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Review Article

Application of nanoparticles in agriculture and vegetable seed germination

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The potential revolutionary impact of nanoparticles in agriculture has made them the subject of considerable interest in recent years. This review investigates nanoparticle's effects on the germination process of vegetable seeds. It analyzes the influence of nanoparticles on seed viability, development dynamics, and the overall health of plants. This review comprehensively examines the extant literature to clarify the mechanisms contributing to improving seed germination *via* nanoparticles. It emphasizes critical elements, including the type and concentration of nanoparticles and the manner of application. In addition, the review examines potential obstacles and apprehensions linked to the application of nanoparticles in agriculture, encompassing safety concerns and ecological ramifications. By analyzing the current research findings, this review offers significant insights into the potential of nanoparticles to enhance the germination of vegetable seeds. Additionally, it establishes a foundation for future research directions in this rapidly developing domain.

Keywords: *nanoparticles, nanotechnology, seed germination, silica nanoparticles, selenium biofortification*

Introduction

The utilization of nanoparticles is on the rise across numerous sectors, including agriculture. Microscopic particles, which generally span a range of 1 to 100 nanometers, exhibit distinct characteristics that may be utilized in agricultural contexts (Usman et al., 2020). Recent advancements in the field of nanotechnology include the utilization of gold nanoparticles for rapid testing of COVID-19 antibodies, the implementation of 3D printing on glass without the need for sintering, and the identification of an unprecedented topological phase within twisted bilayers, all of which hold promise for further revolutionary developments in nanotechnology. These advancements underscore nanotechnology's multifaceted capabilities in materials science, energy, electronics, and medicine. The field of agriculture has witnessed the development of agrochemicals that have the potential to enhance crop yields and mitigate adverse environmental effects (Ali et al., 2018). Nanoscale sensors are more cost-effective, quicker, sensitive, and user-friendly when identifying food, water, and soil pollutants, including heavy metals, pesticides, and diseases. The intelligent properties of agri-inputs, including targeted delivery, controlled release, enhanced solubility, and prolonged shelf life, can be enhanced through nanotechnology-based methods (Chhipa, 2019). In addition, it can facilitate sustainable and precise cultivation; however, some obstacles must be surmounted (Du et al., 2023). The application of nanoparticles in the agricultural sector is on the rise to increase crop yields, improve nutrient absorption, and lessen the environmental damage caused by pesticides. Silver, titanium dioxide, and silica nanoparticles are frequently employed in agriculture (Rastogi et al., 2019). The application of silver nanoparticles involves the management of plant maladies, whereas titanium dioxide nanoparticles are utilized to enhance photosynthesis efficiency and provide UV protection. In addition to facilitating nutrient absorption by plants, silica nanoparticles enhance soil quality and water retention (Mihata et al., 2015). Active research is being conducted to determine the effect of nanoparticles on vegetable germination; thus far, the results have been varied. Specific nanoparticles, including silver nanoparticles, have been shown in some studies to inhibit the germination of seeds and the growth of roots in specific vegetable species (Singh et al., 2013). Certain crops, including soybeans and wheat, may experience enhanced germination and development when nanoparticles are utilized (Iavicoli et al., 2017). Existing studies suggest nanoparticles could influence vegetable seed germination in favorable and unfavorable ways; therefore, additional research is required to evaluate their potential environmental repercussions and safety.

Agricultural applications of various nanoparticles

Nanofertilizers

Nano fertilizers are an innovative type of fertilizers that employ nanotechnology to enhance the absorption of nutrients and promote plant development. These fertilizers are usually made of nanoparticles specifically engineered to gradually and effectively minimize wastage and enhance the fertilizer's efficiency (Ali et al., 2018). Research has demonstrated that nanofertilizers can enhance agricultural productivity, enhance plant well-being, and mitigate the ecological consequences of conventional fertilizers (Verma et al., 2021). Additionally, they have the potential to enhance nutrient utilization efficiency, mitigate fertilizer runoff, and minimize soil and water contamination (Babu et al., 2022). There is increasing concern about the potential hazards that nanoparticles may present to living organisms and ecosystems, including worries about the long-term effects of nanofertilizers on soil health and plant growth. These problems emphasize the necessity for more investigation and meticulous evaluation of nanoparticle utilization in agriculture to guarantee safety and long-term viability (Davarpanah et al., 2016).

Selenium nanofertilizers

Research has demonstrated that selenium nanoparticles (SeNPs) can benefit the development and productivity of vegetables. Studies have shown that SeNPs are less harmful to plants than selenate or selenite. Additionally, they can enhance plant development, antioxidant activity, and the uptake of essential minerals like selenium, zinc, and iron in vegetables (Hernández et al., 2019). Applying Se NPs to tomato plants resulted in higher fruit output and increased levels of lycopene, β-carotene and crucial antioxidants (Hernández et al., 2019). Applying SeNPs enhanced growth and antioxidant activity in lettuce plants, along with the leaves' higher accumulation of selenium, zinc, and iron (Jakhar et al., 2022). However, the effect of selenium nanoparticles on vegetables might differ depending on the concentration used, the type of vegetable, and the environmental circumstances in which they are grown. A thorough study is necessary to fully understand the benefits and potential risks of using Se NPs as a vegetable fertilizer.

Selenium biofortification

Selenium biofortification is increasing the selenium content in crops by using fertilizers that are enhanced with selenium or by implementing specific agricultural procedures. Selenium is a crucial trace element that significantly impacts human well-being, and a lack of it can result in various health issues (Revelou et al., 2022). Research has demonstrated that selenium biofortification can enhance the selenium levels in vegetables, enhancing their nutritious value. Applying selenium fertilizers to broccoli plants has been discovered to enhance the selenium levels in the broccoli florets and their antioxidant activity (Wiesner-Reinhold et al., 2017). Furthermore, research conducted by Golubkina et al. (2019) has demonstrated that applying selenium fertilizers may enhance the selenium levels in many plants, including lettuce, cabbage, and tomato. Prudent management of selenium fertilizers is crucial to prevent excessive application and toxicity to plants and the environment. While selenium biofortification can enhance the nutritional value of vegetables and treat selenium insufficiency in humans, further research is necessary to thoroughly evaluate the benefits and possible risks associated with selenium biofortification. In addition, vegetables belonging to the cruciferous family, as well as garlic and onions, are known for their capacity to collect significant amounts of selenium. The enrichment potential of these vegetables varies from less than 0.5 mg/kg to values ranging between 140 and 300 mg/kg (Sravani et al., 2021). Leafy vegetables loaded with selenium can enhance the amount of selenium humans consume in their diet, leading to long-term health improvements.

Copper oxide nanoparticles

Using copper oxide nanoparticles (CuONPs) in agriculture can improve crop yields and pest resistance. Still, research into these applications and their effects on vegetable cultivation has found that CuONPs may have adverse effects on vegetable propagation, such as suppressing seed germination, stunting the growth of shoots and roots, and reducing crop photosynthetic efficiency (Rajput et al., 2022). Vegetables can be polluted by metal-containing nanoparticles such as CuONPs by their absorption in the leaves. This contamination is due to the increased use of these nanoparticles in urban areas and can lead to phytotoxicity, as mentioned by Xiong et al. (2017) and Margenot et al. (2018). While utilizing CuONPs in agriculture might enhance crop productivity and resistance against pests, it is essential to exercise meticulous control over their administration to avoid adverse environmental or public health impacts (Wu et al., 2020). Studies have demonstrated that CuONPs might adversely affect the growth and development of lettuce and carrots. A study conducted by Rajput et al., 2023 revealed that CuONPs had a detrimental impact on the antioxidative defense and growth of lettuce seedlings. The CuONPs exhibited a correlation between their concentration and the growth in root diameter of lettuce and carrot seedlings. However, they also caused a decrease in the hydraulic conductivity of lettuce roots (Xiong et al., 2017).

Silver nanoparticles

Research indicates that silver nanoparticles (AgNPs) can positively and negatively affect vegetables. These effects might be helpful or destructive. Positively, it has been established that AgNPs can improve the post-harvest shelf life of fruits and vegetables by limiting the formation of microorganisms (Tymoszuk & Wojnarowicz, 2020). AgNPs, on the other hand, have the potential to have phytotoxic effects on vegetables. These effects include the inhibition of seed germination, the reduction of root and shoot growth, and the influence on the biochemical activity of seedlings (Budhani et al., 2019). There is a possibility that AgNPs might induce phytotoxicity in vegetables because they can generate reactive oxygen species, which can cause oxidative damage to plants (Shams et al., 2013). Depending on the kind of vegetable, the concentration of AgNPs, and the length of exposure might impact vegetables.

Zinc oxide nanoparticles

The growth and development of vegetables are adversely and positively impacted by zinc oxide nanoparticles (ZnONPs). The ZnONPs have been observed to promote the growth of various vegetables, such as tomatoes and lettuce, as measured by germination rate, root length, and shoot length (Wang et al., 2012). Research has demonstrated that it has the potential to improve the nutritional content of vegetables by facilitating the absorption of zinc, an essential micronutrient (Mao-Hong et al., 2021). Conversely, ZnONPs may induce vegetable phytotoxicity. This can manifest as antagonizing seed germination, impeding the development of roots and shoots, and impairing the antioxidant capacity of seedlings (Mao-Hong et al., 2021). The phytotoxic effects observed on vegetables may be attributed to the capacity of ZnO NPs to induce oxidative stress in plants by producing reactive oxygen species (Raskar & Laware, 2014). The utilization of metal-containing nanoparticles, including ZnONPs, is expanding in the agricultural sector. The accumulation of these particles in soil and water can result in environmental contamination and detrimental effects on ecosystems (Song & Kim, 2020).

Silica nanoparticles

Silicon (Si) is actually the second most abundant element found in soil. It plays a crucial role in helping plants grow and protects them from various environmental changes. Interestingly, while silicon is important, it’s not classified as an essential element. Recent research has revealed that treating plants with silicon can significantly reduce stress caused by salt, drought, chilling, and freezing conditions (Almutairi, 2016). The application of silicon (Si) has been shown to enhance various agronomic and quality traits in vegetables. Therefore, using Si is recommended as a strategy to boost vegetable crop production. However, it's important to note that research on the role of Si in vegetable dicots is still significantly behind that of cereals (Kaushik & Saini, 2019). The important role of silicon nanoparticles (SiNPs) in helping plants cope with water shortages and salinity stress can be attributed to the high silicon content in their leaves, which helps manage water loss through transpiration. Additionally, the elevated levels of potassium (K^+) in cucumber roots enable these plants to withstand abiotic stresses by maintaining ion balance, regulating osmotic pressure, and controlling stomatal openings. This combination allows them to better adapt to challenges like salinity and water scarcity (Alsaeedi et al., 2019). SiNPs significantly improved the physiological and biochemical issues caused by Orobanche in tomatoes. They notably reinforced the cell walls of the host roots by boosting lignin production, which serves as a physical barrier against the penetration of tubercle haustoria. Additionally, SiNPs led to a marked reduction in ROS production and enhanced both enzymatic and non-enzymatic detoxification systems, with these effects being more pronounced in the roots compared to the shoots of the infected tomato plants. These organ-specific responses were validated through cluster analysis (Madany et al., 2020).

Nanoparticle influence: exploring growth dynamics in vegetable crops

Tomato

Numerous studies have investigated nanoparticles' impact on tomato seeds' germination. Many research studies have investigated the effects of diverse nanoparticles on tomato plants. As an illustration, one study demonstrated that silver nanoparticles (AgNPs) have a beneficial effect on the growth and biochemical activity of tomato seedlings, leading to elevated levels of chlorophyll, roots, and shoots (Wang et al., 2012). An additional investigation revealed that titanium dioxide nanoparticles (TiO_2NPs) had a beneficial effect on the growth and productivity of tomato plants, as well as on the weight and dimensions of the mature produce (Wang et al., 2012). Conversely, certain studies have documented the adverse effects that nanoparticles can have on tomato plants. This can be seen in the findings of Elmer & White (2016), who observed that nickel oxide nanoparticles (NiONPs) induced a decline in the growth of roots and shoots of tomato plants and impeded seed germination. ZnONPs were observed to have a detrimental impact on the growth and productivity of tomato plants. This effect may be attributed to generating reactive oxygen species and introducing oxidative stress. The AgNPs significantly increased tomato seedlings' biomass, root length, stem length, and germination rate (Tymoszuk, 2021). Tomato seedling growth was enhanced by the administration of TiO_2 NPs (Parveen et al., 2022). It was discovered that the application of CuONPs and ZnONPs inhibited tomato germination and growth rate (Mao-Hong et al., 2021; Wang et al., 2012). Hernández-Hernández et al. (2019) found that using 10 mg L^{-1} of selenium nanoparticles (Se NPs) can boost tomato yield by as much as 21%. They observed that both selenium and copper nanoparticles (Cu NPs) enhanced the levels of chlorophyll, vitamin C, glutathione, and several important enzymes like superoxide dismutase (SOD), glutathione peroxidase (GPX), and phenylalanine ammonia lyase (PAL) in the leaves. When it comes to the fruits, these nanoparticles also increased vitamin C, glutathione, flavonoids, firmness, total soluble solids, and titratable acidity. While the combination of Se and Cu NPs at the right concentrations shows promise for improving both the yield and quality of tomatoes. Ahmed et al. (2023) found that applying 100 ppm of ZnO-NPs to the leaves yielded the best results in terms of growth, physiological traits, yield attributes, overall yield, and quality of tomatoes. This same treatment also led to the highest nutrient uptake. Interestingly, the recovery efficiency of zinc was greatest with a foliar application of 75 ppm ZnO-NPs. The most significant yield increased over the control came from the plants treated with 100 ppm ZnO-NPs. When comparing the two varieties, MARDI Tomato-3 (MT3) outperformed MARDI Tomato-1 (MT1). These findings suggest that using zinc oxide nanoparticles for foliar application is more effective than traditional zinc fertilizers.

Brinjal

Numerous studies have examined the impact of nanoparticles on the growth and development of brinjal. The AgNPs significantly enhanced the germination rate, root length, and biomass of brinjal seedlings (Tumpa et al., 2017). According to a separate study, zinc oxide nanoparticles improved the growth and yield of brinjal plants by increasing their zinc intake. A study by Baskar et al. (2018) observed some significant changes in the secondary metabolites, including anthocyanins, total phenolic, and total flavonoid contents in the plants treated with nanoparticles (NP). There was a noticeable increase in the generation of reactive oxygen species (ROS) in these NP-treated plants, which we confirmed through histochemical staining using 4-nitro blue tetrazolium chloride (NBT) and 3,3′-diaminobenzidine (DAB). The DNA damage seen in the eggplant seedlings exposed to NP could be linked to the heightened levels of ROS and malondialdehyde (MDA) production. Interestingly, our study found that NiO nanoparticles were more toxic compared to CuO and ZnO nanoparticles. Beyond their toxic effects, these nanoparticles also had a significant impact on the production of vital secondary metabolites like phenolics and flavonoid compounds. The application of TiO_2 NPs was found to impede the growth and productivity of brinjal plants due to the generation of reactive oxygen species and the induction of oxidative stress (Thunugunta et al., 2018). Anwar et al. (2023) discovered that the growth of Brinjal, particularly when faced with salt stress, is positively influenced by nanoparticles and melatonin treatment. This growth is linked to increased levels of photosynthetic pigments, total soluble sugars, total soluble proteins, and free amino acids. Thus, the study concludes that applying exogenous melatonin alongside Zinc oxide nanoparticles can significantly boost plants' resilience to salt stress. Ahmed et al. (2023) found that applying ZnOPs significantly boosted the growth of brinjal plants even when they were under the stress of NaF. The increased levels of chlorophyll a, chlorophyll b, total chlorophyll content, and carotenoids helped to mitigate the harmful effects of NaF. Notably, a concentration of ZnOPs at 500ppm led to greater biomass production during both the vegetative and reproductive stages.

Bhendi

Limited research has been conducted on the effect of nanoparticles on the germination of bhendi (okra) seeds. Conversely, a study by Tumpa et al. (2017) revealed that bhendi seedlings exposed to silver nanoparticles (AgNPs) exhibited significantly enhanced germination rate, root length, stalk length, and biomass. The ZnONPs inhibited the germination rate of bhendi seeds and promoted the growth of seedlings (Nagarajan et al., 2020).

Lettuce

Numerous studies have examined the effect of nanoparticles on the germination of lettuce seeds. The AgNPs significantly increased the germination rate, root length, branch length, and biomass of lettuce seedlings (Tymoszuk, 2021; Hasan et al., 2021). Zinc oxide nanoparticles enhanced lettuce seeds' germination rate and seedling growth (Pelegrino et al., 2020). It was discovered that lettuce seed germination was inhibited by exposure to TiO_2 NPs and CuONPs (Pelegrino et al., 2020; Lima et al., 2023).

Carrot

The comprehensive investigation of the influence of nanoparticles on carrot seed germination remains limited. The application of TiO_2 NPs and ZnONPs significantly increased the germination rate and root length of carrot seedlings (Elizabath et al., 2019; Wang et al., 2012). Carrot seed germination was observed to be inhibited by AgNPs and CuONPs (Margenot et al., 2018; Sharma et al., 2021).

Radish

Numerous studies have investigated the effect of nanoparticles on radish seed germination. Several research studies have demonstrated that specific varieties of nanoparticles, including silver nanoparticles, may inhibit the growth and germination of radish plants. Additional research has demonstrated that nanoparticles have the potential to promote germination and enhance the development of radish plants. It is critical to acknowledge that the effect of nanoparticles on radish germination can be contingent upon several variables, such as the specific nanoparticle type, the concentration of nanoparticles, and the exposure duration. Zuverza-Mena et al. (2016) found that seedlings treated Ag nano-particle significantly lower levels of calcium, magnesium, boron, copper, manganese, and zinc. The infrared spectroscopy analysis revealed alterations in the bands associated with lipids, proteins, and the structural components of plant cells, including lignin, pectin, and cellulose. These findings indicate that nanoparticles of silver (nAg) could have a notable impact on the growth, nutrient composition, and macromolecular structure in radish sprouts. Application of Fe_3O_4, FeO(OH), α-Fe_2O_3, β-Fe_2O_3, γ-Fe_3O_4, and nZVI nanoparticles (NPs) (Shakoor et al., 2022) increased the zinc, vitamin C, crude protein, essential amino acids (phenylalanine, leucine and isoleucine) contents.

Cauliflower

It has been discovered that Ag NPs at modest concentrations (up to 10 ppm) promote root and plant growth, thereby enhancing the germination of cauliflower seeds. The AgNPs may harm seedlings at higher concentrations (Singh et al., 2017). It has also been demonstrated that higher concentrations (up to 1000 ppm) of zinc oxide nanoparticles promote the germination of cauliflower seeds, resulting in the development of lengthier shoots and roots (Singh et al., 2013). Research has demonstrated that TiO_2NPs can influence the germination of cauliflower seeds in both positive and negative ways, contingent upon the dosage and duration of exposure. Research has demonstrated that prolonged exposure periods and higher doses inhibit germination, whereas brief exposure times and low concentrations (up to 50 ppm) can promote germination (Kang & Lee, 2020). Tang et al. (2015) reported that introducing silver nanoparticles at moderate concentrations (10 ppm) benefited the germination and growth of cauliflower. Applying zinc oxide nanoparticles at modest concentrations (50 ppm) positively impacted cauliflower germination and development.

Leafy vegetables

Titanium dioxide nanoparticles, when applied at modest concentrations of 10 ppm, were found to positively influence the germination and development of lettuce (Sigamoney et al., 2016). The Low concentrations (50 ppm) of zinc oxide nanoparticles applied to spinach also promoted its germination and development (Xiong et al., 2021). Low concentrations (10 ppm) of silver nanoparticles positively influenced the germination and growth of amaranthus (Sharifan et al., 2020). An additional investigation conducted by Rekha et al. (2019) discovered that using copper oxide nanoparticles at minimal concentrations (50 ppm) positively influenced the germination and growth of amaranthus.

Broccoli

Low concentrations (10 ppm) of silver nanoparticles positively influenced broccoli's germination and growth (Al-Shammari & Abbas, 2023). Kapur et al. (2017) found that the germination and growth of broccoli were positively influenced by the application of silicon dioxide nanoparticles at modest concentrations (50 ppm).

Conclusion

Numerous studies were reported on the effect of different nanoparticles on the growth and development of various plant species, including broccoli, cauliflower, lettuce and amaranthus. Based on the results obtained from those studies, applying specific nanoparticles in minute quantities might facilitate the germination and growth of stated plants. It is imperative to bear in mind that the utilization of nanoparticles in agricultural practices is still developing, necessitating additional research to fully grasp the benefits and drawbacks associated with their implementation on plant growth and development. Additionally, environmental and public health safety must be maintained when nanoparticles are utilized in agriculture. It is vital to remember that numerous factors, including the type of plant, the quantity and nature of the particles, and the duration of exposure, can influence how nanoparticles affect plant growth and development.

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AG drafted the manuscript and completed the necessary revisions. Corrections to the manuscript were made by KRK, IAP, ARK, and TV; SS was responsible for the framework, revision, and overall supervision.

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Ethics approval

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