Deep Science Publishing
https://doi.org/10.70593/978-93-49307-12-4_5

DeepScience
Open Access Books

Chapter 5

Nano-Enabled Phytopriming: A Biotechnological Avenue for Enhanced Germination and Abiotic Stress Mitigation

Abhay Singh*, V. Singh, K.N. Shah, D.K. Rana and D. K. Ram

Department of Horticulture, School of Agriculture and Allied Science, H.N.B. Garhwal University (A Central University), Srinagar (Garhwal) Uttarakhand- 246174
**Email: abhaysingh3757@gmail.com*

Abstract: A ground-breaking method for raising plant stress tolerance and germination rates is nano-based seed treatment. By manipulating materials at the nanoscale, nanotechnology offers special qualities that can greatly improve seed performance. The mechanisms by which nanomaterials enhance seed germination, nutrient uptake and resilience to environmental stress are examined in this chapter. Additionally, it looks at several kinds of nanomaterials, including as metal oxides, carbon-based nanoparticles and polymeric nanoparticles, that are employed in seed treatment. With an emphasis on sustainable farming methods, the chapter goes on to address the benefits, possible drawbacks and hopes for the future of nano-based seed treatments.

Keywords: Nanotechnology, Silver nanoparticles, Copper nanoparticles, Stress Tolerance.

Citation: Singh, A., Singh, V., Shah, V.K., Rana, D.K. & Ram, D.K. (2025). Nano-Enabled Phytopriming: A Biotechnological Avenue for Enhanced Germination and Abiotic Stress Mitigation. In *Eco-Friendly Nanotechnology: Harnessing Small-Scale Technologies for a Cleaner and Healthier Planet* (pp. 61-83). Deep Science Publishing. https://doi.org/10.70593/978-93-49307-12-4_5

1 Introduction

World food production must increase 50% by 2050 to meet the needs of 9 billion people (Frona *et al.*, 2019). We are driven to find technology solutions that can ensure food security for future generations due to the world's rapidly changing climate and rising food demand. The main component needed for agricultural development is seed, which contains the genetic potential of the variants and ultimately decides the yield. Environmental factors have a significant impact on seed germination, the crucial initial stage of a plant's life cycle (Lal *et al.*, 2023; Nawaz *et al.*, 2023). Extreme temperatures, salt, drought and nutrient shortages are examples of abiotic stressors that can significantly impair seed germination, resulting in subpar crop establishment and lower yields. Similarly, seed viability and germination success can be jeopardized by biotic stressors, such as pathogenic attacks by bacteria, fungus and pests (Begum *et al.,* 2024).

Under adverse conditions, traditional seed preparation techniques like chemical priming and coating have had only patchy effectiveness increasing germination efficiency and stress tolerance. Because of the special physicochemical characteristics of nanoparticles, including their larger surface area, improved reactivity and capacity to cross biological barriers, nanotechnology presents a possible substitute. In order to improve seed vigour and stress tolerance, nano-based seed treatments can boost seed metabolism, improve nutrient and water uptake and provide pathogen protection. Nanoparticles on the nanoscale (less than 100 nm) have the capacity to contribute to a new technology-based agricultural revolution (Anderson 2021). NPs can load and deliver agrochemicals (e.g., fertilizers and pesticides) with controlled releases, biomolecules (e.g., nucleotides, proteins, activators) and monitoring plant health (e.g., sensors) (An *et al.*, 2020).

Agri-nano sustainability can use NPs to stimulate plant growth, increase crop productivity, protect plants, improve soil quality and detect pathogens and pesticide residues (Dziergowska and Izabela 2022). During the last decade, NPs have been widely used as fertilizers or metal fertilizers (Younis *et al.,* 2019). NPs can enter into cell by direct diffusion, endocytosis and channel process (Nile *et al.*, 2022). The entry of NPs into plant cells can facilitate via the plasmodesmata (Roberts 2003), aquaporins (Madeira *et al.*, 2016), ion channels (Schwab *et al.,* 2016), cuticle membrane and stomata (Chichiricco and Poma 2015), vasculature (Kolitsi *et al.*, 2020). Positive impacts of NPs in plants can be achieved via foliar spray, root exposure and seed priming to improve plant performance under biotic and abiotic stress conditions (Wu and Li 2022 & Fiol *et al.*, 2021).

2 Types of Nanomaterials Used in Seed Treatment

Nanomaterials used in seed treatment can be categorized into multiple classes according on their physical and chemical composition. These include silica-based nanoparticles, metal and metal oxide nanoparticles, carbon-based nanomaterials, and polymeric nanoparticles. Each type of nanomaterial has special properties that make it useful for improving seed germination, stress tolerance, and seedling growth.

2.1 Silver Nanoparticles (AgNPs)

Mechanism of Action: AgNPs, or silver nanoparticles, are well-known for their strong antibacterial capabilities. They produce silver ions (Ag^+), which attach to protein thiol groups and cause infections' cells to malfunction. This encourages proper seedling development and guards against infections spread by seeds. Protecting seeds from fungal and bacterial infections enhances their viability and ensures healthy seedling development. Improved water uptake and stimulated antioxidant enzyme activity promote seed germination and root elongation, leading to stronger plant growth.

2.2 Zinc Oxide Nanoparticles (ZnO NPs)

Amylase and catalase, two enzymes involved in seed metabolism that convert starch to sugars and guard against oxidative stress, are activated by ZnO nanoparticles. ZnO NPs make zinc, a micronutrient that is crucial for plant growth, more readily available. Improves seed vigour and germination rates. Enhances root and shoot growth. Increases tolerance to drought and salt stress by boosting antioxidant enzyme activity.

2.3 Iron Oxide Nanoparticles (Fe_3O_4 NPs)

Iron oxide nanoparticles have magnetic qualities that can affect the orientation and growth of roots and they provide bioavailable iron to seeds, boosting photosynthesis and chlorophyll synthesis. Enhances iron uptake and metabolism. Improves seedling vigor and stress tolerance. Strengthens root and shoot growth under low iron conditions.

2.4 Copper Nanoparticles (Cu NPs)

For a number of enzymes involved in photosynthesis and respiration, copper is an essential cofactor. By releasing copper ions gradually and under control, CuNPs enhance seedling establishment and stress resistance. Stimulates plant defense responses. Improves seed germination and seedling vigor. Enhances resistance to fungal infections.

2.6 Nanomaterials Based on Carbon

The ability of carbon-based nanomaterials, like graphene oxide and carbon nanotubes (CNTs), to improve cell wall permeability, boost seedling growth, and increase nutrient and water intake has attracted attention.

2.6.1 Carbon Nanotubes (CNTs): CNTs have the ability to penetrate seed coverings and form nanochannels, which makes it easier for nutrients and water to be absorbed.

Additionally, they serve as transporters of bioactive compounds, enhancing early seedling development and seed metabolism. Enhances water uptake and seed hydration. Promotes root elongation and seedling vigour. Facilitates targeted delivery of nutrients and bio-stimulants.

2.6.2 Graphene Oxide (GO): Graphene oxide produces an environment that is favourable for the growth of roots and shoots and increases the surface area accessible for nutrient absorption. Improves seed germination rate. Increases root and shoot growth. Enhances stress tolerance by modulating hormone levels.

2.7 Silica-Based Nanoparticles

It is well recognized that silica-based nanoparticles (SiO_2 NPs) can increase plant defense mechanisms, improve nutrient uptake, and increase mechanical strength. SiO_2 NPs increase seeds' tolerance to infections and mechanical stress by fortifying their cell walls and boosting their structural integrity. They also control how much water and nutrients are absorbed. Strengthens seed coat integrity, enhances resistance to drought and salinity and improves nutrient uptake and seed metabolism.

2.8 Polymeric Nanoparticles

Polymeric nanoparticles play a crucial role in agriculture by enabling the controlled and sustained delivery of nutrients, hormones, and bioactive molecules directly to seeds. Chitosan nanoparticles, derived from a biopolymer with antimicrobial and bio-stimulatory properties, form a protective coating around seeds, reducing pathogen attacks and enhancing germination. These nanoparticles improve seedling vigour, regulate the release of nutrients and growth stimulants, and strengthen resistance against fungal and bacterial infections. For instance, chitosan-based nanoparticles have been shown to boost germination rates and seedling strength in rice and wheat under stress conditions. Polyvinyl alcohol (PVA) nanoparticles encapsulate nutrients and bio-stimulants, ensuring controlled and targeted release while improving seed adhesion and water retention. The potential of polymeric nanoparticles to enhance crop resilience and productivity has been demonstrated by the successful improvement in seedling vigor and drought tolerance in soybeans achieved by PVA-based seed coverings.

Table 1. An outline of the traits and impacts of the various metal and metal oxide nanoparticles (NPs) utilized in seed priming.

Type of NMs	Seed name	Concentration of NMs	Key findings	References
Ag	*Asparagus officinalis*	100 mg/L	Levels of ascorbic acid and chlorophyll improved	(An *et al.*, 2008)
	Cabbage (*Brassica oleracea*)	20–40 ppm	increased yield, nutritional quality, seed germination, and seedling growth	(Zhou *et al.*, 2022)
	Eruca sativa	10 mg/L	The length of the roots developed	(Vannini *et al.*, 2013)
	Jasmine rice (*Oryza sativa* cv. KDML105)	10, 20 mg/L	After 24 hours of incubation, the catalase activity of primed seeds increased by 71%	(Mahakham *et al.*, 2017)
	Pea (*Pisum sativum*)	60 ppm	Better germination of seeds	(Mukherjee *et al.*, 2014)
	Potato (*Solanum tuberosum*)	150 ppm	increases the amount of chlorophyll and catalase activity.	(Bagherzadeh Homaee and Ehsanpour, 2016)
	Rice (*Oryza sativa*) (KDML 105)	5 and 10 ppm	Increasing the expression of aquaporin genes to improve seed germination	(Arnott *et al.*, 2021)
	Saffron (*Crocus sativus*)	40, 80, 120 ppm	Root development was enhanced by blocking ethylene and conventional stress signals	(Bagherzade *et al.*, 2017)
	Sugarcane (*Saccharum* spp.)	25 and 50 mg/L	Antioxidant defenses are overpowered by excessive ROS generation	(Bello-Bello *et al.*, 2017)
	Thale cress (*Arabidopsis thaliana*)	0–100 µM	Hormonal signaling-related genes are triggered	(Syu *et al.*, 2014)
		0.01–100 mg/L	Evapotranspiration, biomass, and root length all rise	(Syu *et al.*, 2014)
		0.2 or 0.5 mg/L	The amount of aquaporin transcripts rose	(Qian *et al.*, 2013)
	Vanilla planifolia	25 and 50 mg/L	Enhanced antioxidant responses and nutrient absorption in plantlets	(Spinoso-Castillo *et al.*, 2017)
	Vicia faba	12.5, 25, 50 and 100 mg/L	Micronuclei, chromosome abnormalities, and the mitotic index are all noticeably elevated.	(Patlolla *et al.*, 2012)
	Watermelon (*Citrullus lanatus*)	2 mg/mL	The efficiency of germination has increased.	(Almutairi and Alharbi,2015)

	Wheat (*Triticum aestivum*)	10 mg/L	Changes in the manifestations of roots and shoots	(Vannini *et al.*, 2014)
		0.01–1.0 mg/L	Improvement of root and aerial biomass, seed germination, and seed vigor	(Salachna *et al.*, 2019)
		10 mg/L	Lowers ROS toxicity and promotes early seedling development.	(Kannaujia *et al.*, 2019)
Au	Cabbage (*Brassica juncea*)	0–400 mg/L	Longer roots	(Bisht *et al.*, 2014)
	Flame lily (*Gloriosa superba*)	500–1000 μM	Enhanced vegetative growth and seed germination	(Gopinath *et al.*, 2014)
	Maize (*Zea mays*)	5–15 mg/L	Germination and physiology improved without any toxicity	(Arnott *et al.*, 2021)
		5–15 ppm	Encouragement of the germination of seeds	(Mahakham *et al.*, 2016)
	Mustard greens (*B. juncea*)	10 and 25 mg/L	A higher amount of chlorophyll	(Arora *et al.*, 2012)
	Nicotiana tabacum	30, 100 mg/L	Improvement of growth	(Judy *et al.*, 2011)
	Onion (*Allium cepa*)	100, 500, 1000 μM	A rise in the mitotic index	(Alharbi *et al.*, 2017)
	Pearl millet (*Pennisetum glaucum*)	20–50 mg/L	Lengthening the roots and shoots and increasing seed germination	(Parveen *et al.*, 2016)
	Thale cress (*Arabidopsis thaliana*)	10–80 mg/L	Encouragement of the germination of seeds	(Kumar *et al.*, 2013)
C	Bufalo berry (*Shepherdia canadensis*) green alder (*Alnus viridis*)	20–40 μg/mL	The seedling vigor index and germination rate both increased	(Ali *et al.*, 2020)
	Tomato (*Solanum lycopersicum*)	25 μg/mL	A higher rate of germination	(Lahiani *et al.*, 2015)
		10–40 mg/L	Modification of the seed membrane, accelerated germination, and accelerated plant growth	(Haghighi and Teixeira da Silva, 2014)
			Aquaporin up-regulation promotes tomato seedling germination and development	(Khodakovskaya *et al.*, 2013)
CeO_2	Rapeseed (*Brassica napus*)	0.1 mM	Increased amounts of salicylic acid and better capacity to scavenge ROS.	(Khan *et al.*, 2022)

CuO	Common bean (*Phaseolus vulgaris*)	1–1000 mg/L.	Excessive levels had detrimental impacts on seed germination	(Duran *et al.*, 2017)
	Indian mustard (*Brassica juncea*)	500 mg/L	SOD activity in roots and shoots was markedly elevated	(Nair and Chung, 2015)
	Soybean (*Glycine max*)	100, 200 and 400 mg/L	Soybean roots showed increased expression of the genes PAL, C4H, and CAD	(Nair and Chung, 2014)
	Wheat (*Triticum aestivum*) seeds of varieties galaxy-13, Pakistan-13 and NARC-11.	20–40 ppm	Development of resistance to abiotic stress	(Yasmeen *et al.*, 2017)
FeO	Garden pea (*Pisum sativum*)	75 ppm	Decreased stress from drought	(Mazhar *et al.*, 2023)
	Kobresia capillifolia	10–100 mg/L	Enhanced photosynthetic rate and Rubisco activity	(Sun *et al.*, 2023)
	Mungbean (*Vigna radiata*)	60 mM and 80 mM	Significantly improve the osmotic stress-induced development of plants	(Ul Haq *et al.*, 2023)
	Rice (*Oryza sativa*).	30 µg/mL	High levels of antibacterial activity	(Ahuja *et al.*, 2019)
		10–160 mg/L.	Enhanced absorption of water	(Guha *et al.*, 2022)
	Sorghum (*Sorghum bicolor*)	10–500 ppm	Higher water content in leaves	(Maswada *et al.*, 2018)
	Watermelon (*Citrullus lanatus*) and Nakay varieties).	20–160 ppm	Increased plant growth regulator activity	(Kasote *et al.*, 2019)
	Wheat (*Triticum aestivum*) seeds of varieties galaxy-13, Pakistan-13 and NARC-11.	20–40 ppm	It increases wheat's resistance to abiotic stressors	(Yasmeen *et al.*, 2017)
	Wheat (*Triticum aestivum*), types WL711 (low-iron genotype) and IITR26 (high-iron genotype).	25–1000 µg/mL.	A higher yield of harvest	(Sundaria *et al.*, 2019)
MnO_2	Jalapeno (*Capsicum annuum*)	0.1–1 mg/mL	Development of salinity resistance	(Ye *et al.*, 2020)
Mo	Chickpea (*Cicer arietinum*)	10 mg/L	An increase in harvest and antioxidant enzymes	(Shcherbakova *et al.*, 2017)
Se	Rapeseeds (*Brassica napus*)	150 µmol /L	Enhanced salt tolerance and seed germination	(El-Badri *et al.*, 2022)
SiO_2	Pea seeds (*Pisum sativum*)	2 mg/mL	Increased vitality of seeds and seedlings	(Bravo Cadena *et al.*, 2018)

	Rice (*Oryza sativa*)	125 mg/L	The rice roots showed a considerable rise in lipid peroxidation	(Rico *et al.*, 2013)
	Tomato (*Solanum lycopersicum*) and (*Lycopersicum esculentum*)	8 g/L	Positively affect tomato seed germination	(Siddiqui and Al-Whaibi, 2014)
	Wheat (*Triticum aestivum*)	300–1200 ppm	Reduced cadmium uptake	(Hussain *et al.*, 2019)
TiO_2	Chickpea (*Cicer arietinum*)	10–2500 mg/L	Activate antioxidant systems to shield seedlings from oxidative damage caused on by cold stress.	(Mohammadi *et al.*, 2014)
ZnO	Chilli (*Capsicum annuum*)	750–1250 mg/kg	Strong antibacterial action	(Dileep Kumar *et al.*, 2020)
	Common bean (*Phaseolus vulgaris*)	1–5000 ppm	Enhance biomass	(Savassa *et al.*, 2018)
	Lupin (*Lupin istermis*)	20–60 mg/L.	High salinity resistance	(Abdel Latef *et al.*, 2017)
	Maize (*Zea mays*)	200 ppm	Enhanced seed vigor index and germination %	(Sharma *et al.*, 2022)
		500 ppm	Reduced cobalt uptake and enhanced the photosynthetic machinery to lessen its toxicity	(Salam *et al.*, 2022)
	Moringa oleifera	10 ppm	Enhanced early growth and bioactive compounds	(Garza-Alonso *et al.*, 2021)
	Rice (*Oryza sativa*)	10 μmoL	Improved seed vigor, metabolic profiles, nutrient uptake and yield	(Adhikary *et al.*, 2022)
		50–100 ppm	Promoted early growth and resilience against cadmium toxicity	(Li *et al.*, 2021)
	Sorghum (*Sorghum bicolor*)	10–500 ppm	Improves sorghum germination, seed development, and resistance to salt	(Maswada *et al.*, 2018)
	Wheat (*Triticum aestivum*)	25–100 ppm	Decrease the absorption of cadmium	(Rizwan *et al.*, 2019a)

Table 2. Nano-agrochemical-based future nanosystems for improving seed germination and storage.

Nano systems	**Description**	**Key features**	**Limitations**	**References**
Nanocapsules	Nanoscale vesicular systems composed of a polymeric membrane encircling a liquid core.	Sustained release Incremental agrochemical selectivity efficacy Extremely highly efficient Reproducibility 100 % encapsulation efficiency	limited ability to encapsulate agricultural chemicals, prone to instability and leaking	(Kothamasu *et al.*, 2012)
Nanospheres	A solid sphere with an active ingredient dissolved or disseminated within it that adsorbs or becomes stuck on the surface of a homogenous matrix system	Excellent biodegradability, less toxicity, and increased efficacy of insecticides or fertilizers even at lower dosages	Adhesion issues Hydrophobicity prevents hydrophilic agrochemicals from being loaded	(Pereira *et al.*, 2019)
Nanomicelles	A colloidal structure made of amphiphilic monomers with long hydrophilic tails and hydrophobic heads.	Improved capacity to encapsulate drugs Easy preparation Hydrophilic corona of nano micellar decrease in toxicity	Ineffective loading capacities for agrochemicals Inadequate stability	(Li *et al.*, 2022)
Nanogels	Cross-linked swellable polymer networks were used to create three-dimensional hydrogels that could retain water without dissolving in aqueous solutions.	Agrochemicals are released under control. gives out moisture.	Costly approach There may be harmful traces of surfactants or monomers left behind	(Luo *et al.*, 2021)
Nanofibers	The physical properties of fibers with nanometer-diameter diameters vary	Lightweight, non-toxic, and having a high surface-to-	The process is low yield Needs a lot of voltage. Nanofiber in situ deposition	(Farias *et al.*, 2019)

	depending on the polymer composition.	volume ratio in comparison to other nanoparticles	on many substrates is challenging.	
Nanoemulsions	An emulsion is the heterogeneous dispersion of two immiscible liquids with a mean droplet size of 20–200 nm.	Enhanced stability in the body Improved pesticide absorption is achieved by smaller droplets with a greater surface area.	Minimal toxicity Unpredictable absorption Low solubility	(De Castro e Silva *et al.*, 2019)
Nanosuspension	A submicron colloidal dispersion of nano sized chemical particles stabilized with surfactants.	A submicron colloidal mixture of chemical particles that are nanoscale and stabilized by surfactants.	Preparation requires high energy techniques; Maintenance is costly and Difficult to maintain physical stability	(Sutradhar *et al.*, 2013)
Nanoliposomes	A new technique for encapsulating and delivering bioactive substances, such plant hormones, is submicron bilayer lipid vesicles.	High surface area, a stability profile that is acceptable, and the ability to retain size across the nanoscale range. Both biodegradable and nontoxic.	The mechanical energy employed in the manufacturing process has the potential to break down lipid structures.	(Aguilar-Perez *et al.*, 2020)

3 Mechanism of Action

The unique physicochemical characteristics of nano-based seed treatments-such as their small size, high surface area-to-volume ratio, improved reactivity, and capacity for cellular and molecular interaction—are largely responsible for their efficacy in enhancing germination and stress tolerance. These properties allow nanomaterials to penetrate seed coats, modulate biochemical pathways, enhance nutrient and water uptake and protect against environmental and biological stress factors. The mechanisms through which nano-based seed treatments improve seed performance can be broadly categorized into the following key pathways:

3.1 Enhanced Water Uptake and Nutrient Absorption

Nanoparticles (NPs) have a major impact on improving the availability of water and nutrients, which are essential for seed germination and the early development of seedlings. NPs promote water uptake and nutrient absorption by altering the permeability of the seed coat and affecting ion transport channels. Metal and carbon-based nanoparticles create nano-scale pores in the seed coat, accelerating water imbibition the first step in germination. This rapid hydration activates enzymes and triggers the breakdown of stored nutrients, leading to faster germination and seedling establishment. For instance, carbon nanotubes (CNTs) form nano-channels that enhance water flow, while Fe_3O_4 nanoparticles improve the uptake of iron and other micronutrients, boosting seedling vigour. Additionally, nanoparticles act as carriers for essential nutrients like zinc, iron, and magnesium, increasing their solubility and bioavailability. Metal and metal oxide NPs, such as ZnO and Fe_3O_4, enhance nutrient mobilization by interacting with ion transport channels, ensuring efficient nutrient delivery to the growing embryo. ZnO nanoparticles, for example, improve zinc availability and enzyme activity, while Fe_3O_4 nanoparticles promote iron transport and chlorophyll synthesis, enhancing photosynthesis and overall seedling health.

3.2 Antimicrobial and Antioxidant Effects

Nanomaterials, particularly silver (Ag) and zinc oxide (ZnO) nanoparticles, exhibit strong antimicrobial and antioxidant properties, protecting seeds from fungal and bacterial pathogens that often cause seedling failure. While ZnO and SiO_2 nanoparticles produce reactive oxygen species (ROS) that harm bacterial and fungal cells, their direct antibacterial effect entails the release of metal ions like Ag^+ and Cu^{2+} that destroy microbial cell walls and metabolic processes. This improves seedling establishment and lowers seed-borne diseases. For instance, it has been demonstrated that silver nanoparticles (AgNPs) stop the growth of fungi on rice and wheat seeds, hence avoiding pre-emergence damping-off. Furthermore, the synthesis of antioxidant enzymes including as catalase (CAT), peroxidase (POD), and superoxide dismutase (SOD) is stimulated by metal oxide nanoparticles like ZnO and FeO_4. These enzymes shield seed cells from oxidative damage brought on by environmental stressors like salinity and drought. Increased antioxidant enzyme activity promotes stress tolerance, as observed in maize, where ZnO nanoparticles boost SOD and CAT activity, enhancing seedling survival under salt stress. These multifunctional properties of nanomaterials make them valuable tools for improving seed health and resilience in challenging agricultural conditions.

3.3 Hormonal Regulation and Gene Expression

Nanoparticles play a vital role in regulating plant hormones and influencing gene expression, thereby enhancing seed germination and stress resilience. Nano-based seed treatments can modulate hormone levels, affecting key physiological processes. For instance, nanoparticles interact with hormone biosynthetic pathways, balancing essential hormones such as abscisic acid (ABA), which inhibits germination under stress, gibberellins (GA), which promote seed germination and root/shoot growth, and auxins, which enhance root elongation and cell division. Studies have shown that Fe_3O_4 nanoparticles increase gibberellin levels in rice, accelerating germination, while carbon nanotube (CNT) treatments enhance auxin activity, leading to improved root development. Additionally, nanoparticles influence gene expression by activating or suppressing stress-responsive genes. They upregulate heat shock proteins (HSPs) to protect cells from oxidative damage, activate aquaporin genes to improve water transport, and stimulate defense genes to enhance resistance against pathogens and environmental stress. For example, ZnO nanoparticles have been found to increase aquaporin gene expression in wheat under drought stress, improving water uptake and germination rates. These interactions highlight the potential of nanotechnology in optimizing seed performance and resilience under adverse conditions.

3.4 Controlled Release of Nutrients and Bioactive Compounds

To maximize seedling growth and development, polymeric and silica-based nanoparticles offer a regulated and prolonged release of nutrients, hormones, and biostimulants. In order to avoid nutrient loss from leaching and to ensure sustained availability throughout the early phases of seedling development, these nanoparticles encapsulate vital nutrients and release them in response to environmental conditions like pH and moisture. For example, it has been demonstrated that chitosan nanoparticles containing phosphate and nitrogen increase the effectiveness of nutrient uptake in rice seedlings. Furthermore, nanoparticles make it possible to administer growth regulators and biostimulants precisely to the seed embryo, enhancing stress resilience and encouraging early vigor. A notable example is polyvinyl alcohol (PVA) nanoparticles coated with cytokinin, which stimulated faster cell division and increased shoot biomass in soybean. By regulating nutrient availability and delivering growth-enhancing compounds with precision, nano-based seed treatments contribute to improved seedling establishment, resource efficiency, and overall agricultural sustainability.

3.5 Stress Alleviation and Protection Against Environmental Factors

Seed treatments based on nanotechnology increase stress tolerance by strengthening the seed's resistance to abiotic stresses such salt, drought, and extremely high or low temperatures. In order to maintain cell turgor and avoid dehydration, these nanoparticles promote the accumulation of osmolytes such as proline and carbohydrates, which aid in osmoregulation. Improved water retention allows seeds to survive in arid conditions, as seen in wheat seedlings treated with SiO_2 nanoparticles, which exhibited higher proline levels and improved drought resistance. Additionally, metal oxide nanoparticles such as ZnO and TiO_2 provide thermal and UV protection by absorbing harmful radiation and minimizing heat-induced oxidative stress. For instance, ZnO nanoparticles have been shown to enhance germination rates in barley under high-temperature conditions. By offering protection against environmental stresses, nano-based treatments contribute to improved seed viability, seedling vigour, and overall crop resilience in challenging agricultural conditions.

3.6 Encouragement of Root and Shoot Development

Since they promote cell division, elongation, and structural strength, nanoparticles are essential for promoting the growth of roots and shoots. Because ZnO and FeO_4 nanoparticles increase the flexibility of cell walls, roots can delve deeper into the soil for improved nutrient uptake and anchoring. By encouraging the growth of root hair, carbon nanotubes (CNTs) improve root development even more and improve the plant's capacity to absorb vital nutrients and water. In the meantime, silica nanoparticles fortify the tissues of shoots, enhancing their mechanical resistance to pests and wind. As an illustration of how nanotechnology might improve early seedling growth and overall plant vigor, maize seeds treated with carbon nanotubes showed noticeably longer roots and more nutrient absorption.

4 Benefits of Nano-Based Seed Treatment

Seed germination, seedling vigor, and stress tolerance are all improved by nano-based seed treatment. Nanomaterials' high surface area, nanoscale size, and special reactivity allow them to interact directly with seed cells and metabolic pathways, improving seed performance. By improving water and nutrient uptake, protecting against pathogens, and enhancing stress resilience, nanotechnology provides a powerful tool for sustainable agriculture. One of the primary benefits is the enhanced germination rate and seedling vigour. Nanoparticles improve water uptake and nutrient availability, accelerating the germination process. Their role in activating enzymes and metabolic pathways ensures the efficient conversion of stored nutrients into energy, leading to faster root and shoot development. For example, zinc oxide (ZnO) nanoparticles have been shown to increase the germination rate of maize under drought stress by improving water and zinc uptake, resulting in stronger seedlings.

The enhanced nutrient intake and efficiency made possible by metal and metal oxide nanoparticles, such as ZnO and FeO_4, is another significant benefit. These nanoparticles deliver essential micronutrients directly to seeds, promoting balanced growth and higher seedling biomass. Fe_3O_4 nanoparticles, for instance, have been found to enhance iron availability in rice, leading to improved chlorophyll synthesis and greater photosynthesis efficiency, ultimately boosting crop productivity.

Nano-based seed treatments also provide protection against pathogens, reducing seed mortality and increasing seedling survival rates. Silver (Ag) and copper (Cu) nanoparticles possess strong antimicrobial properties that safeguard seeds from fungal and bacterial infections. Research has demonstrated that silver nanoparticles effectively prevented fungal infections in wheat seeds, leading to higher seedling emergence rates and improved crop establishment.

Additionally, by promoting the synthesis of antioxidant enzymes like catalase (CAT) and superoxide dismutase (SOD), nanotechnology improves stress tolerance. These enzymes aid in reducing oxidative stress, and plants that have better osmoregulation are more resilient to heat, salinity, and drought. By boosting proline formation and fortifying cell walls, silicon dioxide (SiO_2) nanoparticles, for instance, have been shown to improve drought tolerance in wheat, assisting plants in retaining moisture and fending against dehydration. The precise and regulated transportation of growth regulators and nutrients is another important advantage. Polymeric nanoparticles, such as chitosan and polyvinyl alcohol (PVA), allow for the slow and controlled release of essential nutrients and bio-stimulants. This sustained nutrient supply ensures steady seedling development, reducing nutrient wastage. Studies show that chitosan nanoparticles significantly enhance nitrogen uptake in rice, resulting in improved seedling vigour and growth efficiency.

Finally, by reducing the need for excessive fertilizers and pesticides, nano-based seed treatments help to lessen their influence on the environment. Because of their great efficiency, less agrochemicals are needed, which reduces runoff and leaching that pollute the environment. ZnO nanoparticles, for example, have been demonstrated to improve wheat's nutrient use efficiency, lowering reliance on artificial fertilizers and encouraging more environmentally friendly farming methods. Nano-based seed treatments present a viable way to improve crop yield, safeguard the environment, and guarantee food security in a fast-changing climate by incorporating these cutting-edge technologies into contemporary farming.

5 Challenges and Limitations

One major challenge in nano-based seed treatments is the high production cost of nanomaterials, especially metal and polymer-based nanoparticles. Their complex synthesis makes large-scale application economically unfeasible. For instance, silver nanoparticles (AgNPs) offer antimicrobial and growth benefits, but their high-cost limits widespread use. Cost-effective synthesis methods are needed for broader adoption.

Another concern is nanoparticle toxicity and environmental impact. Metal nanoparticles like zinc oxide (ZnO) and copper oxide (CuO) can accumulate in soil, affecting microbial diversity and plant health. They may also enter the food chain, raising bioaccumulation and human health risks. Excessive ZnO exposure, for example, can cause root toxicity in wheat seedlings, underscoring the need for controlled application and risk assessments. Regulatory and safety issues further hinder adoption. The lack of clear guidelines from bodies like the EPA and EU limits investment in nanotechnology research. Standardization challenges also persist due to variations in nanoparticle synthesis, soil conditions, and crop responses. For example, ZnO nanoparticles affect rice and wheat differently depending on soil characteristics, making uniform application difficult.

Lastly, it is yet unknown how nanomaterials may affect agriculture in future generations. Long-term exposure to iron oxide (FeO_4) nanoparticles may decrease beneficial soil microorganisms, according to studies, which could have an impact on soil fertility. To fully comprehend their ecological impact and persistence, more research is required. Unlocking the full potential of nano-based seed treatments in sustainable agriculture requires addressing these issues through long-term research, standardization, regulatory frameworks, environmental assessments, and cost-effective synthesis.

6 Recent Advances and Future Prospects

Silver nanoparticles (AgNPs) have been found to enhance germination rates and stress tolerance by boosting antioxidant enzyme activity while also protecting seeds from fungal and bacterial infections. AgNPs have improved seedling vigor in wheat and rice under salinity stress. Advances in nanotechnology have demonstrated significant improvements in seed germination, stress tolerance, and plant growth through the use of nanoparticles. Recent research has highlighted the promising potential of nano-based seed treatments in improving seed germination, seedling vigor, and stress tolerance across a variety of crops.In a similar vein, it has been demonstrated that carbon nanotubes (CNTs) promote root elongation and seed water intake by increasing cell wall permeability, which in turn promotes the development of root hairs and the movement of nutrients. Research on soybean and maize has shown that seeds treated with carbon nanotubes (CNTs) have greater water absorption and faster root growth. Furthermore, zinc oxide nanoparticles (ZnO NPs) have demonstrated efficacy in boosting the activity of enzymes like catalase (CAT) and superoxide dismutase (SOD), which improves metabolic efficiency in the face of salinity and drought stress. ZnO NPs have been demonstrated to dramatically increase barley germination rates during drought, underscoring their potential to support seedling vigor and stress tolerance. These developments highlight how nanotechnology is revolutionizing contemporary agriculture and opening the door to more sustainable and effective agricultural production.

Future research in nanotechnology for agriculture holds immense promise, particularly in developing biodegradable nanomaterials, smart delivery systems, stress-resilient crops, and precision agriculture integration. The focus should be on eco-friendly nanoparticles like chitosan, silica, and polymer-based materials to minimize environmental impact while reducing soil accumulation and toxicity concerns. Engineered nanoparticles with targeted release mechanisms can enhance nutrient and hormone delivery at critical growth stages, with pH and moisture-responsive nanomaterials optimizing nutrient availability. Moreover, the combination of gene editing and nano-based treatments can improve stress tolerance and disease resistance, with nanoparticles serving as carriers for CRISPR/Cas systems to refine crop genetics. Additionally, the integration of nano-based seed treatments with smart sensors and data-driven techniques can revolutionize precision agriculture, allowing real-time monitoring of crop health and nutrient levels. This holistic approach will pave the way for sustainable farming practices, higher yields, and improved agricultural efficiency.

Conclusions

A major development in agricultural technology, nano-based seed treatment offers higher disease resistance, better stress tolerance and faster germination rates. Nanoparticles can help seeds resist harsh climatic conditions and increase crop output by facilitating improved nutrient uptake and metabolic activation. To ensure the safe and efficient deployment of this technology, however, issues pertaining to toxicity, environmental impact and regulatory control must be resolved. To optimize the advantages of nano-based seed treatment in sustainable agriculture, future research should concentrate on refining nanoparticle compositions, enhancing delivery methods and creating thorough safety regulations.

References

Abdel Latef, A.A.H., Abu Alhmad, M.F., Abdelfattah, K.E., 2017. The possible roles of priming with ZnO nanoparticles in mitigation of salinity stress in lupine (Lupinus termis) plants. J. Plant Growth Regul. 36 (1), 60–70.

Adhikary, S., Biswas, B., Chakraborty, D., Timsina, J., Pal, S., Chandra Tarafdar, J., Banerjee, S., Hossain, A., Roy, S., 2022. Seed priming with selenium and zinc nanoparticles modifies germination, growth and yield of direct-seeded rice (Oryza sativa L.). Sci. Rep. 12, 7103.

Aguilar-Perez, K.M., Aviles-Castrillo, J.I., Medina, D.I., Parra-Saldivar, R., Iqbal, H.M.N., 2020. Insight into nanoliposomes as smart nanocarriers for greening the twenty-first century biomedical settings. Front. Bioeng. Biotechnol. 8, 579536.

Ahuja, R., Sidhu, A., Bala, A., 2019. Synthesis and evaluation of iron(II) sulfide aqua nanoparticles (FeS-NPs) against Fusarium verticillioides causing sheath rot and seed discoloration of rice. Eur. J. Plant Pathol. 155 (1), 163–171.

Alharbi, N.S., Bhakyaraj, K., Gopinath, K., Govindarajan, M., Kumuraguru, S., Mohan, S.al., 2017. Gum-mediated fabrication of eco-friendly gold nanoparticles promoting cell division and pollen germination in plant cells. J. Clust. Sci. 28, 507–517.

Ali, M.H., Sobze, J.M., Pham, T.H., Nadeem, M., Liu, C., Galagedara, L., Cheema, M., Thomas, R., 2020. Carbon nanoparticles functionalized with carboxylic acid improved the germination and seedling vigor in upland boreal forest species. Nanomaterials (Basel) 10 (1).

Almutairi, Z., Alharbi, A., 2015. Effect of silver nanoparticles on seed germination of crop plants. J. Adv. Agric. 4, 280–285.

An, J., Zhang, M., Wang, S., Tang, J., 2008. Physical, chemical and microbiological changes in stored green asparagus spears as affected by coating of silver nanoparticles-PVP. LWT Food Sci. Technol. 41, 1100–1107.

An, Jing & Hu, Peiguang & Li, Fangjun & Wu, Honghong & Shen, Yu & White, Jason & Tian, Xiaoli & Li, Zhaohu & Giraldo, Juan. 2020. Emerging Investigator Series: Molecular mechanisms of plant salinity stress tolerance improvement by seed priming with cerium oxide nanoparticles. Environmental Science: Nano. 7(8):2214-2228.

Anderson do Espirito Santo Pereira. 2021. Nanotechnology potential in seed priming for sustainable agriculture. Nanomaterials.11(2):267

Arnott, A., Galagedara, L., Thomas, R., Cheema, M., Sobze, J.-M., 2021. The potential of rock dust nanoparticles to improve seed germination and seedling vigor of native species: a review. Sci. Total Environ. 775, 145139.

Arora, S., Sharma, P., Kumar, S., Nayan, R., Khanna, P., Zaidi, M.G.H., 2012. Goldnanoparticle induced enhancement in growth and seed yield of Brassica juncea. Plant Growth Regul. 66.

Bagherzade, G., Tavakoli, M.M., Namaei, M.H., 2017. Green synthesis of silver nanoparticles using aqueous extract of saffron (Crocus sativus L.) wastages and its antibacterial activity against six bacteria. Asian Pac. J. Trop. Biomed. 7, 227–233.

Bagherzadeh Homaee, M., Ehsanpour, A.A., 2016. Silver nanoparticles and silver ions: oxidative stress responses and toxicity in potato (Solanum tuberosum L) grown in vitro. Hortic. Environ. Biotechnol. 57, 544–553.

Begum, K., Hasan, N., Shammi, M., 2024. Selective Biotic Stressors’ Action on Seed Germination: A Review. Plant Sci. 346, 112156.

Bello-Bello, J.J., Chavez-Santoscoy, R.A., Lecona-Guzman, C.A., Bogdanchikova, N., Salinas-Ruiz, J., Gomez-Merino, F.C., 2017. Hormetic response by silver nanoparticles on in vitro multiplication of sugarcane (Saccharum spp. Cv. Mex 69-290) using a temporary immersion system. Dose-Response 15, 1559325817744945.

Bisht, G., Zaidi, M.G.H., Sandeep, A., 2014. Impact of gold nanoparticles on physiological and biochemical characteristics of Brassica juncea. J. Plant Biochem. Physiol. https://doi.org/10.4172/2329-9029.1000133.

Bravo Cadena, M., Preston, G.M., Van der Hoorn, R.A.L., Flanagan, N.A., Townley, H.E., Thompson, I.P., 2018. Enhancing cinnamon essential oil activity by nanoparticle encapsulation to control seed pathogens. Ind. Crop. Prod. 124, 755–764.

Chichiricco G and Poma A. 2015. Penetration and toxicity of nanomaterials in higher plants. Nanomaterials. 5(2):851-873.

De Castro e Silva, P., Pereira, L.A.S., de Rezende, E.M., dos Reis, M.V., Lago, A.M.T., Carvalho, G.R., Paiva, R., Oliveira, J.E., Marconcini, J.M., 2019. Production and efficacy of neem nanoemulsion in the control of Aspergillus flavus and Penicillium citrinum in soybean seeds. Eur. J. Plant Pathol. 155 (4), 1105–1116.

Dileep Kumar, G., Raja, K., Natarajan, N., Govindaraju, K., Subramanian, K.S., 2020. Invigouration treatment of metal and metal oxide nanoparticles for improving the seed quality of aged chilli seeds (Capsicum annum L.). Mater. Chem. Phys. 242, 122492.

Duran, N.M., Savassa, S.M., Lima, R.G.d., de Almeida, E., Linhares, F.S., van Gestel, C.A. M., Pereira de Carvalho, H.W., 2017. X-ray spectroscopy uncovering the effects of Cu based nanoparticle concentration and structure on phaseolus vulgaris germination and seedling development. J. Agric. Food Chem. 65, 7874–7884.

Dziergowska K and Izabela M. 2022. The role of nanoparticles in sustainable agriculture. In Smart Agrochemicals for Sustainable Agriculture. Elsevier; Academic Press. 2022. pp. 225-278.

El-Badri, A.M., Batool, M., Mohamed, I.A.A., Wang, Z., Wang, C., Tabl, K.M., Khatab, A., Kuai, J., Wang, J., Wang, B. 2022. Mitigation of the salinity stress in rapeseed (Brassica napus

L.) productivity by exogenous applications of bio-selenium nanoparticles during the early seedling stage. Environ. Pollut. 310, 119815.

Farias, B.V., Pirzada, T., Mathew, R., Sit, T.L., Opperman, C., Khan, S.A., 2019. Electrospun polymer nanofibers as seed coatings for crop protection. ACS Sustain. Chem. Eng. 7 (24), 19848–19856.

Fiol, Diego & Terrile, Maria & Frik, Jesica & Mesas, Florencia & Alvarez, Vera & Casalongue, Claudia. 2021. Nanotechnology in plants: recent advances and challenges. Journal of Chemical Technology & Biotechnology. 96:10.

Frona, D., Szenderak, J., Harangi-Rakos, M. 2019. The Challenge of Feeding the World. Sustainability , 11, 5816.

Garza-Alonso, C.A., Gonz Alez-GarcIA, Y., Cadenas-Pliego, G., Olivares-Saenz, E., Trejo-Tellez, L.I., Benavides-Mendoza, A., 2021. Seed priming with ZnO nanoparticles promotes early growth and bioactive compounds of Moringa oleifera. Not. Bot. Horti. Agrobo. 49, 12546.

Gopinath, K., Gowri, S., Karthika, V., Arumugam, A., 2014. Green synthesis of gold nanoparticles from fruit extract of Terminalia arjuna, for the enhanced seed germination activity of Gloriosa superba. J. Nanostruct. Chem. 4, 115.

Guha, T., Mukherjee, A., Kundu, R., 2022. Nano-scale zero valent iron (nZVI) priming enhances yield, alters mineral distribution and grain nutrient content of Oryza sativa L. cv. gobindobhog: a field study. J. Plant Growth Regul. 41, 710–733.

Haghighi, M., Teixeira da Silva, J.A., 2014. The effect of carbon nanotubes on the seed germination and seedling growth of four vegetable species. J. Crop. Sci. Biotechnol. 17, 201–208.

Hussain, A., Rizwan, M., Ali, Q., Ali, S., 2019. Seed priming with silicon nanoparticles improved the biomass and yield while reduced the oxidative stress and cadmium concentration in wheat grains. Environ. Sci. Pollut. Res. 26 (8), 7579–7588.

Judy, J.D., Unrine, J.M., Bertsch, P.M., 2011. Evidence for biomagnification of gold nanoparticles within a terrestrial food chain. Environ. Sci. Technol. Lett. 45, 776–781.

Kannaujia, R., Srivastava, C.M., Prasad, V., Singh, B.N., Pandey, V., 2019. Phyllanthus emblica fruit extract stabilized biogenic silver nanoparticles as a growth promoter of wheat varieties by reducing ROS toxicity. Plant Physiol. Biochem. 142, 460–471.

Kasote, D., Lee, J., Jayaprakasha, G., Patil, B., 2019. Seed priming with iron oxide nanoparticles modulate antioxidant potential and defense linked hormones in watermelon seedlings. ACS Sustain. Chem. Eng. 7.

Khan, M.N., Li, Y., Fu, C., Hu, J., Chen, L., Yan, J., Khan, Z., Wu, H., Li, Z., 2022. CeO2 nanoparticles seed priming increases salicylic acid level and ROS scavenging ability to improve rapeseed salt tolerance. Global Chall. 6, 2200025.

Khodakovskaya, M.V., Kim, B.-S., Kim, J.N., Alimohammadi, M., Dervishi, E., Mustafa, T., Cernigla, C.E., 2013. Carbon Nanotubes as Plant Growth Regulators: Effects on Tomato Growth, Reproductive System and Soil Microbial Community. Small 9 (1), 115–123.

Kolitsi LI and Yiantsios SG. 2020. Transport of nanoparticles in magnetic targeting: Comparison of magnetic, diffusive and convective forces and fluxes in the microvasculature, through vascular pores and across the interstitium. Microvascular Research.130:104007.

Kothamasu, P., Kanumur, H., Ravur, N., Maddu, C., Parasuramrajam, R., Thangavel, S., 2012. Nanocapsules: the weapons for novel drug delivery systems. Bioimpacts 2 (2), 71–81.

Kumar, V., Guleria, P., Kumar, V., Yadav, S.K., 2013. Gold nanoparticle exposure induces growth and yield enhancement in Arabidopsis thaliana. Sci. Total Environ. 461-462, 462–468.

Lahiani, M.H., Chen, J., Irin, F., Puretzky, A.A., Green, M.J., Khodakovskaya, M.V., 2015. Interaction of carbon nanohorns with plants: uptake and biological effects. Carbon 81, 607–619.

Lal, M.K., Tiwari, R.K., Altaf, M.A., Kumar, A., & Kumar, R., 2023. Editorial: Abiotic and biotic stress in horticultural crops: insight into recent advances in the underlying tolerance mechanism. Frontiers in Plant Sci. 14.

Li, W., Niu, Y., Zheng, Y., Wang, Z., 2022. Advances in the Understanding of Reactive Oxygen Species-Dependent Regulation on Seed Dormancy, Germination and Deterioration in Crops. Front. Plant Sci. 13.

Li, Y., Liang, L., Li, W., Ashraf, U., Ma, L., Tang, X., Pan, S., Tian, H., Mo, Z., 2021. ZnO nanoparticle-based seed priming modulates early growth and enhances physiobiochemical and metabolic profiles of fragrant rice against cadmium toxicity. J. Nanobiotechnology 19, 75.

Luo, J., Gao, Y., Liu, Y., Huang, X., Zhang, D.X., Cao, H., Jing, T., Liu, F., Li, B., 2021. Self-Assembled Degradable Nanogels Provide Foliar Affinity and Pinning for Pesticide Delivery by Flexibility and Adhesiveness Adjustment. ACS Nano 15 (9), 14598–14609.

Madeira A, Moura TF and Soveral G. 2016. Detecting aquaporin function and regulation. Frontiers in Chemistry. 4:3.

Mahakham, W., Sarmah, A.K., Maensiri, S., Theerakulpisut, P., 2017. Nanopriming technology for enhancing germination and starch metabolism of aged rice seeds using phytosynthesized silver nanoparticles. Sci. Rep. 7 (1), 8263.

Mahakham, W., Theerakulpisut, P., Maensiri, S., Phumying, S., Sarmah, A.K., 2016. Environmentally benign synthesis of phytochemicals-capped gold nanoparticles as nanopriming agent for promoting maize seed germination. Sci. Total Environ. 573, 1089–1102.

Maswada, H.F., Djanaguiraman, M., Prasad, P.V.V., 2018. Seed treatment with nano-iron (III) oxide enhances germination, seeding growth and salinity tolerance of sorghum. J. Agron. Crop Sci. 204 (6), 577–587.

Mazhar, M.W., Ishtiaq, M., Maqbool, M., Ullah, F., Sayed, S.R.M., Mahmoud, E.A., 2023. Seed priming with iron oxide nanoparticles improves yield and antioxidant status of garden pea (Pisum sativum L.) grown under drought stress. S. AFR. J. BOT. 162, 577–587.

Mohammadi, R., Maali Amiri, R., Mantri, N., 2014. Effect of TiO2 nanoparticles on oxidative damage and antioxidant defense systems in chickpea seedlings during cold stress. J. Plant Physiol. 61.

Mukherjee, A., Peralta-Videa, J.R., Bandyopadhyay, S., Rico, C.M., Zhao, L., Gardea-Torresdey, J.L., 2014. Physiological effects of nanoparticulate ZnO in green peas (Pisum sativum L.) cultivated in soil. Metallomics 6, 132–138.

Nair, P.M., Chung, I.M., 2014. A mechanistic study on the toxic effect of copper oxide nanoparticles in soybean (Glycine max L.) root development and lignification of root cells. Biol. Trace Elem. Res. 162, 342–352.

Nair, P.M., Chung, I.M., 2015. Study on the correlation between copper oxide nanoparticles induced growth suppression and enhanced lignification in Indian mustard (Brassica juncea L.). Ecotoxicol. Environ. Saf. 113, 302–313.

Nawaz, M., Sun, J., Shabbir, S., Khattak, W.A., Ren, G., Nie, X., Bo, Y., Javed, Q., Du, D., Sonne, C., 2023. A review of plants strategies to resist biotic and abiotic environmental stressors. Sci. Total Environ. 900, 165832.

Nile, SH., Thiruvengadam, M. and Wang, Y. 2022. Nano-priming as emerging seed priming technology for sustainable agriculture—Recent developments and future perspectives. Journal of Nanobiotechnology. 20(1):1-31.

Parveen, A., Mazhari, B.B.Z., Rao, S., 2016. Impact of bio-nanogold on seed germination and seedling growth in Pennisetum glaucum. Enzym. Microb. Technol. 95, 107–111.

Patlolla, A.K., Berry, A., May, L., Tchounwou, P.B., 2012. Genotoxicity of silver nanoparticles in Vicia faba: a pilot study on the environmental monitoring of nanoparticles. Int. J. Environ. Res. Public Health 9, 1649–1662.

Pereira, A.d.E.S., Oliveira, H.C., Fraceto, L.F., 2019. Polymeric nanoparticles as an alternative for application of gibberellic acid in sustainable agriculture: a field study. Sci. Rep. 9 (1), 7135.

Qian, H., Peng, X., Han, X., Ren, J., Sun, L., Fu, Z., 2013. Comparison of the toxicity of silver nanoparticles and silver ions on the growth of terrestrial plant model Arabidopsis thaliana. J. Environ. Sci. 25, 1947–1956.

Rico, C., Morales, M., McCreary, R., Castillo-Michel, H., Barrios, A., Hong, J., Tafoya, A., Lee, W.-Y., Varela-Ramirez, A., Peralta-Videa, J. 2013. Cerium oxide nanoparticles modify the antioxidative stress enzyme activities and macromolecule composition in rice seedlings. Environ. Sci. Tech. 47.

Rizwan, M., Ali, S., Ali, B., Adrees, M., Arshad, M., Hussain, A., Ur Rehman, M.Z., Waris, A.A., 2019. Zinc and iron oxide nanoparticles improved the plant growth and reduced the oxidative stress and cadmium concentration in wheat. Chemosphere 214, 269–277.

Roberts A. 2003. Plasmodesmata and the control of symplastic transport. Plant and Cell Environment. 26:103-124.

Salachna, P., Byczynska, A., Zawadzinska, A., Piechocki, R., Mizielinska, M., 2019. Stimulatory effect of silver nanoparticles on the growth and flowering of potted oriental lilies. Agronomy. 9.

Salam, A., Khan, A.R., Liu, L., Yang, S., Azhar, W., Ulhassan, Z., Zeeshan, M., Wu, J., Fan, X., Gan, Y., 2022. Seed priming with zinc oxide nanoparticles downplayed ultrastructural damage and improved photosynthetic apparatus in maize under cobalt stress. J. Hazard. Mater. 423, 127021.

Savassa, S., Duran, N., Rodrigues, E., Almeida, E., Gestel, C., Bompadre, T., de Carvalho, H.W.P., 2018. Effects of ZnO nanoparticles on Phaseolus vulgaris germination and seedling development determined by X-ray spectroscopy. ACS Appl. Nano Mater. 1.

Schwab F, Zhai G, Kern M, Turner A, Schnoor JL and Wiesner MR. 2016. Barriers, pathways and processes for uptake, translocation and accumulation of nanomaterials in plants-Critical review. Nanotoxicology. 10(3):257-78.

Sharma, P., Urfan, M., Anand, R., Sangral, M., Hakla, H.R., Sharma, S., Das, R., Pal, S., Bhagat, M., 2022. Green synthesis of zinc oxide nanoparticles using Eucalyptus lanceolata leaf litter: characterization, antimicrobial and agricultural efficacy in maize. Physiol. Mol. Biol. Plants 28, 363–381.

Shcherbakova, E., Shcherbakov, A. andronov, E., Gonchar, L., Kalenska, S., Chebotar, V., 2017. Combined pre-seed treatment with microbial inoculants and Mo nanoparticles changes composition of root exudates and rhizosphere microbiome structure of chickpea (Cicer arietinum L.) plants. Symbiosis 73.

Siddiqui, M.H., Al-Whaibi, M.H., 2014. Role of nano-NPs in germination of tomato (Lycopersicum esculentum seeds Mill.). Saudi. Aust. J. Biol. Sci. 21 (1), 13–17.

Spinoso-Castillo, J.L., Chavez-Santoscoy, R.A., Bogdanchikova, N., Perez-Sato, J.A., Morales-Ramos, V., Bello-Bello, J.J., 2017. Antimicrobial and hormetic effects of silver nanoparticles on in vitro regeneration of vanilla (Vanilla planifolia Jacks. Ex Andrews) using a temporary immersion system. PCTOC 129, 195–207.

Sun, H., Qu, G., Li, S., Song, K., Zhao, D., Li, X., Yang, P., He, X., Hu, T., 2023. Iron nanoparticles induced the growth and physio-chemical changes in Kobresia capillifolia seedlings. Plant Physiol. Biochem. 194, 15–28.

Sundaria, N., Singh, M., Upreti, P., Chauhan, R.P., Jaiswal, J.P., Kumar, A., 2019. Seed priming with iron oxide nanoparticles triggers iron acquisition and biofortification in wheat (Triticum aestivum L.) grains. J. Plant Growth Regul. 38 (1), 122–131.

Sutradhar, K.B., Khatun, S., Luna, I.P. 2013. Increasing possibilities of nanosuspension. J. Nanotechnol. 2013, 346581.

Syu, Y.-y., Hung, J.-H., Chen, J.-C., Chuang, H.-w., 2014. Impacts of size and shape of silver nanoparticles on Arabidopsis plant growth and gene expression. Plant Physiol. Biochem. 83, 57–64.

Ul Haq, T., Ullah, R., Khan, M.N., Nazish, M., Almutairi, S.M., Rasheed, R.A., 2023. Seed priming with glutamic-acid-functionalized iron nanoparticles modulating response of Vigna radiata (L.) R. Wilczek (Mung Bean) to induce osmotic stress. Micromachines 14, 736.

Vannini, C., Domingo, G., Onelli, E., De Mattia, F., Bruni, I., Marsoni, M., 2014. Phytotoxic and genotoxic effects of silver nanoparticles exposure on germinating wheat seedlings. J. Plant Physiol. 171, 1142–1148.

Vannini, C., Domingo, G., Onelli, E., Prinsi, B., Marsoni, M., Espen, L., 2013. Morphological and proteomic responses of Eruca sativa exposed to silver nanoparticles or silver nitrate. PLoS ONE 8, e68752.

Wu H and Li Z. 2022. Nano-enabled agriculture: How nanoparticles cross barriers in plants? Plant. Communications. Pp:100346.

Yasmeen, F., Raja, N.I., Razzaq, A., Komatsu, S., 2017. Proteomic and physiological analyses of wheat seeds exposed to copper and iron nanoparticles. Biochim. Biophys. Acta, Proteins Proteomics 1865, 28–42.

Ye, Y., Cota-Ruiz, K., Hernandez-Viezcas, J.A., Valdes, C., Medina-Velo, I.A., Turley, R.S., Peralta-Videa, J.R., Gardea-Torresdey, J.L., 2020. Manganese nanoparticles control salinitymodulated molecular responses in Capsicum annuum L. through priming: A sustainable approach for agriculture. ACS Sustainable. Chem. Eng. 8 (3), 1427–1436.

Younis M, Abdel-Aziz H and Heikal Y. 2019. Nanopriming technology enhances vigor and mitotic index of aged Vicia faba seeds using chemically synthesized silver nanoparticles. South African Journal of Botany.125:393-401.

Zhou, X., Jia, X., Zhang, Z., Chen, K., Wang, L., Chen, H., Yang, Z., Li, C., Zhao, L., 2022. AgNPs seed priming accelerated germination speed and altered nutritional profile of Chinese cabbage. Sci. Total Environ. 808, 151896.