017; Manzoor et al., 2022) (Table 2). Overall, the application of nanoparticles is essential for helping plants withstand drought and salinity, maintaining their normal functions, promoting environmental health, and sustaining crop yield.

Nanopesticides - Propitious effect on fruit crops

Nanotechnology is used extensively in plant protection to enhance crop yield (Moulick*et al*., 2020). Conventional crop protection methods often involve using large quantities of fungicides, herbicides, and insecticides. Approximately 90% of pesticides are ultimately lost in the environment or do not effectively reach their intended targets for pest control (Tudi *et al*., 2021). Having active chemicals at the right concentration in a formulation is of the utmost importance for protecting plants from pests and preventing crop loss. Agricultural research has focused on developing innovative plant protection formulations called Nanoformulation, or pesticide encapsulation, that have transformed plant protection technology (Zhao *et al*.,2017). Nanoformulation, often known as pesticide encapsulation, has transformed the plant protection sectors. Nanoencapsulation of pesticides involves coating active ingredients with nano-sized materials; the materials (Yadav *et al*., 2022) that are encapsulated are called the coated nanomaterials' internal phase, and the materials that are capsulated are called the core material's external phase (pesticides).

Pesticide encapsulations provide a controlled release of active ingredients into root areas or inside plants, all without impacting efficacy (Maluin&Hussein, 2020). Conventional pesticide or herbicide formulations, on the other hand, limit pesticide water solubility while also injuring other organisms, resulting in increasing resistance to target organisms. For a sustainable agro-environmental system, nanomaterials in pesticide formulations provide advantageous properties such as improved durability, flexibility, stability under heat, solubility, crystallinity, and biodegradability (Mattei *et al*., 2022). Using active substances in a timely and controlled manner reduces the need for pesticides for pest and disease control (Table 3), an essential aspect of IPM. Sustainable agriculture requires minimal use of agrochemicals to prevent environmental degradation and harm to non-target species; thus, nano-pesticides sparingly minimize agricultural production costs (Shang *et al*., 2019).

Nanocoatings

Increased consumer awareness regarding fresh fruits' health and nutritional advantages has led to a consistent rise in their demand. However, due to their high moisture content, fruits are highly perishable, creating an ideal environment for the growth of pathogenic and spoilage microbes. This diminishes their shelf life and compromises safety and quality (Mohammad &Ahmad, 2024). Nanocoatings, thin films (<100 nm) applied to a substrate to enhance its properties and performance, offer notable benefits over traditional coatings. These include resistance to stains, antibacterial and antioxidant properties, odor management, and even distribution of active agents. In the fruit industry, nano-coating is frequently utilized in packaging applications (Figure 2). By integrating active bioactive ingredients, nanocoatings provide active food packaging with antibacterial and antioxidant features (Gago et al., 2020). Specific types of food packaging are coated with nanoparticles to enhance shelf life, security, and package quality (Figure 3). Active packaging coatings, a promising technology in food packaging, utilize preservatives and nanocoatings to serve as antimicrobial, antifungal, and antibacterial agents, as well as protective coatings and self-cleaning surfaces for food contact

(Table 4). Using edible films containing nanocoatings to coat fruit products has made significant strides in recent years, enhancing food safety.

Nanopackaging

Nanotechnology has shown great promise in the food processing industry to improve post-harvest technologies that help prevent neglect and lower losses. (Liu *et al*., 2022). To address the worldwide issue of fresh product security, the farming sector should prioritize protecting fruits and vegetables (Ijaz *et al*., 2020). Controlling pre-harvest and post-harvest conditions can improve the shelf life of fresh fruit(Figure 3) (Carbone *et al*., 2016). The primary reason for adopting nano in food packaging is to improve the protective barrier qualities of packaging materials (Ozkan*et al*., 2016). Nano-based alimentary packaging materials also provide antibacterial properties, operate as oxygen scavengers, and act as moisture barriers (Rai *et al*., 2019).

Nanocomposite materials

Nanocomposite materials encompass one-dimensional, two-dimensional, and three-dimensional components mixed at the nanometer scale. In contrast to conventional packaging materials, nanocomposites offer added advantages such as increased strength, enhanced biodegradability, and superior management of gaseous molecules (Rovera*et* al., 2022), crucial for the development of high-performing packaging materials (Kalia &Parshad, 2015). Typically, a nanocomposite material (Table 5) consists of three distinct components: the matrix material, filler, and filler interface material (Sharma *et al*., 2022), with at least one component at the nanoscale.

Bio-based packaging

Bio-based packaging uses biodegradable films to regulate moisture transfer and gas exchange during the packaging of food goods. This improves safety and preserves nutritional and sensory quality. Such packaging supplies are considered more environmentally friendly than other standard packaging films (Chandra *et al*., 2022). Bio-based packaging protects food products from environmental factors such as microbes, relative humidity, and gas conditions. Biodegradable packaging films possess the ability to be broken down by living organisms, distinguishing them from other packaging options. This package type is seen as more environmentally friendly. Bio-based packaging encompasses improved, active, and smart packaging (Figure 4) (Kuswandi, 2017).

Active packaging

Nanomaterials are utilized in active packaging to improve product protection by directly interacting with the food or environment. Nano-silver, nano-copper oxide, nano-magnesium oxide, nano-titanium dioxide, and carbon nanotubes are expected to have potential use in antimicrobial food packaging (Agriopoulou*et al*., 2022). It is an oxygen-scavenging packaging with enzymes between polyethylene layers. Active packaging can prevent microbial development after opening and rewrapping using an active film (for example, Anti-microbial film, Oxygen scavenging films, and UV-absorbing films).

Improved packaging

Nanocomposites, which contain up to 5% w/w nanoparticles and clay nanoparticles (Welsey*et al*., 2014), improve barrier properties (80-90% reduction) in packaging materials (e.g., nanocoating, nanolaminates, clay nanoparticles).

Smart packaging

Nanomaterials in smart packaging detect biochemical or microbiological changes in food, such as pathogens and spoilage gases (Rastogi *et al*., 2022). Reactive particles in packing materials can provide information about the product's status (Eg.Nanosensors). Nanosensors act upon external stimuli to communicate, inform, and identify products, ensuring their quality and safety.

Precision farming in fruit crops

Nanomaterial engineering is a leading research field for sustainable agricultural development. Nanomaterials in precision agriculture minimize expenses, boost efficiency, and promote sustainable growth (Shang *et al*., 2019). Precision fruit culture is becoming increasingly crucial for assessing and tracking the growth of trees, soil parameters (moisture, nutrients, pH, EC, and so on), disease detection, pesticide penetration, and environmental impact using nanosensors. Precision fruit culture enhances fruit quality while ensuring the health of soil and plants, promoting ecological sustainability and environmental security (Zude*et al*., 2016). Nanomaterial engineering is used in high-tech fruit cultivation to provide a more specific surface area for the sustainable development system. The primary use of nano-fruit cultivation is to produce high-quality fruit with cheap input costs while maintaining ecological sustainability. In this culture, nanosensors, nanotechnology-based GPS, supercomputers, and remote sensing devices are used (Mittal *et al*., 2020).

Nanosensors

Nanosensors enable plants to communicate, making it more straightforward to understand dynamic changes in plants' environment and physiological states. Nanosensors have been created to suit the demands of agricultural development. These sensors provide accurate and real-time monitoring of individual plants on a micro-scale with excellent temporal resolution (Giraldo *et al*., 2019). They also help to translate optical, wireless, and electrical signals into plant signaling molecules (Vurro *et* al., 2024). Nano-sensors and nano-biosensors have potential uses in the food industry, including monitoring food processing, quality assessment, packaging, storage, shelf life, food safety, microbial contamination, toxin, and residual contamination. Nanosensors are often designed for specific applications in food and agriculture (Srivastava & Karmakar, 2017). Nano-biosensors have the potential to be an extremely useful instrument for intelligent delivery systems, enhancing soil health, irrigation safety, pesticide detection, and plant pathology. Nanobiosensors can also detect seed viability, fruit shelf life, and plant nutrient requirements (Figure 4). Furthermore, they play a crucial part in protecting crops as well as advancing the idea of sustainable agriculture. Nanoparticles, including gold, silver, and magnetic nanoparticles, as well as graphene oxide, carbon nanotubes, and wireless nanosensors, have been used to improve sensing (Table 6). Commercializing nanosensors requires substantial intellectual property and patent rights to ensure long-term viability.

Conclusion

Presently a lot of technological innovation is being developed and utilised at various phases of fruit production. One such innovation is nanotechnology which has the potential to increase fruit yield with diminished farm risks and has a more comprehensive application such as nano-fertilizers, nano-pesticides, nano-coatings, post-harvest dips, packaging, increasing water use efficiency, and plant defense measures, all of which play essential roles in boosting the development of plants, improving reproductive growth, and blossoming, thus increasing efficiency, the quality of the product, shelf-life, and reducing fruit waste. Nanomaterials are utilized for targeted site-specific pest and disease management, targeted and slow nutrient supply (smart delivery), and pest and disease detection in fruit crops via biosensor delivery (Figure 5).

Nanomaterials are quick, inexpensive, and environmentally friendly. They may be developed quickly, with minimal effort, and without affecting the environment. The use of nanoparticles in fruit production will revolutionize it, increasing productivity while using less input. The application of nanoparticles in fruit production holds considerable promise for enhancing sustainable and precise fruit production in developing countries.

Future Perspectives and Challenges

Nanotechnology offers tremendous potential in transforming fruit cultivation by enhancing productivity, fruit quality, and sustainability of the produce. The recent innovations in nanotechnology include nano-fertilizers, nano-pesticides, nano-coatings, nanosensors, nanopackaging, and other nanomaterials like carbon nanotubes, silica nanoparticles, and biodegradable nano-coatings derived from polymers such as chitosan. Nanotechnology also facilitates the early detection of pests and diseases using nanosensors and enhances plant resistance through advanced delivery systems. Post-harvest management includes nano-coatings that prolong the shelf life of the fruits, smart packaging, and technologies that regulate the ripening process. Additionally, nanotechnology promotes sustainable agriculture by reducing inputs, improving water use efficiency, and stress management in fruit crops. The integration of nanosensors with smart farming enables real-time monitoring of soil, water, and nutrients. However, challenges such as high production costs, regulatory barriers and environmental safety needed to be addressed to ensure safe and effective implementation of nanotechnology in fruit crops. By overcoming these limitations, nanotechnology provides innovative solutions to enhance fruit crop productivity and sustainability, by addressing the growing demands of global food systems.

Author contributions

Ramya S: Data curation, Formal Analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. Auxcilia James: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Visualization, Writing – review & editing. Dr. D. Jeya Sundara Sharmila: Conceptualization, Project administration, Resources, Supervision, Writing – review & editing. P. Irene Vethamoni: Conceptualization, Project administration, Resources, Supervision, Writing – review & editing. Sheela Venugopal:

Conceptualization, Project administration, Supervision, Writing – review & editing. N. Indra: Investigation, Project administration, Supervision, Writing – review & editing. KizhaeralSubramanian: Conceptualization, Project administration, Resources, Supervision, Writing – review & editing. Biswaranjan Paital: Conceptualization, Formal Analysis, Resources, Supervision, Writing – review & editing. Dipak Kumar Sahoo: Conceptualization, Supervision, Investigation, Resources, Writing – review & editing.

Competing Interest statement

The authors have no competing interests to declare.

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Legends to figures and tables

Fig. 1. Role of nanotechnology in fruit crops.

An overview of the role of nanotechnology in fruit crops are depicted in the figure. A tree graph representing the significance of nanotechnology in fruit cultivation. It has been reviewed that nanotechnology has multidimensional use in the agriculture fields, starting from farming to post-harvest management of crops. As a result an increased productivity shall be obtained in cropping plants. Various nano-based products are utilized in fruit crops. Disease management and safety storage of post-harvested crops are the most challenging issues in agriculture. So, the use of nano-products such as nanofertilizers, nano pesticides, and nanofungisides is used even in post-harvest packaging.

Fig. 2. Role of nanofertilizers and shelf-life in fruit crops.

Several pieces of evidence fortifying the idea of the use of nano-fertilizers are clear. Less amount of use with cheap price and high efficiency are the main advantages. Positive impacts of nanofertilizers on tree growth and development, as well as soil health, have been documented. It increases the resistance capacity of plants along with better growth. Factors affecting the shelf life of fruits after harvest can also be influenced by nanomaterials. Usually, ripened fruits are more prone to damage during transport, sorting, and grading. Microbial activity and environmental factors can also enhance the degrading process. Nanomaterials can be used at each stage to protect the post-harvested fruits.

Fig. 3. Role of nanocoatings and nano-packaging in fruit crops.

Post-harvested fruits are more damaged under several conditions, and packaging and coating of fruits with compatible materials now are a challenge from a health point of view. So, nano-coatings are now used to increase the self-life of ripened fruits. It also protects fruits against microbial damage. Nano-based packaging in fruit crops also is proposed to be used. Nano-based packaging enhances the self-life of post-harvested fruits, especially at their ripening stage. So, rapid involvement and more research in this field are warranted.

Fig.4. Types of biobased nanopackaging system and the working model of nano-based fruit crop management.

Several modes of packaging are adapted to protect fruits from post-harvest damage. The use of nano-materials is suggested to improve post-harvest management. Working of Nanosensors in fruit crops. Sensors transmit information about the tree's condition, which is analyzed and passed along to the decision support system.

Fig.5. A schematic presentation of application of nanotechnology in management of fruiting crops and their associated products.

Table 1. Beneficial role of nanofertilizers in various fruit crops.

Table 2. Role of nanoparticles in mitigating abiotic stress

Table 3. Effects of employing nanopesticides in fruit crops.

Table 4. Nanocoatings and their properties in fruit crops.

Table 5. Nanocomposite-based packaging in fruit crops.

Table 6. Types of nanosensors used in fruit crops.

Table 1(on next page)

Table 1. Beneficial role of nanofertilizers in various fruit crops.

1 **TABLE 1:** Beneficial role of nanofertilizers in various fruit crops.

Fruits	**Variety**	**Nanofertilizers**	**Properties**	**References**
Apple	Red delicious	Nano calcium	Quantitative and qualitative character	Ranjbar *et al*., (2020)
Grapes	Flame seedless	Nano fertilizers (amino-minerals, orgland active-Fe, Boron-10, Amino-zn, Super –Fe)	Improved berry colouration and high fruit quality	Wassel *et* al., (2017)
Grapes	Flame seedless	carbon nano-tubes (CNTs) from total nitrogen	Increased leaf area, leaf fresh weight and leaf dry weight, shoot length, shoot diameter and number of leaves per shoot of grapevines	Abdel-Hak *et al*., (2018)
Apple	Anna	Ag and Zn nanofertilizer	Increased total chlorophyll content, fruit set percentage, fruit yield, fruit's physical and chemical characteristics	Muhsin *et al*., (2022)
Mango	Kiette	Nanoboron	Increased shoot length, thickness, leaf area, and number of leaves per shoot.	Abdelaziz *et al*., (2019)
Grapes	Crimson seedless	Nano-powder potassium sulfate	Leaf area, internode length	Shalan (2020)
Pomegranate	Malase Saveh	Nano-Se	Higher leaf NPK content	Zahedi *et al*., (2019)

Strawberry	Queen elisa	Nano-silicon oxide	Salt tolerance	Mozafari *et al*., (2019)
Strawberry	Chandler	Nano zinc	Increased number of leaves	Kumar *et al*., (2017)
Mango	Ewais	Nano-ZnO and Si	Salt stress tolerance	Elsheery *et al*., (2020)
Mango	Zebda and Ewasy	Nanozinc	Highest number and weight of fruits, total tree yield, and percentage of TSS in fruits, Reduced malformation	Zagzog and Gad (2017)
Pomegranate	Ardestani	Nano-iron and Nano-Boron	Number of fruits, iron content of leaves, total sugars, and the total yield	Davarpanah *et al.,* (2016)
Datepalm	Zaghloul	Nano NPK	Higher fruit yield, bunch weight, total soluble solids, total sugars and pulp percentage	Roshdy and Refaai (2016)

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Table 2(on next page)

Table 2. Role of nanoparticles in mitigating abiotic stress.

Table 2: Role of Nanoparticles in mitigating abiotic stress in fruit crops

Fruits	Nanoparticles	Properties	References
Strawberry	Se-NPs	Tolerance to salinity, and subsequently yield, which were attributed to their ability to protect photosynthetic pigments	Zahedi *et al*.,2019
Pomegranate	Se-NPs	Fruit cracking caused by drought stress was reduced	Zahedi *et al*.,2021
Banana	Chitosan - NPs	Improve plant resilence to chilling injury – suitable in cold affected regions, Serves as osmoprotectant	Wang *et al*., 2021
Mango	Chitosan - NPs	Retards the senescence process	Silva *et al*., 2017
Sweet Orange	Sio2 - NP	Tolerant to salt stress	Mahmoudet *et al*., 2022
Strawberry	Fe_3O_4 NPs	Decreased level of H_2O_2	Orooji *et al*., 2020
Grapefruit	ZnO - NPs	Photocatalytic activity	Nava et al*.,* 2017
Pineapple	Ag - NPs	Increase the content of pigments	Tejada – Alvarado *et al*., 2023
Pear	SiO_2 - NPs	Si and K content increased	Zarafsharet *et al*., 2015
Loquat	SiO_2 - NPs	Chilling tolerance	Wang *et al*., 2020
Olive	Nano - Si	Tolerant to water stress	Hassan *et al*., 2022
Plum	Chitosan- Arginine NPs	Chilling tolerance	Mahmoudie *et al*., 2022

Table 3(on next page)

Table 3. Effects of employing nanopesticides in fruit crops.

1 **TABLE 2:** Effects of employing nanopesticides in fruit crops.

Fruits	Varieties	Nanopesticide	Pathogen	Mode of action	References
Sweet orange	Pineapple	Nano-ZnO	Citrus canker	Fruit canker incidence reduced from 63 to 7%	Sharma *et al*., (2020)
Grapefruit	Ruby	Nano- CuO	Citrus canker	Fruit infection reduced to 25% from 60%	Young *et al*., (2017)
Citrus	Tankan	Nano-Calcium cabronate ($CaCo_3$)	Oriental fruit fly	Insecticide - Damage caused by Oriental fruit flies decreased	Hua *et al*., (2015)
Guava		Insect pheromone nanogel	Fruit fly	Improved insects catch in the fly for insecticide formulation apparatus for nanogel formulation	Bhagat *et al*., (2013)
Apple		Nano - sulphur	Apple scab	Fungicide - Inhibited 93% of the fungal growth	Rao *et al*., (2013)
Strawberry		Nano-chitosan	Anthracnose	Fungicide	Wu *et al*., (2024)

Table 4(on next page)

Table 4. Nanocoatings and their properties in fruit crops.

1 **TABLE 3:** Nanocoatings and their properties in fruit crops.

Fruits	Nanomatrix and Bioactive compound	Property	References
Apple - Fuji (Fresh cut)	Sodium alginate + Lemongrass oil	Antimicrobial activity	Salvia *et al*., (2015)
Strawberry	Chitosan + Thymol	Antimicrobial activity	Robledo*et al*., (2018)
Papaya (Redtainung)	Hydroxylpropyl methylcellulose + carnauba wax	Reduce moisture loss	Miranda *et al*., (2019)
Pineapple (Fresh cut)	Sodium alginate + citral	Increase in antimicrobial activity	Prakash*et al*., (2020)
Mandarin - Nova	Carnauba wax + oleic acid	Antimicrobial activity	Miranda *et al*., (2021)
Pears (Barlett)	Chitosan + Cellulose nanocrystal and oleic acid	Increased adhesion , delayed ripening	Deng *et al*., (2017)
Mangoes (Fresh cut)	Sodium alginate + chitosan	Firmness, microbial protection	Souza *et al*., (2015)
Citrus	Carboxymethy cellulose + Chitosan	Enhanced fruit glossiness and prevented weight loss	Arnon*et al*., (2014)
Mango	Polystyrene sulfonate sodium salt + Poly diallyldimethyammonium chloride	Improved hydrophilicity of the surface	Kittitheeranun*et al.*, (2010)
Strawberry	Nanocomposite Zinc Oxide-Chitosan coatings + Polyethylene films	Increase quality and shelf life of fruit and antimicrobial activity	Jafarzadeh*et al*., (2021)
Banana -	*Aloe vera* and *Moringa*	Improved efficiency	Odetayo*et al*., (2022)

Cavendish	plant extract edible coatings + chitosan nanoparticles	and increased the storage life of banana	
Strawberry	Methylcellulose-based edible coating	Maintenance of fruit quality during storage	Nadim *et al*., (2015)
Strawberry	Chitosan tripolyphosphate nanoparticles suspension	Acts as an antibacterial agent	Melo *et al*., (2020)
Blueberry	Chitosan	Delays mould and yeast formation	Li *et al*., (2021)
Mango	Nano-hitosan	Firmness of fruits	Ngo *et al*., (2021)
Apple	nano- Zno	Increased shelf life by 6 days	Li *et al*., (2011)
Peach	*Bacillus circulans* + Nano - ZnO	Enhanced shelf life	Shi *et al*., (2024)
Guava	Urticadiocia leaf extracts + Nano- ZnO, CuO	Enhanced shelf life of guava	Kalia *et al*., (2021)

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Table 5(on next page)

Table 5. Nanocomposite-based packaging in fruit crops.

1 **Table 4.** Nanocomposite-based packaging in fruit crops.

Fruits	**Matrix + Nanoparticles**	**Microbistatic effect**	**Reference**
Strawberry	LDPE + Silver and titanium dioxide nanoparticles	*Aspergillus flavus*	Yang *et al*., (2010)
Orange juice	Polyethylene + Silver and titanium dioxide nanoparticles	*Aspergillus flavus*	Emamifar *et al*., (2010)
Pineapple Juice	Polyethylene + Silver nanoparticles	*Bacillus subtilis*	Fortunati *et al*., (2019)
Kiwi	Polyethylene + Silver nanoparticles	*Bacillus subtilis*	Fortunati *et al*., (2019)
Grapes	Polyethylene + Silver nanoparticles	*Bacillus subtilis*	Fortunati *et al*., (2019)
Apples	Nanoparticles	*Enterobacterae rogenes*	Esmailzadeh *et al*., (2016)
Strawberry	Cellulose nanocrystals + Silver	*Escherichia coli*	He *et al*., (2021)
Cherries	Sodium alginate + Silver	*Salmonella aureus* & *Escherichia coli*	Sun *et al*., (2021)
Papaya	HPMC + Silver	*C. gloeosporioides*	Viera *et al*., (2020)
Banana	Chitosan + ZnO	*Bacillus subtilis*	La *et al*., (2021)
Guava	Chitosan + ZnO	*Salmonella aureus*	Kalia *et al*., (2021)
Banana	Carboxymethyl cellulose + TiO2	*Listeria monocytogenes*	Ezati *et al*., (2022)

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Table 6(on next page)

Table 6. Types of nanosensors used in fruit crops.

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1 **Table 5.**Types of nanosensors used in fruit crops.

Fruits	Nanosensors	Detection	References
Grapes	ZnO-based films	Grapevine virus A-type (GVA) proteins (GVA-antigens)	Tereshchenko *et al*., (2017).
Citrus	cdTe quantum dots Nanocarbon dots	Fluorometric immunoassay - Citrus tristeza virus	Shojaei *et al*., (2016)
Apple **Pears** **Grapefruit**	Carbon based screen printed electrode	Plum pox virus	Fernandez-baldo *et al*., (2010)
Apple	IR thermography (DIRT)	Apple scab	Oerke *et* al., (2005)
Citrus	Microfluidic electrochemical immunosensor (nanochip)	Yellow shoot disease (Huanglongbing)	Dhiman *et al*., (2019)

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Figure 1

Fig. 1. Role of nanotechnology in fruit crops.

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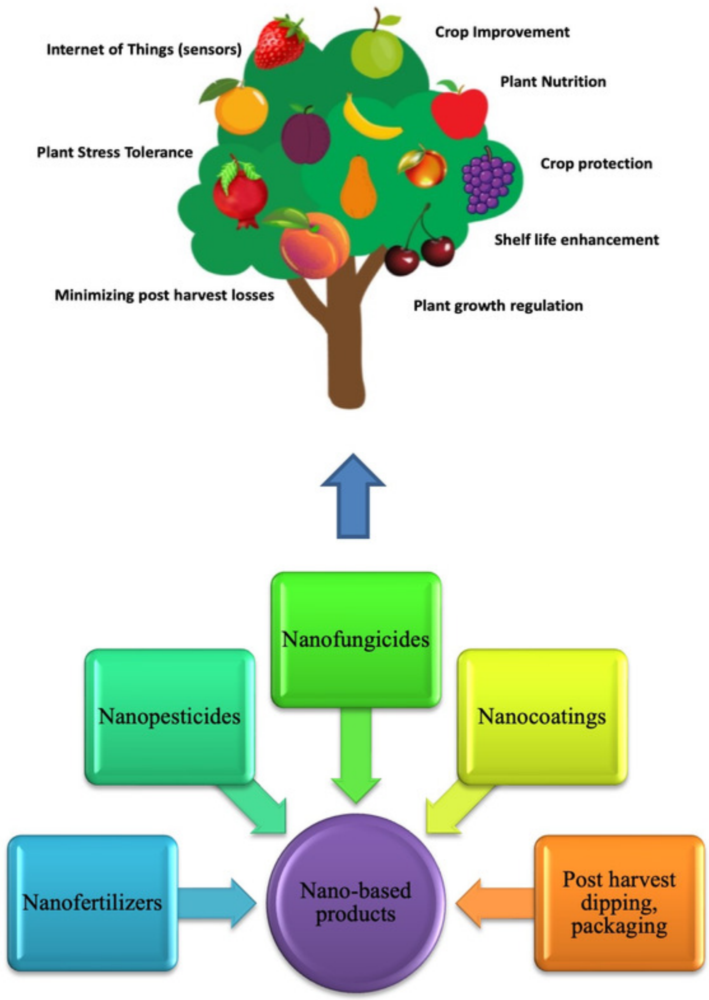
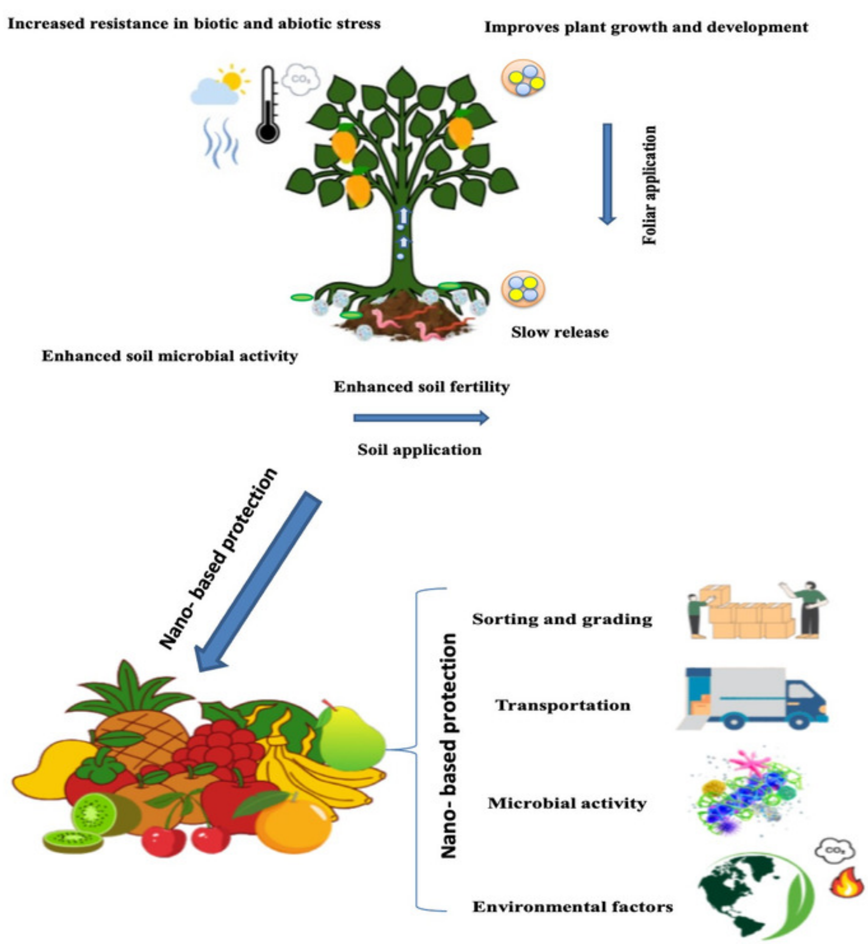

Internet of Things (sensors)
Crop Improvement
Plant Nutrition
Plant Stress Tolerance
Crop protection
Shelf life enhancement
Minimizing post harvest losses
Plant growth regulation
Nanofungicides
Nanopesticides
Nanocoatings
Nanofertilizers
Nano-based products
Post harvest dipping, packaging

Figure 2

Fig. 2. Role of nanofertilizers and shelf-life in fruit crops.

Several pieces of evidence fortifying the idea of the use of nano-fertilizers are clear. Less amount of use with cheap price and high efficiency are the main advantages. Positive impacts of nanofertilizers on tree growth and development, as well as soil health, have been documented. It increases the resistance capacity of plants along with better growth. Factors affecting the shelf life of fruits after harvest can also be influenced by nanomaterials. Usually, ripened fruits are more prone to damage during transport, sorting, and grading. Microbial activity and environmental factors can also enhance the degrading process. Nanomaterials can be used at each stage to protect the post-harvested fruits.



Increased resistance in biotic and abiotic stress
Improves plant growth and development
Foliar application
Slow release
Enhanced soil microbial activity
Enhanced soil fertility
Soil application
Nano- based protection
Sorting and grading
Transportation
Nano- based protection
Microbial activity
Environmental factors

Figure 3

Fig. 3. Role of nanocoatings and nano-packaging in fruit crops.

Post-harvested fruits are more damaged under several conditions, and packaging and coating of fruits with compatible materials now are a challenge from a health point of view. So, nano-coatings are now used to increase the self-life of ripened fruits. It also protects fruits against microbial damage. Nano-based packaging in fruit crops also is proposed to be used. Nano-based packaging enhances the self-life of post-harvested fruits, especially at their ripening stage. So, rapid involvement and more research in this field are warranted.

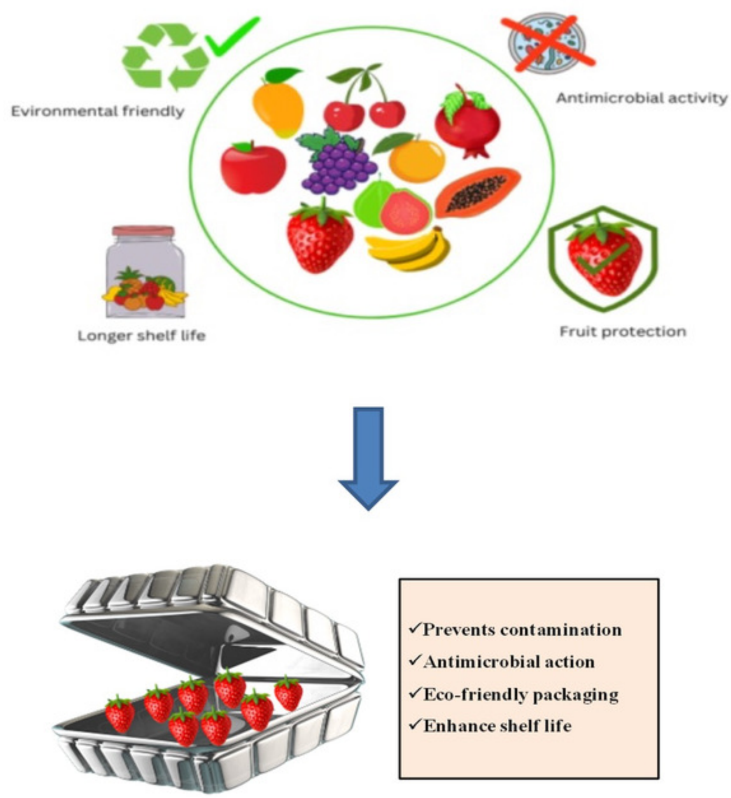


Figure 4

Fig. 4. Types of biobased nanopackaging system and the working model of nano-based fruit crop management.

Several modes of packaging are adapted to protect fruits from post-harvest damage. The use of nano-materials is suggested to improve post-harvest management. Working of Nanosensors in fruit crops. Sensors transmit information about the tree's condition, which is analyzed and passed along to the decision support system.

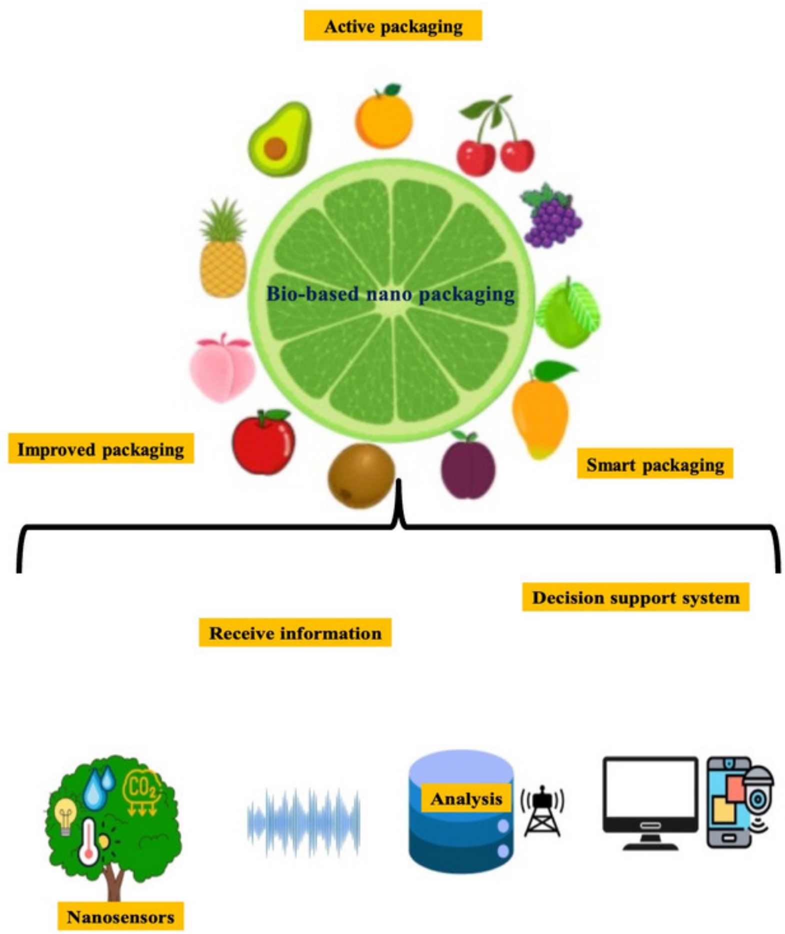


Figure 5

Fig. 5. A schematic presentation of application of nanotechnology in management of fruiting crops and their associated products.