

IMPACT OF NANO TECHNOLOGY IN AGRICULTURE

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Abstract

Nanotechnology has emerged as a transformative force in agriculture, offering innovative solutions to improve crop production, enhance nutrient management, and address pressing challenges such as pest control, water scarcity and environmental degradation. The application of nanomaterials, including nano-fertilizers, nano-pesticides and nano-biosensors, promises significant improvements in nutrient uptake efficiency, targeted pesticide delivery and real-time monitoring of soil and crop health. Additionally, nanotechnology aids in soil remediation, crop breeding and food preservation, further advancing agricultural sustainability. However, the widespread adoption of nanotechnology in agriculture raises concerns about potential environmental and health risks. It is crucial to develop regulatory frameworks and conduct thorough risk assessments to ensure the safe and responsible application of nanomaterials. This review explores the potential benefits, challenges and future directions of nanotechnology in agriculture, highlighting its role in enhancing productivity while minimizing environmental impact.

Keywords: Nano fertilizers, nano sensors, application and crop protection

Introduction

Nanotechnology has garnered significant attention in recent years due to its extensive applications across various fields, including medicine, pharmaceuticals, catalysis, energy and materials science. Nanoparticles, characterized by their small size and large surface area (1–100 nm), hold immense potential for applications in medicine, industry, and agriculture. Moreover, nanotechnology offers tremendous opportunities for energy and environmental applications by manipulating materials at the molecular scale. Nanomaterials such as carbon nanotubes, graphene, and nano-catalysts exhibit unique optical, electrical, and mechanical properties, making them ideal for use in renewable energy generation, energy storage, and pollution remediation. With the rapid growth of the global population, energy consumption has surged, intensifying environmental pressures. In India, energy demand is expected to grow faster than in any other major economy over the next 25 years. To meet its development goals sustainably, the country must expand its energy infrastructure while minimizing environmental impacts. The responsible utilization of nanomaterials could play a transformative role in achieving this balance.

Scientists have made substantial progress in synthesizing nanoparticles using various approaches, including physical, chemical, and biological methods (Ghidan et al., 2017). However, these methods often face challenges such as difficulties in scaling up, complexities in separating and purifying nanoparticles from microemulsions (comprising oil, surfactants, co-surfactants, and aqueous phases), and the high consumption of surfactants (Pilarska et al., 2013). In contrast, green synthesis using plant extracts offers a simple, convenient, and eco-friendly alternative that requires less reaction time and minimizes environmental impact. The green synthesis of nanoparticles using plant extracts provides several advantages: it is simple, convenient, eco-friendly, and

requires less reaction time (Ghidan et al., 2017). Nanomaterials produced through these sustainable methods have the potential to enhance agricultural practices by improving fertilization processes, acting as plant growth regulators, and serving as efficient pesticides (Hofmann, 2014).

Over the past decade, nanotechnology in agriculture has gained significant momentum, supported by substantial public funding. While the field has seen notable advancements, its development remains influenced by the unique characteristics of agricultural production. Unlike industrial systems, farming operates as an open system where energy and matter are exchanged freely, resulting in a large-scale demand for input materials and limited control over the application of nanomaterials (Mukhopadhyay, 2014). Despite these challenges, nanotechnology offers innovative agrochemical agents and advanced delivery mechanisms to enhance crop productivity while reducing reliance on pesticides.



Precision farming techniques can enhance crop yields while minimizing damage to soil and water resources. These methods can also reduce nitrogen loss through leaching and emissions, preserving soil microorganisms. Nanotechnology applications in agriculture include nanoparticle-mediated gene or DNA transfer to develop insect-resistant plant varieties, innovations in food processing and storage, and the extension of product shelf life. Additionally, nanotechnology has the potential to advance biomass-to-fuel production (Ghidan and Antary, 2019). Experts emphasize the need to balance the promising benefits of nanotechnology in agriculture,

food, fisheries, and aquaculture with concerns about its impact on soil, water, the environment, and workers' occupational health.

Nanotechnology is being actively explored in food technology and agriculture, with applications aimed at reducing the use of plant protection products and enhancing crop yields. Tools such as nano capsules and nanoparticles are being utilized for disease detection and treatment. Additionally, nanotechnology-derived devices are being investigated for plant breeding and genetic transformation. While the potential of nanotechnology in agriculture is significant, challenges such as comprehensive risk assessment still need to be addressed.

The Need for Nanotechnology in Indian Agriculture

Indian agriculture has faced challenges post-Green Revolution, with a decline in nutrient use efficiency and crops no longer responding effectively to added nutrients such as fertilizers.

- **Environmental Damage:** The indiscriminate and imbalanced application of fertilizers has caused severe damage to croplands and natural water bodies. For instance, the excessive use of subsidized urea has contaminated groundwater, contributed to eutrophication, and degraded soil health.
- **Food and Nutritional Security Challenges:** Achieving food security in the face of climate change is increasingly difficult, further compounded by multi-nutrient deficiencies in Indian soils. This necessitates the development of efficient input delivery and management systems to ensure an adequate nutrient supply.
- **Other Agricultural Issues:** Indian agriculture also faces significant challenges such as pests and diseases, which lead to major crop losses, water shortages, and post-harvest losses due to spoilage. Nanotechnology has the potential to address these issues and improve overall agricultural sustainability.

Nano-fertilizers offer an effective solution to address the deficiency of essential micronutrients like zinc and copper in agriculture. These fertilizers encapsulate nutrients within nanomaterials, allowing for controlled release and slow diffusion into the soil.

Significance of Zinc and Copper Micronutrients in Agriculture:

- **Zinc:** Supports enzyme function, plant growth, and development.
- **Copper:** Plays a key role in enzymatic activities, chlorophyll production, and seed development.

Previously, IFFCO's nano-liquid urea and nano-liquid Di-Ammonium Phosphate (DAP) received approval under the Fertilizer Control Order (FCO), which is governed by the Department of Agriculture Cooperation under the Essential Commodities Act of 1955. The FCO outlines the substances that qualify for use as fertilizers, the licensing procedure, and more. The approval of these nanofertilizers marks a significant step toward the growing integration of nanotechnology in agriculture.

Applications of Nanotechnology in Agriculture

Nano-Fertilizers:

These can significantly enhance nutrient uptake in plants, achieving 90–100% utilization efficiency and boosting crop yields.

Nano-Pesticides:

These deliver active ingredients directly to pests in a targeted manner, reducing the need for large chemical applications and minimizing harm to non-target organisms. For example, nano-silver has demonstrated strong bactericidal properties and broad-spectrum antimicrobial activity.

Nano-Biosensors:

These devices accurately monitor soil conditions, crop health, and environmental factors, providing real-time data to farmers. This enables more informed decision-making regarding irrigation, nutrient management, and pest control.

Nanomaterials for Soil Improvement

- Clay Nanoparticles: Enhance soil structure, improve water retention, and increase nutrient-holding capacity.
- Nanomagnets: Used for removing soil contaminants.
- Remediation: Nanoparticles play a key role in pollution sensing and the remediation of contaminated agricultural lands. For instance, photocatalysis uses UV-activated nanoparticles to efficiently degrade pollutants.

Crop Protection

- Applying silica nanoparticles to plant leaves helps protect them from extreme temperatures and intense UV radiation.

Nanotechnology in Crop Breeding

Nanotechnology aids in developing genetically modified crops by allowing precise manipulation of plant genes at the nanoscale.

- Nano-Fiber Arrays: Enable the rapid and efficient delivery of genetic material to plant cells.
- Single-Walled Carbon Nanotubes (SWNTs): Serve as effective nano-transporters for delivering DNA and small dye molecules into plant cells, making them valuable for small treatment delivery systems in plants.

Nano technology in Food Processing

- Food Packaging and Preservation: Nanomaterials, such as nanocomposites, can be utilized to create antimicrobial coatings and oxygen barriers, reducing spoilage and minimizing food waste.
- Food Safety: Researchers have successfully used single bacterial cells to create tiny bio-electronic circuits, which could potentially be used in the future to detect bacteria, toxins, and proteins, enhancing food safety.

Challenges

Limited Availability of Specific Carrier Molecules

There is a lack of specific hybrid carriers for delivering active agents, including nutrients, pesticides, and fertilizers, that align with the principles of green chemistry and environmental sustainability.

Inadequate Research on Nanomaterial Life-Cycle Assessment

There are no standardized methods for conducting risk and life-cycle assessments of nanomaterials, nano-pesticides, and nano-fertilizers. Additionally, the potential impacts (e.g., phytotoxic effects) on non-target organisms and the occurrence of synergistic effects remain largely unexplored.

Field Analysis of Nanosensors

Although theoretical knowledge about nanosensors in the food supply chain exists—covering crop cultivation, harvesting, food processing, transportation, packaging, and distribution—their real-world applications for field analysis remain unexpectedly scarce.

Studies on Resistance Mechanisms

Assessing the ability of target organisms to develop resistance against nanomaterials is crucial. For instance, pathogens have evolved mechanisms to resist nanomaterials, such as effector proteins, biofilm formation, and genetic adaptation.

Development of Green Nanomaterials

The development of environmentally friendly nanomaterials faces challenges such as raw material availability, lack of standardization, scalability, production costs, and ecotoxicological concerns.

- Example: Iron oxide nanoparticles synthesized via green methods may leach iron into water bodies, potentially disrupting aquatic ecosystems.

Impact on Workers and Consumer Safety

- Example: Nano-silver particles in food packaging, while antimicrobial, may leach into food and affect gut microbiota.
- Example: Workers applying nano-pesticides could inhale nanoparticles like silica or copper oxide, leading to respiratory irritation or chronic lung inflammation.

High Costs of Development and Application

Nanotechnology in agriculture involves high research, development, and production costs, making it unaffordable for small-scale farmers.

- Example: Nano-encapsulated fertilizers or pesticides are significantly more expensive than traditional products, limiting adoption in developing countries.

Ethical and Social Concerns

Some stakeholders raise ethical concerns about the potential "unnaturalness" of nano-based agricultural solutions.

- Example: Debate around the use of nanotechnology for genetic modifications in crops—such as nanoparticle-mediated gene editing—may delay public acceptance.

Future Directions and Way Forward

The potential of nanotechnology in improving crop production, protection, and the entire food supply chain is vast. However, addressing its associated constraints requires further research and data-driven decision-making.

Key strategic areas to focus on include:

- Developing specific hybrid carrier molecules (e.g., bio-zeolites).
- Conducting risk assessment studies on residual effects, particularly on nano-pesticide fate.
- Harnessing nanobots for targeted delivery.
- Deploying AI-enabled nanosensors in the food supply chain.
- Ensuring sustainability by developing eco-friendly green nanomaterials (e.g., bio-CMNs in tomato for stress tolerance).

Additionally, establishing robust regulatory frameworks, promoting public engagement and transparency, and encouraging interdisciplinary research and collaboration will be essential to address ethical and social concerns. Through these efforts, the agricultural sector can harness nanotechnology to achieve sustainable productivity.

Conclusion

Nanotechnology holds great promise for transforming agriculture by enhancing crop production and management. However, challenges remain, particularly concerning the potential environmental and health risks associated with nanoparticles.

To address these concerns, it is essential to establish regulatory frameworks that ensure the safe and responsible development of nanomaterials in agriculture. Conducting proper risk assessments, as outlined in the guidelines by the Department of Biotechnology (DBT) and the FCO Order 2021, will be crucial for ensuring safe usage.

References:

Alaa Y. Ghidan and Tawfiq M. Al Antary. 2019. Applications of Nanotechnology in Agriculture. Chapter metrics overview. DOI: 10.5772/intechopen.88390

Ghidan AY, Al-Antary TM, Salem NM, Awwad AM. Facile green synthetic route to the zinc oxide (ZnONPs) nanoparticles: Effect on green peach aphid and antibacterial activity. Journal of Agricultural Science. 2017a;9(2):131-138

Huang S, Wang L, Liu L, Hou Y, Li L. Nanotechnology in agriculture, livestock, and aquaculture in China. A review. Agronomy for Sustainable Development. 2015.35:369-400

Kah M, Hofmann T. Nanopesticide research: Current trends and future priorities. Environment International. 2014.63:224-235.

Mukhopadhyay SS. Nanotechnology in agriculture: Prospects and constraints. Nanotechnology, Science and Applications. 2014.7:63-71.

Pilarska A, Wysokowski M, Markiewicz E, Jesionowski T. Synthesis of magnesium hydroxide and its calcinates by a precipitation method with the use of magnesium sulfate and poly (ethylene glycols). Powder Technology. 2013.235:148-157