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# Scope and applications of nanotechnology for wheat production: A review of recent advances

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#### **Abstract**

Wheat (Triticum aestivum) is main staple food grain crop, grown in a range of environments over an area of 221.6 million hectares (M ha) with an annual production likely to reach more than 750.4 million metric tons in 2016-17 (Foreign Agricultural Service, USDA, 2018). Despite of this significant growth, the world population in some parts is still facing hunger crisis due to insufficient availability of food grains. To meet the future food demands imposed by overwhelming increasing population which is expected to reach nine billions in 2050, the world wheat production must continue to increase by 2% annually. This challenge of increasing wheat production is daunting as the wheat cropping system at present is constrained by climatic fluctuations, poor soil health and has increased risk of epidemic outbreak of diseases and insect-pests. To address these challenges, innovative technologies with a potential of increasing the sustainability of the present day cropping systems are required to be introduced in modern agriculture. Among these technological advancements, nanotechnology is gathering significant contemplations due to its wide spectrum applications in agriculture and allied sectors. It has a wider application in the field of crop production, food security, sustainability and climate change and is being utilized for developing several precise tool sets like nanofertilizer, nanopesticide, nanoherbicide, nanosensor and smart delivery systems for controlled and sustained release of agrochemicals. Recent research evidences indicated that intervention of nanotechnology in wheat farming is still in its early stages, although have bright prospects for efficient nutrient utilization through nanoformulations of fertilizers, breaching yield barriers through bionanotechnology, surveillance and management of pests and diseases and development of new-generation pesticides etc.

Keywords: Nano-formulations, wheat, delivery systems, productivity

#### 1. Introduction

Agriculture being the main occupation of about 80 % of poor people in rural areas is playing a vital role in the economy of the country by providing food, improved livelihoods and income for many people (Pinstrup-Andersen and Watson 2011). Still the world will have the challenge to meet the daunting food demand of an

estimated population of 9.6 billion by 2050. Wheat meets 21 % of the world's food demand and is grown on 200 M ha (494 million acres) of farmland globally (Tsvetanov  $\it et al., 2016$ ). It is estimated that 85 % and 82 % of the global population depends on wheat for basic calories and protein, respectively (Chaves  $\it et al., 2013$ ).

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According to an estimate, the global wheat demand by 2050 is expected to incline by 70 %, requiring an annual production increase from its present level of <1 to 1.7 % (Chenu et al., 2017). Moreover, the future global climate scenarios forecast an increase in the occurrence of exceptionally hot days, together with an increase in average global temperatures and its implications on global food production. Asseng et al. (2015) reported that the global wheat production is estimated to fall by 6 % for each °C of further temperature increase and become more variable over space and time. In Indian perspective, temperature changes from 1980 to 2008 had a bigger impact on national wheat production, where over 90 % of wheat is irrigated (Singh and Mustard, 2012), than changes in precipitation (Lobell et al., 2011).

Rice-wheat cropping system, one of the most important cropping patterns in South Asia, is facing immense pressure because of heat stress and degraded soil health due to high cropping intensity and tillage (puddling) for growing rice, and over-exploitation of the natural resources (Joshi et al., 2007). The most affected locations of South Asia are eastern Gangetic plains, central and peninsular India and Bangladesh, whereas the problem is moderate in north western parts of Indo-Gangetic Plains (IGP). Besides, a substantial proportion of cultivated land under wheat in South Asia is salt affected. It is estimated that around 4.5 mha area under wheat is salt affected in India (Singh and Chatrath, 2001) where as this figure is 6.0 mha in Pakistan. Although, soil reclamation and provision of proper drainage may be more effective solution, it does not seem possible in near future due to huge acreage affected by salt. Another hurdle to productivity is deficiencies of macro-nutrients like zinc, sulfur, iron, manganese and boron which are being observed in some pockets of northern India, Bangladesh and Nepal due to imbalanced fertilization, over mining of essential plant nutrients and burning of crop residues (Chatrath, 2004). Above all, water is also becoming scarce as the water table is going down due to over mining of ground water in intensive rice-wheat cultivation and comparatively less water recharge from monsoon rains (Singh, 2000).

Amongst the biotic stresses, rusts continue to be the major threat (Khan *et al.*, 2017; Savadi *et al.*, 2017; Singh *et al.*, 2006). Out of three rusts prevalent in Indian sub continent, leaf rust is the major disease which affects almost whole of India, parts of Bangladesh and Nepal.

Spot blotch caused by *Bipolaris sorokiniana* (Sacc.) Shoem (syn. Helminthosporium sativum, Teleomorph Cochliobolous sativus) is also considered an important disease in the eastern part of South Asia (Joshi et al., 2007). In addition, other diseases viz, Karnal bunt, powdery mildew and wheat blast also affect wheat crop to some extent (Singh 2017). Similarly, wheat crop is also a host of more than 100 species of arthropods that reduce grain quality and yield and increase production costs (Hatchett et al., 1987). Earlier, the problem of insect-pests was not serious in wheat but with changing climate and promotion of new crop production technologies like conservation agriculture technologies, minor and occasional insect-pests are now becoming major and regular pests of wheat which requires regular crop monitoring. Some of these insectpests are foliar aphid complex in irrigated wheat, root aphids in loose soils, pink stem bores in fields having rice stubbles, cut worms in residues, termites in raised beds and brown mites in rainfed conditions (Katare et al., 2015). Grasshoppers can also cause serious damage to wheat seedlings of November-sown crop in many rice-wheat areas of eastern Gangetic plains of India (Joshi et al., 2004). Among other biotic stresses, weeds are also playing a key role in deciding the productivity of wheat as they are more resistant to abiotic stresses due to their higher nutrient absorption capacity than the wheat crop. Moreover, extensive use of herbicide is causing concern due to problem of ground water contamination, food safety, health hazards, protection of endangered species and herbicide resistant weeds.

To cope up the major hurdles in meeting the productivity targets of wheat, nanotechnology (NT) is being visualized as a rapidly evolving field that has potential to revolutionize food systems and counter the present day challenge of food security (Scrinis and Lyons, 2007; Kashyap et al., 2015). It takes agriculture from the era of genetically modified crops to the brave new world of atomically modified organisms. The application of nanotechnology in the past decade results in an increase in crop productivity, reduce production costs and can increase the stability of crop production by reducing the losses due to abiotic and biotic stresses (Kashyap et al., 2017a; Kashyap et al., 2017b). Nanotechnology has the ability to change the entire scenario of the current agricultural and food industry through development of new tools or devices for detection and measurement of plant nutrient status, insect-pests, pathogens, weeds, moisture level, soil fertility and temperature etc. which helps in real time monitoring of the crop growth and provide essential data for precision farming (Kashyap *et al.*, 2013; Kashyap *et al.*, 2015).

Tools like nanosensors along with other field sensing devices can provide information about optimal times for planting and harvesting of crops and provide useful information for timely application of agrochemicals (Chowdappa and Gowda, 2013). Nanobiosensors and other smart delivery systems will also help the agricultural industry to fight against different crop pathogens. It is assumed that in the near future nanostructured catalysts will be available which will increase the efficacy of commercially available pesticides and insecticides and also reduce the doses level required for crop plants (Rai and Ingle, 2012; Dimetry and Hussein, 2016).

Nanotechnology, in respect of both research and development, though at a nascent stage, it can be effectively directed towards understanding and creating improved materials, devices and systems, and in exploiting the nano-properties for different application in agriculture. However, despite the exciting results obtained by involvement of path-breaking nanotechnology in agriculture so far, their relevance have not yet reached at the farmers' fields. This is mainly attributed to the lack of realistic approach in experimental design, small scale bench-top researches, biosafety concerns, nanotoxicity, regulatory issues and negative public opinion. As a result, there exist several knowledge gaps that remain to be addressed. Hence, this review provides a comprehensive overview of step by step advancements in wheat production starting from green revolution to nano-revolution. More emphasis has been given on the practical applicability of biosynthesized nanomaterials for the benefit of agriculture in general with special focus on quality wheat production and highlight challenges that need to be overcome to achieve millennium agenda of global food security.

## 2. Nanotechnology toolbox and wheat crop production

The study of the properties of structures smaller than 100 nano-meters (nm) is called as "nano-science", and designing and development of such structures in this size range alongwith their applications in a particular field is referred as Nanotechnology. The Royal Society

defines nanotechnology as the design, characterization, production and application of structures, devices and systems by controlling shape and size at nanometer scale (RSRAE, 2004). In nanotechnology, prefix "nano" comes from Greek word "dwarf". Several nanomaterials like nanoporous zeolites, nanocapsules, nanosensors and carbon nano tubes (Fig 1 and 2) have the tremendous potential to protect host plants from biotic and abiotic stresses (Kashyap et al., 2015; Hallberg, 2010). Nanomaterials possess important properties of self-assembly, stability, specificity, encapsulation and biocompatibility (Kashyap et al., 2015). Besides, nanobiotechnology can be used to enhance the yield and nutritional values of crops as well as increase the plant's ability to resist insect pests (Kitherian 2017; Bhattacharyya et al., 2010).

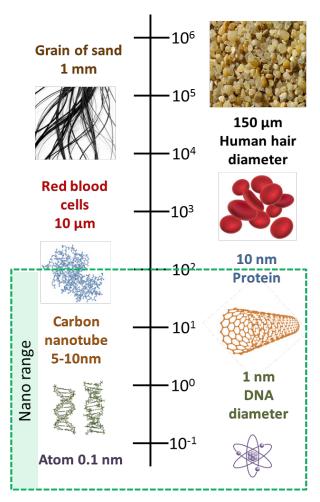


Fig. 1 Nano-size range in comparison to commonly known materials

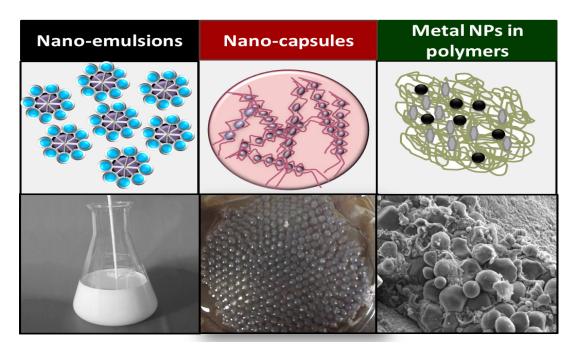


Fig. 2 Different kinds of nanomaterial(s) used in agriculture



Fig. 3 Scope of nanotechnology for wheat crop production

Recent evidences indicated that wheat is sensitive to climate change due to direct effects of changes in temperature, precipitation and carbon dioxide concentrations, and also due to indirect effects through changes in soil moisture and the distribution and frequency of infestation by pests and diseases (Abeysingha *et al.*, 2016; Ludwig *et al.*, 2009). Kumar *et al.* (2014) predicted 6–23 and 15–25 % reduction in the wheat yield in India during 2050s and 2080s, respectively, under projected

climate change scenarios. Nanotechnology holds immense potential in wheat farming (Fig 3). Several studies showed that nanotechnology play vital role in alleviating stress-induced alterations in plants. The possible use of nanotechnology includes delivery of nanocides, nanomaterials encapsulated pesticides, for controlled and targeted release, as well as the stabilization of pesticides with nanomaterials (Kashyap *et al.*, 2015; Kashyap *et al.*, 2017b).

Recently, nanotechnology has gathered remarkable contemplation due to its potential to improve seed germination, growth and wheat protection through the controlled release of agrochemicals, with the ensuing reduction in the amounts of agrochemicals applied and the minimization of nutrient losses from fertilizer application during wheat cultivation. The current status of research regarding the impact of nanotechnology on wheat growth and development is summarized in following sections.

2.1 Wheat growth and development: Nanoparticles (NPs) containing essential metals are considered in formulations of fertilizers to enhance plant nutrition in soils with low metal bioavailability. However, in various studies researchers have reported that multi-walled-carbon nanotubes (MWCNTs) have a magic ability to influence the seed germination and plant growth. They induce the water and essential Ca and Fe nutrients uptake efficiency that could enhance the seed germination and plant growth and development (Villagarcia et al., 2012). Under laboratory conditions, Miralles et al. (2012) demonstrated that industrial-grade MWCNTs (2,560 mg kg-1) enhanced germination and root elongation of wheat. Remarkably, CNTs were adsorbed onto the root surfaces of wheat without significant uptake or translocation. In another study, Tripathi and Sarkar (2015) noticed that water soluble CNTs inside the wheat plants were able to induce the root and shoot growth in light and dark conditions. Hu and Zhou (2014) reported a novel and biocompatible hydrated graphene ribbon (HGR) could promote germination of aged wheat seed and enhance resistance to oxidative stress. The metabonomics analysis indicated that HGR could upregulate carbohydrate, amino acid, and fatty acids metabolism that determined secondary metabolism, nitrogen sequestration, cell membrane integrity, permeability, and oxidation resistance.

Titanium dioxide nanoparticles (nTiO $_2$ ) are promising as efficient and beneficial nutrient source for plants to improve biomass production due to enhanced nitrogen assimilation, photoreduction activities of photosystem II and electron transport chain, scavenging of reactive oxygen species, and (Raliya *et al.*, 2015; Morteza *et al.*, 2013). Larue *et al.* (2012) reported no impact of various sized TiO $_2$ NPs on seed germination in wheat, although, NPs were able to internalize through roots and translocate up to the leaves. The study suggested that a size threshold

may occur for NPs translocation to the leaves which they reported to be <36 nm; while accumulation of TiO<sub>2</sub>NPs in the wheat root could only occur if NPs are <140 nm in diameter, with higher accumulation that occurred when NPs were much smaller (14-22 nm) (Larue et al., 2012). Mahmoodzade and Aghili (2014) showed that nano titanium dioxide at its optimal concentration (1200 ppm) has a stimulating effect on the growth of root and shoot of the wheat. They also showed that the fresh and dry weights of the root remarkably are affected by nTiO<sub>2</sub>. Jaberzadeh et al. (2013) reported that  ${\rm TiO_2NPs}$  augmented wheat plant growth and yielded components under water deficit stress condition. TiO, NPs regulate enzymes activity involved in nitrogen metabolism such as nitrate reductase, glutamate dehydrogenase, glutamine synthase, and glutamic-pyruvic transaminase that helps the plants to absorb nitrate and also favors the conversion of inorganic nitrogen to organic nitrogen in the form of protein and chlorophyll, that could increase the fresh weight and dry weight of plant (Mishra et al., 2014).

Riahi-Madvar et al. (2012) reported that foliar application of wheat seedlings with  $\mathrm{nAl_2O_3}$  (<50nm) decreased the root length and as result of oxidative stress the activity of superoxide dismutase and catalase enzymes increased. In another work, Ramesh et al. (2014) reported that lower concentration of ZnO NPs exhibited beneficial effect on seed germination of wheat. However, higher dose of nZnO impaired seed germination. The explanation for this can be attributed to the fact that nZnO are insoluble in water and the particles are rapidly lost from solution, probably due to sedimentation as a result of aggregation or sensitivity of the present test organism. Moreover, the effect of NPs on germination depends on concentrations of NPs and varies from plants to plants.

Copper oxide nanoparticles (NPs) are used in an expanding range of industries including a potential for agricultural applications as a fungicide. Cu-NPs have the potential to enhance growth and yield of wheat but their effect is concentration dependent. Hafeez *et al.* (2015) revealed that Cu-NPs either do not affect seed germination at lower concentration (up to 0.8ppm) or impair germination at 1 ppm and above. Lower concentration of Cu-NPs (<1.0 ppm) in solution culture and less than 50 ppm in pots was not toxic for wheat plants. Maximum growth and yield was recorded with 30 ppm in pots.

Cerium oxide (CeO<sub>2</sub>) NPs is among the most studied nanoparticles based on their transformation in plants. They have been considered highly stable in environmental and biological surroundings with limited dissolution in soil and plant tissues (Gaiser *et al.*, 2009; Xia *et al.*, 2010). Another study investigated the effects of cerium oxide (CeO<sub>2</sub>) exposure on wheat by using hydroponic plant culture. CeO<sub>2</sub> NPs have only minor effects and no growth reduction or toxic response was observed (Schwabe *et al.*, 2013), but catalase and ascorbate peroxidise activity significantly increased.

Mesoporous silica is actually largely used in catalysis, drug delivery, and imaging and thus released in the environment. Nair et al. (2010) demonstrated that uptake of nonporous silica nanoparticles (25nm) labeled with fluorescein isothiocyanate (FITC) had no effect on seed germination at concentrations up to 50 mg L-1. In the present study (Hussain et al., 2017) mesoporous silica nanoparticles functionalized with amine cross-linked fluorescein isothiocyanate were absorbed by wheat. These NPs have a dimension of around 20 nm with interconnected pores of around 2 nm. The uptake and distribution were examined during seed germination, in roots and leaves of plants. After germination of wheat in solution with NPs, they were found within cells, in cell wall of roots, and in the xylem and other cells for the transport of elements. The toxicity of the biosynthesized silver nanoparticles on wheat was studied by soaking wheat grains in 100 mg L<sup>-1</sup> AgNPs and its effect on seedling growth of wheat was observed. AgNPs has a non-significant inhibitory effect on germination percentage of wheat, dry weight and pigment fractions. The biosynthesized AgNPs has a noticeable stress effect by reducing chlorophyll and dry weight. There was a clear different effect of AgNPs on soluble proteins and antioxidant enzymes as catalase and peroxidase in wheat plants (Farghaly and Nafady, 2015).

2.2 Drought stress alleviation: Drought is a severe environmental stress and the major constraint on wheat productivity with an evident effect on growth (Nezhadahmadi et al., 2013; Rampino et al., 2006). Global climate models predict changed precipitation patterns with frequent episodes of drought. Although drought impedes wheat performance at all growth stages, it is more critical during the flowering and grain-filling phases (terminal drought) and results in substantial yield losses. For instance, post-anthesis mild drought reduced the wheat yields by 1-30 % while prolonged mild drought at flowering and grain filling reduced the grain yields by

58-92 %. The effects of terminal drought on wheat yields are likely to increase in the near future (Araus *et al.*, 2002).

The effect of the application of nanoparticles of an analcite to soil (at 0, 500, 1000 and 1500 mg L-1) on drought resistance of wheat was studied by Zaimenko et al. (2014). Application of analcite showed enhanced seed germination, seedlings growth criteria as well as content of photosynthetic pigments, while characteristics of water balance less deviated from the norm under water deficit. Moreover, application of analcite nanoparticles induced sharp accumulation of protective antioxidants (flavonoids and carotenoids) under soil drought. In another study, Taran et al. (2017) reported that colloidal solution of Cu, Zn-nanoparticles decreased the negative effect of drought stress on wheat. In particular, increased activity of antioxidative enzymes reduced the level of accumulation of thiobarbituric acid reactive substances (TBARS) and stabilized the content of photosynthetic pigments and increased relative water content of leaves. Moreover, the changes in plant morphometric indexes such as leaf area and relative water content in leaves are the result of the adaptation mechanism triggered by colloidal solution of Cu, Zn-nanoparticles under drought conditions. Similarly, another research finding of Yasmeen et al. (2017) indicated that Cu NPs improve the tolerance of wheat varieties to drought stress. Cu NPs improved the yield and drought stress tolerance of wheat by mediating starch degradation, glycolysis, and tricarboxylic acid cycle in wheat varieties (Yasmeen et al., 2017).

2.3 Salinity stress alleviation: It is well known that salinity has been considered as a major environmental threat for wheat cultivation. More than 45 million hectares (M ha) of irrigated land which account to 20% of total land have been affected by salt worldwide and 1.5 M ha are taken out of production each year due to high salinity levels (Negrão et al., 2017; Munns and Tester 2008). Poor germination and seedling establishment are the results of soil salinity, which adversely affects plants growth and development and results in to low agricultural production (Sharma et al., 2015; Miransari and Smith, 2007). The effects of salinity at seedling stage of wheat range from reduction in germination percentage, fresh and dry weight of shoots and roots to the uptake of various nutrient ions (Darko et al., 2017; Yang et al., 2014). Salt stress decreases the growth, mineral nutrients, grain yield, chlorophyll content and gas exchange characteristics in wheat (Rehman et al., 2016). However, application of nanoparticles provided elevated

levels of plant growth and improved seed performance in wheat under salinity stress.

Mohamed *et al.* (2017) showed that seed priming with Ag NPs alleviate the salt stress in wheat by decreasing the oxidative stress through modification of antioxidant enzyme activities depending upon the doses of Ag NPs applied. Priming with a lower concentration of Ag NPs (2-5mM NaCl) might be an effective strategy to alleviate the negative effect of salt stress on wheat. Seed priming with Ag NPs (15-29nm) enhanced the shoot fresh and dry weight of salt-stressed plants. Seed priming with NPs may help the wheat plants to reduce Na translocation from roots to shoots which ultimately led to increase in plant growth. Moreover, the combined application of Ag NPs (2-5mM) and salt stress (150mM NaCl) increased the soluble sugars and proline contents, while it decreased catalse activity and increased peroxidase activity.

2.4 Surveillance and detection of wheat storage pests and pathogens: Rapid detection technologies with high sensitivity and selectivity for plant pathogens and insect pests are essential to prevent disease spread and minimize losses to assure optimal productivity and food security (Sharma et al., 2017; Kashyap et al., 2011). Traditional laboratory techniques used for pest diagnosis are time consuming, labour intensive and require complex sample handling. The sensitive nature of functionalized nanoparticles can be used to design phytopathogen detection devices with smart sensing capabilities for field use. Singh et al. (2010) used nanogold-based immunosensors that could detect Karnal bunt disease in wheat (Tilletia indica) using surface plasmon resonance (SPR). Gold nanoparticles have been used in biosensors due to their ease in alternation of their optical or electrochemical procedures to identify pathogens (Kashyap et al., 2017b; Thaxton et al., 2006). Campagnoli et al. (2011) developed electronic nose (EN) equipped with metal-oxide-semiconductor (MOS) sensors and used it as a screening tool for the recognition of durum wheat naturally contaminated by deoxynivalenol. Further, Eifler et al. (2011) showed that the metalloporphyrin-based E-nose can be used to qualitatively detect and correctly classify dry, whole, Fusarium-infected wheat grains. The developed electronic nose was capable of distinguishing between four wheat Fusaria species with an accuracy higher than 80 %, which allowing them to be excluded from the food or feed chain. Similarly, Wu et al. (2013) assessed the feasibility of the application of electronic nose technology to detect insect infestation in wheat. They used an alpha MOS

FOX-3000 electronic nose (e-nose) equipped with 12 metal oxide semiconductor (MOS) sensors was used to evaluate the presence of rusty grain beetle and red flour beetle (RFB) in wheat. The e-nose detect the presence of RFB in wheat with the high infestation level (20 insects  $kg^{-1}$ ) at 14 and 16 % moisture content. These results clear indicated that E-nose could be used to detect other species in stored grains.

2.5 Controlled and targeted release of agrochemicals: Nanofertilizers are new generation of the synthetic fertilizers which contain readily available nutrients in nano scale range. They are more soluble and effective than their bulk counterparts (DeRosa et al., 2010; Rameshaiah et al., 2015). Application of nano-fertilizers improves solubility and dispersion of insoluble nutrients in soil, reduce nutrient immobilization (soil fixation) and increase the bio-availability (Naderi and Danesh-Shahraki, 2013). Moreover, nano- fertilizers can be easily absorbed by plants and provide nutrient supply in soil or on plant for longer duration (Rameshaiah et al., 2015). Zhang et al. (2006) investigated the effects of controlled release fertilizers cemented and coated by nanomaterials on crop. They demonstrated that the nanocomposites were safe for wheat seed germination, emergence and growth of seedlings. Additionally, they can also provide a regulated, responsive and on time delivery of nutrients to plants. Abdel-Aziz et al. (2016) investigated the delivery of chitosan nanoparticles loaded with nitrogen, phosphorus and potassium (NPK) for wheat plants by foliar uptake. The results revealed that wheat plants grown on sandy soil with nano chitosan-NPK fertilizer induced significant increases in harvest index, crop index and mobilization index of the determined wheat yield variables. Moreover, the life cycle of the nano-fertilized wheat plants was shorter than normal-fertilized wheat plants. However, the response of plants to nanofertilizers varies with the type of plant species, their growth stages and nature of nanomaterials.

Mishra et al. (2014) studied the efficiency of biosynthesized AgNPs (10-20 nm) in controlling infection of B. sorokiniana which causes spot blotch disease in wheat. The results revealed that application of AgNPs (4 µg ml<sup>-1</sup>) strongly inhibited B. sorokiniana infection in wheat. Further, it was noticed that decrease in plant growth after pathogen challenge was overcome when wheat plants sprayed with AgNPs. Savi et al. (2015) studied the efficacy of zinc compounds in controlling Fusarium head blight and

deoxynivalenol formation in wheat. The study clearly demonstrated that ZnO-NP (30 nm) efficiently reduced *F. graminearum* and DON formation in the wheat grains at low concentration (100 mM). Zn remained within the international recommended level for consumption and the treatment did not cause any damage to wheat grains. In another study, Panyuta *et al.* (2016) showed the effect of pre-sowing seed treatment with metal nanoparticles (Zn, Ag, Fe, Mn and Cu) on the formation of the defensive reaction of wheat seedlings infected with Pseudocercosporella herpotrichoides. The investigation led to the conclusion that nonionic colloidal solutions of biogenic metals have the antioxidant effect through the inhibition of the synthesis of lipid peroxidation products.

The antimicrobial activity of chitosan nanoparticles (CS/NPs) has been recently studied and it has been demonstrated that CS/NPs has the ability to control of *Fusarium* head blight of wheat. Kheiri *et al.* (2016) demonstrated that CS/NPs have significant inhibitory effects on the fungal growth, colony formation and conidial germination of *F. graminearum*. They also revealed that plant protection by CS/NPs is dependent on time period. Plant can be protected of disease with spraying of them at anthesis, twice or thrice in time of plant growing.

Nano-silica, a type of unique nanomaterial, widely used for the development of different kinds of nano-pesticides (Barik et al., 2008). The mechanism of control of insect pest using nano-silica is based on the fact that insect pests used a variety of cuticular lipids for protecting their water barrier and thereby prevent death from desiccation. But nano-silica gets absorbed into the cuticular lipids by physio sorption and thereby causes death of insects purely by physical means when applied on leaves and stem surface. Surface charged modified hydrophobic nano-silica (3–5nm) could be successfully used to control a range of agricultural insect pests and animal ectoparasites of veterinary importance (Ulrichs et al., 2005). Yang et al. (2009) demonstrated the insecticidal activity of polyethylene glycol-coated nanoparticles loaded with garlic essential oil against adult Tribolium castaneum insect found in stored products. It has been observed that the control efficacy against adult *T. castaneum* was about 80%, presumably due to the slow and persistent release of the active components from the nanoparticles.

Teodoro et al. (2010) for the first time studied the insecticidal activity of nanostructured alumina against two insect pests viz., Sitophilus oryzae and Rhyzopertha dominica, which are

major insect pests in stored food supplies throughout the world. They reported significant mortality after 3 days of continuous exposure to nanostructured aluminatreated wheat. Therefore, as compared to commercially available insecticides, inorganic nanostructured alumina may provide a cheap and reliable alternative for control of insect pests, and such studies may expand the frontiers for nanoparticle-based technologies in pest management. Silica nanoparticles have high toxicity on R. dominica and *T. confusum* adults. *R. dominica* was more susceptible than *T.* confusum. However, the mortality of both species increased with increasing concentrations and time exposed to each concentration. At low concentrations, Aerosil was more effective than Nanosav. Silica nanoparticles were more effective in wheat grains than barley. Results indicated that the initial mortality was so high that the impact of food source on delay mortality was unclear in most cases. Silica nanoparticles were efficient against tested species and can be used effectively in a stored grain integrated pest management program (Ziaee and Ganji, 2016)

2.6 Plant genetic modifications: A breeder has to spend many years to develop a new variety with enhanced yield and improved diseases or insect resistance and quality traits using traditional approaches. With the invention of new nano-genomics-based methods, the breeders have got new opportunities for selecting and transferring genes with greater precision. These new techniques not only have reduced the time needed to eliminate unnecessary genes, but has also allowed the breeder to access useful genes from distant plants. Thus, nanotechnology presents new plant gene delivery and nanopore DNA sequencing systems to improve yield and resistance against crop pests and increase food security.

Nanodiagnostic tools similar to microfluidics, nanomaterials, bioanalytical nanosensors, etc. has the potential to solve many more problems related to plant health, production, and prevention and can possibly be used in living plants in field-based assays for transgene expression (Stewart, 2005). The genes to the target plant cells can been transferred through the use of a variety of nanotools, including nanoparticles that encapsulate and deliver DNA to target cells, in addition to nanostructured surfaces that capture and release DNA to cells (Rai et al., 2012). The most common nanoparticles which can be used for DNA delivery are zinc, starch, calcium phosphate, carbon materials, silica, gold, magnetite, strontium phosphate, magnesium phosphate and manganese phosphate

(Sokolova and Epple, 2008). Besides, nanoparticles, nanofibers, and nanocapsules are also used to transfer foreign DNA and chemicals that change genes (Torney et al., 2007). Nanoparticle-mediated gene or DNA transfer can also be done for the development of disease or insect-pest resistant varieties of crops by introduction resistance genes in plant cells using nano-tools which will minimize the cost of pest management methods especially the agrochemicals required for pest control (Sekhon, 2014). In this direction, the field of nanobiotechnology is playing a key role in applying nanotools for crop improvement.

Zinc (ZnS) nanoparticles are considered as a desirable gene transporter to deliver DNA into intact plant by using ultrasound-mediated technique (Fu et al., 2012). Gonzalez et al. (2007) reported that different type of microscopic methods can be used to visualize and follow the transport and deposition of nanoparticles, as well as to verify the possibility of concentrating nanoparticles into targeted area of plant using small magnet. As plant transgenic vehicle, the nanoparticles labeled with fluorescent starch can be used, to design the nanoparticle biomaterial in such a way that it binds the gene and transports it across the cell wall of plant cells by inducing the formation of transient membrane pores in cell wall, cell membrane and nuclear membrane by using ultrasound method (Sun et al., 2016).

Recently, Abd-Elsalam and Alghuthaymi (2014) documented that micro-injection with carbon nanofibers (CNFs) containing foreign DNA has been used to genetically modify golden rice enriched with extra vitamin A. In light of the above-mentioned reports, it is clear that the applications of nanobiotechnology in wheat breeding are gradually moving from the theoretical possibilities into the applicable area and will play an important role in improving the existing wheat breeding techniques in future.

#### 3. Future challenges and directions

The integration of nanotechnology with wheat farming has immense potential to cope with global challenges of food production, sustainability and climate change. However, despite the emerging picture of potential applications of nanotechnology in wheat improvement so far, their relevance has not reached up to the field conditions. Hence, there is a need to make extensive and focussed research efforts on following directions.

- Nanotechnology can have both positive and negative impact on agro-ecosystem. Therefore, it is necessary to vigilantly study the relationship of NPs and wheat microbiome. Further, in order to understand the interaction of NPs with the different molecules that are present in plant cells, studies on the analysis of any changes in gene expression under the influence of nanoparticles are also necessary.
- Nanotechnology can provide tools to fine tune the properties of wheat plant, their productivity and tolerance to biotic and abiotic stresses. Hence, a clear picture of the interaction of different nanomaterials with wheat crop and their mechanism for genetic and molecular modification are required to be explored.
- Experimental validation of the permissible limit of use of nanoparticles dosage within safety limits need to be clarified. The interaction of nanomaterials with plants differs with the type of NPs, the applied concentration of NPs, the time of treatment, the plant genotype and the stage of development etc. So, these facts should be kept in mind while performing nanotoxicity studies and selection of permissible level together with studying transgenerational and trophic chain transfer effects.
- Surface functionalized MSNs allow site-targeted simultaneous delivery of both DNA and effector molecules in a controlled fashion by penetrating through plant cell wall. Thus, the nanomaterial-mediated transformation methods will need to be explored for generating transgenic wheat with desired traits.
- Research on nanosensor is of high value for rapid diagnosis and effective pest management. Therefore, it will be interesting to explore the application of nanosenors for sensing wheat pests in fields and in grain storage structures.

Despite of these potential benefits, the application of nanotechnology in wheat improvement could come with risks for the environment non-target plants, beneficial soil microbes and other life forms which could be affected if nano-materials are misused. Therefore, a better understanding of the agro-ecological consequences of nanotechnology, especially it relates to dose response, release of ions, and nanoparticle specific effects of mineral nutrients is important to fully harness its promised benefits as nano-formulation applications.

Presently, no knowledge base so far exists for the transformations and bioavailability of nano-particles to plants and organisms in soils.

There is a pressing need exists to elucidate the basic properties of nano-particles and different processes that govern their fate in soil and plant and, their bioavailability. This understanding will help us to reap the benefit of nanotechnology without producing adverse ecological consequences.

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