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Review Article

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Enhancing Crop Productivity and Sustainability: Unleashing the Potential of Nanotechnology in Seed Treatment

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Abstract

The field of nanotechnology has emerged as a transformative one with enormous potential in many sectors, including agriculture. The purpose of this review paper is to explore the application of nanotechnology to seed treatment and its role in increasing crop productivity, as well as in promoting the sustainability of agricultural practices. Various types of nanomaterials are employed in seed treatments, and their mechanisms of action, and their effects on plant growth and development are described in the paper. Furthermore, it discusses the positive impacts of nanotechnology-based seed treatments on plant growth, nutrient uptake, pest, and pathogen resistance, as well as overall crop yield. Additionally, the paper addresses sustainability issues related to nanotechnology, such as reducing chemical usage, maximizing resource utilization, and reducing environmental harm. In the paper, the potential challenges associated with nanotechnology applications are explored, including safety concerns and regulatory frameworks, as well as future research directions and integrating nanotechnology into agriculture. Reviewing the advancements in nanotechnology for seed treatment, this study underscores how it can contribute to global food security and environmental preservation by improving crop productivity and sustainability.

Keywords

Nanotechnology, Seed treatment, Crop productivity, Sustainability, Nanomaterials, Mechanisms of action, Plant growth, Nutrient uptake, Pest protection, Environmental impact

Introduction

Seed treatment plays a role in agriculture by establishing and nurturing crops. This process involves applying chemicals to seeds to enhance germination, protect plants from pests and diseases and promote plant health [1]. With the world's growing population, meeting the demand for food production is increasingly important. To achieve this while minimizing impact sustainable practices are necessary [2, 3]. One potential transformative approach in agriculture is the application of nanotechnology including gene therapy. Nanotechnology involves manipulating and engineering materials at the nanoscale typically ranging from 1 to 100 nm [4]. These materials possess properties and behaviors that make them well-suited for a range of applications, on this scale shown in figure 1. By incorporating nanotechnology into seed treatment methods, we can significantly improve crop yield and sustainability. Applying nanomaterials with properties as seed treatments can enhance plant growth and seed performance by influencing absorption and fortifying plant defense mechanisms.

At times researchers have been investigating types of nanomaterials that can be used to treat seeds. For example, metallic nanoparticles (NPs), like silver

Figure 1: Use of nanotechnology in agriculture.

(Ag), gold (Au), and copper (Cu) possess properties that help safeguard seeds against microorganisms. On the hand carbon-based nanomaterials, like graphene and carbon nanotubes possess mechanical and electrical characteristics that boost the growth and vitality of seedlings while also allowing for the controlled release of beneficial substances. Using metal oxide NPs, like zinc oxide (ZnO) and titanium dioxide (TiO_2) has the potential to enhance availability and improve plant resilience against stresses. Lipid-based nanomaterials, such as liposomes and solid lipid nanoparticles (SLNs) offer a method for delivering agrochemicals [5-10].

Nanotechnology has the potential to not boost crop productivity but also contribute to the sustainability of practices. Using nanotechnology-based seed treatments, we can reduce the need for chemical inputs, which in turn improves soil health and minimizes contamination. Additionally, by delivering nutrients and plant protectants we can significantly cut down on resource waste like water and fertilizer [11]. By combining precision agriculture methods with nanotechnology, we can achieve resource usage. Lessen our impact on the environment, through targeted and controlled application techniques.

Implementing nanotechnology as a seed treatment method comes with challenges despite its advantages. We must be cautious about nanomaterials that can be toxic and have long-term impacts on the environment and human wellbeing. It is crucial to assess these concerns. Additionally for reliable outcomes, it is important to establish regulations for the use of nanotechnology in agriculture. Responsible utilization of nanotechnology in seed treatment can be achieved through collaboration, among researchers, industry experts and regulatory agencies.

In this paper we delve into the world of nanotechnology and its application, in seed treatment. Our aim is to explore how nanomaterials can positively impact plant growth and development, ultimately increasing crop productivity and ensuring sustainability. Additionally, we will focus on the challenges and prospects of employing nanotechnology-based seed treatments in agriculture. By utilizing nanotechnology to revolutionize seed treatment practices this review paper underscores the importance of this field in addressing food security and protecting our environment.

Nanomaterials for Seed Treatment

Nanomaterials have unique properties and capabilities that make them a great option for seed treatments. In this part, we'll give you an overview of the types of nanomaterials in figure 2 frequently employed in seed treatments and their specific roles.

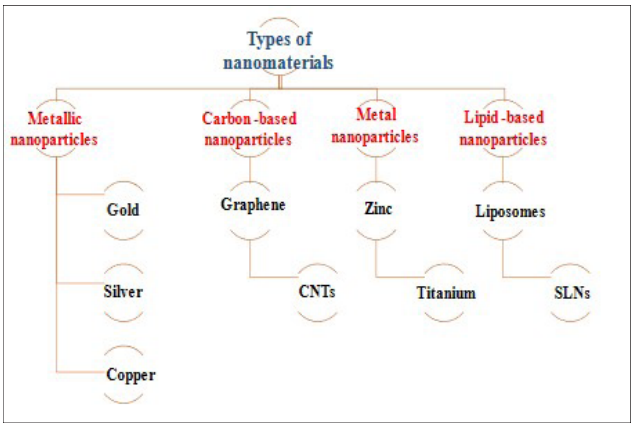

Figure 2: Types of nanomaterials used in agriculture sector.

Metallic NPs

The use of metallic NPs in seed treatment applications has received attention due to their ability to combat antimicrobial properties, particularly Ag, Au, and Cu. Unlike traditional NPs, these NPs particles have a high surface-to-volume ratio making them more reactive and effective against microbes found in seeds. Regarding seeds, Ag NPs have been shown to effectively suppress bacterial infections. Furthermore, Au NPs offer defense against pathogenic fungi because of their antifungal properties. owing to their ability to fight against fungal infections. Employing Cu NPs has proven successful in combating bacterial pathogens in seeds due to their strong antibacterial properties [12]. Figure 3 shows the use of metallic NPs in agriculture.

Ag NPs

Ag NPs possess antimicrobial characteristics and exhibit the potential to reduce the adverse impact of pathogens like *Gibberella fujicuroi* on rice seeds [12, 13] lengthen the lifespan of gerbera cut flowers [14] promote the growth and development of *in vitro*-cultivated potatoes [15], enhance the growth and antioxidant state of *Brassica juncea* L. seedlings [16], and markedly improve biomass in *Brassica rapa* L. under *in vitro* conditions [17]. Ag NPs toxicity is dependent on variables including size, shape, surface coating, duration of exposure, plant species, and growth stage. It is still uncertain whether the toxicity results directly from the NPs or Ag ions alone. The particle nature of Ag NPs is the primary contributor to plant toxicity. Ag NPs' toxicity in living cells is attributed to the release of high levels of Ag ions, according to the Trojan Horse phenomenon [18]. Increasing understanding of Ag

Figure 3: Metallic NPs in agriculture.

uptake and its relationship with toxicity is necessary for a comprehensive assessment of Ag NPs impact on plant health [19].

The accessible knowledge shows that a fixed number of studies have investigated the impact of Ag NPs. Plant species, particle size, and application pace impact the seen consequences, which might be advantageous, impartial, or detrimental. A recent study found that ten-sided Ag NPs showed exceptional potential for enhancing root growth in *Arabidopsis* seedlings, contrasting with the lack of noticeable RGP by spherical Ag NPs, which however resulted in the highest anthocyanin accumulation. The Cu/Zn superoxide dismutase yields from circular and decahedral Ag NPs were the highest and lowest, respectively. The study indicates that Ag NPs act as inhibitors of ethylene sensing, which may disrupt ethylene production in *Arabidopsis* plants. Furthermore, different-sized, and shaped Ag NPs influenced protein concentrations and gene expression connected to cellular activities. As Rezvani and Sorooshzadeh [20] demonstrated, Ag NPs fostered root growth in *Crocus sativus* by limiting ethylene action. Research conducted reported an increase in root length in barley but limited in lettuce. In addition, the effects of Ag NPs on the growth of 11 aquatic plant species (*Lolium multiflorum*, *Panicum virgatum*, *Carex lurida*, *C. scoparia*, *C. vulpinoidea*, *C. crinita*, *Eupatorium fistulosum*, *Phytolacca*, *Scirpus cyperinus*, *Lobelia cardinalis*, and *Juncus effusus*), they discovered that just one animal category (E.) had a higher germination rate after exposure to Ag NPs. *Allium fistulosum* agro-industrial waste materials were employed by Acharya et al. [21]. Nano Ag application during seed treatment significantly improves seedling vigor, crop growth, and fruit quality. Spagnoletti et al. [22] successfully produced stable Ag NPs utilizing a budget-friendly, environmentally benign approach that exploits the exudate of *Macrophoma phaseolina* fungus, soybean seed germination was analyzed in response to varying Ag NPs doses to evaluate its potential as a seed safeguard. Acharya et al. [21] found that onion extract could be employed to nano Ag seeds internalization. Field and laboratory studies have confirmed that this technique leads to notable enhancements in seedling emergence, growth, and produce. Kannaujia et al. [23] research has uncovered the possibility of using biologically generated nano Ag as a wheat growth accelerator, without the adverse consequences generally connected to chemically manufactured nano Ag. Research by Mahakham et al. [24] showed that Ag NPs infiltrated seed coats, leading to enhanced water absorption and heightened expression of genes involved in water uptake.

Au NPs

The versatility of Au NPs is attributed to their size and shape, allowing them to be utilized in various fields, such as antimicrobial agents, biosensors, antioxidants, anticancer agents, and pest control. Increasing focus has been directed toward investigating the influence of Au NPs on seed sprouting, vegetation development, and genetic expression [25].

Research on Au NPs for plant productivity is scarce. Numerous researchers globally have discovered favorable results. Au NPs have been found to stimulate seed germination in cucumber, *Boswellia ovalifoliolata*, and *Gloriosa supernova*. We also identified that Au NPs improvement of *Arabidopsis* seed germination and antioxidant system, along with changes in miRNA expression levels, which govern multiple plant traits. While previous studies indicated Au NPs' beneficial effects on aquaporins, Shah et al. [26] found that these particles have adverse consequences on their functionality. Thorough investigations into the impact of Au NPs on plant physiology are crucial to fully understand their benefits. Mahakham et al. [24] examined the capacity of nano Au to improve seedling emergence and growth in aged maize seeds. Investigations disclosed that nano priming can lower Au migration from seeds into plant organisms. Another investigation demonstrated the potential of Au NPs to improve the growth and seed production of *B. juncea*. Gopinath et al. [27] investigated the effect of Au NPs created from fruit extracts of *Terminalia arjuna* on *Gloriosa superba* seed germination in 2014. The study showed that nano Au significantly affected the seed sprouting and plant growth of *G. superba*. Additionally, a research study conducted Ndeh et al. [28]. Research revealed that Au NPs manufactured using *Tiliacora triandra* boost seed vitality and exhibit biological compatibility.

Cu NPs

Nanoscale Cu particles are utilized in farming to minimize ecologically harmful substances and boost crop yields. Scarce data exists regarding the effects of Cu-based nanomaterials on plant development [29]. Cu NPs exposure to rice seedlings causes modifications in the ascorbate-glutathione cycle, which can result in cellular damage, excessive ROS (reactive oxygen species) and H_2O_2 concentrations, and higher proline levels [30]. Four times more of the CuO (Copper oxide) NPs accumulated inside duckweed plants upon polymer coating. Furthermore, ROS production in plants was augmented, and the NPs' polymer coating influenced cellular processes at the plant level according to Perreault et al. [31]. Nair and Chung [32] discovered that the exposure to CuO NPs caused heightened ROS production in chickpeas. Zuverza-Mena et al. [33] discovered that CuO NPs significantly increased biomass output in cilantro. CuO NPs application in aquatic macrophyte *Elodea nuttallii* did not cause any detrimental impacts as observed by Regier et al. [34]. Wang et al. [35] investigated the impact of CuO NPs on gene expression and ROS activity (notable increase) in the roots of rice seedlings. Zhao et al. [36] utilized H-NMR and GC-MS to examine the metabolic profile of cucumber (*Cucumis sativus*). CuO NPs exposure led to a substantial boost in cucumber's metabolite deposition. CuO NPs exposure affected the fruit's metabolism. GC-MS analysis revealed notable increases in sugar, organic acid, amino acid, and lipid concentrations in plants exposed to CuO NPs compared to the control. Previous studies have demonstrated that applying 0.02 mg of Cu NPs per liter of Hoagland solution results in optimal crop growth and yield. Researchers globally have discovered harmful consequences of utilizing Cu NPs when employed at elevated concentrations beyond recommended limits. Studies showed that seedlings of mung bean, wheat, and yellow squash were negatively influenced by Cu NPs application at these rates. Ninety percent less zucchini biomass was observed following the application of metallic Cu NPs at 1000 mg/L after the seedlings had been incubated in Hoagland solution for 14 days, relative to the control (without Cu). Research has shown that the growth rate of lettuce seeds can be significantly improved using Cu NPs. Studies by Shah and Belozerova [37], a 35% rise in waterweed's photosynthetic rate was observed in a 3-day incubation experiment utilizing low concentrations of Cu NPs, with application levels ≤ 0.25 mg requiring approximately 0.01 mg Mo/L soil solution. Taran et al. [38] investigated the effectiveness of different combinations of N-fixing bacteria and Mo NPs through an experimental process. The control was administered distilled water. The study displayed that mixing microbes and Mo NPs dramatically increased the beneficial microbes in the rhizosphere. Combining these elements noticeably enhanced the root number, nodule count per plant, and nodule weight per plant when compared to the control.

Carbon-based nanomaterials

CNTs (carbon nanotubes) and graphene-related materials exhibit thermal and electrical properties that are highly suitable for seed treatment applications. By leveraging their surface areas and high aspect ratios CNTs enable control over the release of plant growth regulators and pesticides. Improved seedling vigor is the outcome and accelerated plant establishment. Graphene-based nanomaterials on the hand possess adsorption capabilities that facilitate the efficient delivery of bioactive substances to seeds.

CNTs' impressive attributes have attracted significant attention. The efficacy of CNTs in plant nutrition is currently unconfirmed. Several studies have demonstrated the advantageous effects of multi-walled CNTs (MWCNTs) on seed germination and plant growth. The proposed mechanism involves the induction of water channel proteins due to the surface charges of CNTs, leading to improved water and nutrient absorption efficiency, ultimately benefiting seed germination and plant growth and development [39]. Research has revealed that single-walled CNTs (SWCNTs) embedded in chloroplasts can significantly enhance photosynthesis and enable plants to detect nitric oxide. Nanotech-based plant modification could result in groundbreaking photo-functionalities. Although comprehensive investigation is necessary to fully understand the effects of CNTs on final products like sugars and glucose during photosynthesis [40, 41]. Findings suggest that MWCNTs can significantly enhance seed germination in these three crop species. MWCNTs were discovered to enhance tomato growth through improved water uptake and therapeutic potential. Scientists have found that water-soluble CNTs within wheat plants contribute to improved root and shoot development under diverse lighting situations. Some researchers have documented negative effects of CNTs at higher concentrations. Khodakovskaya et al. [42] conducted a study which demonstrated that CNTs possess the ability to penetrate the thick seed coat of tomato plants, thereby facilitating water uptake and resulting in faster germination and higher biomass production. The researchers postulated that the positive impact of MWCNTs on seed germination was due to their capacity to penetrate the seed coat and promote water uptake. Water uptake is a crucial factor in seed germination, as mature seeds are relatively dry and require a substantial amount of water to initiate cellular metabolism and growth. The hypothesis was supported by the measured water moisture content of seeds and the detection of CNTs within the seeds [43]. However, the specific mechanisms of penetration through the seed coat and the enhancement of water uptake by CNTs were not reported. Zinjarde [44] investigated the effects of both SWCNTs and MWCNTs on the germination of rice seeds and observed that carbon nanotubes increased seed germination. Yugandhar and Savithramma [45] observed that carbon-based NPs accelerated seed germination and seedling growth, resulting in the highest germination rate (92%), seedling vigor index (892), root length (2.3 cm), shoot length (7.4 cm), and seedling dry weight (212 mg) compared to the control. The study reported that MWCNTs were able to penetrate the seed coat by creating new pores, thereby enhancing water uptake, and significantly increasing seed germination, plant growth, and biomass compared to the control in wheat, maize, peanut, and garlic [46]. Cañas et al. [47] reported that SWCNTs had a significant impact on root elongation in tomato, cabbage, carrot, and lettuce, while promoting the growth of onion and cucumber within 24 to 48 h. Among the six species tested, tomato exhibited the highest degree of sensitivity to SWCNTs. While NPs such as fullerene, CNTs, and metal oxides can cause toxicity, MWCNTs have been found to positively affect the germination and seedling growth of *B. juncea* and *Phaseolus mungo* [48].

Metal oxide NPs

Metal oxide NPs, like ZnO and TiO_2, have gained popularity in seed treatment due to their properties. ZnO NPs possess the ability to effectively safeguard seeds against bacterial and fungal infections due to their antimicrobial properties. Additionally, they aid in the absorption of phosphorus by plants by making it soluble [49, 50].

ZnO NPs

Numerous researchers across the globe have directed their attention toward investigating the impact of ZnO NPs on crop growth and productivity. Notably, among all micronutrients, it is the most extensively researched in the field of plant science on a global scale [51-53]. This versatile micronutrient has been the subject of extensive research in the field of plant science, and its benefits are undeniable [54]. From mung beans to cucumbers, radishes to ryegrass, the positive effects of ZnO NPs on growth and yield parameters have been consistently observed. However, it is important to note that the optimal concentration of ZnO NPs varies depending on the crop, and higher doses may hinder growth rates. Nevertheless, the potential of ZnO NPs to improve seed germination, plant biomass, and protein synthesis cannot be ignored. As we continue to explore the wonders of micronutrients, ZnO NPs remain a crucial player in the world of plant science. The optimal concentration of ZnO NPs required for application varies depending on the crop. For instance, the application of 20 mg/L ZnO NPs to mung bean plants resulted in a significant increase in root length, root biomass, shoot length, and shoot biomass. However, higher doses of ZnO NPs caused a decrease in growth rates. Similarly, the application of ZnO NPs at the rate of 400 and 800 mg/kg caused a significant increase in the growth and yield parameters of cucumber. However, the same rates caused only a slight increase in dry fruit weight. In other experiments, the application of ZnO NPs at lower concentrations improved seed germination and growth parameters in crops such as peanuts, soybean, wheat, pearl millet, tomato, and onion [55]. Furthermore, the application of ZnO NPs has been observed to improve plant biomass, shoot, and root growth, root area, chlorophyll, and protein synthesis in *Cyamopsis tetragonoloba* [56]. These findings suggest that ZnO NPs have a positive impact on the growth and productivity of various crops. The researchers made a remarkable discovery - the application of 2 mg/L metallic Zn NPs led to a significant improvement in the growth parameters of ryegrass (*Lolium perenne*). But that's not all, the team also found that lower concentrations of ZnO NPs had a positive impact on seed germination in peanuts, soybean, wheat, pearl millet, tomato, and onion. In yet another experiment, the team observed a significant improvement in the plant biomass, shoot and root growth, root area, chlorophyll, and protein synthesis of *Cyamopsis tetragonoloba* [33]. These findings are truly groundbreaking and could pave the way for a new era of agricultural practices. The groundbreaking research conducted by Mukherjee [57] has shed light on the impact of alumina doped ZnO NPs treatments on green peas. Their findings have revealed that these treatments have a more detrimental effect on the growth and development of green peas when compared to bare and coated ZnO NPs. In fact, a higher dose of the alumina doped ZnO NPs (100 mg/kg) has been shown to impair the seed germination of green peas. However, the coated ZnO NPs have been found to increase the biomass in green peas, as reported by Mukherjee [57]. Similarly, the work of Hashemi et al. [58] on soybean using ZnO NPs (0.0, 0.2, and 0.4 ppm) has demonstrated positive effects on seed germination, root and shoot growth. These results suggest that bioengineered ZnO NPs interact with meristem cells, triggering biochemical pathways that are conducive to an accumulation of biomass, as reported by Venkatachalam et al. [59]. In contrast, Liu et al. [60] examined the effects of CuO, ZnO, MnO_2, and Fe_3O_4 NPs on lettuce (*Lactuca sativa*). Their findings have revealed that in low concentrations, these NPs have a positive impact on the growth and development of lettuce. However, higher concentrations of these NPs have been shown to have negative effects. These findings highlight the importance of understanding the dosage and concentration of NPs to maximize their benefits while minimizing their negative impacts [61].

Lipid-based nanomaterials

Lipid-based nanomaterials, like liposomes and SLNs, play a role in delivering ingredients to seeds during treatment. Liposomes, which are made up of lipid bilayers can encapsulate both hydrophobic and hydrophilic substances. By protecting the encapsulated compounds, they ensure stability and controlled release, making them more effective in seed treatment [62, 63]. On the hand SLNs, being lipid-based NPs offer improved bioavailability and efficacy due to their extended release and enhanced ability to penetrate seeds. Not only do these nanomaterials improve the protection of seeds, deliver due nutrients and release of compounds but they also offer a versatile platform, for seed treatment purposes. Along with promoting the establishment of seedlings enhancing absorption and increasing resistance to stresses their distinct properties and functionalities ensure precise control over the release and availability of active ingredients. When selecting seed treatment nanomaterials, it is crucial to consider their compatibility with seeds, environmental safety aspects and cost-effectiveness. Additionally optimizing dosage and application methods is essential to minimize any impact while achieving desired outcomes. Advancements in research and development in this field will contribute to the exploration of nanomaterials well as the improvement of existing ones. This will expand the applications of nanotechnology in seed treatment [63].

The unique antibacterial and anti-oxidative properties of lignin NPs are attributed to their surface chemistry and shape. Kacsó et al. [64] conducted a study in which zein and lignin-based NPs were utilized to treat soybean seeds. The application of azoxystrobin-loaded lignin NPs as a seed treatment resulted in nearly complete antifungal protection against *Rhizoctonia solani* in soybean. These findings suggest that nano zein and lignin can serve as safe and effective delivery systems for active compounds in seed treatments. Falsini et al. [65] synthesized lignin nano-capsules, which were employed as potential vectors for delivering bioactive compounds to tomato and miller seeds. The results indicated that lignin nano-capsules enhanced the growth and development of tomato and miller seeds. Further studies are required to elucidate the precise mechanisms responsible for the differential effects of nano-lignin on seeds.

Mechanisms of Action

Various mechanisms play a role, enhancing the growth, development, and defense mechanisms of plants through nanotechnology-based seed treatments shown in figure 4. The utilization of nanomaterials in seed treatment has led to the observation of the following modes of action.

Penetration and delivery of active ingredients

Nanotechnology-based seed treatment works by

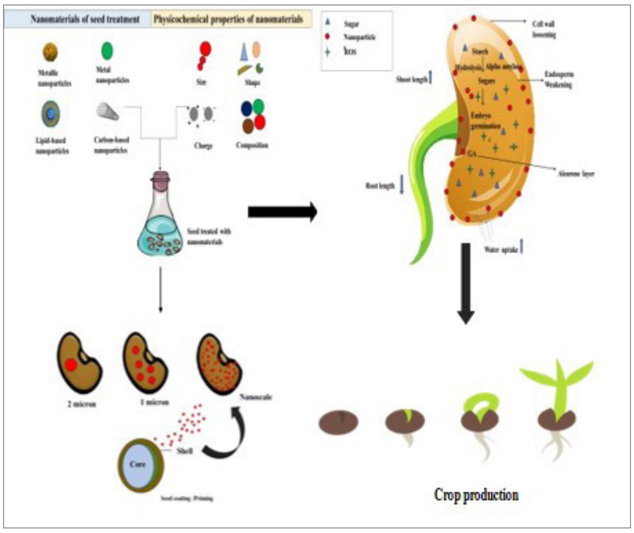

Figure 4: Mechanism of action of NPs in seed germination.

penetrating and transporting ingredients into the inner tissue of the seed. Nanomaterials have properties that enable them to interact with and enter the seed coat ensuring that encapsulated or bound bioactive compounds are distributed precisely. Because nanomaterials are incredibly small in the nanometer range, they can easily navigate through micropores, cracks, or natural gaps in the seed coat [66]. Their small size allows them to overcome obstacles effortlessly and reach the tissues of the seed effectively. Furthermore, NPs have a high surface area to volume ratio, which maximizes their contact with the seed surface and facilitates interaction and absorption [67]. Researchers can improve inter interaction seen nanomaterials and the seed coat by modifying their surfaces. By adding groups to NPs surfaces scientists can alter their charge, hydrophobicity, or chemical properties to enhance adhesion to the seed surface. These modifications extend the time that nanomaterials remain on the seed surface ultimately promoting their penetration and enhancing their effectiveness [68].

Delivering bioactive compounds to the inner tissues by penetrating the seed's protective layer, nanotechnology-enhanced seed treatments provide numerous benefits. The benefits entail better seed germination, enhanced nitrogen uptake, and increased seedling vigor. Nanomaterials with controlled release mechanisms help foster plant growth and development through the provision of nutrients or protective substances [69]. Moreover, the focused delivery of active components reduces the overall quantity of chemicals required. This reduction in chemicals not only helps to minimize environmental impact but also increases sustainability. In general, the application of nanomaterials enhances the penetration and diffusion of active ingredients in seed treatment. The promotion of agricultural productivity and sustainability is enhanced by this increase in effectiveness [70]. Nanotechnology offers exciting options to optimize seed treatment formulations and improve sustainable agriculture. The exploitation of nanoparticles involves leveraging their special attributes, such as their small scale, surface customization, and precise release mechanisms.

Enhancement of nutrient uptake

The utilization of nanotechnology-based seed treatments has demonstrated an increase in nutrient assimilation by plants. This results in increased nutrient availability and plant nutrition. The following mechanisms contribute to the increased nutrient uptake seen in seed treatments based on nanotechnology. Nanomaterials can alter the physicochemical characteristics of nutrients, enhancing their solubility and bioavailability in soil or growing media. For instance, micronutrients or fertilizers can be transported by NPs [71-73]. The developing seedling benefits from a regulated supply of nutrients thanks to this. Maximizing plant root uptake is achieved through a controlled release of nutrients, ensuring availability when and where needed. Nanomaterials can interact with the rhizosphere, or the soil around the root zone, altering its physicochemical properties. The result may be a surge in nutrient intake. Efficient nutrient uptake by plant roots can be promoted through nanomaterial influence. Modifying soil pH, cation exchange capacity, or water-holding capacity allows them to achieve this. Improving soil structure can also enhance root penetration and surface area for nutrient absorption. Nutrient transport within plants can be enhanced with NPs. Enhanced nutrient transportation occurs across cell membranes and tissues. The small size and distinct surface features of NPs enable them to interact with cellular structures. This interaction boosts nutrition intake by increasing cell membrane permeability. This improved transport enables effective nutrient transfer from roots to shoots. The availability of nutrients is ensured for multiple physiological functions. Nanomaterials can stimulate specific nutrient uptake pathways in plants. More efficient absorption and utilization of nutrients is achieved through this stimulation [74]. As an illustration, NPs can activate nutrient transporters in root cells. Potassium, phosphorus, and nitrogen uptake are improved, which are vital elements. Nanomaterials can influence the expression of genes associated with nutrient absorption and assimilation, further enhancing nutrient utilization efficiency. Nanotechnology-based seed treatments promote nutrient uptake, contributing to increased crop yield, nutrition, and growth [70, 75, 76].

Induction of plant defense mechanisms

Plant defense mechanisms can be activated by seed treatments utilizing nanotechnology. By fortifying the plant's resistance to biotic stresses like pest infestations and pathogen attacks, positive effects can be observed. Seed treatments employing nanotechnology aid in the induction of plant defense systems. The plant's innate immune system can be activated by NPs. When activated, defense mechanisms against pathogens and pests are triggered. Plants may interpret NPs as possible dangers or stress signals. The active state of signaling pathways linked to defense would be induced. Creating defense-related substances is part of the activation mechanism that supports plant defence. The substances comprise phytochemicals, antioxidants, and antimicrobial peptides. Systemic acquired resistance (SAR) can be developed by plants in reaction to nanomaterials. SAR occurs as a defensive response in both the infection site and other parts of the plant. By priming the plant's defence mechanisms, NPs can trigger SAR and help the plant react more quickly and successfully to future pathogen or pest attacks. The activation of defense-related genes and the buildup of defense chemicals brought on by this priming effect result in improved defense against biotic stressors [77-79].

Using seed treatments based on nanotechnology to induce plant defense mechanisms has various benefits for sustainable agriculture. These treatments help reduce the use of chemical pesticides and encourage environmentally benign pest control methods by triggering the plant's immunological responses, preparing its defense mechanisms, and offering direct or indirect protection against pests and pathogens. Additionally, systems that are activated might increase plant resistance to biotic stressors, resulting in healthier and more productive crops.

Regulation of plant growth and development

The targeted delivery of growth regulators can improve seed germination, root growth, and overall plant health. These growth regulators include auxins, cytokinins, or gibberellins. Nanomaterials can promote developmental processes, resulting in increased plant growth, via modulating hormone levels and signaling. Seed germination rates and early seedling establishment can be enhanced using nanotechnology-based seed treatments. Seedling hydration during germination can be ensured by nanomaterials, which can modify water intake and retention capacity [13]. They can also help seedlings absorb nutrients, which are necessary for growth. Nanomaterials contribute to increased seedling vigor and establishment by boosting these important early-stage activities. In addition to affecting root development and architecture, nanomaterials can also increase nutrient uptake. The interactions of nanomaterials with plant cells and root tissues can facilitate lateral root development and elongation [80, 81]. The ability for plants to absorb nutrients is expanded by this. Seed treatments utilizing nanotechnology can confer tolerance to abiotic factors such as drought and salinity. Plant water status can be regulated by nanomaterials. Increasing water usage efficiency and reducing transpiration can lead to achieving this. They can also improve plant osmotic balance and modulate stomatal behavior, reducing water stress during droughts. Furthermore, nanomaterials can promote the production of antioxidant enzymes. Shielding plants from drought or salinity stress helps prevent oxidative damage. Nanomaterials can influence hormone signaling pathways and physiological processes to regulate plant growth and development. By utilizing NPs functionalized with growth-promoting substances, plant germination, root development, and overall plant vigor can be improved. Additionally, nanomaterials can improve seeding establishment and drought tolerance by modifying water uptake and retention.

Seed treatments that utilize nanotechnology to regulate plant growth and development present opportunities for advancing agricultural performance and production. Nanomaterials improve plant health and productivity by influencing hormone signaling pathways, by promoting seed germination, nanomaterials support early seedling establishment, enhancing root development and nutrient uptake, Abiotic stress tolerance is promoted in plants using nanomaterials, and through promoting flowering, nanomaterials contribute towards yield enhancement [74, 82] Plants can experience numerous beneficial impacts due to them. Higher crop yields may be the outcome, enhanced utilization of resources, leading to greater agricultural sustainability.

Protection against pests, pathogens, and abiotic stresses

Crop resilience and sustainability are improved by nanotechnology-based seed treatments, which provide effective protection against pests, pathogens, and abiotic stresses [67, 70, 83]. Nanotechnology-based seed treatments offer protection through multiple mechanisms. Nanomaterials can operate as physical barriers or have inherent insecticidal characteristics, successfully managing pests and insects. Broad-spectrum antibacterial and insecticidal effects have been demonstrated by NPs, including Ag NPs. Including these NPs in seed treatments can hinder the growth and reproduction of insect populations. Minimizing crop damage caused by pests is aided by this. Using nanotechnology-based seed treatments can help prevent crops from various diseases. The diseases' growth and activity are inhibited by these treatments. Directly targeting pathogenic microorganisms is possible with the antimicrobial property of nanomaterials. By disrupting pathogen cell membranes, interfering with their metabolic processes, or inducing oxidative stress, they suppress pathogen growth. In addition, the activation of the plant's immune response can be improved by nanomaterials, resulting in a heightened ability to combat diseases. Nanomaterials can help mitigate abiotic stresses like drought, salinity, and extreme temperatures [70, 75, 76]. By employing nanomaterials, plants can be safeguarded from ultraviolet (UV) light through filtration or reflection. Plant growth and development can be protected from the negative effects of UV exposure through the absorbing and diffusing properties of TiO_2 NPs. Plant productivity is increased, and UV-induced toxicity is minimized using nanotechnology-based seed treatments. Using nanomaterials can enhance nutrient efficiency and minimize nutrient loss [67, 73].

In addition to providing protection from pests, pathogens, and abiotic stresses, nanotechnology-based seed treatments contribute to sustainable agriculture. This treatment helps minimize environmental impacts and promote long-term crop sustainability by reducing reliance on chemical pesticides. In addition, it helps to avoid disease outbreaks, minimize abiotic stresses, and enhance nutrient efficiency. The outcome of increased crop resilience and protection against various stresses is higher crop yields, quality, and productivity [7, 84-86].

Effects on Crop Productivity

The considerable potential is displayed by nanotechnology in seed treatment to enhance crop yield through improved plant growth and nutrient uptake. Seeds and young seedlings can experience enhanced nutrient delivery efficiency thanks to nanomaterials like NPs. These NPs work as carriers, ensuring that important nutrients reach the plant precisely when they are required, yielding improved efficiency in absorbing and utilizing nutrients. Consistent nutrient supply throughout the plant's growth phases is guaranteed by controlled release from nanomaterials, Creating conditions for better crop productivity through improved health and strength. Increased nutrient availability and utilization result in increased biomass production and, therefore, it results in elevated agricultural productivity [87-89]. Nanotechnology-based seed treatments offer efficient pest and disease protection, A decrease in crop losses is observed. Seeds and seedlings can be safeguarded against soil-borne pathogens using antimicrobial NPs, which leads to decreased infections and enhanced plant establishment. In addition, nanoemulsions comprising of bioactive agents namely plant extracts or essential oils, act as environmentally friendly options to replace synthetic pesticides. By enveloping the seeds in protective barriers, nanoemulsions keep pests and pathogens away without having any negative effect on beneficial species. With its ability to reduce pest influence, nanotechnology contributes to increased crop preservation while minimizing productivity losses.

Yet another advantage of applying nanotechnology in seed treatment is its capability to boost the consistency and resilience of yield even amidst changing environmental factors. Enhancing plant tolerance to abiotic challenges like drought, heat, and salinity can be achieved by utilizing nanomaterial-based seed treatments [66, 90-93]. By increasing soil moisture retention and reducing water stress in plants, nanoparticles offer a promising approach to enhancing drought resistance, increasing their drought resistance. Furthermore, NPs can scavenge ROS and alleviate oxidative stress generated by environmental factors, leading to increased stability of agricultural yields amidst changing circumstances. With climate change and unpredictable weather becoming more prominent, improving yield stability is essential for maintaining a secure and sustainable food supply.

Sustainability Aspects

Recently, the field of nanotechnology has become a potential solution for transforming agriculture, Specifically, its application shows great potential in treating seeds. A key benefit it offers is the capacity to combat the sustainability challenges that conventional agricultural practices face. Allows to examine more closely the ways that utilizing nanotechnology for seed treatment can help foster sustainable farming techniques.

Reducing chemical usage in agriculture

In traditional agriculture, the utilization of chemical pesticides and fertilizers is essential for crop protection against pests and for improving their growth. Sadly, the excessive application of these chemicals can cause environmental contamination, endanger helpful organisms, and even present health dangers for humans. By utilizing nanomaterials, nanotechnology presents an alternative approach to deliver pesticides and nutrients in a targeted and controlled manner. By employing NPs as a means of enclosing and discharging these elements solely when required. The overall chemical usage can be significantly reduced, and reducing harm to both the environment and human health is essential, which calls for minimizing adverse effects [2, 66, 94-96].

Optimizing resource utilization

In various locations, there is an immediate worry about water scarcity which influences the efficiency of agriculture. Furthermore, ineffective application of fertilizers can cause nutrient depletion and deterioration of soil quality. Nanotechnology-based seed treatments can enhance water and nutrient use efficiency in crops [2, 95, 97, 98]. Incorporating NPs can assist in preserving soil moisture, this leads to lower water needs and improved resilience to drought for plants. Additionally, nanotechnology facilitates controlled nutrient release, which guarantees plants obtain optimal nutrients at the required time. This optimized resource utilization not only boosts crop productivity and helps in water conservation leading to reduced wastage of fertilizers.

Minimizing environmental harm and ecological impact

The negative consequences of conventional agricultural practices on the environment and biodiversity have sparked worries. Runoff from chemical pesticides and fertilizers can contaminate water bodies and harm aquatic life. The utilization of nanotechnology enables the creation of environmentally friendly and easily decomposable nanomaterials that can be securely integrated into seed treatments. The purpose of these nanomaterials is to disintegrate into safe constituents, by decreasing the potential for environmental pollution and ensuring ecosystem protection [72, 95].

Addressing concerns about bioaccumulation and long-term effects

If chemicals are applied in farming practices, which can lead to bioaccumulation along the food chain, potentially endangering consumer health Applying nanotechnology has the potential to alleviate these concerns. Seed treatments involving NPs. They can be modified to minimize toxicity and exhibit reduced longevity in the environment. The implication is that their accumulation in plants or transfer to higher trophic levels in the ecosystem is reduced. By ensuring that nanomaterials have minimal long-term effects [99, 100]. Research institutions and farming communities must collaborate to establish sustainable agricultural practices that give priority to consumer safety.

In conclusion, the sustainability aspects of nanotechnology in seed treatment provide a hopeful way to promote environmental friendliness and resource efficiency in agriculture. Through the optimization of chemical usage, optimizing resource utilization, and mitigating environmental damage, nanotechnology is instrumental in developing a sustainable and resilient agricultural system. Moreover, it tackles worries regarding the long-lasting impacts. Through ongoing research and development, scientists are further investigating and enhancing the uses of nanotechnology in agriculture, we edge nearer towards attaining our objectives of food security and preserving the environment. On the other hand, it is imperative to undertake meticulous studies and enforce conscientious strategies to tap into the complete potential of nanotechnology for enhancing agriculture while protecting the environment. It is important to ensure that the use of nanotechnology is done in a responsible and sustainable manner [99-103].

Challenges and Future Directions

Nanotechnology's application in seed treatment and agriculture, while promising, Involves some obstacles and considerations regarding safety. While exploring this area, numerous important concerns require attention to secure the ethical and long-lasting application of nanomaterials in agriculture.

Significant concerns arise regarding the potential toxicity and risks of nanomaterials when used in seed treatment and agriculture. Nevertheless, more investigation is necessary to comprehensively grasp the magnitude of these risks and devise suitable safety protocols. Due to their unique properties and small size, nanomaterials may have different interactions with living organisms than larger particles. This prompts inquiries about their potential danger to plants, beneficial organisms, and humans. To comprehend the behavior of nanomaterials in the agricultural ecosystem and their effects on plant growth, soil microorganisms, and non-target organisms, conducting thorough toxicity studies is crucial. This comprises advantageous bugs and fauna [104-107].

In addition, it is important to research the potential gathering of nanomaterials in crops. An assessment of their consequences on food safety is also warranted. The possibility of nanomaterials entering the food chain and causing health risks to consumers through bioaccumulation raises concerns. Nevertheless, further examination is essential to fully grasp the extent of these risks and formulate adequate safety measures. To maintain consumer health and environmental safety, it is imperative to comprehend the long-term effects and potential risks of NPs as they can endure in the environment [108, 109].

Moreover, introducing nanomaterials into the environment through seed treatments can have unintended consequences on ecological systems. While a few NPs can be broken down by natural processes, others can linger in the environment for a prolonged time. Significant ecological implications could arise from this. The biodiversity of plants and animals can be affected, and natural ecosystems disrupted when nanomaterials are released and accumulate in soil and water. Comprehending these potential ecological impacts is essential for minimizing any adverse effects on the environment and ecological balance [102, 110].

The specific qualities and potential risks of nanomaterials in agriculture may not be adequately covered by current regulations, considering that nanotechnology is a relatively new development. Ensuring the safe and responsible use of nanomaterials in this industry requires proper regulations. Consequently, ensuring the responsible and safe use of nanomaterials requires robust regulatory considerations and policy frameworks. The development of standardized safety assessment protocols and guidelines for risk management and labeling is required from governments and regulatory agencies. Ensuring transparent and effective stakeholder communication, which encompasses researchers, industry professionals, policymakers, and the wider public, are fundamental for formulating regulations that have a real impact. The policy discourse should incorporate ethical aspects like fair technology access and the possible consequences for small-scale farmers. It is crucial to have international collaboration and standardized regulations because of the worldwide scope of agriculture and trade. play a critical role in ensuring efficient agricultural practices and smooth trading operations worldwide. Promoting the transfer of knowledge and establishing standardized safety measures worldwide [15, 43, 67, 70, 108, 109, 111].

In closing, although nanotechnology holds great promise for enhancing crop productivity and sustainability. Addressing potential toxicity, environmental risks, and regulatory challenges ensuring that nanomaterials are utilized in agriculture with utmost safety precautions. By conducting extensive studies, embracing safety precautions, and developing impactful policies, we can utilize the advantages of nanotechnology. This will help safeguard human health, in addition, it also promotes environmental preservation and agricultural sustainability [2, 94, 112].

Conclusion

In conclusion, nanotechnology in seed treatment holds immense potential to revolutionize agriculture Furthermore, it can effectively tackle urgent issues concerning food security and the conservation of our environment. Enhancing crop productivity and sustainability in agriculture is a promising opportunity provided by nanotechnology. By employing nanomaterials including NPs, nanoclays, and nanoemulsions, nutrients can be delivered through customized seed treatments that also provide protection against pests and diseases while enhancing overall plant growth and development. The transformative power of these advancements in seed treatment technology can reshape agriculture. have the potential to revolutionize agriculture.

By employing controlled release mechanisms, nanomaterials promote efficient resource utilization and minimize chemical usage, thereby supporting sustainable farming practices., contributing to sustainable farming practices. Nanotechnology-based seed treatments exhibit noteworthy progress in enhancing crop yield, nutrient absorption efficiency, and the ability to withstand stressful conditions. It showcases the boundless opportunities presented by this technology to transform modern agriculture. With the continuous increase in the global population, ensuring food security emerges as a crucial concern.

Meeting the growing need for food requires innovative solutions, and one promising approach is leveraging nanotechnology in seed treatment to enhance crop productivity while minimizing agricultural losses. In addition, nanotechnology helps to promote sustainable practices. aid in the preservation of the environment. Decreased reliance on chemical substances and enhanced resource management aid in reducing the harmful impact that conventional farming practices have on our ecosystem.

Through the encouragement of green and ethical farming techniques, nanotechnology provides a route to guarantee food security while protecting ecosystems and preserving natural resources. Collaborative efforts are crucial to fully exploit the advantages of nanotechnology in agriculture, collaborative efforts are essential. Overcoming challenges requires the close cooperation of researchers, farmers, policymakers, as well as industry stakeholders to overcome challenges. By collaborating, we can guarantee the secure and efficient application of seed treatments using nanotechnology.

The significance of continuous research and innovative practices cannot be overstated to explore new nanomaterials, understanding their interactions with plants and the environment, and optimizing their performance in seed treatments. Safer and more efficient nanomaterials will be uncovered through investments in research and development. It will further promote the progress of sustainable agricultural practices. In closing, the immense impact of nanotechnology in seed treatment should not be underestimated. is of utmost importance.

Research Directions and Future Prospects

The domain of nanotechnology in seed treatment presents plenty of prospects for further exploration and experimentation. Scholars can dive into the extensive domain of nanomaterials. Tailoring their properties for specific agricultural applications involves exploring various combinations and surface modifications. Multifunctional nanomaterials with the potential to deliver nutrients, offer protection against pests, and enhance stress tolerance in plants may be developed. By combining NPs with nanoclays, researchers may enhance the controlled release of agrochemicals. The outcome of this can be sustained protection and nutrient supply. In addition, employing nanoemulsions to transport beneficial microorganisms or growth-promoting substances to seeds has the potential to cultivate symbiotic connections with plants.‡

Understanding the mechanisms of nanomaterial interactions with seeds and plants is a crucial aspect of future research. By comprehensively studying how nanomaterials penetrate seed coats, interact with cellular structures, and influence biochemical pathways. Design optimization allows scientists to maximize efficacy and ensure safety. To adequately gauge the lasting effects of nanotechnology-based seed treatments on soil health, microbial communities, and the broader ecosystem, longitudinal studies are indispensable. By examining the impacts of these treatments over time, these studies offer valuable insights that help researchers better comprehend their effects on various environmental aspects. It is vital to understand how nanomaterial residues persist or degrade over time to ensure the sustainable use of nanotechnology in agriculture.

The establishment of standardized safety testing protocols is crucial for enabling safe and responsible implementation. Different plant species, beneficial organisms, and soil organisms should be encompassed by these protocols, covering a range of biological models. Accuracy and reproducibility in safety assessments can be enhanced through the utilization of advanced analytical techniques and modern toxicity assays. It is vital to create risk assessment frameworks tailored to nanomaterials in seed treatments for the early detection of potential hazards during their development. Taking this measure will contribute to the safety of both the environment and human health. Risk mitigation strategies can focus on engineering nanomaterials with reduced toxicity. To minimize off-target effects, one can explore eco-friendly options and design-controlled release mechanisms.‡

It is crucial to conduct regular environmental monitoring to identify any unintended effects of seed treatments that utilize nanotechnology in agricultural settings. Monitoring programs should span different regions and crop types to assess the wider environmental implications of nanomaterial use. Clear and informative labeling of nanotechnology-based seed treatments Farmers, regulators, as well as consumers all consider this aspect to be necessary. Transparent communication regarding nanomaterial usage, safety data, and potential benefits will foster confidence and support making well-informed choices. To achieve broader adoption of nanotechnology in agriculture, The economical aspect plays a crucial role. Ongoing investigation into economical production methods and widespread manufacturing thereby improving the availability of nanomaterials for farmers. Spreading knowledge and offering education regarding the advantages and proper application of nanotechnology is vital. Farmer training programs, extension services, and workshops can disseminate knowledge and dispel misconceptions, encouraging responsible adoption.

Governments and regulatory bodies can promote the responsible adoption of nanotechnology in agriculture via the utilization of different supportive policies and guidelines. They can foster public-private partnerships, research and development can be motivated by them, and establish clear safety regulations to encourage innovation and commercialization. Academic institutions, industries, and government agencies working together lead to the exchange of knowledge and fast-tracked technology development. Forming research alliances and platforms for sharing open data has the capacity to stimulate innovation while minimizing redundant work.

In conclusion, the prospects of nanotechnology in seed treatment offer vast potential to positively transform agriculture. By exploring diverse nanomaterials, understanding mechanisms, implementing safety strategies, and collaborating to scale up adoption, we can tap into the complete advantages offered by nanotechnology to improve crop productivity levels as well as sustainability and ensure food security. Realizing the full potential of nanotechnology requires ensuring its safe and responsible implementation, with a focus on safeguarding human health, the environment, and agricultural systems for future generations. Giving priority to research and regulation is crucial with the aim of tackling possible risks and securing the future of nanotechnology.

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Conflict of Interest

None.

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