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Application of Nanotechnology in Improving Seed Quality and Crop Productivity : Prospects and Developments - A Review

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Abstract

Ensuring food security in developing countries is highly challenging because of low productivity of the agriculture sector, high post farming losses, degradation of natural resources, less or no value addition and high population progress. Researchers are striving to adopt newer technologies to enrich supply and to narrow down the food-demand gap. Nanotechnology, a new promising and interesting field of science and it has a great applications in the field of agriculture like input managements, plant protection, seed treatments, biotechnology etc. agriculture. Nanotechnology deals with manipulation of matter with a minimum of one-dimension sized ranges from 1 to 100 nanometer. One nanometre (nm) is equivalent to one-billionth of a metre, 10^{-9} m. In modern agriculture, sustainable production and efficiency are unimaginable without the application of agrochemicals, pesticides, fertilizers, etc. The applications of nanotechnology in agriculture currently focuses on target farming that comprises the use of nanoparticles with unique properties to enhance crop and livestock productivity. Nanotechnology has the potential to extend food quality, detection of plant and animal diseases, plant protection, monitoring of plant growth, global food production and improving seed quality. Through nanoparticles as a treatment, seeds can speed up germination, increases seedling strength, vigour and improve seed quality. The current review is an endeavour to summarize and assess the prospects of application of nanotechnology in improving seed quality either by pre-sowing or pre-storage treatments through nanoparticles.

Keywords : Nanoparticles, Seed quality, Enhancement, Crop production, Seed storage

The foremost universal challenge on our planet is the demand of establishing food security for a hastily increasing population in the world. Estimates suggest that food demand is likely to increase from 59 to 98 per cent for the world population which is going to reach about 9 billion by 2050 (Duro *et al*., 2020). Farmers throughout the world will focus on using new novelties and technologies for augmenting the production of crops through intensive and extensive agriculture. These efforts further strengthen through the use of nano-modified stimulants and precision farming. Agricultural efficiency, soil improvement, secure water use, distribution of food in stores, and its quality are basic aspects of food security that may be amended via advances in nanotechnology research (Ashraf *et al*., 2021 and Sastry *et al.,* 2011). In modern agriculture, sustainable production and proficiency are unimaginable without the use of agrochemicals such as pesticides, fertilizers, etc. Still, every agrochemical has some potential issues including water pollution or deposits on food products that are harmful to the human being and environmental health, thus the precise management and control of inputs could allow reducing this risk. There is a need to use the advanced technique which can help agriculture to improve the quality and increase yield under diverse agroclimatic situations. The development of alternate approach with use of engineered smart nanotools could be excellent strategy to make a revolution in agricultural system and thus eradicate the effect of modern agriculture on the environment as well as to boost both the quality and quantity of yields (Sekhon, 2014). Nanotechnology is the emerging field which has unbelievable potentials to modernize agriculture and allied fields. No doubt that the sustainable development of agriculture totally depends on the new and advanced techniques like nanotechnology. In the field of agriculture, nanotechnology accentuate currently on target farming that involves the use of nanoparticles with unique properties to enhance crop and livestock production and productivity.

The main objective of nanotechnology is to improve the efficiency and sustainability of agricultural practices by putting less input like nano fertilizers and producing less waste than conventional products and approaches. Nanotechnology has huge potentials in agricultural uprising, high reactivity, better bio-availability, bio-activity and the surface properties of nanoparticles. There is a rising demand for interference of ecologically safe and sound, environmentally compatible techniques in crop production which will provide universal food security and improved agricultural produces. To accomplish this object, application of nanoparticles or nanomaterial is a potential alternate to traditional agricultural techniques which have severely damaged the agro-ecosystem (Fig. 1).

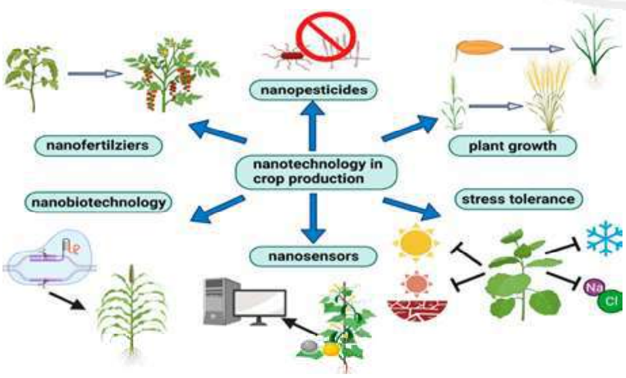

Fig. 1: Role of nanotechnology in Agriculture (Adapted from Liu *et al*., 2021)

Recent studies have revealed that nanoparticles have effects on seeds and plants (Acharya *et al.*, 2019). Some nanoparticles have inhibitory effects on the germination or phytotoxicity in seedlings (Pelegrino *et al.*, 2020). However, others can act as stimulants, enhancing seed metabolism, seedling vigour and plant growth by acting in cellular signalling pathways (Acharya *et al.*, 2019 and Mahakham *et al.*, 2017). These effects depend on properties of nanoparticle (physical-chemical) such as size, shape, zeta potential and concentration, which are some of the factors that regulate the biological responses (Acharya *et al.*, 2019). The zeta potential is related to the net surface charge that nanoparticles have. It is one of the key properties of the particle that can affect the particle stability as well as its cell adhesion. Knowledge of zeta potential can be used to help optimize formulation development for suspensions or nanoparticle dispersions. These properties have key roles in nanoparticle uptake and translocation in plants. As an example, small-sized nanoparticles cross biological barriers more effectively. The surface charge of the nanoparticles is also very important. Positively or negatively charged nanoparticles can be taken up by the leaves and translocated to the roots, but only negatively charged nanoparticles are taken up by the roots. Positive charges encourage the production of mucilage, which prevents their uptake by plants (Spielman-Sun *et al.*, 2019). Nano-treatment can be advocated to seeds in order to provide protection during storage, improve germination and other criteria, besides plant growth, as well as increased resistance of crops to abiotic or biotic stresses. Furthermore, it can also help to reduce the required quantities of pesticides and fertilizers. Novel studies showed that seed nano treatment is able to stimulate different genes during the germination, especially those genes related to plant stress resistance. The usage of nanotechnology for seed treatment is a new area of research, although studies have already shown promising results (Mahakham *et al.,* 2017 and Abbasi Khalaki *et al.,* 2021) (Fig. 2). Nano seed treatment can be used for seed protection, as many nanoparticles have antimicrobial activities and also can load antimicrobial agents (Bambo *et al*., 2019 and Abbasi Khalaki *et al*., 2021).

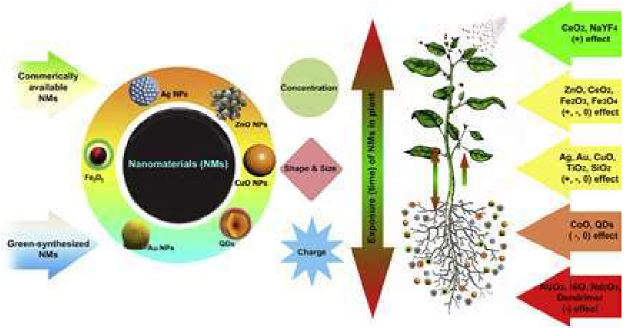

Fig. 2 : Potential of nanoparticles on seed germination and vigour (Adapted from Verma *et al.,* 2018)

Enhancement of Seed Quality through Nanotechnology

The germination of seeds is a complex phase in the life cycle of plant, which enables seedling development, survival and population dynamics. However, seed germination is largely affected by different factors including environmental aspects, genetic trait, moisture availability and soil fertility. In this regard, an extensive number of studies have revealed that the application of nanomaterials has positive effects on germination as well as plant growth and development. A few studies have established that nano materials have the potential to penetrate the seed coat and improve the ability of absorption and utilization of water, which stimulates enzymatic system and ultimately improves germination and seedling growth (Lu *et al*., 2002 and Banerjee *et al*., 2016). However, the mechanism of nano material induced water uptake inside the seed is still an enigma.

Nano-Seed Priming

Seed priming is a good old technique used in agriculture to promote seed germination and plant establishment, based on a primary preparation of seeds prior to sowing. Seed nano-priming is a novel technology that uses nanomaterials, mainly nanoparticles, for seed priming (Mahakham *et al*., 2017; Kasote *et al*., 2019 and Shukla *et al*., 2019). There is a crucial difference between seed priming and nano-seed priming, since conventional seed priming mainly contains water (hydropriming) or solutions containing materials (nutrients, hormones, or biopolymers) that adsorb on the seed and can result in seed coating or dressing. In nano-seed priming, the media used are suspensions or nano formulations, where the nanoparticles may or may not be taken up by the seeds (Acharya *et al*., 2019). Even when nanoparticle uptake occurs, the highest fraction is retained on the seed surface as coating (Savassa *et al.,* 2018; Duran *et al*., 2017 and Montanha *et al.,* 2020). Seed coating can be used to treat seeds with fungicides or bactericides in order to protect against pathogens in the field or during storage (Gross *et al*., 2020). The first studies showing the potential of nanomaterials to affect seed germination was reported by Khodakovskaya *et al*. (2009). These authors demonstrated that carbon nanotubes could be taken up by tomato seeds. The carbon nanotubes increased water uptake, resulting in tomato plants with a 2-fold increased number of flowers (Khodakovskaya *et al.,* 2009). Other studies have also demonstrated that carbon nanotubes can moderate seed metabolism in plants, such as tomato, barley, soybean and maize, increasing the gene expression of several types of water channel proteins (Lahiani *et al*., 2013). Different nanomaterials (metallic, biogenic metallic and polymeric nanoparticles) have also shown potential for seed nano-priming (Mahakham *et al*., 2017 and Falsini *et al*., 2019), resulting in the stimulation of plant growth and enhancement in morphological and metabolic traits. This process can promote fast root and shoot development, with changes in the expression of genes that moderate metabolic processes, such as phytohormone production. Seed nano-priming changes the activity of the seed defense system, increasing the antioxidant levels and enzyme activities, so that the plants become more resistant to pests and other biotic and abiotic stresses under field conditions (Acharya *et al.*, 2019 and Mahakham *et al.*, 2017).

Application of Nanoparticles

The potential applications of nanoparticles will be considered in two groups: (i) active nanoparticles and (ii) sustained release nanocarrier systems. Table 1 shows systems that have been engaged for seed priming / coating, together with their potential effects as stimulants or against biotic and abiotic stresses.

TABLE 1

Nano seed priming and coating to assess the seed quality parameters and plant protection

Nanoparticle system	Main effects	Reference
Biosynthesized silverNanoparticles produced using lime leaf extracts	In rice seeds it has increased water uptake, aquaporin gene expression, enzyme activity, seedling vigor and also plant morphology and biomass	Mahakham *et al*., 2017
Iron oxide nanoparticles	Enhanced growth, biomass accumulation and net photosynthesis in sorghum and also increased seedling vigor, biochemical activity, biomass and water content in leaves	Maswada *et al*., 2018
Biogenic iron nanoparticles produced using onion extracts	Increased seedling vigor, plant morphology, enzyme activity and plant growth regulator in watermelon	Kasote *et al*., 2019
Zinc oxide and iron oxidenanoparticles	In wheat, it enhanced plant morphology, biomass, biochemical activity, cadmium uptake and biofortification	Rizwan *et al*., 2019
Silicon nanoparticles	In wheat, it has shown rapid germination, increased biomass accumulation and water absorption potential of seeds	Hussain *et al*., 2019
Biogenic zinc nanoparticles produced using brown seaweed (*Turbinaria ornata*) extracts	Enhanced seedling vigor, antioxidant enzymes and bio fortification in rice	Itroutwar *et al*., 2019
Nanoparticles of zinc,titanium, and silver	In chilli, it has increased seed and seedling vigor, plant morphology, enzyme activity and plant growth regulator	Kumar *et al*., 2020
Chitosan/ tripolyphosphatenanoparticles	Enhanced growth physiology, increased metabolites, enzymatic activities andanatomical properties of plants in wheat	Li *et al*., 2019
Manganese oxidenanoparticles	In maize, it has increased water uptake, aquaporin gene expression, enzyme activity, seedling vigor and also plant morphology and biomass	Ye *et al*., 2020
Iron sulphide aqua nanoparticles	Increases seedling vigor, plant morphology, enzyme activity and plant growth regulator in rice	Ahuja *et al*., 2019
Copper nanoparticles	Enhanced growth, biomass accumulation and net photosynthesis in beans. It also increased seedling vigor, biochemical activity, biomass and water content in leaves	Duran *et al*., 2017
Zinc nanoparticles	Enhanced seedling vigor, antioxidant enzymes and bio fortification in common bean	Savassa *et al*., 2018
Chitosan nanoparticles	In rice, it has increased water uptake, enzyme activity, seedling vigor and also plant morphology and biomass	Divya *et al*., 2019

Nanoparticle system	Main effects	Reference
Zinc nanoparticles	Enhanced growth physiology, increased metabolites, salinity resistance, biochemical activity and ROS levels in lupin	Abdel Latef *et al*., 2017
Iron nanoparticles	Enhanced seedling vigor (dose dependent), plant morphology and yield in wheat	Sundaria *et al*., 2019
Copper and iron nanoparticles	Enhanced enzymatic activity, biochemical activity, anti-oxidant activity, abiotic stress resistance in wheat	Yasmeen *et al*., 2017
Molybdenum nanoparticles	In chickpea, it has enhanced seedling vigor, plant morphology and yield	Shcherbakova *et al*., 2017

Seed nano-priming with nanochemicls based on above mentioned metals (Table 1) have shown considerable potential for agricultural applications. For example, Kumar *et al*. (2020) primed chilli seeds with metal oxide nanoparticles (zinc, titanium and silver) and found that zinc oxide nanoparticles improve germination and seedling development, while these effects are not observed for the other tested metal-based nanoparticles (titanium and silver). Itroutwar *et al*. (2019) found that biogenic zinc nanoparticles produced from brown seaweed (*Turbinaria ornata*) extracts increased seed germination, vigor index and seedling establishment. In addition, the plants showed high contents of antioxidant enzymes and there was a dose-response accumulation of zinc in the seedlings, according to the concentration used for seed priming. Mahakham *et al*. (2016) primed aged maize seeds with biogenic gold nanoparticles synthesized by galangal rhizome extracts. They found that, 10 ppm concentration has improved the emergence from aged seeds by 83 per cent and seed vigor index by 3-fold, compared to the control. Mahakham *et al*. (2017) found that priming rice seeds with biogenic silver nanoparticles made by using kaffir lime leaf extract improved the amylase activity and water uptake of the seeds, improving both germination and plant biomass (Pelegrino *et al*., 2020). Kasote *et al*. (2019) primed watermelon seeds with biogenic iron nanoparticles produced by onion extracts, which resulted in the increase of germination and plant growth. The nanoparticle doesn't cause adverse antioxidant and chlorophyll effects, compared to the effects of the bulk chemicals ($FeCl_3$ and Fe_2O_3). The nanoparticles are taken up and translocated into the seed endosperm, leading to increased non-enzymatic antioxidant levels in the seeds. Acharya *et al*. (2019) primed onion seeds with biogenic silver and gold nanoparticles produced using onion extract. They observed increase in seedling emergence, number of leaves, plant biomass, and productivity, compared to unprimed and hydro-primed seeds. However, the gold nanoparticles provided better results compared to silver nanoparticles.

Polymeric nanoparticles used for seed coatings are generally larger than 100 nm (Falsini *et al.,* 2019), providing slow release of active compounds used to modify plant metabolism or to fight against pathogens (Shakiba *et al*., 2020 and Falsini *et al*., 2019). Many nanocarrier systems based on biopolymers have the potential to be used for seed treatment, including alginate (Du *et al*., 2019), zein (De Oliveira *et al*., 2019), cellulose (Coelho *et al*., 2018), synthetic biopolymers (poly-epsilon-caprolactone, poly (lactic-co-glycolic acid), poly(lactic acid) and lipid nanoparticles. Chitosan is another biopolymer that has been used to formulate nanocarrier systems for agricultural applications. This polymer has fungicidal properties and also acts in plant metabolism, activating defense mechanisms (Maluin *et al*., 2020 and Kashyap *et al*., 2015). In addition to germination, nanoparticles, such as ZnO, TiO2, MWCNTs, FeO, ZnFeCu-oxide, and hydroxyfullerenes increase crop growth and development with quality enhancement in many crop species including peanut, soybean, mungbean, wheat, onion, spinach, tomato, potato and mustard (Dubey *et al*., 2016 and Shojaei *et al*., 2019).

Effect of Nanoparticles on Plant Metabolism under Abiotic and Biotic Stresses

An abiotic and biotic stress reduces production and increases economic losses. Abiotic stresses include environmental factors, such as drought, flood, heat or cold, salinity, or nutrient-deficient soils. Biotic stresses are caused by microbial pathogens (bacteria or fungi), insects, or weeds that compete for nutrients (Zhao *et al*., 2020 and Camara *et al*., 2019). The application of seed nano-priming in agriculture can improve the quality of seeds and increase resistance against stress conditions. Nanoparticles can directly act against pathogens, as well as alter the metabolism of seeds and plants, consequently enhancing the innate immune system, altering hormone production and making the plants more resistant to diseases or abiotic stress (Panyuta *et al*., 2016) - (Fig. 3).

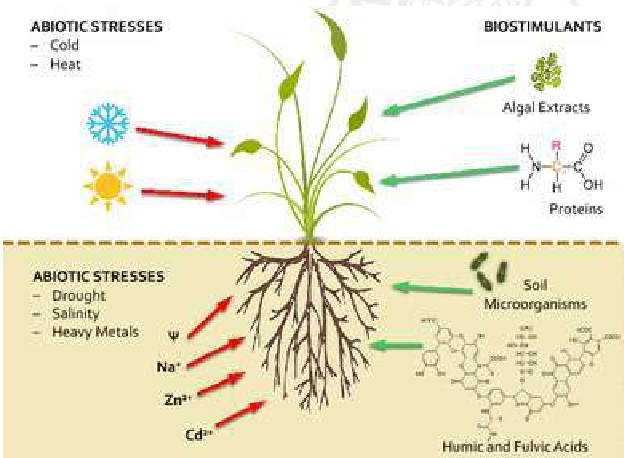

Fig. 3 : Application of nanoparticles to sustain biotic and abiotic stresses (Adapted from Van Oosten *et al*., 2017)

The nanoparticles uptake under seed coating can stimulate the ROS production, acting in different metabolic pathways, increase the level of active gibberellins, and the mobilization of storage proteins (Chandrasekaram *et al*., 2020). In addition, the effect of nanoparticles in increasing water uptake by the seeds can cause sufficient stress to activate germination, increasing the activities of enzymes in phases I and II of the process (Joshi *et al*., 2018). Seed nano-priming has been shown to increase germination, since these systems are able to keep ROS levels in the optimum range covered by the oxidative window that promotes seed germination (Kasote *et al*., 2019 and Guha *et al*., 2018).

During stress conditions, nanoparticles can act to reduce seed ROS levels, due to increased activity of enzymes, such as superoxide dismutase, catalases and peroxidase, hence reducing seed cell damage (Guha *et al*., 2018). The storage of seeds for long duration at low temperatures results in aging, which can greatly decrease the germination rate (Mahakham *et al.,* 2016). After long periods of seed storage, the cells produce excess ROS and reduce antioxidant levels, causing metabolic side effects that result in decrease of the germination index. The use of biogenic metallic nanoparticles has been shown to be able to ROS at optimum levels, resulting in enhanced germination of aged seeds. The biogenic nanoparticles can be coated with many compounds that are natural reducing agents and act to reduce ROS levels in seeds (Mahakham *et al*., 2017 and Guha *et al*., 2018).

Several systems have been shown to be active against pathogens. Ahuja *et al*. (2019) demonstrated that iron (II) sulfide nanoparticles were more active than the fungicide Carbendazim to control the fungus *Fusarium verticillioides* in rice seeds. Silver nanoparticles are effective against plant pathogens, including *Aspergillus flavus, Aspergillus niger, Aspergillus fumigatus* and *Colletotrichum capsica,* showing great potential for seed protection. Metallic nanoparticle systems can be used for both seed priming and seed defence, as demonstrated for nanoparticles composed of iron (Ahuja *et al*., 2019), copper (Van Nguyen *et al.,* 2022), silver (Mahakham *et al*., 2017) and silica. Sathiyabama and Muthukumar, (2020) have primed rice seeds with chitosan / guar nanoparticles, which have showed improved plant development, higher levels of chlorophyll and anti-fungal activity (71%) against the rice pathogen *Pyricularia grisea.* Kumar *et al*. (2020) showed that nanoparticles of zinc, titanium and silver could decrease pathogen infections caused by *Aspergillus flavus, Aspergillus niger, Aspergillus fumigatus* and

Colletrotrichum capsica in Chilli seeds. It was also found that these nanoparticles are active against insects and pests. Diagne *et al.* (2019) examined the effectiveness of silica nanoparticles against *Caryodon serratus* at different concentrations (0.17, 0.33, 0.67 and 1.7 mg/kg) on their mortality and fecundity. Consequence showed that silica nanoparticles have high toxicity on *C. serratus* adults and mortality increased with concentrations and time of exposure. Up to 100 per cent mortality was observed with high concentrations (0.67 and 1mg/kg) after 6 and 7 days exposure, respectively. Therefore, the silica nanoparticles can be used as a valuable tool for control of *C. serratus* in stored groundnut and to increase the shelf life of groundnut. Maswada *et al.* (2018) proved that sorghum seeds treated with nano-iron (III) has improved germination, with the plants showing increased chlorophyll contents and improved growth under saline conditions. These results indicate that this system could be used not only to increase seed germination but also to elude stress conditions. In another study, priming lupin seeds with zinc nanoparticles enhanced plant development under saline conditions, due to increased levels of photosynthetic pigments, phenols, organic molecules, and antioxidant enzymes. In case of heavy metal contamination, Rizwan *et al*. (2019) reported that priming of wheat seeds with iron and zinc nanoparticles reduced the absorption of cadmium, resulting in low cadmium concentrations in the grains. Hussain *et al.* (2019) revealed that, when seed germinated in soil contaminated with cadmium, seed priming with silicon nanoparticles was able to decrease cadmium uptake, increase plant biomass, photosynthetic rate, and levels of carotenoids and chlorophylls a and b, and reduce the formation of reactive oxygen species (ROS) and antioxidant enzymes activity. These results revealed the potential of seed-nano priming to relieve plant stress caused by saline conditions, drought, and the presence of heavy metals, or nutrient deficiency, with the modulation of metabolism to resist stress conditions and increase plant growth.

In the field of agriculture, nanotechnology has been used to enhance the crop production with quality enrichment by improving farming systems. Seed-nano priming is one of the tools that can be engaged to promote sustainability. The use of nano-based technology for seed treatment has prospective to move the traditional agriculture based on the use of agrochemicals to a more sustainable agriculture, once these systems stimulate the establishment of plants, as well as provide protection against biotic and abiotic stresses, resulting in enhancements of productivity and food quality. It has been explained by several scientists that nanoparticles can effectively speed up germination, enhances seedling strength, vigour and improve seed quality. Despite a lot of research carried with nanoparticles in the field of agriculture and its well understood that nanoparticles have both positive and negative effects on germination and seed quality. The toxicity of many nanoparticles is still indefinable; it depends on the size, concentration and duration of the exposure of nanoparticles. Although this review describes the potential level of this technology for improving seed quality, more research on the application and specified toxicity levels for the beneficial effects of nanoparticles is required in order to provide a better understanding of this technology's potential as well as to address biosafety concerns with nanotechnology in agriculture. In the majority of countries, there is no consistent or even clear statutory framework for nano products. Despite major advancements in nanoscale research, this has unintentionally delayed its commercialisation. This requires a thorough analysis of the issues preventing the development of nanotechnology related legislation. Federal regulations must take public opinion into considerations about nanotechnology enabled products used in agriculture. Building of standards and laboratories for testing, validating, and certifying nanomaterials for commercial usage would be crucial in addition to law.

References

Abbasi Khalaki, M., Moameri, M., Asgari Lajayer, B. and Astatkie, T., 2021, Influence of nano-priming on seed germination and plant growth of forage and medicinal plants. *Plant Growth Regul.*, **93** (1) : 13 - 28.

Abdel Latef, A. A. H., Abu Alhmad, M. F. and 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**: 60 - 70.

Acharya, P., Jayaprakasha, G. K., Crosby, K. M., Jifon, J. L. and Patil, B. S., 2019, Green-synthesized nanoparticles enhanced seedling growth, yield and quality of onion (*Allium cepa* L.). *ACS Sustain. Chem. Eng.*, **7** : 14580 - 14590.

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

Ashraf, S. A., Siddiqui, A. J., Abd Elmoneim, O. E., Khan, M. I., Patel, M., Alreshidi, M., Moin, A., Singh, R., Snoussi, M. and Adnan, M., 2021, Innovations in nanoscience for the sustainable development of food and agriculture with implications on health and environment. *Sci. Total Environ.*, **768** : 144990.

Banerjee, J. and Kole, C., 2016, Plant nanotechnology : An overview on concepts, strategies and tools in plant nanotechnology. *Springer:* Cham, Switzerland, pp. : 1 -14.

Bombo, A. B., pereira, A. E. S., Lusa, M. G., De Medeiros Oliveira, E., De Oliveira, J. L., Campos, E. V. R., De Jesus, M. B., Oliveira, H. C., Fraceto, L.F., Mayer, J. L. S., 2019, A mechanistic view of interactions of a nanoherbicide with target organism. *J. Agric. Food Chem.*, **67** (16) : 4453 - 4462.

Camara, M. C., Campos, E. V. R., Monteiro, R. A., Pereira, A. E. S., De Freitas Proença. and P. L., Fraceto, L. F., 2019, Development of stimuli-responsive nano-based pesticides : Emerging opportunities for agriculture. *J. Nanobiotechnology,* **17** : 1 - 19.

Chandrasekaran, U., Luo, X., Wang, Q. and Shu, K., 2020, Are there unidentified factors involved in the germination of nanoprimed seeds. *Front. Plant Sci.*, **11** : 832.

Coelho, C. C. S., Michelin, M., Cerqueira, M. A., Gonçalves, C., Tonon, R. V., Pastrana, L. M., Freitas-Silva, O., Vicente, A. A., Cabral, L. M. C. and Teixeira, J. A., 2018, Cellulose nanocrystals from grape pomace : Production, properties and cytotoxicity assessment. *Carbohydr. Polym.,* **192**: 327 - 336.

De Oliveira, J. L., Campos, E. V. R., Germano-Costa, T., Lima, R., Vechia, J. F. D., Soares, S. T., De Andrade, D. J., Gonçalves, K. C., Do Nascimento, J. and Polanczyk, R. A., 2019, Association of zein nanoparticles with botanical compounds for effective pest control systems. *Pest Manag. Sci.,* **75** : 1855 - 1865.

Diagne, A., Diop, B. N., Ndiaye, P. M., Andreazza, C. and Sembene, M., 2019, Efficacy of silica nanoparticles on groundnut bruchid, *Caryedon serratus* (Olivier) (Coleoptera, Bruchidae). *Afr. Crop Sci. J.*, **27** (2) : 229 - 235.

Divya, K., Vijayan, S., Nair, S. J. and Jisha, M. S., 2019, Optimization of chitosan nanoparticle synthesis and its potential application as germination elicitor of *Oryza sativa* L. *Int. J. Biol. Macromol.*, **124** : 1053 - 1059.

Du, B. D., Ngoc, D. T. B., Thang, N. D., Tuan, L. N. A., Thach, B. D. and Hien, N. Q., 2019, Synthesis and *in vitro* antifungal efficiency of alginate-stabilized Cu2O-Cu nanoparticles against *Neoscytalidium dimidiatum* causing brown spot disease on dragon fruit plants (*Hylocereus undatus*). *Vietnam J. Chem.*, **57** : 318 - 323.

Dubey, A. and Mailapalli, D. R., 2016, Nanofertilisers, nanopesticides, nanosensors of pest and nanotoxicity in agriculture. *In Sustainable Agriculture Reviews. Springer*: Cham, Switzerland, pp. : 307 - 330.

Duran, N. M., Savassa, S. M., Lima, R. G. D., De Almeida, E., Linhares, F. S., Van Gestel, C. A. M. and Pereira De Carvalho, H. W., 2017, X-ray spectroscopy uncovering the effects of Cu cased nanoparticle concentration and structure on *Phaseolus vulgaris* germination and seedling development. *J. Agric. Food Chem,* **65** : 7874 - 7884.

DURO, J. A., LAUK, C., KASTNER, T., ERB, K. H. AND HABERL, H., 2020, Global inequalities in food consumption, cropland demand and land-use efficiency : A decomposition analysis. *Glob. Environ. Change*, **64** : 102124.

FALSINI, S., CLEMENTE, I., PAPINI, A., TANI, C., SCHIFF, S., SALVATICI, M. C., PETRUCCELLI, R., BENELLI, C., GIORDANO, C. AND GONNELLI, C., 2019. When sustainable nanochemistry meets agriculture : Lignin nanocapsules for bioactive compound delivery to plantlets. *ACS Sustain. Chem. Eng*., **7** : 19935 - 19942.

GROSS, M. S., BEAN, T. G., HLADIK, M. L., RATTNER, B. A. AND KUIVILA, K. M., 2020, Uptake, metabolism and elimination of fungicides from coated wheat seeds in Japanese Quail (*Coturnix japonica*), *J. Agric. Food Chem*., **68** : 1514 - 1524.

GUHA, T., RAVIKUMAR, K. V. G., MUKHERJEE, A., MUKHERJEE, A. AND KUNDU, R., 2018, Nanopriming with zero valent iron (NZVI) enhances germination and growth in aromatic rice cultivar (*Oryza sativa* Cv. Gobindabhog L.). *Plant Physiol. Biochem.,* **127** : 403 - 413.

HUSSAIN, A., RIZWAN, M., ALI, Q. AND 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** : 7579 - 7588.

ITROUTWAR, P. D., GOVINDARAJU, K., TAMILSELVAN, S., KANNAN, M., RAJA, K. AND SUBRAMANIAN, K. S., 2019, Seaweed-based biogenic ZnO nanoparticles for improving agro-morphological characteristics of rice (*Oryza sativa* L.). *J. Plant Growth Regul*., **39** (2) : 717 - 728.

JOSHI, A., KAUR, S., DHARAMVIR, K., NAYYAR, H. AND VERMA, G., 2018, Multi-walled carbon nanotubes applied through seed-priming influence early germination, root hair, growth and yield of bread wheat (*Triticum aestivum* L.) : Multiwalled carbon nanotube influence on bread wheat. *J. Sci. Food Agric*., **98** : 3148 - 3160.

KASHYAP, P. L., XIANG, X. AND HEIDEN, P., 2015, Chitosan nanoparticle based delivery systems for sustainable agriculture. *Int. J. Biol. Macromol*., **77** : 36 - 51.

KASOTE, D. M., LEE, J. H. J., JAYAPRAKASHA, G. K. AND PATIL, B. S., 2019, Seed Priming with iron oxide nanoparticles modulate antioxidant potential and defense-linked hormones in watermelon seedlings. *ACS Sustain. Chem. Eng*., **7** : 5142 - 5151.

KHODAKOVSKAYA, M., DERVISHI, E., MAHMOOD, M., XU, Y., LI, Z., WATANABE, F. AND BIRIS, A. S., 2009. Carbon nanotubes are able to penetrate plant seed coat and dramatically affect seed germination and plant growth. *ACS Nano*, **3** : 3221 - 3227.

KUMAR, G. D., RAJA, K., NATARAJAN, N., GOVINDARAJU, K. AND 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** : 492.

LAHIANI, M. H., DERVISHI, E., CHEN, J., NIMA, Z., GAUME, A., BIRIS, A. S. AND KHODAKOVSKAYA, M. V., 2013, Impact of carbon nanotube exposure to seeds of valuable crops. *ACS Appl. Mater. Interfaces*, **5** : 7965 - 7973.

LI, R., HE, J., XIE, H., WANG, W., BOSE, S. K., SUN, Y., HU, J. AND YIN, H., 2019, Effects of chitosan nanoparticles on seed germination and seedling growth of wheat (*Triticum aestivum* L.). *Int. J. Biol. Macromol.*, **126** : 91 - 100.

LIU, C., ZHOU, H. AND ZHOU, J., 2021, The applications of nanotechnology in crop production. *Molecules,* **26** (23) : 7070.

LU, C., ZHANG, C., WEN, J., WU, G. AND TAO, M. X., 2002, Research of the effect of nanometer materials on germination and growth enhancement of *Glycine max* and its mechanism. *Soybean Sci.,* **21** (3) : 168 - 171.

MAHAKHAM, W., SARMAH, A. K., MAENSIRI, S. AND THEERAKULPISUT, P., 2017, Nanopriming technology for enhancing germination and starch metabolism of aged rice seeds using phytosynthesized silver nanoparticles. *Sci. Rep*., **7** : 8263.

MAHAKHAM, W., THEERAKULPISUT, P., MAENSIRI, S., PHUMYING, S. AND 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.

Maluin, F. N., Hussein, M. Z., Yusof, N. A., Fakurazi, S., Idris, A. S., Hilmi, N. H. Z. and Daim, L. D. J., 2020, Phytotoxicity of chitosan-based agro nanofungicides in the vegetative growth of oil palm seedling. *PLoS One*, **15** (4) : e0231315.

Maswada, H. F., Djanaguiraman, M. and 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** : 577 - 587.

Montanha, G. S., Rodrigues, E. S., Marques, J. P. R., De Almeida, E., Colzato, M. and Pereira De Carvalho, H. W., 2020, Zinc nanocoated seeds : An alternative to boost soybean seed germination and seedling development. *SN Appl. Sci*., **2** : 857.

Panyuta, O., Belava, V., Fomaidi, S., Kalinichenko, O., Volkogon, M. and Taran, N., 2016, The effect of pre-sowing seed treatment with metal nanoparticles on the formation of the defensive reaction of wheat seedlings infected with the eyespot causal agent. *Nanoscale Res. Lett*., **11** : 92.

Pelegrino, M. T., Kohatsu, M. Y., Seabra, A. B., Monteiro, L. R., Gomes, D. G., Oliveira, H. C., Rolim, W. R., De Jesus, T. A., Batista, B. L. and Lange, C. N., 2020, Effects of copper oxide nanoparticles on growth of lettuce (*Lactuca sativa* L.) seedlings and possible implications of nitric oxide in their antioxidative defense. *Environ. Monit. Assess*., **192** (4) : 1 - 14.

Rizwan, M., Ali, S., Ali, B., Adrees, M., Arshad, M., Hussain, A., Zia Ur Rehman, M. and 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.

Sastry, R. K., Rashmi, H. B. and Rao, N. H., 2011, Nanotechnology for enhancing food security in India. *Food Policy*, **36** (3) : 391 - 400.

Sathiyabama, M. and Muthukumar, S., 2020, Chitosan guar nanoparticle preparation and its *in vitro* antimicrobial activity towards phytopathogens of rice. *Int. J. Biol. Macromol.*, **153** : 297 - 304.

Savassa, S. M., Duran, N. M., Rodrigues, E. S., De Almeida, E., Van Gestel, C. A. M., Bompadre, T. F. V. and 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**: 6414 - 6426.

Sekhon, B. S., 2014, Nanotechnology in agri-food production : An overview. *Nanotechnol. Sci. Appl*., **7** : 31.

Shakiba, S., Astete, C. E., Paudel, S., Sabliov, C. M., Rodrigues, D. F. and Louie, S. M., 2020, Emerging investigator series: polymeric nanocarriers for agricultural applications: synthesis, characterization, and environmental and biological interactions. *Environ. Sci. Nano*, **7** : 37 - 67.

Shcherbakova, E. N., Shcherbakov, A. V., Andronov, E. E., Gonchar, L. N., Kalenskaya, S. M. and Chebotar, V. K., 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.). *Symbiosis*, **73** : 57 - 69.

Shojaei, T. R., Salleh, M. A. M., Tabatabaei, M., Mobli, H., Aghbashlo, M., Rashid, S. A. and Tan, T., 2019, Applications of nanotechnology and carbon nanoparticles in agriculture. In synthesis, technology and applications of carbon nanomaterials. *Elsevier: Amsterdam*, The Netherlands, pp. : 247 - 277.

Shukla, P., Chaurasia, P., Younis, K., Qadri, O. S., Faridi, S. A. and Srivastava, G., 2019, Nanotechnology in sustainable agriculture : Studies from seed priming to post-harvest management. *Nanotechnol. Environ. Eng.,* **4**: 11.

Spielman-Sun, E., Avellan, A., Bland, G. D., Tappero, R. V., Acerbo, A. S., Unrine, J. M., Giraldo, J. P. and Lowry, G. V., 2019, Nanoparticle surface charge influences translocation and leaf distribution in vascular plants with contrasting anatomy. *Environ. Sci. Nano*, **6** (8) : 2508 - 2519.

SUNDARIA, N., SINGH, M., UPRETI, P., CHAUHAN, R. P., JAISWAL, J. P. AND 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** : 122 - 131.

VAN NGUYEN, D., NGUYEN, H. M., LE, N. T., NGUYEN, K. H., NGUYEN, H. T., LE, H. M., NGUYEN, A. T., DINH, N. T. T., HOANG, S. A. AND VAN HA, C., 2022, Copper nanoparticle application enhances plant growth and grain yield in maize under drought stress conditions. *J. Plant Growth Regul.,* **41** (1) : 364 - 375.

VAN OOSTEN, M. J., PEPE, O., DE PASCALE, S., SILLETTI, S. AND MAGGIO, A., 2017, The role of biostimulants and bioeffectors as alleviators of abiotic stress in crop plants. *Chem. Biol. Technol. Agric*., **4** (1) : 1 - 12.

VERMA, S. K., DAS, A. K., PATEL, M. K., SHAH, A., KUMAR, V. AND GANTAIT, S., 2018, Engineered nanomaterials for plant growth and development: a perspective analysis. *Sci. Total Environ*., **630** : 1413 - 1435.

YASMEEN, F., RAJA, N. I., RAZZAQ, A. AND KOMATSU, S., 2017, Proteomic and physiological analyses of wheat seeds exposed to copper and iron nanoparticles. *Biochim. Biophys. Acta - Proteins Proteom.,* **1865** : 28 - 42.

YE, Y., COTA-RUIZ, K, HERNÁNDEZ-VIEZCAS, J. A., VALDÉS, C., MEDINA-VELO, I. A., TURLEY, R. S., PERALTA-VIDEA, J. R. AND GARDEA-TORRESDEY, J. L., 2020, Manganese nanoparticles control salinity-modulated molecular responses in *Capsicum annuum* L. through priming: A sustainable approach for agriculture. *ACS Sustain. Chem. Eng*., **8** : 1427 - 1436.

ZHAO, L., LU, L., WANG, A., ZHANG, H., HUANG, M., WU, H., XING, B., WANG, Z. AND JI, R., 2020, Nano-biotechnology in agriculture : Use of nanomaterials to promote plant growth and stress tolerance. *J. Agric. Food Chem*., **68** : 1935 - 1947.