**Nanotechnology Applications in Advanced Horticulture: A Comprehensive Review**

**Abstract**

The cutting-edge field of nanotechnology has become well-known in horticulture due to its revolutionary effects on resource management, plant health, and crop yield. Because of their special qualities, nanoparticles provide novel approaches to crop protection and enhancement. By improving nutrient uptake efficiency, nanomaterials like nanofertilizers lessen their negative effects on the environment and maximize resource use. Likewise, nanopesticides are more effective in controlling pests and diseases, which lessens the need for traditional chemical treatments. Additionally, nanotechnology is essential for controlling plant growth. Growth regulators can be released under controlled conditions thanks to nanoscale delivery systems, which allow for exact control over plant growth and blooming. This focused strategy reduces environmental effects while increasing agricultural yield and quality. Additionally, nanosensors help to monitor environmental conditions in real time, providing important information for precision farming. Notwithstanding its encouraging uses, horticulture's use of nanotechnology is beset by issues with ethical issues, regulatory frameworks, and environmental damage. In order to guarantee the responsible and sustainable application of nanotechnology in agriculture, it is imperative that these issues be addressed. The application of nanotechnology in horticulture is broad and dynamic. Nanotechnology has the ability to significantly improve sustainable and effective horticultural techniques, from improving fertilizer management to transforming insect control and growth regulation. But to fully reap the benefits and minimize any risks related to nanotechnology in horticulture, a balanced strategy that takes ethical, environmental, and regulatory factors into account is necessary. This review centres on the function of nanotechnology in horticulture.

**Keywords**

Nanotechnology, nanoparticles, efficacy, nanosensors, agriculture, crop improvement

**Introduction**

The foundation of human civilization, agriculture has supplied vital resources, economic stability, and food for innumerable generations. The significance of agriculture is greater than ever as we approach the turn of the twenty-first century. Food security, sustainability, and climate change resilience are difficult tasks for the agricultural industry to handle in light of the world's growing population and environmental issues. Given this, the nexus between nanotechnology and agriculture offers creative answers to these worldwide problems and has the potential to completely transform the agricultural sector [1]. A vital industry that guarantees the supply of safe, wholesome, and reasonably priced food for the world's expanding population, agriculture is more than just a component of the economy. The need for food rises in unison with the world's population growth. By 2050, there will be 9.7 billion people on the planet, according to UN estimates, and food production will need to rise by 70% to keep up with demand. Agriculture is under tremendous pressure to increase production and improve efficiency as a result of this demographic shift [2, 3]. The continual growth of the world's population makes it extremely difficult to meet the present and future demands for food. Crop production must be increased immediately to meet this challenge; estimates indicate that this increase may reach 70%. Traditional fertilizers have helped farmers a lot, but their extensive usage has been shown to degrade soil quality and endanger both the environment and human health. Improving resource efficiency and carefully implementing contemporary technologies are essential to the agriculture sector's progress. Particularly in underdeveloped countries, nanotechnology shows promise as a means of improving agricultural sustainability. Targeted distribution, slow/controlled release, and conditional release mechanisms are used in nanostructured formulations to meet biological demands and possibly revolutionize agricultural systems. Increased nutrient consumption efficiency results from fertilizers that are nanosized, which improves nutrient availability to plant pores at the nanoscale. Via effective absorption, nanoparticles promote increased plant growth by accelerating seed germination, increasing agricultural output, and improving chlorophyll content [14].

A key component of agriculture, food security is closely related to a country's prosperity and well-being. It includes not just food availability but also supply stability, use, and accessibility. Producing a variety of nutrient-dense foods that satisfy the nutritional demands of a world population that is expanding and becoming more urbanized is more important for achieving food security than simply increasing food production [3].

A revolutionary paradigm shift has been brought about in a number of fields by nanotechnology, which operates at the nanoscale, which is normally one to 100 nanometers. Its use in agriculture, sometimes known as "nanotech-agriculture" or "agri-nanotechnology," has enormous potential to solve problems in the field and boost output. The special qualities and behaviors that nanoparticles display are at the core of nanotechnology's potential in agriculture. The potential of nanoparticles, nanofertilizers, and nanopesticides to transform crop farming has drawn a lot of attention. The way that nutrients, insecticides, and other bioactive substances are delivered to plants may be precisely controlled because to these nanomaterials. They make it possible for regulated and targeted release, which reduces waste, lessens environmental contamination, and improves crop development and protection [4].

Additionally, nanotechnology improves the health and quality of soil, increases the effectiveness of fertilizer and water utilization, and makes it possible to create crops that are resistant to disease and stress. Nanotechnology's interdisciplinary nature encourages cooperation between disciplines including chemistry, biology, material science, and agriculture, resulting in creative and comprehensive solutions for the agricultural industry. One prominent use of nanotechnology is in nanofertilizers, which improve a plant's capacity to absorb nutrients. Zn, Cu, and Fe are examples of nanofertilizers that improve photosynthetic efficiency and solve soil fixation issues. Research shows that using nanofertilizers reduces the frequency of necessary treatments, mitigates soil toxicity, enhances nutrient usage efficiency, and lessens the negative consequences of overdose [9, 6]. Nanotechnology has great potential in the quest for sustainable agriculture, offering creative answers to the problems of environmental impact and food production [5]. This review's objective is to examine the vast amount of research and advancements in the topic, using knowledge from both academic publications and real-world applications. It aims to provide a thorough review of nanotechnology's role in contemporary agriculture using a multidisciplinary approach, emphasizing both the transformative potential of nanotechnology and the significance of using nanomaterials responsibly and sustainably. The ultimate goal of this analysis is to provide insight into the multidisciplinary research needed to advance agriculture into a new era of resilience and sustainability. The principles of nanotechnology and the various nanomaterials utilized in agriculture will be covered in detail in the sections that follow. We'll look at how nanotechnology is being used to improve soil management, increase crop quality and growth, and manage pests and diseases. After discussing safety and environmental issues, an analysis of upcoming developments and trends in the field of agricultural nanotechnology will be conducted [6, 7, 8].

**Foundations of Nanotechnology**

The manipulation, engineering, and use of materials, structures, and devices at the nanoscale are the focus of the multidisciplinary area of nanotechnology. Materials have distinct physical and chemical characteristics at the nanoscale that set them apart from their macroscopic counterparts. One billionth of a meter is called a nanometer (nm), and structures and phenomena in nanotechnology are usually found in the 1–100 nanometer range. New applications in a variety of fields are made possible by this developing area, which allows engineers and scientists to manipulate and design matter at the atomic and molecular levels [7].

**Fundamentals of nanotechnology**

A number of fundamental ideas form the basis of nanotechnology [8,9]:

**Size-Dependent Properties:** Materials' optical, electrical, magnetic, and catalytic qualities all become size-dependent at the nanoscale. This implies that changing a nanoparticle's size, shape, or structure can result in significant changes to its properties.

**Both top-down and bottom-up Approach:** These methods can be used to create nanomaterials. Top-down methods break down bigger materials into nanoscale structures, whereas bottom-up methods produce materials atom by atom.

**Control and Accuracy:** Nanotechnology places a strong emphasis on accurate control and nanoscale material manipulation. Advanced fabrication and characterization techniques are used to obtain this control.

**Interdisciplinary Collaboration:** Nanotechnology benefits greatly from cooperation between a variety of academic fields, such as materials science, engineering, physics, chemistry, and biology. The development of novel applications and solutions requires this interdisciplinary approach [10, 11].

**A Novel Approach to Agricultural Development: Nano-Farming**

One of the most recent technical advancements that exhibits distinct targeted properties with increased strength is nanoparticle engineering. Even though the term "nanotechnology" has been used for a long time in many different fields, the notion that nanoparticles (NPs) could be useful for agricultural development is a relatively new technological advancement that is still being developed [10, 11]. Recent developments in the production of nanomaterials in a variety of sizes and shapes have produced a broad range of uses in environmental science, agriculture, food processing, and medicine. These developments have always been beneficial to agriculture [5]. Furthermore, the advent of nanotechnology has presented promising uses for precision agriculture, given the myriad of unprecedented challenges facing agriculture, including decreased crop yields brought on by biotic and abiotic stresses, such as nutrient deficiencies and environmental pollution. In recent years, the term "precision agriculture" or "farming" has gained popularity to refer to the advancement of wireless networking and the shrinking of sensors used to track, evaluate, and regulate agricultural operations. A notable scientific accomplishment is the targeted delivery of CRISPR (clustered regularly interspaced short palindromic repeats)/Cas (CRISPR-associated protein) mRNA and sgRNA for crop genetic modification (GM) using recent developments in tissue engineering and engineered nanomaterials [12,13,14]. Furthermore, a growing variety of environmental problems have good answers thanks to nanotechnology. For instance, the creation of nanosensors offers numerous opportunities for monitoring environmental stress and boosting plants' ability to fight off illnesses [15,16]. Therefore, there is a great chance that these ongoing advancements in nanotechnology, with a focus on problem identification and the creation of cooperative strategies for sustainable agricultural growth, will yield wide-ranging social and equitable advantages.

**Nanofertilizers**

When used alone or in combination, nanofertilizers—nanoscale nutrient carriers with dimensions between 1 and 100 nm—are used to improve plant growth, yield, and overall performance. These cutting-edge fertilizers are made by adding nanomaterials to traditional fertilizers that have been derived from different plants or plant parts. These formulations, which go by a number of names, including nano-carriers, nano-enabled fertilizers, bionanofertilizers, controlled-release nanofertilizers, NPs-based nutrient, and nano-based delivery systems of micronutrients, guarantee accurate nutrient delivery at the best times and places. Nanofertilizers have a profound effect on physiological and biochemical processes. By improving food availability, they promote better metabolic processes and meristematic activity, which in turn leads to increased apical growth and larger photosynthetic areas [6, 19, 20]. To increase productivity, product quality, and fruit shelf life, this improvement is essential for boosting both vegetative and reproductive growth, including flowering. Importantly, nanofertilizers keep nitrogen, phosphorus, and other macronutrients released in a balanced manner, avoiding nutrient losses and unfavorable interactions with air, water, and microbes [5]. Since nanofertilizers can adjust to a variety of environmental conditions, including temperature changes, soil moisture content, and soil acidity, they can optimize the rate at which nutrients are supplied to plants. When it comes to controlled nutrient delivery, nanofertilizers stand out from conventional fertilizers due to their exceptional efficiency and ease of absorption by roots and shoots [16, 17, 18]. They successfully reduce nitrogen loss from emissions, leaching, and extended contact with soil microbes. Nutrient-loaded nanomaterials, macronutrient nanoformulations, and micronutrient nanoformulations are the different types of nanofertilizers that can have different designs, such as moisture release, pH release, heat release, ultrasonic release, magnetic release, specific release, slow release, and rapid release. By reducing nitrogen loss through leaching, their application improves nutrient delivery to the soil [21].

**Utilizing Nanofertilizers in Horticulture**

They have the ability to solve the unique needs and difficulties connected with growing fruits, vegetables, and decorative crops, nano-fertilizers are becoming more and more significant in horticulture. For horticulture to produce the best crop quality and yields, accurate fertilizer control is essential. Because they allow for the precise and regulated release of nutrients to plants, nano-fertilizers provide a viable remedy [22, 23]. This accuracy ensures that crops get the right nutrients in the right amounts at the right times, leading to stronger plants that are more resistant to pests and diseases. Additionally, horticultural crops frequently exhibit certain nutrient shortages that can be addressed by using nano-fertilizers. Their nanoscale properties make it easier for them to enter plant tissues, which enhances nutrient absorption and utilization. This minimizes groundwater contamination and nitrogen runoff, which not only cuts down on fertilizer waste but also supports sustainable farming methods. Furthermore, horticulture's negative environmental effects may be mitigated with nano-fertilizers. By improving the efficiency of nutrient consumption, they can lessen the negative effects of overfertilizer application, like soil deterioration and water contamination. As horticulturists work to satisfy the growing demand for superior fruits, vegetables, and decorative plants, nano-fertilizers show up as a useful instrument for accomplishing these goals while also taking sustainability and environmental concerns into account. To guarantee their safe and efficient usage, thorough study, appropriate application techniques, and respect to legal requirements are necessary for their integration in horticulture [24, 25].

**Nano-sensors**

Temperature, humidity, and wetness are just a few of the many values that nanosensors are useful for detecting or sensing. Nanosensors can detect and quantify physical volumes on the nanoscale by utilizing the special qualities of nanomaterials. In order to measure physical quantities and transform them into observable signals for analysis, these nanoscale devices are essential. Molecular self-assembly, bottom-up assembly, and top-down lithography are some of the methods used in the creation of nanosensors. Numerous kinds of nanosensors have hit the market recently and are being developed for a variety of uses, most notably in the environmental, healthcare, and defense industries. These sensors all work in the same way, regardless of their different uses: they bind to an analyte selectively, interact with the bio-element to produce signals, and then convert those signals into useful measures [26, 27].

**Nanosensor Application in Horticulture**

Significant improvements in horticulture are being brought about by nanosensors, which are revolutionizing crop management and monitoring. Made of nanomaterials, these tiny sensors are used in agricultural settings to gather data in real time on variables that are vital to crop productivity and well-being. Nanosensors are essential in horticulture because they can measure soil parameters with remarkable accuracy, such as pH, nutrient content, and moisture levels. This information enables horticulturists to maintain perfect soil conditions for crop growth, manage irrigation schedules, and guarantee timely fertilizer supply to plants. By adjusting resource management to the unique needs of crops and soil, nanosensors help to conserve water, use less fertilizer, and encourage sustainable farming methods. Nanosensors also play a crucial role in managing pests and diseases. They can spot early warning indicators of pest invasions or disease infestations by keeping an eye on alterations in plant physiology or the presence of particular biomarkers. Because of this early detection, growers can minimize crop losses and reduce their need on chemical treatments by implementing timely interventions [28, 29]. In horticulture, nanosensors are also essential for precision agriculture since they offer information on microclimatic factors including light levels, humidity, and temperature. Through microscale data collection, horticulturists can establish ideal growing conditions in greenhouses or other controlled environments, guaranteeing the year-round production of high-value crops. To sum up, nanosensors improve horticulture techniques' production, sustainability, and efficiency. They establish nano sensors as important assets in modern horticulture by providing growers with data-driven decision-making tools that enable increased agricultural yields, better crop quality, and less environmental impact [30].

**Nanopesticides**

In order to overcome the drawbacks of traditional insecticides, nano-pesticides offer an alternative. Both the active ingredient and the carrier molecule in these plant protection compounds were created through the use of nanotechnology. The word 'nano', which emphasizes the particles' greatly diminished size, comes from the Greek word meaning dwarf. By improving chemical performance, the main goal of developing nanopesticides is to reduce the environmental hazards connected to the active chemicals in pesticides. The benefit comes from the particles' minuscule size, which usually ranges from 1 to 100 nanometers (one nanometer is one billionth of a meter). Particles provide a significant surface area at this scale, allowing for greater interaction with pests. Because of their tiny size and form, nanoparticles are said to be able to penetrate. The active agent, carrier molecule, and surfactants are the same components of nanopesticide formulations as they are of traditional pesticide formulations. Because of their smaller size and bigger surface area, nanoparticles have several important benefits, such as better mobility, improved formulation stability, improved solubility of active ingredients, and progressive release of the active ingredient. It is anticipated that, in comparison to bulk materials, nano-pesticides will improve the mode of action against the target pests. Furthermore, nanoformulations support their beneficial use in agriculture by offering systemic qualities, consistent leaf coverage, and enhanced soil features [28, 30, 31].

**Application of nanopesticides in Horticulture**

The need for more effective, environmentally responsible, and sustainable pest management techniques has led to the development of nano insecticides as a revolutionary tool in modern horticulture. These novel formulations offer many advantages in horticultural settings by precisely and efficiently delivering pesticides through the use of nanoparticles. Targeted pest management is one of the main benefits of nanopesticides. Due to their nanoscale size, they can stick to plant surfaces more effectively, providing thorough coverage and making it easier to get past pests' exoskeletons and other defense mechanisms. By using fewer pesticides and increasing the effectiveness of pest control, this focused approach lessens the impact on the environment and the possibility of harm to creatures that are not the intended target. Furthermore, it is possible to create nanopesticides that release their active ingredients gradually, offering extended defense against illnesses and pests. Growers save money and lessen their environmental impact because this controlled release not only increases crop yield and quality but also reduces the need for frequent pesticide applications. In horticulture, where food quality and appearance are crucial, nanopesticides are a game-changing instrument [32, 33].

**Utilizing nanomaterials in horticulture to cover seeds**

With the potential to maximize plant development, crop yield, and resource utilization, the use of nanomaterials in seed coating has attracted a lot of interest in horticulture. Nanomaterial seed coverings offer many benefits in the highly precise field of horticulture. These nanoscale-engineered coatings give seedlings a protective covering that promotes safe germination and early development. The capacity of nanomaterial seed coverings to protect seeds from environmental stresses including pests, diseases, and unfavorable climatic conditions is one of their main advantages. By acting as a barrier, nanoscale materials enhance germination rates and promote the development of stronger, healthier plants by shielding seeds during critical germination and early growth. Additionally, vital nutrients, chemicals that promote growth, or advantageous microbes can be encapsulated by nanomaterials in seed coats, enabling precise and regulated distribution to growing seedlings. This guarantees that plants get the resources they need for healthy growth and development. Nanomaterial seed coverings increase crop vigor and productivity by improving nutrient uptake and cultivating symbiotic partnerships with advantageous microbes. Furthermore, these coatings increase seed adherence to the soil, which lowers seed waste during planting and boosts planting efficiency—two important aspects of horticulture where exact seed placement and spacing are essential for the best crop growth. Although there are many potential advantages to using nanomaterial seed coatings in horticulture, it is crucial to utilize them responsibly, taking safety and legal issues into mind. By improving crop quality, yields, and encouraging sustainable and effective cultivation techniques, nanomaterial seed coverings have the potential to completely transform horticultural practices when used sparingly and in accordance with regulations [34, 35].

**Nanomaterials' application in horticulture for crop protection**

In horticulture, nanomaterials have emerged as a potential field that offers creative crop protection solutions for the production of fruits, vegetables, and decorative plants. These nanoscale materials, which are precisely and effectively engineered to protect plants from pests, diseases, and environmental stresses, tackle the particular difficulties encountered in horticulture. Nanoparticles encapsulating pesticide active components allow for targeted and regulated release, making this a noteworthy application in the field of nanopesticides. This accuracy guarantees efficient insect targeting while lowering the amount of pesticides needed and minimizing the impact on the environment. As physical barriers against infections, insects, and environmental stresses, nanomaterials are also used in the development of protective coatings for plant surfaces. This safeguard improves overall crop quality and promotes plant health. To provide proactive defense against illnesses and pests, nanoparticles can also be loaded with antimicrobial drugs or substances that trigger plant defense mechanisms. By increasing nutrient availability, facilitating real-time soil condition monitoring, and boosting soil water retention, nanomaterials provide benefits in horticulture when it comes to soil and water management. This makes it possible to use resources more effectively, which lowers waste of water and nutrients. All things considered, the use of nanomaterials in horticulture has enormous potential for effective and sustainable crop protection and resource management [36].

**Utilizing nanotechnology to enhance soil in horticulture**

In horticulture, nanotechnology has enormous promise for improving soil quality by addressing the vital elements of crop quality and soil health. Nanotechnology offers creative answers to particular problems in the accurate control of soil conditions in horticulture operations. The application of nanomaterials and nanoparticles improves nutrient management and soil fertility. These nanoscale carriers have the ability to encapsulate essential nutrients, such as micronutrients, phosphorus, and nitrogen, allowing for their regulated and targeted release straight into the plant root zone. This method lessens the environmental impact of excessive fertilizer use, maximizes nutrient uptake, and minimizes waste. Additionally, nanotechnology helps horticulture settings improve soil structure and moisture management [37, 38]. Improved root growth, greater drought resistance, and general plant health are the outcomes of nanoparticles' contributions to soil aggregation, water retention, and aeration. Crops that require precise moisture regulation and well-structured soil for optimal growth would especially benefit from these qualities. Apart from these advantages, nanotechnology provides ways to clean up polluted soils in horticulture. Pollutants and heavy metals can be bound by nanoparticles, which immobilizes them and reduces their bioavailability to plants. This restorative action guarantees the production of safe and superior crops while also assisting in the revitalization of soil health [39].

**The advantages of nanotechnology in horticulture**

* Nanoscale carriers allow for precise nutrient delivery, saving fertilizer consumption, decreasing environmentally hazardous nutrient runoff, and guaranteeing plants receive the best nutrients possible [41].
* Nano pesticides offer more effective and targeted pest control by more efficiently penetrating plant tissues and insect exoskeletons, limiting pesticide application, and lessening the impact on the environment [42].
* Better aeration, less soil erosion, and more drought resilience in crops are all results of nanomaterials' improved soil structure and moisture retention, which promotes healthier plant growth [43].
* By employing nanotechnology to control temperature, moisture, and gas exchange in packing materials, harvested fruits and vegetables can have their shelf lives extended, minimizing food waste and preserving product quality [44].
* By lowering chemical use, maximizing resource use, and limiting environmental effect, nanotechnology supports sustainable horticultural practices [45].
* Crop management and resource use efficiency are improved by accurate decision-making and resource allocation made possible by real-time data on soil and environmental conditions obtained from nanosensors and monitoring systems.
* Nanotechnology-enabled controlled release of biopesticides or beneficial microorganisms promotes natural pest management techniques and lessens reliance on chemical pesticides.
* Higher crop yields and better crop quality are the outcomes of nanotechnology's improved overall health and productivity of plants.
* By facilitating effective irrigation water use, nanoscale sensors and moisture control systems help preserve this essential agricultural resource.
* Nanotechnology allows for precise and flexible crop management by enabling solutions to be tailored to particular horticulture needs.

**Nanotechnology's Limitations in Horticulture**

Nano fertilizers in horticulture offer numerous benefits for growing high-quality, high-yield crops, making them invaluable resources for farming systems and sustainable agricultural methods. There are both advantages and disadvantages to plants' possible uptake of nanoparticles as well as to their biotransformation and translocation processes. However, the research and application of nanoparticles as nanofertilizers are hindered by the absence of established formulas, thorough monitoring, and risk management [46]. Since nanomaterials can alter intercellular activity, they have been shown to interact with soil microorganisms and affect how nutrients are absorbed by plants [47]. Since nanoparticles can easily penetrate biological systems and pass through cell membranes when sprayed, there are health risks to humans since they may reach critical organs like the liver, brain, or heart [48]. According to findings, nanofertilizers have detrimental effects, highlighting the necessity of systematic evaluations that include food security, ecosystem impacts, human health concerns, uniform crop formulations, and standards [49]. Stable, consistent formulations of nanofertilizers must be developed in order to guarantee safety and avoid negative effects. Notwithstanding the many benefits, there are some restrictions and difficulties with nanotechnology in horticulture. Because poorly managed nanoparticles can build up in soil and water ecosystems and impact non-target creatures as well as the environment, safety and environmental considerations are of utmost importance. For responsible use, ongoing study into the long-term effects of nanoparticle exposure is essential. Cost is still a barrier because it can be costly to develop and produce nanomaterials, making them inaccessible to small-scale farmers or horticultural businesses with limited resources. For wider usage, cost-effective scaling up of nanotechnology technologies is essential [50]. Furthermore, the regulatory environment surrounding nanotechnology in agriculture is changing, making the development of safety standards necessary. A crucial problem is striking a balance between safety and creativity [51, 52]. Horticultural experts must be trained in the use of nanotechnology since its implementation calls for certain knowledge and skills. Challenges with public acceptability and perception also exist, highlighting how crucial it is to communicate openly about the advantages and possible concerns of nanotechnology in order to win over the public.

**Conclusion**

Nanotechnology has been applied in horticulture to enhance farming systems and increase crop yields with quality enrichment. Because of their novelty, rapid expansion, and scale in order to fulfill the projected global food demand, engineered nanomaterials and their applications in sustainable agriculture have completely changed the agricultural landscape. In sustainable agriculture, preventing pollution of the environment is the primary goal of commerce, and nanomaterials offer a guarantee of improved input management and conservation for plant production. Nanomaterials' potential promotes a new green revolution with lower farming hazards. We still don't fully understand the ecotoxicity, acceptable limit, and absorption capacity of many nanomaterials, nevertheless [9]. Therefore, further research is desperately needed to understand the fate and behavior of modified agricultural inputs as well as how they interact with biomacromolecules found in ecosystems and living systems.

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