**Applications and Challenges of Nanotechnology in the Agriculture Sector**

Sania Zaib1, 2, \*, Sadia Banaras3 and Muhammad Tariq4

1Department of Biological Sciences, Faculty of Sciences, International Islamic University, Islamabad, Pakistan

2Department of Biochemistry, Faculty of Biological Sciences, Quaid-i-Azam University, 45320

Islamabad, Pakistan.

3Department of Biotechnology, Faculty of Biological Sciences, Quaid-i-Azam University, 45320

Islamabad, Pakistan

4 The Faculty of Pharmaceutical Sciences, Lahore University of Biological & Applied Sciences, 53400, Lahore Pakistan

\*Correspondence: saniazaibsz@gmail.com

**Abstract**

It is the need of time to fulfill the food demands of rapidly growing world population. Utilization of conventional farming practices results in the huge loss of food crops. So, the use of alternative innovative techniques like nanotechnology can assist for sustainable agricultural development. Nanomaterials play an important role in transforming the modern agricultural practices. Various nano-material based formulations such as nano-fertilizers, nano-pesticides, nano-herbicides, nano-microbicides, nano-sensors and nano-fibers play important roles in plant growth and development as well as in mitigating the environmental stress challenges. However, evaluation of toxicity and risk assessment associated with these novel nanomaterials need to be addressed. Furthermore, regulation and legislation are also mandatory for regulating the manufacturing, processing and proper disposal of these nanomaterials. Besides, awareness as well as acceptance of nano-based agricultural products by public is also very mandatory, so that nanotechnology could be used as a safe and sustainable alternate in the agriculture sector.

Agriculture is the backbone and acts as a primary pillar for the economy of most developing countries. World population is raising at an alarming rate especially in the developing countries and there is need to enhance the agricultural production accordingly. Due to industrialization, agricultural sector has to face several challenges such as unpredictable changes in climate, harmful effects of pesticides, herbicides and fertilizers as well as the ever escalating food demands for the rapidly growing population ([Pouratashi & Iravani, 2012](#_ENREF_49); [Sekhon, 2014](#_ENREF_53)).

**Nanotechnology**

Nanotechnology is the science that deals with nanomaterial (NMs) objects ranging between 1 and 100nm. A nano meter is one billionth of a meter ([He et al., 2019](#_ENREF_24)). These nanoparticles are usually formed from the natural or artificial manipulation of metals or other compounds. The very small components which are found in the nanomaterials, have ability to influence the propertied of materials at the macro level ([Singh et al., 2023](#_ENREF_58)).

**Types of Nanomaterials**

Nanomaterials are usually divided into four groups:

**Carbon-based nanomaterials:** They are usually made up of carbon and are of various forms such as spherical, elliptical or hollow tubes. Fullerenes, carbon nanotubes, carbon nanofibers, carbon onion, carbon black and graphene are some of the examples of carbon-based NMs ([Singh et al., 2023](#_ENREF_58)).

I**norganic-based nanomaterials:** These include metal and metal oxides like Ag, Au, Si, ZnO and TiO2 etc.([Singh et al., 2023](#_ENREF_58)).

O**rganic-based nanomaterials:** They are made up of organic compounds. Non-covalent interactions transform the organic nanomaterials into desirable structures such as liposomes, dendrimers, micelles and polymers etc. ([Singh et al., 2023](#_ENREF_58)).

**Composite-based nanomaterials:** They are multiphase nanomaterials formed by combining nanoparticles with either other nanoparticles or with bulkier materials like hybrid nanofibers or with more complex structures like metalorganic frameworks. In composites metal, ceramic or organic bulk components may be combined with metal, organic or carbon nanomaterials ([Singh et al., 2023](#_ENREF_58)).

Nanoparticles are being synthesized by various methods such as biological, chemical and physical methods ([Ghidan et al., 2017](#_ENREF_21)). These methods have certain drawbacks like difficulty in scaling up, consumption of large amount of surfactant and difficulty in separation and purification of nanoparticles from micro-emulsion i.e. oil, surfactant, co-surfactant and aqueous phase ([Pilarska et al., 2013](#_ENREF_48)). Nanoparticles synthesized through green methods from plant extracts are beneficial as they are simple and convenient to be synthesized, besides they are ecofriendly and they need less reaction time. The nanoparticles synthesized through green synthesis could enhance agriculture potential for improving fertilization process and plant growth ([Pilarska et al., 2013](#_ENREF_48)). Besides, they also help in minimizing the environmental pollutants by reducing the amount of injurious chemicals ([Huang et al., 2015](#_ENREF_25)).

**Application of Nanomaterials in Agriculture**

Nanotechnology is widely being used in various fields of life having a positive impact on society. After the publication of first roadmap by the US Department of Agriculture in September, 2003, it started heading towards the agriculture industry ([Doa, 2003](#_ENREF_16)). It skyrocketed in the last decade ([Nandita & Shivendu, 2018](#_ENREF_38); [Peters et al., 2016](#_ENREF_47)) and is getting good momentum in all aspects of this field. This technology assists in enhancing the agricultural production([Ghidan et al., 2017](#_ENREF_21)). The various applications of nanotechnology in agriculture sector are given below:

**Role of NMs for Plant Growth Promotion**

The application of nanoparticles helps in plant growth and development by influencing several factors such as seedling vigor, photosynthesis and shoots and roots growth etc. The interaction between plants and nanomaterials could better be understood by the development of new protocols as well as by the utilization of various analytical techniques such as Magnetic Resonance Imaging, Microscopy and Fluorescence Spectroscopy etc. ([Fraceto et al., 2016](#_ENREF_20)).

**Nano-Fertilizers**

According to US Food and Agricultural Organization, the global demand for fertilizers is rising day by day. Hence, the use of intelligent strategies for sustainable agriculture such as nanotechnology are imperative. Nano fertilizers or smart fertilizers are ecofriendly which ensure the nutrients availability and reduce their loss ([Dimkpa & Bindraban, 2017](#_ENREF_14)). Nano fertilizers release the nutrients gradually and in a controlled manner at the targeted sites and this helps in the prevention of contamination of environment and water bodies ([Dwivedi et al., 2016](#_ENREF_18)). For enhancing the uptake of nutrients, fertilizers are usually encapsulated in nano form. These nano formulations minimize the nutrient loss, reduce the risk of environmental pollution and enhance the crop quality and yield.

Macro-nutrient nano-fertilizers, micro-nutrient nano-fertilizers and nano-particulate nano-fertilizers are the three types of nan-fertilizers ([Chhipa, 2017](#_ENREF_8)). Macronutrient nano fertilizers usually consist of combination of macro elements such as calcium (Ca), magnesium (Mg), nitrogen (N), phosphorus (P) and potassium (K). There is critical need of macronutrient fertilizers in the agricultural sector as according to one estimation the demand of these fertilizers would increase up to 263 million tons in 2050. According to one study the foliar application of Mg and Fe nano particles enhanced the photosynthetic efficiency and yield of black eyed pea plants ([Delfani et al., 2014](#_ENREF_12)). Similarly, in another study the application of Ca nano particles helped in improving the seedling growth of peanut plants ([Xiumei et al., 2005](#_ENREF_64)).

Micronutrients are the nutrients required in small amount and include Zinc (Zn), Iron (Fe), Manganese (Mn), Nickle (Ni), Copper (Cu) and Molybdenum (Mo) etc. They are important for the healthy growth of plants. Composite formulations of micronutrients are more effective for providing sufficient amount of nutrients and by causing less environmental contamination. The composite of three micronutrients nanoparticles i.e. CuO, ZnO and B2O3 was found to be effective for mitigating the drought stress in soybean plants ([Dimkpa et al., 2017](#_ENREF_15)). Nanoparticles such as SiO2, TiO2 and carbon nano tubes (CNTs) are being used in the nano particulate fertilizers. The mixture of SiO2 and TiO2 enhanced N2 fixation and improved the germination of seeds and growth of soybean plants ([Changmei et al., 2002](#_ENREF_6)).

There are three ways by which fertilizers are encapsulated within nanoparticles i.e., nutrients can be either 1) encapsulated inside nano porous materials, or 2) coated with thin polymer film, or 3) delivered as emulsions or particles of nanoscale dimensions ([Rai et al., 2012b](#_ENREF_51)). So, nano particles could be used as potential fertilizers for field crops (Liu and Lal, 2015). The role of nano fertilizers for sustainable agriculture is well established ([El-Ramady, 2014](#_ENREF_19)).

**NMs Provide Protection Against Environmental Stresses**

During their growth and development plants have to face severe environmental stress challenges ([Mittal et al., 2020](#_ENREF_34)). Several biotic and abiotic stress factors such as pathogens, drought, salt stress, UV rays, extreme temperatures, metals and mineral toxicity etc. affect plant health and decrease crop yield. Nanoparticles not only help plants to grow but they also provide protection against various stresses. The foliar application of nano fertilizers helps in mitigating the stress in plants ([Tarafdar et al., 2012](#_ENREF_60)). Nanoparticles help in reducing the availability of toxic metals by binding to toxic metals due to their large surface area and small size. Similarly, nanoparticles can help in scavenging oxidative stress through mimicking the activity of antioxidant enzymes ([Sharifi et al., 2020](#_ENREF_55)). According to one previously reported study, the use of SiO2 nanoparticles helped in improving transpiration rate, chlorophyll content and the activity of carbonic anhydrase enzyme in the pumpkin plant under salt stress condition ([Siddiqui et al., 2014](#_ENREF_57)). During abiotic stress, production of ROS increases. Despite equipping with enzymatic machinery, plants face a situation where the stresses overcome the defense system. Nanomaterials assist in alleviating such stress situations though providing nutrients, by accumulating osmolytes and by activating specific defense genes ([Mittal et al., 2020](#_ENREF_34)).

**Nano-Pesticides**

Plant diseases are mostly caused by pests and insects. Conventional pesticides are usually being used in agriculture for enhancing the crop yield and efficiency ([Jampílek & Kráľová, 2017](#_ENREF_26)). However, use of pesticides was found to be toxic and lethal for human and animal health as well as for the environment. Several pesticides have been banned by the international authorities owing to several issues associated with them like soil infertility, degradation of ecosystem and the disruption of microbiota ([Meena et al., 2020](#_ENREF_33)). Nanotechnology provides a novel and improved solution for the preparation of safe and effective pesticides ([Sasson et al., 2007](#_ENREF_52)). Nano pesticides are specifically applied to diseased part of the plant affected by pest. Also the nano carriers are self-regulated meaning pesticides of only required amount is delivered to plant tissue ([Mousavi & Rezaei, 2011](#_ENREF_36)).

Nanotechnology assists the agricultural sciences and protect the environment by producing eco-friendly nanomaterials. Several nanomaterials such as gold nanoparticles, iron oxide nano perticles and polymeric nanoparticles could be easily synthesized and exploited/used as pesticides ([Sharon et al., 2010](#_ENREF_56)). The nano formulations of nano pesticides include metal nanoparticles (inorganic), polymers (organic) and various surfactants in the size range of nanometer. Lack of water solubility is the major challenge for hydrophobic pesticides. For this purpose, microencapsulation is used which helps in increasing their dispersion in aqueous media and allows a controlled release of active compounds ([Sekhon, 2014](#_ENREF_53)).

**Nano-Microbicides**

Many nano particals such as Ag, Au, ZnO, MgO, SiO2 and TiO2 are being used as antimicrobial agents. Among these silver nanoparticles are of great importance. In 2009, FDA approved a direct use of Ag as a disinfectant agent for commercial water, owing to its effectiveness as an antimicrobial agent ([Necula et al., 2010](#_ENREF_39)). Zinc nanocrystals depicted antifungal and antibacterial activity ([Duncan, 2011](#_ENREF_17)). Gold is thermostable and has low volatility and it is found to be effective antifungal agent and also depicted good antibacterial effects against 150 different bacterial strains ([Kumar & Münstedt, 2005](#_ENREF_29)). Beside these, other nanoparticles like TiO2 and ZnO were also reported to have good antibacterial characteristics ([Kim et al., 2003](#_ENREF_28)). Fungal diseases cause more than 70% of damages to major crops ([Godfray et al., 2016](#_ENREF_22)), as a result a severe loss of crop yield occurs and it effects the economy of a country. Conventional fungicides although found to be effective against fungal pathogens, but, they also target other useful microbes and hence disturb the natural balance of biodiversity ([Patel et al., 2014](#_ENREF_45)). Silver (Ag) nanoparticles are widely used as disinfectant ([Baker et al., 2005](#_ENREF_2)). Both Ag and Cu nano particles were found to be effective in combating fungal strains ([Ouda, 2014](#_ENREF_44)). Similarly, MgO an ZnO nanoparticles displayed antifungal activity against various strains of fungus ([Wani & Shah, 2012](#_ENREF_63)).

**Nano-Herbicides**

Weeds pose a greater threat to crops by utilizing the nutrients required by the growing plants. Conventional method of picking weeds by hands requires lot of efforts and is also time consuming. Several herbicides available in the market although effective for killing weeds, but they also damage the healthy plants and effect the soil fertility. Nano herbicides are effective ecofriendly alternatives for weed control without harming the soil fertility ([Pérez-de-Luque, 2017](#_ENREF_46)). Nano capsules containing conventional herbicide atrazine depicted most effective herbicidal activity on mustard plants when compared to commercial atrazine formulation ([Oliveira et al., 2015](#_ENREF_41)).

**Nano-Sensors/Nano-Biosensors**

Regular monitoring of soil health and possible occurrence of any disease is important. There is need of development of accurate handy and portable sensing system for the real time monitoring of large areas of field ([Yao et al., 2014](#_ENREF_65)). Nano sensors could be effective for pathogen detection, for crop cultivation, harvesting as well as for detecting the parameters of soil such as nutrients and pH. Nanoparticles have unique surface chemistry, thermal and electrical properties and enhanced sensitivities and detection limits. These characteristics make them better choice for sensing systems ([Yao et al., 2014](#_ENREF_65)). Nanomaterials like cadmium telluride (CdTe)-quantum dots (QDs) were used on the basis of fluoro immunoassay-based sensing system for the detection of 2,4-dichlorophenoxyacetic acid ([Vinayaka et al., 2009](#_ENREF_61)).

Various nanomaterials like QDs and Au nanoparticles are being employed in the optical based immune sensors for increasing the signal amplification ([Chen et al., 2010](#_ENREF_7)). In one study Au nanoparticles were used for the detection of pesticides found in the water coming from the agricultural fields and other sources ([Lisha et al., 2009](#_ENREF_31)). Gold nanoparticles function is realized for immune chromatographic test strips for detecting various pesticides.

The nano sensors can assist in the effective utilization of natural resources i.e. nutrients, water and chemicals etc. These nano-sensors when disseminated in the field help in the detection of viruses or other pathogens of plants as well as the level of nutrients of soil ([Brock et al., 2011](#_ENREF_5); [Jones, 2014](#_ENREF_27)). Nano smart dust and gas sensors can quickly evaluate the levels of environmental pollution ([Mousavi & Rezaei, 2011](#_ENREF_36)). Bio-nanosensors allow the rapid detection and quantification of viruses and bacteria ([Otles & Yalcin, 2010](#_ENREF_43)).

Plants produce volatile compounds when they get infected with any pathogen and the detection of these volatile compounds could assist in the confirmation of any infection in plants (Mittal et al., 2020). Nano-biosensors are used for sensing pathogens, fertilizers, pesticides, insecticides, herbicides, soil pH, and moisture content. The controlled and effective use of these nano sensors could support the sustainable agriculture for increasing the crop productivity ([Rai et al., 2012a](#_ENREF_50)). Despite having lot of potential, this area is still in its infancy stage and need to be realized for the applications in the real field.

**Role of NMs for Managing Post Harvest Waste Products of Agriculture**

Nanotechnology also plays vital role in the recycling of agricultural waste products. For instance, some of the cellulose or fibers left after the processing of cotton into garment are usually discarded as waste. Cellulose could be efficiently used for the synthesis of nan cellulose and natural fibers ([Dai & Fan, 2013](#_ENREF_10)). By the use of electro spinning technique, 100nm fibers (nano fibers) are produced that can act as fertilizer or pesticide absorbent ([Lang, 2003](#_ENREF_30)). Besides, they are also used for encapsulating chemical pesticides in order to prevent the scattering of these pesticides in the water, soil and environment which ensures the durable and secure application of pesticides. After the bio degradation of nanofibers, pesticides are released slowly in the soil. Likewise, nano fibers based fabrics could be used for the capturing and isolation of pathogens. Nano fibers are embedded with antibodies against specific pathogens. After wiping across a surface, the presence of pathogens on the fabric can be detected by the change in color ([Hager, 2011](#_ENREF_23)).

The large amount of lignocellulose found in the agricultural waste could be used for the preparation of functional nanomaterials like nano cellulose ([Shahabi-Ghahafarrokhi et al., 2015](#_ENREF_54)), nanocomposite ([Othman, 2014](#_ENREF_42)) etc. Nano cellulose called aerogels are very hydrophilic, that could be used as adsorption material due to their nano fibrillary structure having large surface area and high adsorbing properties ([Muñoz-García et al., 2015](#_ENREF_37)). Silica an excellent source of micro and nano silica could be extracted from rice husk. Nano-silica conjugated with validamycin could be used for the controlled release of hydrophilic pesticides ([Liu et al., 2006](#_ENREF_32)). Similarly, nano silica conjugated with methyl methoxy silane was found to be effective nano fungicide for mildew disease ([Huang et al., 2015](#_ENREF_25)).

**Toxicological Impact, Associated Risks and Health Hazards of NMs**

Despite the potential benefits of nanotechnology i.e. improving the nutritional value and quality of food, less is known about the safety aspects of nanotechnology ([Sekhon, 2014](#_ENREF_53)). Little efforts have been made in understanding the risk and health hazards associated with nano-materials. There is need of research advancement in the fields of nano-safety, policy making, risk assessment, risk management and risk communication among the various stakeholders such as researchers, industries, general public and policy makers. There is two-way approach adopted by nano-safety researchers ([Bos et al., 2015](#_ENREF_4)). First approach is the understanding of human health toxicity and second is environmental health risk. So, plant based nano-safety research is based on the direct exposure of food crops to nanomaterials i.e. nano-fertilizers, nano-pesticides and nano-herbicides or indirect exposure i.e., leaching, runoff of nanoparticles and spray drifting. Physiochemical properties of nanoparticles need to be addressed on primarily basis as they have a direct impact on human health and environmental hazards. From the toxicology point of view, size and concentration of the nanoparticles are the most important properties. Due to small size and greater surface area, higher uptake of these nano-particles occur in plants ultimately generating the adverse effects ([Nel et al., 2006](#_ENREF_40)). Awareness and acceptance of food nanotechnology by public is another important aspect being ignored by researchers, and authorities ([Arnaldi & Muratorio, 2013](#_ENREF_1); [Cormick, 2009](#_ENREF_9)). Consumers are still not well aware about nanotechnology. In the case of acceptance of these novel foods, the ultimate disposal of waste into the environment may effect fauna, flora and ecosystems. Proper disposal methods have not been discussed so far either by researcher, government agencies or food companies. There are no specific risk assessment procedures, so an uncertainty is found regarding the extent and nature of possible risks in various cases ([Sekhon, 2014](#_ENREF_53)). Besides, very few *in vivo* toxicity data about nanomaterials is available, particularly about the potential chronic effects of these nanomaterials on human organs ([He et al., 2019](#_ENREF_24)).

There could be adverse effects of engineered nanoparticles on edible plants ([Suppan, 2013](#_ENREF_59)). A global debate is going on regarding the potential benefits and risks of using nano-silver as an antibacterial agent ([Boholm & Arvidsson, 2014](#_ENREF_3)). Detection of elevated level of cerium in the tomato fruits exposed to cerium oxide nanoparticles shed light on long term effects of these nanoparticles on plant health and also their implications for our food security and safety ([Wang et al., 2012](#_ENREF_62)). There is need of regulatory systems for the management of risks associated with nano-foods and utilization of nanotechnology in the food industry ([Momin et al., 2013](#_ENREF_35)). The main reason of limited regulation of nanomaterials is the limited knowledge about the toxicity and risk associated with them ([Dasari et al., 2014](#_ENREF_11); [Deng et al., 2018](#_ENREF_13)). There are several studies focusing only on *in vitro* toxicity of nanoparticles, however, less data is available regarding the *in vivo* toxicity ([Duncan, 2011](#_ENREF_17)).

There is urgent need of getting insight into toxicity evaluation and risk assessment of novel nanao-materials for the purpose of legislation and the public acceptance. In this situation green synthesized or biosynthesized nano-particles can provide an alternative solution for applying nanomaterials in food industry with relatively acceptable negative impact ([He et al., 2019](#_ENREF_24)).

**Concluding Remarks and Future Perspectives**

The potential benefits and uses of nanotechnology are numerous for agriculture and food industries. Plants more efficiently utilize water, fertilizer and pesticides through nanotechnology. Through nano-sensors or nano-biosensors detection of pathogens and soil quality as well as monitoring of soil health get possible. The main focus of experts in the near future is the designing of nano-particulate agro-formulations with higher efficacy and bio-availability. There is need that the potential benefits of nanotechnology agriculture, food etc. need to be balanced against concerns for the water, soil health of occupational workers as well as environment.

Despite the fact that nanotechnology has promising applications in various fields of life, however this could not be ignored that most of the knowledge gathered is based on the laboratory experiments. An uncertainty is found about the practical application of these nanomaterials without understanding about their toxicity for human health and environment. Similarly, the absence of proper guidelines and regulatory bodies creates hurdles for the selling of novel nanoparticles based agrochemicals. So, there is need of execution of large trials for implications at the field level. There is need of public awareness through government awareness programs. A more practical strategy is needed for determining the risk associated with the utilization of nanoparticle based products in the agricultural sector. There is need of identification of minimum concentration dose of nanoparticles which would be nontoxic and beneficial for field applications (Mittal et al., 2020).

**References**

Arnaldi, S., & Muratorio, A. (2013). Nanotechnology, uncertainty and regulation. A guest editorial. In (Vol. 7, pp. 173-175): Springer.

Baker, C., Pradhan, A., Pakstis, L., Pochan, D. J., & Shah, S. I. (2005). Synthesis and antibacterial properties of silver nanoparticles. *Journal of nanoscience and nanotechnology*, *5*(2), 244-249.

Boholm, M., & Arvidsson, R. (2014). Controversy over antibacterial silver: implications for environmental and sustainability assessments. *Journal of Cleaner Production*, *68*, 135-143.

Bos, P. M., Gottardo, S., Scott-Fordsmand, J. J., Van Tongeren, M., Semenzin, E., Fernandes, T. F., . . . Irfan, M.-A. (2015). The MARINA risk assessment strategy: a flexible strategy for efficient information collection and risk assessment of nanomaterials. *International journal of environmental research and public health*, *12*(12), 15007-15021.

Brock, D. A., Douglas, T. E., Queller, D. C., & Strassmann, J. E. (2011). Primitive agriculture in a social amoeba. *Nature*, *469*(7330), 393-396.

Changmei, L., Chaoying, Z., Junqiang, W., Guorong, W., & Mingxuan, T. (2002). Research of the effect of nanometer materials on germination and growth enhancement of Glycine max and its mechanism. *Soybean Science*, *21*(3), 168-171.

Chen, Y., Ren, H. L., Liu, N., Sai, N., Liu, X., Liu, Z., . . . Ning, B. A. (2010). A fluoroimmunoassay based on quantum dot− streptavidin conjugate for the detection of chlorpyrifos. *Journal of agricultural and food chemistry*, *58*(16), 8895-8903.

Chhipa, H. (2017). Nanofertilizers and nanopesticides for agriculture. *Environmental chemistry letters*, *15*, 15-22.

Cormick, C. (2009). Why do we need to know what the public thinks about nanotechnology? *Nanoethics*, *3*(2), 167-173.

Dai, D., & Fan, M. (2013). Green modification of natural fibres with nanocellulose. *Rsc Advances*, *3*(14), 4659-4665.

Dasari, T., Deng, H., McShan, D., & Yu, H. (2014). Nanosilver-based antibacterial agents for food safety. *Food poisoning: outbreaks, bacterial sources and adverse health effects. Food and beverage consumption and health. Nova Science Publishers, Hauppauge*, 35-62.

Delfani, M., Baradarn Firouzabadi, M., Farrokhi, N., & Makarian, H. (2014). Some physiological responses of black-eyed pea to iron and magnesium nanofertilizers. *Communications in soil science and plant analysis*, *45*(4), 530-540.

Deng, H., Zhang, Y., & Yu, H. (2018). Nanoparticles considered as mixtures for toxicological research. *Journal of Environmental Science and Health, Part C*, *36*(1), 1-20.

Dimkpa, C. O., & Bindraban, P. S. (2017). Nanofertilizers: new products for the industry? *Journal of agricultural and food chemistry*, *66*(26), 6462-6473.

Dimkpa, C. O., Bindraban, P. S., Fugice, J., Agyin-Birikorang, S., Singh, U., & Hellums, D. (2017). Composite micronutrient nanoparticles and salts decrease drought stress in soybean. *Agronomy for Sustainable Development*, *37*, 1-13.

Doa, U. (2003). Nanoscale science and engineering for agriculture and food systems: a report submitted to cooperative state research, education and extension service. *Washington, DC: Department of Agriculture*.

Duncan, T. V. (2011). Applications of nanotechnology in food packaging and food safety: barrier materials, antimicrobials and sensors. *Journal of colloid and interface science*, *363*(1), 1-24.

Dwivedi, S., Saquib, Q., Al-Khedhairy, A., & Musarrat, J. (2016). Understanding the role of nanomaterials in agriculture. InMicrobial Inoculants in Sustainable Agricultural Productivity 2016. In: Springer, New Delhi.

El-Ramady, H. R. (2014). Integrated nutrient management and postharvest of crops. *Sustainable Agriculture Reviews: Volume 13*, 163-274.

Fraceto, L. F., Grillo, R., de Medeiros, G. A., Scognamiglio, V., Rea, G., & Bartolucci, C. (2016). Nanotechnology in agriculture: which innovation potential does it have? *Frontiers in Environmental Science*, *4*, 20.

Ghidan, A. Y., Al-Antary, T. M., Salem, N. M., & Awwad, A. M. (2017). Facile green synthetic route to the zinc oxide (ZnONPs) nanoparticles: Effect on green peach aphid and antibacterial activity. *Journal of Agricultural Science*, *9*(2), 131-138.

Godfray, H. C. J., Mason-D'Croz, D., & Robinson, S. (2016). Food system consequences of a fungal disease epidemic in a major crop. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1709), 20150467.

Hager, H. (2011). Nanotechnology in agriculture. In.

He, X., Deng, H., & Hwang, H.-m. (2019). The current application of nanotechnology in food and agriculture. *Journal of food and drug analysis*, *27*(1), 1-21.

Huang, S., Wang, L., Liu, L., Hou, Y., & Li, L. (2015). Nanotechnology in agriculture, livestock, and aquaculture in China. A review. *Agronomy for Sustainable Development*, *35*, 369-400.

Jampílek, J., & Kráľová, K. (2017). Nanopesticides: preparation, targeting, and controlled release. In *New Pesticides and Soil Sensors* (pp. 81-127). Elsevier.

Jones, P. (2014). A Nanotech Revolution in Agriculture and the Food Industry. Blacksburg, VA: Information Systems for Biotechnology; 2006. In.

Kim, B., Kim, D., Cho, D., & Cho, S. (2003). Bactericidal effect of TiO2 photocatalyst on selected food-borne pathogenic bacteria. *Chemosphere*, *52*(1), 277-281.

Kumar, R., & Münstedt, H. (2005). Silver ion release from antimicrobial polyamide/silver composites. *Biomaterials*, *26*(14), 2081-2088.

Lang, S. (2003). Waste fiber can be recycled into valuable products using new technique of electrospinning, Cornell researchers report. In.

Lisha, K. P., Anshup, & Pradeep, T. (2009). Enhanced visual detection of pesticides using gold nanoparticles. *Journal of Environmental Science and Health Part B*, *44*(7), 697-705.

Liu, F., Wen, L.-X., Li, Z.-Z., Yu, W., Sun, H.-Y., & Chen, J.-F. (2006). Porous hollow silica nanoparticles as controlled delivery system for water-soluble pesticide. *Materials research bulletin*, *41*(12), 2268-2275.

Meena, R. S., Kumar, S., Datta, R., Lal, R., Vijayakumar, V., Brtnicky, M., . . . Jangir, C. K. (2020). Impact of agrochemicals on soil microbiota and management: A review. *Land*, *9*(2), 34.

Mittal, D., Kaur, G., Singh, P., Yadav, K., & Ali, S. A. (2020). Nanoparticle-based sustainable agriculture and food science: Recent advances and future outlook. *Frontiers in Nanotechnology*, *2*, 579954.

Momin, J. K., Jayakumar, C., & Prajapati, J. B. (2013). Potential of nanotechnology in functional foods. *Emirates journal of food and agriculture*, *25*(1), 10-19.

Mousavi, S. R., & Rezaei, M. (2011). Nanotechnology in agriculture and food production. *J Appl Environ Biol Sci*, *1*(10), 414-419.

Muñoz-García, R. O., Hernández, M. E., Ortiz, G. G., Fernández, V. V., Arellano, M. R., & Sánchez-Díaz, J. C. (2015). A novel polyacrylamide-based hydrogel crosslinked with cellulose acetate and prepared by precipitation polymerization. *Química Nova*, *38*, 1031-1036.

Nandita, D., & Shivendu, R. (2018). An introduction to food grade nanoemulsions. *An introduction to food grade nanoemulsions*.

Necula, A. M., Dunca, S., Stoica, I., Olaru, N., Olaru, L., & Ioan, S. (2010). Morphological properties and antibacterial activity of nano-silver-containing cellulose acetate phthalate films. *International Journal of Polymer Analysis and Characterization*, *15*(6), 341-350.

Nel, A., Xia, T., Madler, L., & Li, N. (2006). Toxic potential of materials at the nanolevel. *Science*, *311*(5761), 622-627.

Oliveira, H. C., Stolf-Moreira, R., Martinez, C. B. R., Grillo, R., de Jesus, M. B., & Fraceto, L. F. (2015). Nanoencapsulation enhances the post-emergence herbicidal activity of atrazine against mustard plants. *PLoS One*, *10*(7), e0132971.

Othman, S. H. (2014). Bio-nanocomposite materials for food packaging applications: types of biopolymer and nano-sized filler. *Agriculture and Agricultural Science Procedia*, *2*, 296-303.

Otles, S., & Yalcin, B. (2010). Nano-biosensors as new tool for detection of food quality and safety. *LogForum 6, 4*, *7*.

Ouda, S. M. (2014). Antifungal activity of silver and copper nanoparticles on two plant pathogens, Alternaria alternata and Botrytis cinerea. *Research Journal of Microbiology*, *9*(1), 34.

Patel, N., Desai, P., Patel, N., Jha, A., & Gautam, H. K. (2014). Agronanotechnology for plant fungal disease management: a review. *Int J Curr Microbiol App Sci*, *3*(10), 71-84.

Pérez-de-Luque, A. (2017). Interaction of nanomaterials with plants: what do we need for real applications in agriculture? *Frontiers in Environmental Science*, *5*, 12.

Peters, R. J., Bouwmeester, H., Gottardo, S., Amenta, V., Arena, M., Brandhoff, P., . . . Pesudo, L. Q. (2016). Nanomaterials for products and application in agriculture, feed and food. *Trends in Food Science & Technology*, *54*, 155-164.

Pilarska, A., Wysokowski, M., Markiewicz, E., & Jesionowski, T. (2013). Synthesis of magnesium hydroxide and its calcinates by a precipitation method with the use of magnesium sulfate and poly (ethylene glycols). *Powder Technology*, *235*, 148-157.

Pouratashi, M., & Iravani, H. (2012). Farmers’ knowledge of integrated pest management and learning style preferences: Implications for information delivery. *International Journal of Pest Management*, *58*(4), 347-353.

Rai, V., Acharya, S., & Dey, N. (2012a). Implications of nanobiosensors in agriculture. J Biomater Nanobiotechnol 3: 315–324. In.

Rai, V., Acharya, S., & Dey, N. (2012b). Implications of nanobiosensors in agriculture. J Biomater Nanobiotechnol 03: 315–324. In.

Sasson, Y., Levy-Ruso, G., Toledano, O., & Ishaaya, I. (2007). Nanosuspensions: emerging novel agrochemical formulations. In *Insecticides design using advanced technologies* (pp. 1-39). Springer.

Sekhon, B. S. (2014). Nanotechnology in agri-food production: an overview. *Nanotechnology, science and applications*, 31-53.

Shahabi-Ghahafarrokhi, I., Khodaiyan, F., Mousavi, M., & Yousefi, H. (2015). Preparation and characterization of nanocellulose from beer industrial residues using acid hydrolysis/ultrasound. *Fibers and Polymers*, *16*, 529-536.

Sharifi, M., Faryabi, K., Talaei, A. J., Shekha, M. S., Ale-Ebrahim, M., Salihi, A., . . . Hasan, A. (2020). Antioxidant properties of gold nanozyme: A review. *Journal of Molecular Liquids*, *297*, 112004.

Sharon, M., Choudhary, A. K., & Kumar, R. (2010). Nanotechnology in agricultural diseases and food safety. *Journal of Phytology*, *2*(4).

Siddiqui, M. H., Al‐Whaibi, M. H., Faisal, M., & Al Sahli, A. A. (2014). Nano‐silicon dioxide mitigates the adverse effects of salt stress on Cucurbita pepo L. *Environmental toxicology and chemistry*, *33*(11), 2429-2437.

Singh, P., Singh, D. N., & Debbarma, S. (2023). Macro-and micro-mechanisms associated with valorization of waste rubber in cement-based concrete and thermoplastic polymer composites: A critical review. *Construction and Building Materials*, *371*, 130807.

Suppan, S. (2013). Nanomaterials in soil. *Institute for Agriculture and Trade Policy*.

Tarafdar, J., Xiong, Y., Wang, W.-N., Quinl, D., & Biswas, P. (2012). Standardization of size, shape and concentration of nanoparticle for plant application. *Applied Biological Research*, *14*(2), 138-144.

Vinayaka, A., Basheer, S., & Thakur, M. (2009). Bioconjugation of CdTe quantum dot for the detection of 2, 4-dichlorophenoxyacetic acid by competitive fluoroimmunoassay based biosensor. *Biosensors and Bioelectronics*, *24*(6), 1615-1620.

Wang, Q., Ma, X., Zhang, W., Pei, H., & Chen, Y. (2012). The impact of cerium oxide nanoparticles on tomato (Solanum lycopersicum L.) and its implications for food safety. *Metallomics*, *4*(10), 1105-1112.

Wani, A., & Shah, M. (2012). A unique and profound effect of MgO and ZnO nanoparticles on some plant pathogenic fungi. *Journal of Applied Pharmaceutical Science*(Issue), 40-44.

Xiumei, L., Fudao, Z., Shuqing, Z., Xusheng, H., Rufang, W., Zhaobin, F., & Yujun, W. (2005). Responses of peanut to nano-calcium carbonate. *Plant Nutrition and Fertitizer Science*, *11*(3), 385-389.

Yao, J., Yang, M., & Duan, Y. (2014). Chemistry, biology, and medicine of fluorescent nanomaterials and related systems: new insights into biosensing, bioimaging, genomics, diagnostics, and therapy. *Chemical reviews*, *114*(12), 6130-6178.