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**International Journal of Agricultural Invention**

**(online available at www.agriinventionjournal.com)**

***International Journal of Agricultural Invention* 8(2): 170-181: December, 2023**

**ISSN: 2456 – 1797 (P)**

# Nano-Priming: An innovative tool for seed quality enhancement for sustainable agriculture

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**ARTICLE INFO**

**Review Article**
Received on May 16, 2023
Revised on June 25, 2023
Accepted on July 13, 2023
Published on October 15, 2023

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**PUBLICATION INFO**
International Journal of Agricultural Invention (IJAI)
**RNI:** UPENG/2016/70091
**ISSN:** 2456-1797 (P)
**Vol.:** 8, **Issue:** 2, **Pages:** 170-181
**Journal Homepage URL**
*http://agriinventionjournal.com/*
**DOI:** 10.46492/IJAI/2023.8.2.5

## ABSTRACT

Nano-priming, an emerging field in agricultural science, offers an innovative approach to enhance seed quality and promote sustainable agriculture. This chapter explores the potential of nano-priming as a tool for seed quality enhancement and its implications for sustainable agricultural practices. Nano-priming involves the application of nanoscale materials to seeds, enabling targeted delivery of essential nutrients, improved germination rates, and enhanced stress tolerance. The advantages of nano-priming include enhanced seed germination, increased nutrient uptake efficiency, improved water management, enhanced disease and pest resistance, and overall crop resilience. By reducing the reliance on chemical inputs, nano-priming contributes to environmental preservation, decreased water and soil contamination, and reduced carbon footprint. However, the adoption of nano-priming also presents challenges, including the potential environmental impacts of nanomaterials, health and safety concerns, regulatory frameworks, and the need for cost-effectiveness. Addressing these challenges through further research, responsible development, and effective regulation will be crucial for the successful implementation of nano-priming in agriculture. Nano-priming holds significant promise as an innovative tool to enhance seed quality, improve crop productivity, and promote sustainable agricultural practices, but careful consideration of its benefits and potential drawbacks is essential to ensure its safe and responsible use.

**KEYWORDS**

Nanoparticles (NPs), Nano-Priming, Zinc Oxide (ZnO), Silver (Ag), Carbon Nanotubes (CNT)

**HOW TO CITE THIS ARTICLE**

Chaithanya, G., Rao, D. (2023) Nano-Priming: An innovative tool for seed quality enhancement for sustainable agriculture, *International Journal of Agricultural Invention*, 8(2): 170-181. DOI: 10.46492/IJAI/2023.8.2.5

Seed is the basic input in agriculture upon which all other inputs influence the performance of seeds under varied conditions. A good vigorous seed utilizes all the resources and realized a reasonable output to the grower. It is considered an asset to the farmer and good seeds in good soil realize good yield. According to seed technology, any propagating material, which results in the complete regeneration of the seedling into a new plant, is considered a seed. It might be a true seed in which, the embryo is embedded in food-rich endosperm and protected by a seed coat or a vegetative propagule, or a synthetic seed produced by tissue culture.

It is the carrier of new technology where in; the final yield of the crop always depends on the quality of the seeds and the seed treatments subjected prior sowing of the seed. A high-quality seed is always a responsible mean to secure food supply and crop yield in unfavorable conditions. Several conventional and molecular-assisted breeding methods are used to produce pure lines and hybrids, which can withstand adverse conditions and produce promising yields. However, the complete transfer of QTLs or genes responsible for stress tolerance from the donor to the susceptible parent is less achieved.

Hence, an alternative and easy method of making the seed to induce stress tolerance is by exposing them to stress conditions for a few hours or by a method called seed invigoration. It includes all the treatments like seed priming, coating, pelleting, and physical/chemical/biological seed treatments, which enhances the seed vigor and is called seed invigoration. There are several ways to enhance the vigor of the seed in which the use of nanoparticles is gaining importance in recent days. Nanotechnology is the manipulation of matter with at least one dimension sized from 1 to 100 nm. The word *nano* is derived from a Greek word, which means dwarf. According to IUPAC, particles of any shape with dimension in $10^{-9}$ and $10^{-7}$m range and possess distinct physical, chemical and biological properties are called Nanoparticles. They exhibit changes in their properties as the size of the particle increases. The main properties include:

### High Surface Area to Volume Ratio

Nanoparticles due to their small size possess high surface area, which in turn enters into the seed more efficiently and easily as compared to other chemicals.

### High Stability

The nanoparticles are stable in adverse conditions as well and enhance the seedling survivability by increasing the metabolic activity.

### High Water Solubility

Some of the nanoparticles are water-soluble which enhances the uptake by the seedling when applied. However, some nanoparticles are soluble in organic solvents like ZnO and Ag NPs whose application needs further standardization of uptake.

### High Biocompatibility

The majority of the nanoparticles are less hazardous at low concentration.

### Low Toxicity

The nanoparticles are less toxic when applied at a desired concentration. However, increased concentration harms the seedling, which may impair its normal growth.

A critical increment in agricultural production can be achieved through the utilization of past and current knowledge in the field of nanotechnology for the productive conveyance of chemical and biological pesticides using nano-sized formulations. It also helps to undertake effective plant protection measures, precision agriculture, and many others. The use of conventional fertilizers is helping to boost the yield level in many crops, but it is severely affecting the environment by causing eutrophication and contaminating the water bodies. Thus, the supply of essential nutrients in the form of nanoparticles could improve the nutrient uptake by the crops with reduced environmental impact (Rafique *et al.*, 2018).

Recent studies have revealed that the use of different nanoparticles enhanced seed quality, crop productivity levels, and protection against biotic and abiotic stress under field and laboratory conditions in crops, such as rice, maize, wheat and many others. Further, it was reported that the use of metal and metal oxide nanoparticles enhanced germination, seed health and seed viability. Nano-encapsulation technique is in vogue nowadays for the slow release of fertilizers and chemicals with enhanced efficiency (Agarwal and Rathore, 2014). Hence understanding the role of nanotechnology in seed science research helps in broadening the utilization and its role in enhancing seed germination is crucial.

### Source of Nanoparticles

Nanoparticles occur naturally in the environment. It may be in the form of water vapor or the molecules escaped into the environment during volcanic eruptions or due to anthropogenic activities by the release of smoke from factories, automobiles, etc., or deliberately synthesized for scientific purposes. Both the mode of NPs synthesis has a direct effect on biotic factors. Nanoparticles entering the soil through the intentional use of NP-based agrochemicals have a direct effect on crop growth. Hence understanding the desirable concentration of NPs for good growth and development of the plants needs to be ascertained. Nanoparticles are generally synthesized by two broad methods.

### Top-down Approach

Creating Nano-scale materials by breaking down a larger material either physically or chemically.

### Bottom–up Approach

Assembling the Nanomaterials atom-by-atom or molecule by molecule (self-assembling or positional assembling).

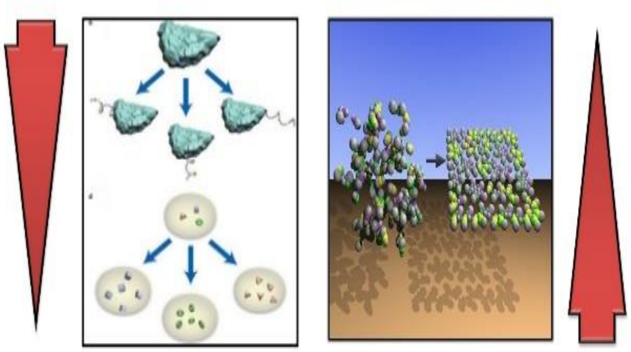

**Fig 1. Synthesis of Nanoparticles**

Nanoparticles are also synthesized by Physical methods (by grinding or breaking), Chemical methods (Chemical reactions) and biological methods (use of microorganisms, plants, etc.) among which, the biological method has been found the safer for plant-based applications.

### Nanotechnology in Seed Quality Enhancement

Nanotechnology has emerged as an innovative scientific field, which manipulates the properties at a both physiological and molecular level. It has the potential to revolutionize agriculture and allied fields, through the early detection of pest and diseases, enhancing nutrient uptake by plants, nano-biosensors, which detects weather and climatic changes, and others. Nanoparticles have emerged as vehicles for carrying agrochemicals effectively to the target site and delivery of particles or emulsions at the nanoscale enhances the growth and yield of the plants. Many metallic and non-metallic NPs are used in agriculture to increase the quality of the produce. Among them, Zinc Oxide (ZnO), silver (Ag), silver oxide ($Ag_2O$), titanium dioxide ($TiO_2$), gold (Au), calcium oxide (CaO), silica (Si), copper oxide (CuO), magnesium oxide (MgO) and Carbon-based nanoparticles are extensively used in seed quality enhancement.

The beneficial use of nanoparticle-based priming has been reported in many cultivated crops. Treating with ZnO NPs has enhanced the germination rate in lentils, Maize, Onion, etc. (Ananthan and Natarajan, 2017). Similarly, $CeO_2$ helps to improve its defense mechanism against many biotic and abiotic stresses in paddy (Cyril *et al.*, 2013). Nano-priming effect on seed quality has been studied in this chapter at the physiological, biochemical, and molecular levels.

### Physiological Aspects of Nano-Priming

Many researchers have reported the positive effect of nanoparticles on seed quality enhancement. The positive correlation between the dosage of NPs treated and seed quality enhancement is attributed to its penetration and uptake by the seed coat. Conventionally applied chemicals fail to penetrate effectively into the seed and reach the target site to manipulate the physiological properties of the seeds. When Carbon Nano-Tubes (CNT-10µg/ml) were treated with the tomato seeds, due to their nano size and high surface area, they penetrated the seed coat and enhanced the final germination percent and vigor of the young seedling. Seed germination rate primarily depends on how fast the moisture has been taken up by the seed in which, CNTs due to their high affinity towards water molecules, enhanced the faster uptake of the moisture as compared to the control (Khodakovskaya *et al.*, 2009).

Similarly, the germination rate is primarily affected by the enzyme activation and mobilization of food reserve to the growing embryo. ZnO NPs are widely used in nano-priming, which enhanced the activity of the α-amylase enzyme and promoted faster germination in onions at 20µg/ml (Lawere and Raskar, 2014). In addition, the plant height, number of leaves per plant, days required to flower, and seeded fruits per umbel were enhanced in nano-primed seeds as compared to the control. It plays an important role in the synthesis of indole acetic acid (IAA) which regulates plant growth, chlorophyll synthesis, and carbohydrate formation (Vitosh *et al.*, 1994). Titanium dioxide ($TiO_2$) is an important nanoparticle, in which Ag-$TiO_2$ promoted seedling height, leaf dimensions and number of leaves, photosynthesis, and nitrogen metabolism in spinach at the lowest concentrations of 2% (Gordillo *et al.*, 2020).

Seed priming with micronutrient NPs revealed as a new promising mechanism for improving the rate of seed germination, seedling vigor, and development. The yield parameter of paddy is widely influenced by the application of Silicon which imparts a sturdy stem and reduces insect infestation. But when Silica is applied in nano-form, it reduced the seedling lodging and enhanced the final yield by alleviating the Arsenic and Cadmium- ion toxicity (Wang, *et al.*, 2021). In addition, the application of silica NPs increased the seed germination, root-shoot length, photosynthesis, and dry weight of maize seedlings (Suriyaprabha, 2012). The priming of wheat seeds with various concentrations of iron oxide ($Fe_2O_3$) NPs leads to ameliorated germination potential, enhanced germination uniformity, and significant total germination percentage (Sundaria *et al.*, 2019). Enhanced germination and consistency of the metabolism are attributed to cell repair via the absorption of moisture and increased synthesis of metabolites. The large changes in morphological parameters have been distinctly pertinent to the increase in physiological attributes such as uplift in enzyme activities, greater photosynthetic rate and significant nitrogen and phosphorus metabolism. Hence, with the effective dosage of Nano-priming, seed physiological parameters were enhanced in several field crops.

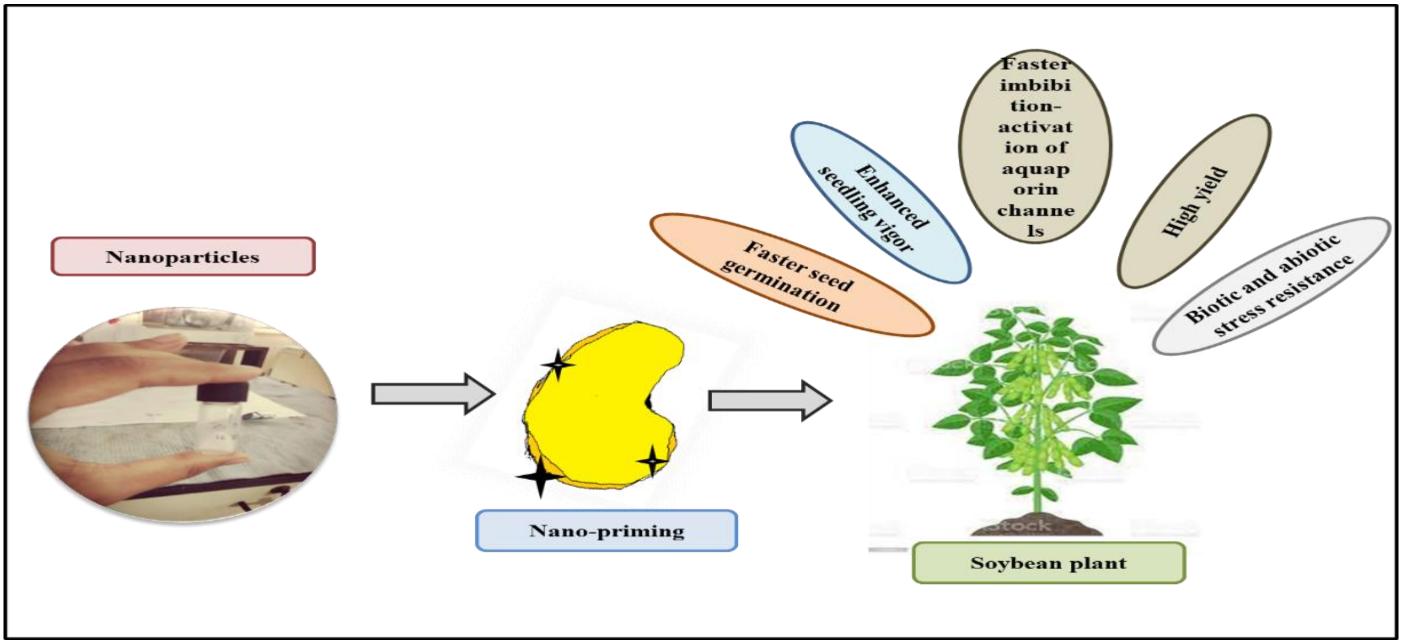

**Fig 2. Physiological aspects of Nano-priming: Increased germination%, seedling vigor and plant growth characteristics**

## Biochemical Aspects of Nano-Priming

Several enzymes and hormones play an important role in seed germination. Increased activity of antioxidant enzymes like catalase, peroxidase, super-oxide dismutase, and ascorbate peroxidase controls the ROS production in the cells maintaining the level within the oxidative window, which enhances seed germination. Many researchers have reported that nano-priming boosts the activity of several antioxidant enzymes and transcription factors. The generation of nano-pores on seed coat increased the intake of water, bootstrapping ROS/antioxidant network in seeds and resulting in a faster breakdown of starch.

Seed polymer coating with Zn and Fe NPs entered the seeds via the cracks present on the seed coat and enhanced the enzyme activity thereby reducing the oxidative damage and enhancing seed germination in pigeon peas (Korishettar *et al.*, 2017). The ZnO Nano-priming of 10mg/L in cluster bean remarkably increased the contents of chlorophyll, completely soluble leaf protein, and activities of various enzymes like acid phosphatase, alkaline phosphatase and phytase. The total lipids, proteins, amino acids, and thiols, were significantly increased after being treated with varying concentrations of zinc oxide NPs as compared to control (Pratap *et al.*, 2013). The reactive oxygen window is crucial for the seed to germinate.

The minimum level of ROS is necessary to initiate the biochemical activity but if it exceeds, the nascent oxygen reacts with the blipped layer of the cell membrane and disrupts the basic structure, leading to electrolyte leakage. However, nano-priming with titanium dioxide ($TiO_2$) NPs decreased the hydrogen peroxide ($H_2O2$), malondialdehyde (MDA) and electrolyte leakage in chickpea (*Cicer arietinum* L.) as compared to the control (Mohammadi *et al.,* 2014). In addition, several transcription factors are involved in ROS regulation. Metallothionein is one of important transmembrane proteins that regulate the entry of elements into the cell organelle. However, the induction of metallothionein genes (MT1 and MT4) in tomato seeds treated by nano-priming indicates their probable participation in ROS signaling during the germination of NPs treated seeds (Anand *et al.,* 2019). A considerably enhanced level of antioxidant enzymes, namely superoxide dismutase (SOD) and catalase (CAT) was observed in nano-primed seeds compared to control. Thus, the greater level of $H_2O_2$ detected in nano-primed seeds could serve as a signaling agent and was coherent with the concept of oxidative windows, leading to greater germination and hastened seedling growth compared to unprimed and primed seeds.

Increased Photosynthetic efficiency in nano-primed seeds is expected due to a direct correlation with the effect on photosynthetic apparatus. The photosystem I and II, electron transport chain efficiency is proven to be increased in nano-primed seeds. The improved light absorption by chlorophyll molecules via the plasma resonance effect is associated with the promotion by NPs of light-captured photosynthetic phase photochemical reactions. Metal NPs reduce the PSII chlorophyll from excessive excitation, absorb the energy of excited electrons and act as a kind of protector against oxidative stress (Das *et al.,* 2019). Metal NPs not only influence the antioxidant defense system (AOS) enzymes but also increases the accumulation of antioxidant-proline, glutathione, and carotenoids in plant tissues (Hong *et al.,* 2015).

## Molecular Aspects of Nano-Priming

Genes at molecular level control the physiological and biochemical responses of seeds.

Several genes and transcriptional factors regulate the uptake and utilization of an externally applied input in an efficient manner. The nano-primed seeds' better performance as compared to the control is attributed to changes in the seeds at molecular level. Several transcriptional factors, which regulate the phytohormone level and trans-membrane protein integrity, are up regulated in nano-primed seeds. When rice seeds were nano-primed with Zinc NPs, the genes OsGA3Ox2 and OsGAMYB responsible for gibberellic acid synthesis were up regulated at 20 mg/l. Similarly, in *Brassica rapa* seeds, nano-priming affected GA, by enhancing the expression levels of BnGA20ox, BnGA3ox and BnCPS, thereby increasing the germination in primed seeds, which indicated that the NPs are correlated with increases in bioactive GAs synthesis (Nakaune *et al.,* 2012) and the ABA catabolism genes initially expressed higher and as germination continued, the level of BnCYP707A4 reduced gradually indicating the reduced ABA level in nano-primed seeds.

One of the major constraints in seed germination is the protrusion of the radicle from the seed. Enough potential gradients are required to overcome the resistance produced by the endosperm cap and the hard seed coat in which Expansin a group of genes controlling the cell wall expansion plays a crucial role. When *Brassica rapa* seeds were nano-primed with ZnO and Se NPs, the differential expression level of BnEXP4 in nano-primed seeds verified the nano-priming impact on seedling growth and development. This gene is one of the various genes working on the cell wall loosening process, resulting in the weakening of the micropylar endosperm cap during seed germination (Pirrello *et al.*, 2006). Similarly, lignin also plays an important role in the protection of young seedlings from biotic and abiotic stress. Genes responsible for lignin synthesis i.e. ZmPAL, ZmCCR2 (Cinnamoyl-CoA reductase), and ZmCAD6 (Cinnamyl alcohol dehydrogenase) were enhanced in lanthanum oxide nano-primed maize seeds. Increased chlorophyll and carotenoid content in nano-primed seeds were attributed to the expression level of CYB and ZEP1 genes. The silver (Ag) nano-primed seeds exhibited higher carotene content in rice, turnip and Chinese cabbage seedlings responsible for improved photosynthetic efficiency.

## Biotic and Abiotic Stress Management of Nano-Priming

Biotic and abiotic stresses are the main factors that inhibit successful establishment of seedling under field conditions. Presence of insect/disease causing organism's inoculum in the seed (seed infection) or on the seed (seed infestation) or contaminated with the seeds (concomitant contamination) makes the seed vulnerable to germinate. However, when the seeds were nano-primed prior sowing has significantly reduced the incidence of pest and disease attack on the growing seedlings and enhanced the field establishment. *Alternaria porri* an important seed borne plant pathogen causing purple blotch of onion was effectively controlled when the onion seeds were nano-primed with 250 ppm of ZnO NPs (Chaithanya *et al.,* 2023). Similarly, Silver nanoparticles are considered antifungal in nature, which inhibits growth and establishment of several plant pathogen fungi in many field crops.

Disruption of hyphal membrane by production of free radicles and boosting the antioxidant enzyme activity in nano-primed seeds is known to be the mechanism behind antifungal nature of Ag NPs. Under laboratory conditions, Ag Nps at 25 µg/ml completely inhibited the growth of *Alternaria solani* causing early blight of potato (Ismail *et al,* 2016). Similarly, when paddy seeds were treated with nickle-chitosan, it significantly reduced the infection of paddy blast (*P. grisea*) and the treated plants showed a significant increase in the rate of seed germination and growth (Parthasarathy *et al*, 2023).

Metal nanoparticle's antifungal activity is affected by its concentration, exposure time, suspension preparation method, and on fungal strain type. The chitosan-based nanoparticles interact with phospholipid components of the fungal membrane and causes cell contents to leak, resulting in cell death. In addition, Zinc oxide nano-primed cluster bean seeds showed higher germination percent and resistance to several bacterial strains like *staphylococcus aureus, Pseudomonas aeruginosa, Salmonella typhimurium, Bacillus cereus, Candida glabrata, and Candida albicans* (Rexlin *et al.*, 2022).

Majorly, all the nanoparticles due to its nano-size get enter into the hyphal membrane and interact with the biochemical reactions and produces the reactive oxygen species such that, cell membrane of the hypha results in disruption and leads to failure in establishment of an inoculum on the growing seeds. Climatic conditions prevailing during the crop growth has direct impact on final yield. Changing environment in present scenario creates stress like drought, flood, heat and cold stress, and altered soil properties like acidic, alkaline, sodic and saline sodic soils has direct impact on stand establishment of the crop under field conditions. Hence, it requires huge budget for soil reclamation and protect against unpredictable weather. The best possible solution for reducing the abiotic stress impact can be by nano-priming. Many nanoparticles impart stress resistance by maintaining the ion-homeostasis in the cell sap, boosting the antioxidant enzyme activity, accumulation of stress related proteins and osmotic solutes which stabilizes the cell membrane structure (Chandrasekaran *et al*., 2020). A Nano-primed maize seed with TiO2 nps has induced the salinity stress by enhancing the accumulation of phenylalanine, potassium ions and vacuolar compartmentalization of excess sodium ions from the cell sap (Shah *et al*., 2021).

Similarly, ZnO nano-primed paddy seeds have improved the antioxidant enzyme activity and biomass accumulation under drought stress. Many nanoparticles protect the plants from toxicity induced by specific or combination of metals. This is achieved by activating the transmembrane proteins, which allows accumulation of only essential elements, and boosting the defense mechanism in the young plants. ZnO nanoparticles is known to alleviate cobalt, cadmium and lead toxicity in maize and wheat respectively by maintaining the ultrastructure of the cell and increasing the Zn accumulation in the cells thereby boosting the enzyme activity (Salam, 2022). Similarly, Iron nanoparticles along with Zinc oxide are known to alleviate the Cadmium ion-toxicity in wheat by increasing the accumulation of essential minerals in the growing seedlings (Rizwan *et al*, 2019). Hence, in-depth research is needed to understand the mechanism behind the imparting biotic and abiotic stress response by nanoparticles in field crops.

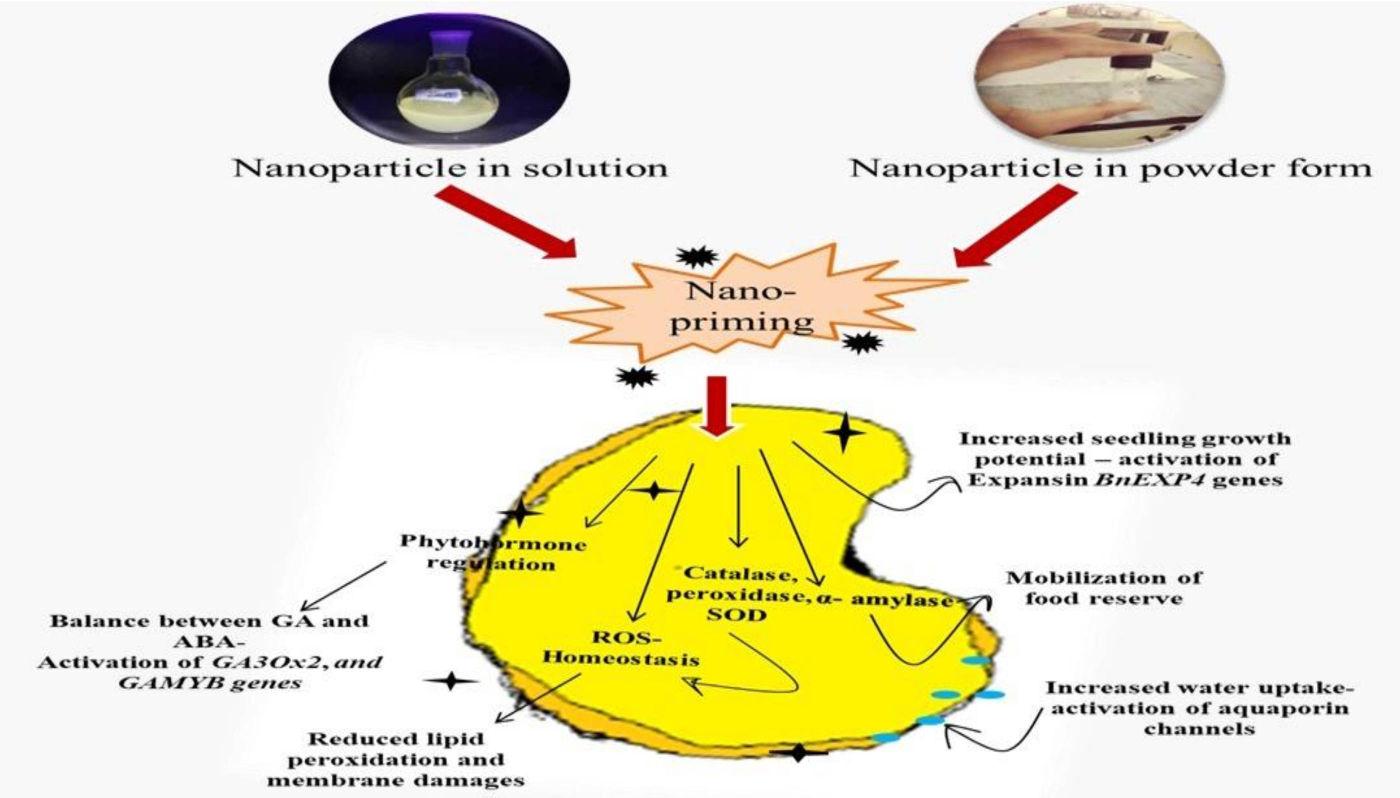

**Fig 2. Effect of Nano-priming on biochemical and molecular properties in Seeds**

## Advantages and Disadvantages of Nano-Priming

Nano-priming is a novel seed priming technology that improves seed germination, seed growth, and yield by increasing plant tolerance to diverse stresses and is far more effective than all other seed priming techniques (Nile *et al*., 2022). The main characteristics of nanoparticles (NPs) in seed priming include electron exchange and increased surface reaction capabilities connected with diverse plant cell and tissue components. Nanoparticles (NPs) appear to be more effective than other priming strategies, such as bulk materials or hydro-priming, in regulating growth, quality, yield, and reactive oxygen species (ROS) homeostasis in plant seeds. Increased seed metabolism by activating the enzyme -amylase, which rapidly mobilizes the food reserve to the growing embryo and faster establishment of seedling under both normal and stress conditions. Enhanced seedling length and faster development of primary and secondary branches leads to increased photosynthetic efficiency and food reserve synthesis. Also, enhanced activity of antioxidant enzymes, phytohormones and cell repair mechanism by maintaining the ROS homeostasis. The advantages of seed nano-priming include:

### Cost-Effective Approach

Application of materials at nano-scale enhances the uptake by the plants, increased interaction with cell organelles helps in maintaining the membrane integrity, and ion-homeostasis leads to normal growth and development of seedling under varied environmental conditions.

### Enhanced Seed Germination

Nano-priming involves applying nanoscale materials to seeds, which can improve germination rates. These materials can provide a protective coating around the seed, preventing damage from pests, pathogens, and adverse environmental conditions. This leads to higher seedling emergence and overall crop establishment.

### Increased Nutrient Uptake

Nanoparticles can be engineered to carry essential nutrients and deliver them directly to plant cells. By enhancing nutrient uptake, nano-priming can improve plant growth, vigor, and overall crop yield. It ensures that plants have access to the necessary elements for their optimal development and by increasing the efficiency of nutrient delivery, nano-priming reduces the amount of fertilizers needed.

**Table 1. List of different nano-priming treatments and its effect on agricultural crops**

| Nanoparticles | Crop & dosage | Effect | Reference |
|---|---|---|---|
| **ZnO** | *Triticum aestivum*-10 mg/l | Promoted seed germination and vigor index and enhanced biochemical activity in germinated seeds. | Rai-Kalal and Jajoo (2021) |
| **ZnO** | *Elucina coracana*-1000 ppm | Enhanced growth, yield and Zn content in the seeds. | Rameshraddy *et al*. (2017) |
| **ZnO** | *Cicer arietinum* -10 ppm | Enhanced biomass and antioxidative enzymes activity in germinating seeds | Burman *et al.* (2013) |
| **ZnO** | *Oryza sativa* -25ppm | Increased seed and straw yield under drought conditions | Waqas Mazha *et al*. (2022) |
| **Ag** | *Citrullus lanatus* 31.3 µg ml−1 | Increased Seed germination, growth and yield characters. | Acharya *et al.* (2020) |
| **Ag** | *Oryza sativa* -10 mg/l | Increased germination, rebooting ROS/antioxidant systems and starch metabolism as compared to untreated seeds. | Mahakham *et al*. |
| **Ag** | Chinese cabbage-40 mg/L | Enhanced the essential amino acid content and final yield. | Zhou *et al*. (2022) |
| **Carbon nanotube** | L. *esculentum*-50 µg/ml | Increased seed germination by activating aquaporin channels. | Khodakovskaya *et al*. (2013) |
| **TiO2** | *Petroselinum crispum*-30mg/l | Enhanced germination rate index, root and shoot length, vigor index, and chlorophyll content of seedlings. | Dehkourdi and Mosavi (2013) |
| **TiO2** | *Hordeum vulgare*-100 mg/l | Increased root length and Relative Growth Index compared to control groups. | Değer and Çevik, S. (2021) |
| **MgO** | *Vigna radiata-100 mg/l* | Increased seed germination and seedling vigour as compared to untreated seeds. | Anand *et al*. (2020) |
| **CaO** | *Canola*-75 ppm | improved germination percentage and seedling fresh weight and antioxidant enzyme activity under drought stress | Mazhar *et al*. (2022) |
| **Mn** | *Capsicum annuum* L- 0.5 mg/l | Increased salinity stress tolerance and root growth | Ye *et al*. (2020) |
| **Fe2O3** | *Cicer arietinum* -12 µg/ml | Increased seed germination and growth parameters. | Pawar *et al*. (2019) |
| **γ-Fe2O3** | *Triticum aestivum*- 200-400 ppm | Increased accumulation of iron content in grain, germination % and shoot length | Sundaria *et al.* (2018) |
| **Plant based synthesised Fe NPs** | *Phaseolus vulgaris*- 5% | Increased physiological and biochemical activity in nanoprimed seeds as compared to control | Ighaiee *et al*. (2021) |
| **Boron nitride** | *Helianthus annus*- 0.2% | Enhanced seed germination and vigor indices | Geetha *et al*. (2018) |
| **Carbon nanotube** | *Zea mays*-25 mg/l | Increased germination rate under drought stress | Shahriari et *al*. (2019) |
| **Chitosan** | *Vicia faba-0.05%* | Enhanced total phenol content and antioxidant enzyme | Abdel-Aziz, H. (2019) |
| **Green-Sulfur Nps** | *Helianthus annus*-0.5 mg/l | Enhanced the antioxidant defense system under Manganese toxicity | Ragab and Saad-Allah, (2021) |

This reduces nutrient runoff and leaching, which can lead to water pollution in nearby water bodies. Additionally, it helps prevent the overloading of ecosystems with excess nutrients, such as nitrogen and phosphorus, which can cause eutrophication and harm aquatic life.

### Efficient Water Management

Water scarcity is a significant concern in agriculture. Nano-priming can help in the efficient utilization of water by enhancing the activity of aquaporin channels, which increases the seed imbibition rate. A nanomaterial applied to the soil also improves water retention, reducing water loss through evaporation and improving water availability to plants. This technology also helps in managing irrigation schedules more effectively, resulting in water conservation.

### Enhanced Disease and Pest Resistance

Nanoparticles can be designed to have antimicrobial and insecticidal properties. Nano-priming can bolster plant defenses against diseases and pests, reducing the need for chemical pesticides. This approach provides a more eco-friendly and sustainable solution for crop protection, minimizing environmental impact and potential health risks.

### Improved Nutrient and Chemical Delivery

Nanotechnology enables precise and targeted delivery of fertilizers, pesticides, and other agrochemicals to plants. Nano-priming allows for controlled release and efficient utilization of these inputs, reducing wastage and environmental contamination. It also reduces the amount of agrochemicals required, leading to cost savings for farmers.

### Stress Tolerance and Resilience

Nanoparticles can help plants cope with various stressors, such as drought, salinity, and extreme temperatures. Nano-priming can enhance plant resilience by improving their ability to withstand adverse conditions. This technology helps crops maintain productivity even under challenging environmental circumstances.

### Sustainable Farming Practices

By improving nutrient efficiency, reducing chemical inputs, and enhancing water management, nano-priming promotes improving soil health.

They can help to retain moisture in the soil, prevent soil erosion, and enhance nutrient availability to plants. By promoting soil health and fertility, nano-priming supports sustainable agricultural practices and helps, maintain the long-term productivity of agricultural land. It also enables farmers to achieve higher yields with fewer resources, reducing the environmental footprint of agriculture and promoting long-term sustainability.

### Decreased Environmental Contamination

Nano-priming can reduce environmental contamination associated with traditional agricultural practices. By improving the targeted delivery and controlled release of agrochemicals, it minimizes their unintended release into the environment. This reduces the risk of soil, water, and air pollution, as well as the potential negative impacts on beneficial organisms, such as pollinators and soil microorganisms.

### Climate Change Mitigation

The improved efficiency in nutrient uptake and water utilization facilitated by nano-priming can contribute to climate change mitigation efforts. Increased plant productivity and resilience can help sequester more carbon dioxide from the atmosphere, acting as a carbon sink. Furthermore, water conservation practices supported by nano-priming can help reduce greenhouse gas emissions associated with irrigation.

Overall, nano-priming offers the potential to minimize the environmental footprint of agriculture by reducing chemical usage, improving resource efficiency, and promoting sustainable farming practices. While nano-priming in agriculture offers several advantages, there are also potential disadvantages and challenges associated with its use. Here are some of the drawbacks to consider:

### Environmental Impact of Nanomaterials

The environmental impact of nanomaterials used in nano-priming is still not fully understood. Some studies suggest that certain nanoparticles may have adverse effects on ecosystems and organisms. It is crucial to conduct comprehensive research to assess the potential long-term impacts on soil, water and non-target organisms before widespread adoption.

## Lack of Regulatory Framework

The regulatory framework surrounding the use of nanomaterials in agriculture is still developing. There may be a lack of specific regulations and guidelines for the safe use and disposal of nano-priming products. This can lead to uncertainties regarding their potential risks and appropriate application methods.

## Health and Safety Concerns

Nanoparticles used in nano-priming may pose risks to human health and safety. The inhalation or dermal exposure to nanoparticles during handling or application could have adverse effects on workers and farmers. It is essential to establish safety protocols and guidelines to minimize exposure risks and ensure the responsible use of nanomaterials.

## Potential for Unintended Consequences

The introduction of nanomaterials into agricultural systems could have unforeseen consequences. For example, nanoparticles may interact with soil microorganisms, potentially altering soil ecology and nutrient cycling. It is crucial to study and assess these potential unintended consequences to minimize any negative impacts on ecosystem functions and biodiversity.

## Cost Considerations

The production and application of nanomaterials can be expensive, potentially posing financial challenges for farmers, especially those in resource-constrained settings. The cost-effectiveness of nano-priming must be carefully evaluated, considering the potential benefits in terms of increased crop yield, resource efficiency, and reduced chemical usage.

## Resistance Development

The prolonged and widespread use of nanomaterials in agriculture may lead to the development of resistance in pests and pathogens. This can reduce the effectiveness of nano-priming as a pest and disease management strategy. Careful stewardship practices, such as rotation of nano-priming products and integrated pest management, are necessary to mitigate resistance development.

## Ethical and Social Implications

The adoption of nanotechnology in agriculture raises ethical and social concerns. Some stakeholders may have reservations about the use of nanomaterials in food production due to perceived risks or unknown long-term effects. Transparent communication, public engagement, and addressing ethical considerations are important to foster public acceptance and trust in nano-priming technologies.

## Adverse Impact on Plants

The nano-priming in several crops is sensitive for the concentration of nanoparticles applied. At higher concentrations, it has several adverse impacts on normal metabolic activity. Development of micronuclei may have a mutagenic effect resulting in breakages in helical structure of DNA resulting in abnormal nucleus and cell division (Luzhna *et al*., 2013). The Nps may also disrupt cell cycle checkpoints, interact with antioxidant enzymes or induce ROS formation by cellular constituents, resulting in protein inhibitory and altered gene expression (Wang *et al*., 2013). It is essential to address these potential disadvantages through further research, responsible development, and effective regulation to ensure the safe and sustainable implementation of nano-priming in agriculture.

## Conclusion and Future Prospects

Agriculture is currently confronting numerous problems, which is raising concerns about food security and safety. Traditional agriculture practices, such as the widespread use of fertilizers, agrochemicals, and pesticides, harm the environment and endanger the food chain. To enhance agricultural sustainability, innovative and ecologically friendly methods must be devised and implemented. Exploitation of nanotechnology through seed priming could be a more user-friendly way to attain this goal. It has been tested as a simple and cost-effective strategy to agricultural sustainability, with the potential to be the solution of near future. Nano-priming has the potential to transform the traditional farming system by increasing tolerance to biotic and abiotic stress and, eventually the crop productivity. The objective of nano-priming is to minimize the environmental impact of runoff of excess fertilizers and other agrochemicals.

All of these features, when combined, can ensure the acceptance of a safer system for farmers and consumers and minimize the environmental damage caused by traditional farming methods. However, the precise mechanisms behind NPs' protective effects against abiotic stress have yet to be completely investigated. Extensive study shall be required in the future to unveil the underlying processes of nano-priming-induced alterations and subsequent stress tolerance at the molecular and hormonal levels. Furthermore, the NP content and exposure period should be optimized for optimum plant growth and productivity to get the required results. Furthermore, the introduction of new NPs, as well as the interaction of NPs with phytohormones and plant-growth-promoting microorganisms, is a new field that deserves additional investigation. The literature on the synergistic interaction of NPs in promoting plant development and stress management is currently limited. We reviewed past studies in this study. Further research into nano-priming should concentrate on the synergistic interplay of nano-materials for stress reduction, bringing up new options for future research.

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