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Nanotechnology in agriculture: Promises, risks and challenges

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Abstract
In recent years, nanotechnology has emerged as an innovative solution in agriculture, providing an array of potential benefits such as enhanced crop productivity, improved soil health and efficient pest management. Nevertheless, the integration of nanotechnology into agricultural practices also brings forth corresponding risks and challenges that need to be thoroughly assessed and addressed. This article provides a comprehensive review of the risks, challenges and benefits associated with the utilization of nanotechnology in agriculture.
The risks associated with nanotechnology in agriculture primarily revolve around its potential environmental and health impacts. Nanoparticles introduced into the agricultural system can enter the soil, water and plant tissues, leading to concerns regarding their long-term effects on ecosystems and human health. Moreover, the inadvertent release of engineered nanoparticles into the environment poses an ecological risk as they can affect beneficial microbes, pollinators and other organisms.
Challenges associated with nanotechnology implementation in agriculture include uncertainties regarding regulatory frameworks, public acceptance and economic viability. Adequate regulation and guidelines are necessary to ensure the safe and responsible use of nanotechnology in agriculture. Moreover, engaging with stakeholders, including farmers, retailers, consumers and policymakers, is crucial for addressing concerns and fostering public acceptance.
Despite these risks and challenges, nanotechnology offers numerous potential benefits to agriculture. Nanoparticles can serve as delivery vehicles for controlled and targeted release of fertilizers, pesticides and growth promoters, thereby reducing their overall usage and minimizing environmental impact. Additionally, nanosensors enable real-time monitoring of plant health, allowing for proactive responses to diseases, nutrient deficiencies and water stress. Moreover, nanoparticles can improve soil fertility, water management and crop yield through enhanced nutrient uptake and water holding capacity.

Keywords: Agriculture, nanotechnology, fertilizers, pesticides, nanoparticles

Introduction
The most pressing global issue we face today is ensuring food security for a rapidly growing population. According to predictions, the demand for food is expected to increase from 59 to 98% by 2050 for the world's population, which is estimated to reach 9 billion (Duro *et al*., 2020) [6]. Despite an increase of the world population particularly in developing countries, the global food supply interrupted by the expenditure of bio-resources for production of energy, manufacturing chemicals, high post farming loss, less value addition, inefficient distribution and marketing systems, and other factors (Barrett, 2021; Sekhon, 2014) [3, 18]. Farmers worldwide are using new technologies to enhance crop production through intensive and extensive agriculture. These efforts are being further boosted by the use of nano-modified stimulants and precision farming techniques.

What is nanotechnology?
Nanotechnology is defined by the US Environmental Protection Agency as the science of understanding and control of matter at dimensions of roughly 1–100 nm, where unique physical properties make novel applications possible. This definition is slightly rigid with regard to size dimensions. Greater emphasis could have been placed on the problem-solving capability of the materials. Other attempts to define nanoparticles from the point of view of agriculture include "particulate between 10 and 1,000 nm in size dimensions that are simultaneously colloidal particulate" (Nakache *et al*., 1999) [14].

The scale of demand of input materials is always being large in contrast with industrial nanoproducts with the absence of control over the input of the nanomaterials in contrast with industrial nanoproducts (Mukhopadhyay, 2014) [13]. Nanotechnology can increase agricultural production and its applications include.

1. Nanoformulations of agrochemicals can be used to apply pesticides and fertilizers for crop improvement.
2. Nanosensors can be used in crop protection to identify diseases and residues of agrochemicals.
3. Nanodevices can be used for genetic engineering of plants.
4. Plant disease diagnostics can be improved through the use of nanotechnology.
5. Nanotechnology can improve animal health, breeding, and poultry production.
6. Postharvest management can also be improved through the use of nanotechnology.

Nanotechnology in pesticides and fertilizers

The effects of different Nanoparticles on plant growth and phytotoxicity were reported by several workers including magnetite (Fe_3O_4) nanoparticles and plant growth (Shankramma *et al*., 2016) [19], alumina, zinc, and zinc oxide on seed germination and root growth of five higher plant species; radish, rape, lettuce, corn, and cucumber, silver nanoparticles and seedling growth in wheat (Lin *et al*., 2007) [10], sulfur nanoparticles on tomato (Salem *et al*., 2016) [17], zinc oxide in mungbean, nanoparticles of AlO, CuO, FeO, MnO, NiO and ZnO (Ghidan *et al*., 2018) [8]. Silver nanoparticles can stimulate wheat growth and yield. Soil applied 25 ppm SNPs had highly favorable growth-promoting effects on wheat growth and yield.

Magnesium oxide (MgO) is important inorganic materials with many uses such as adsorbents, fire retardants, advanced ceramics, toxic waste remediation, and photo electronic materials. Therefore, various techniques and routes for synthesis of MgONPs have been reported (Ghidan *et al*., 2017) [9]. MgOH was synthesized by green methods using nontoxic neem leaves extract (Moorthy *et al*., 2015) [12], *Citrus limon* leaves extract, *acacia* gum (Awwad and Ahmad, 2014) [2].

Nanotechnology application as nano-fungicides

The use of nanosilver has been studied recently against phytopathogen Colletotrichum gloeosporioides (Aguilar *et al*., 2016) [1]. Other nanoparticles (Fe, Cu, Si, Al, Zn, ZnO, TiO_2, CeO_2, Al_2O_3 and carbon nanotubes) have been reported to have some adverse effects on plant growth apart from the antimicrobial properties (Rico *et al*., 2010) [16]. Sometimes, nanoparticles also have an effect on the growth of useful soil bacteria, such *as Pseudomonas putida KT*$_{2440}$ (Gajjar *et al*., 2009) [7]. Various research groups focused their interest on the usage of eco-friendly pesticides. Similar to chemical pesticides, nanoparticle-based pesticides and herbicides are being explored for the application of the antimicrobial agents to protect crops from various diseases. Extensive studies on nanoparticle-based systems may eliminate the intensive use of pesticides in the agricultural sector (Barauh and Dutta, 2009) [5]. The antifungal properties of nanoparticles can help to formulate nanoparticle-based pesticides (Aguilar *et al*., 2016) [1]. Among the different inorganic nanoparticle-based antimicrobial agents, silver has been extensively studied by many researchers because of its several advantages over other nanoparticles such as copper, zinc, gold, ZnO, Al_2O_3 and TiO_2.

Nanotechnology in Food packaging

Nanomaterials perform very well in enhancing food security to support the development of food manufacturing industry. Depositing of food manufacturing equipment (via biofilm coating), nanofabricated filters, sieves and membranes, nanocomposite based and nanosized adsorbents and catalytic agents are also utilization areas for provision of assistance in the processing of food (Bartolucci, 2017) [4]. Adding nanomaterials into the packing of food are supposed to modify the hindrance felt during materials packing and can help decrease the involvement of valued raw ingredients and waste production (Sozer and Kokini, 2009) [20].

Risks in nanotechnology

Following point are considered as a risk of nanotechnology application (Maynord, 2006) [11].

- The risks associated with nanotechnology are varied and include environmental, health, occupational and socio-economic risks due to its heterogeneous nature.
- When organisms come in contact with nanoparticles or nanomaterials, it can lead to toxicological effects.
- The potential for direct human contact with nanoparticles in various applications can result in adverse toxic effects.
- Research shows that nanoparticles can reach different parts of the body and have adverse effects.
- Nanoparticles can disrupt cellular, enzymatic, and organ-related functions, leading to potential health hazards.
- Non-biodegradable nanoparticles can lead to the formation of a new class of non-biodegradable pollutants during disposal.
- The use of nanotechnology increases the risk of environmental pollution, including water, soil and air pollution, as well as health hazards.
- There is limited research on nanotoxicity in agriculture, which poses a potential risk to plants, microbes, animals and humans.
- The greatest current risk associated with nanotechnology is to the occupational health of workers involved in the production, packaging, or transportation of nanomaterials.
- Due to health hazards, it is necessary to assess the different types of environmental and non-environmental risks.

Challenges in nanotechnology

The challenges in the field of nanotechnology can be summarized as follows (Rajkishore and Lakshmanan, 2012) [15].

- Producing nanomaterials in large quantities with standardized quality and at an affordable cost.
- Supplying nanomaterials in a form that allows for integration into various processes, including proper particle size, surface chemistry and compatibility etc.
- Developing an engineering framework that customizes the use of nano-based systems according to local requirements.
- Ensuring environmental health and safety concerns are taken into account when using and disposing of nano products/materials.
- Bridging the gap between basic research and practical applications.

- Addressing cost, risk, and technical knowledge barriers to implementing nanotechnology.
- Overcoming regulatory challenges and improving inter-agency coordination to ensure safe and effective use of nanotechnology.

Conclusion

Nanotechnology has the potential to revolutionize the agriculture and food industry by improving crop production, developing efficient pesticides and fertilizers and enhancing food packaging. However, there are also risks and challenges associated with the application of nanotechnology in these sectors. The potential health and environmental risks of nanoparticles need to be carefully studied and addressed. Additionally, there are challenges in ensuring the scalability, affordability, and integration of nanomaterials into existing processes. Regulatory frameworks and inter-agency coordination are also crucial for the safe and effective use of nanotechnology. Overall, nanotechnology offers promising solutions to global food security, but its implementation must be done with caution and proper risk assessment.

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