Nano World Journal

https://doi.org/10.17756/nwj.2023-s5-052

Review Article

Open Access

Review on Applications of Nanotechnology in Agriculture

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Received: October 20, 2023
Accepted: December 21, 2023
Published: December 27, 2023

Citation: Kaur A, Bhatt DP, Raja L. 2023. Review on Applications of Nanotechnology in Agriculture. *NanoWorld J* 9(S5): S277-S282.

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Abstract

The major industry that generates money is agriculture, which also plays a key role in feeding the world's growing population and supplying the food sector with raw materials. Plant diseases are now harming both the amount and quality of food produced, as has been observed over the past few years. The most promising area that can be used to deal with these problems is nanotechnology. It has been generating a lot of interest recently since it may be applied at all phases of agriculture, from seedling development through plant growth. To increase the quality and quantity of food crops, the current study will discuss how nanotechnology may be applied at various phases of crop production and offer potential future applications.

Keywords

Nanotechnology, Nanofertilizers, Nano-pesticides, Nanosensors

Introduction

Traditional agricultural methods led to the usage of chemically created fertilizers, which caused several issues such as soil salinity, acidity, and water contamination, as well as insect resistance in some crops [1]. Nanotechnology has applications in various fields, including physics, pharmacology, chemistry, computer science, engineering, and agriculture. Nanoparticles (NPs) possess unique physical, chemical, and biological characteristics, allowing them to alter materials and technological components. NPs are organic, inorganic, or polymeric, with dimensions between 1 and 100 nm, and are made from natural or manmade materials. Nanotechnology has the potential to revolutionize agriculture by reducing the environmental impact and enhancing yields [2]. While the bottom-up strategy focuses on assembling organic and inorganic components into clearly defined structures, the top-down strategy includes creating nanoscale structures from smaller-scale structures. Numerous industries, including medical, electronics, telecommunications, and agriculture, use NPs with a variety of features, including optical and biological ones [3]. By reducing nutrient losses, soil contamination, and chemical runoff, high-level agricultural systems and the use of nanoparticles might revolutionize agricultural methods. This would ultimately lead to higher yields through effective management. To accomplish these objectives, cutting-edge instruments like nano-pesticides and nanofertilizers can be deployed. Overall, the sector of agriculture might undergo major change because of nanotechnology, improving both the quality and quantity of harvests [4].

Agriculture-related nanotechnology research has grown tremendously in recent years. However, few analyses include all elements of agricultural production's usage of nanotechnology, particularly the recently developed nanosensors and nanobiotechnology. In this review, we discussed nanofertilizers, and nano-pesti-

cides, Nanotechnology regulates seed germination, and plant growth, and uses nanosensors for monitoring plant growth.

Agriculture with Nanotechnology

Uncontrolled and prolonged application of conventional fertilizers in agriculture poses significant environmental issues, including eutrophication, nutrient depletion, and increased nitrate content. A quick rise in residue content in soil and water because of excessive nitrogen loading or uncontrolled fertilizer usage in agriculture is harming the environment [5, 6]. Conventional fertilizers have only 30 - 50% efficiency, making it crucial to find sustainable solutions. By delivering plant nutrients site-specifically and enhancing crop yield, nanotechnology has the potential to be a miracle cure for agriculture. It is anticipated that conventional farming methods will give way to precision farming methods since precision farming is essential for boosting crop output by keeping an eye on environmental factors and taking focused action. Nanotechnology can produce nano supplements for enriched feed, nano-antibiotics for livestock productivity, and nano-biosensors for precision farming [7]. Nanotechnology enables the application of the necessary number of fertilizers and pesticides to crops, preserving ecological harmony and minimizing excess runoff. The use of nano-formulation, nano-encapsulation, and functionalized NPs offers new possibilities in the manufacturing of new fertilizers, pesticides, herbicides, insecticides, and sensors. The solubility of inefficient substances is increased by nano-formulation, and it protects against early degradation [8]. In the pesticide sector, agrochemical companies are utilizing nanotechnology to develop chemical emulsions at nanoscale or nano-capsules containing active ingredients that can split open in response to insect conditions or heat and sunlight. In the food sector, nanotechnology can solve many problems in the food supply system, such as food polymers and polymer assemblages, contributing to food safety and quality improvement (Figure 1) [9].

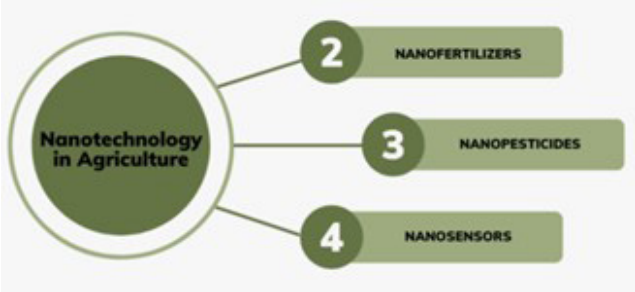

Figure 1: Nanotechnology applications in agriculture.

Nanofertilizers

Fertilizers made from chemicals are essential for contemporary agriculture, but since their effectiveness has declined, they are now more likely to pollute water and soil and emit greenhouse gases. It's possible that nanotechnology will support sustainable agriculture. To increase fertilizer uptake by crops and reduce fertilizer runoff, mineral nutrients are encapsulated with NPs to create nanofertilizers [10]. These macronutrients, which can be employed to increase fertilizer absorption and decrease outflow, include carbon, nitrogen, potassium, phosphorus, calcium, sulfur, and magnesium. NPs have a large specific surface area, are stable, and are biocompatible, which increases the release efficiency of NP fertilizer composites. For example, urea-hydroxyapatite (HA) NPs have shown potential for enhancing releasing time and reducing the demand for nitrogen fertilizer [11]. Urea and HA nanohybrids boost agronomic nitrogen usage efficiency by around 30%. The use of nanofertilizers holds a lot of potential for enhancing fertilizer uptake and boosting agricultural yields. When N, P, and K are combined with chitosan NPs, cultured coffee plants are better able to absorb those nutrients than untreated controls by 17.04%, 16.31%, and 67.50%, respectively. Magnesium oxide NPs considerably raised the yield of seed cotton by 42.2%. Nanofertilizers also limit fertilizer loss and lessen soil deterioration. The pH value of the soil was markedly raised, and P absorption was greatly reduced by phosphate-ion-loaded layered double hydroxide [12]. Nanohybrids with plenty of holes and a small volume make it easier for plants to absorb nutrients, and they are not easily harmed by weather conditions like rain and wind. The effectiveness and stability of fertilizers are boosted because of chemical interactions between NPs and fertilizers that reduce and homogenize particle size. Nanomaterials including chitosan, zinc oxide nanoparticles (ZnO NPs), copper nanoparticles (Cu NPs), and calcium NPs contain micronutrients like iron, boron, manganese, copper, zinc, and molybdenum. These micronutrients are essential for processes including photosynthesis, enzyme components, and enzyme activators, which are physiological and chemical processes in plants [13]. Micronutrient based nanofertilizers encourage plant development and boost harvests. In contrast to zinc sulfate, ZnO NPs fertilization of strawberries increased fruit setting and grain production. B insufficiency impairs pollen germination and shoot growth, whereas calcium borate nanoparticles ($CaO_2B_2O_3.10H_2O$ NPs) in lettuce increased B accumulation by 1.54 and 3.95 folds in the shoots and roots, respectively. Micronutrient fertilization boosts photosynthesis and antioxidant enzyme activity, enhancing dry weights, shoot lengths, root lengths, and biomass in plants. Nanotype micronutrients greatly boost yields and encourage plant development when applied topically or by drenching [14]. The effectiveness of fertilization is greatly influenced by NPs, and nanotype fertilizers have smaller particles and greater specific surface areas. The connection between the roots and leaves enhances plant uptake. Due to their special characteristics, NPs are resistant to hydrolysis, photolysis, evaporation, and weathering. NPs can enter cells through ion channels or molecular transporters because of their porous architectures and modest size profiles, triggering signalling pathways for phytohormones and growth factors (Figure 2) [15].

Nano-pesticides

Insecticides, herbicides, fungicides, and bactericides can be nano-formulated or encapsulated with nanomaterials to increase crop yield, reduce chemical pesticide dosages, and support sustainable development [16]. Polymeric, inorganic, non-metallic, and metallic NPs all function as nano-pesticide carriers. Nano-pesticides are more effective in controlling pests and are less likely to have negative effects on people, accord-

Figure 2: Application model of nanofertilizers and nano-pesticides.

ing to studies. Upon encapsulation, nano insecticide particles shrink and become more concentrated, enhancing their activity, and lowering their toxicity toward people [17]. Concentrated NPs effectively limit virus, bacteria, and pest development due to their biological toxicity. In contrast to pheromones, which have been shown to be a promising pest management strategy, metallic NPs have been utilized to eradicate *Sitophilus oryzae* on stored rice. The benefits of sex pheromones can be amplified by composites of nanocarriers and pheromones. One example is the use of nanogels laden with methyl eugenol in guava orchards [18]. Since their commercial manufacture, herbicides, which are frequently employed to eradicate weeds, have demonstrated a variety of negative side effects, including toxicity to living things, water pollution, soil contamination, and air pollution [19]. Encapsulating herbicides in NPs can reduce environmental residues and improve weed control efficiency. Solid lipids are the most effective nanocarriers due to their chemical stability and simple metabolism. For instance, compared to traditional herbicides, foliar application of polysaccharide NPs loaded with metsulfuron-methyl to weeds growing in wheat resulted in a significant reduction in weed biomass. By incubating cells, it was also possible to compare the cytotoxicity of nano-herbicides with conventional herbicides, and the findings revealed that herbicide-loaded NPs were less hazardous than unloaded herbicides [20]. Compared to conventional herbicides, solid lipid NP-based nano-herbicides had improved release patterns and herbicidal action, according to different research studies. *Raphanus raphanistrum* (a weed species) development was greatly slowed down when atrazine was encapsulated by solid lipid NPs as opposed to the untreated group. Additionally, *Zea mays* was not hazardous to the measured nano-herbicide concentration [21]. The ability to create nano-bactericides and nano-fungicides using metallic NPs appears to be particularly unique, as was previously highlighted. In comparison to free-leaf extracts, nano-bactericides comprising holy basil leaf extract and silver nanoparticles (Ag NPs) illustrated greater suppression of *Xanthomonas axonopodis* pv. punicae on pomegranate. Cu NPs prevented the growth of five different bacteria, including *Pseudomonas savastanoi* pv. *Savastanoi*, *Dickeya dadantii*, *Erwinia amylovora*, *Agrobacterium tumefaciens*, and *Dickeya dadantii*. While metallic NPs prevent bacteria and fungus, non-metallic NPs manage plant diseases. For instance, in comparison to the untreated group, chitosan NPs efficiently suppressed *Xanthomonas campestris* infection in jalapeo peppers [22]. Metallic NPs also prevent the growth of fungus. Nickel ferrite and cobalt ferrite NPs reduced Fusarium wilt incidence in plants, without affecting capsicum growth. These NPs have concentrated particle size distributions, large surface areas, and longer fungicide release times. Studies show fungicides in NPs are efficient in controlling fungus. Chitosan-hexaconazole NPs crosslinked with tripolyphosphate increased Gano-derma boninense growth inhibition [23].

Monitoring Plant Using Nanosensors

In agro-environmental research, nanosensors have several important applications, including managing nutrient intake, observing growth, assessing pest and disease activity, assessing soil quality, producing food, and detecting plant hormones [24]. They may keep an eye on certain plants in real-time utilizing techniques including surface-enhanced Raman scattering, corona-phase molecule identification, electrochemical nanosensors, and piezoelectric nanosensors. These sensors can pick up a variety of plant molecules that communicate, including electrical, chemical, and gas signals like oxygen and nitric oxide. Fluorescent ratiometric single-walled carbon nanotube sensors are a single-molecule detection method that may work in challenging settings [25]. Fundamental signalling molecules in animals, such as electrical and Ca^{2+} signalling molecules, are connected to several abiotic and biotic stressors. The most fundamental regulators of plant development that are present throughout all phases of plant life are phytohormones [26]. Food quality and plant stressors are linked to chemical signals like volatile organic compounds (VOCs). These chemical signals may be detected, which helps with stress tolerance, loss reduction, and shelf-life prediction [27]. Nanosensors for identifying plant diseases are essential for keeping an eye on plant health and acting quickly to defend it. Nanosensors that are lightweight, affordable, and precise help scientists identify plant infections quickly. Nanosensors can detect volatile organic chemicals, proteins, and DNA as targets of plant disease [28]. Nanosensors commonly use the antigen-antibody binding mechanism to detect plant pathogens. Anti-CTV (citrus tristeza virus) antibody-coupled cadmium-telluride quantum dots fluoresced when CTV was bound, but competitive interaction with the CTV coat protein inhibited the fluorescence [29]. In conclusion, nanosensors enable managers to track molecular plant health, greatly enhancing the effectiveness of plant management. When used in agricultural systems, however, the stability of these nanosensors still must be considered [30]. Future research is anticipated to address the sensitivity and dependability of nanosensors used in agricultural productivity. The detection of sucrose and glucose has improved over the past several decades, and the FRET technique is now commonly employed to track the flow of these two substances [31]. A flexible electronic sensing device that is wearable for daily life has also been developed to continually monitor the movement of water, sap, and nutrients. Deep tissue damage brought on by dehydration and ultraviolet radiation was accurately detected by wearable nanosensors consisting of vapor-printed polymer electrodes [32, 33].

Nanotechnology Regulates Seed Germination and Plant Growth

Nanotechnology enhances crop yields and quality in agricultural production through seed germination and plant development [34]. Studies have shown that NPs have positive effects on seed germination in a range of agricultural plants, such as maize, pearl millet, wheat, rice, tomato, and soybean [35]. Antioxidant enzyme activity and rates of oxygen and water uptake are connected to seed germination. Wheat germination rates were greatly increased by ZnO NPs, but oyster millet germination was significantly enhanced by gold NPs. Titanium dioxide NPs boost water and oxygen intake, which quickens seed germination. By improving water absorption capacity, multi-walled carbon nanotubes (MWCNTs) can improve seed germination in a variety of crops. Soybean, barley, and maize seeds were air-sprayed with MWCNTs, which at least 25% higher seed germination rates. MWCNTs dramatically increased the gene expression of genes associated with water channels by penetrating seed surfaces as well [36]. The impacts of NPs such as Ag NPs, ZnO NPs, Titanium dioxide NPs, silica NPs, and MWCNTs on growth, photosynthesis, and yield enhancement are beneficial to several crop species [37]. Superoxide dismutase and catalase activities are two examples of crop antioxidant enzymes that are influenced by NPs, which speed up plant growth. Additionally, they alter the shape of plant cells and raise their protein and organic chemical content [38, 39]. Silica NPs were added to the soil to enhance maize growth, especially in terms of the height of the plants and length of roots. The silica-NP-exposed plants had stronger cell walls and more silica bodies in the root cells than the control plants. NPs activate genes involved in controlling growth and nutrition absorption. Using bioinformatics, researchers can better comprehend these consequences [40, 41]. The balance of plant hormones may also be controlled by NPs. Ag NPs applied topically to two types of common beans caused the auxin signalling pathway's genes to be expressed, which increased the amount of auxin in plants. When used in high quantities, NPs can cause intracellular oxidative stress, genetic damage, decreased crop yields, and physiological problems [42]. Metallic NPs are suitable for nano-pesticides but may also hinder plant growth and development due to their side effects from toxicity. When compared to the untreated control, squash biomass was considerably reduced by Ag NPs at 500 mg/L by 74%, and by Cu NPs at 100 mg/L when grown in Hoagland's solution. Therefore, it is important to identify the appropriate doses of different NPs for specific varieties of crops (Figure 3) [43, 44].

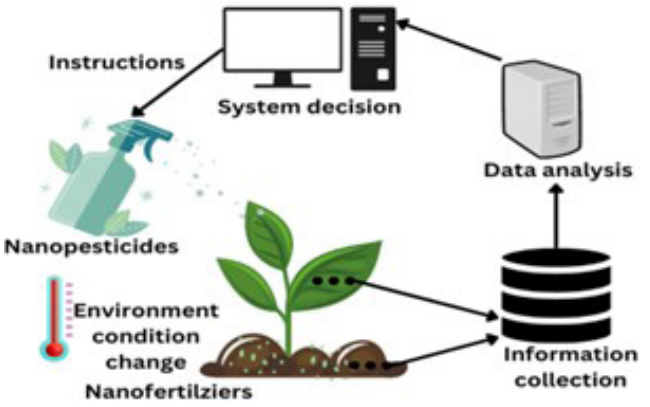

Figure 3: Application model of nanosensors in crops.

Conclusion

The use of nanotechnology has the potential to enhance the environment and boost agricultural quality and yield. Nanotechnology is now being studied for nano-pesticides, nanofertilizers, and nanosensors. Between laboratory research and agricultural output, there are still gaps. Further research on NPs concentrations in various crop species is required since they can be both hazardous and advantageous. Finding a practical use for nanomaterials that combines environmental preservation with agricultural productivity is also essential. There are distinctions between plants converted using NPs and traditional ways, and researchers are also investigating the sensitivity and dependability of nanosensors for agricultural usage. Despite these difficulties, there is rising hope that nanotechnology will be able to supply the need for human food.

Acknowledgements

None.

Conflict of Interest

None.

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