NANOTECHNOLOGY IN AGRICULTURE: OPPORTUNITY AND CHALLENGES

Abstract

Using chemical fertilizers, pesticides, and other agrochemicals to boost crop yields negatively impacts ecosystem health because it depletes soil fertility and biodiversity. In recent years, nanotechnology in agriculture has garnered greater interest than traditional agricultural methods. Farmers favor using nanoparticles (NPs) over other conventional treatments because of their small size, ease of handling, shipping, and storage, long shelf lives, reduced soil leaching, reduced toxicity, and increased site-specific uptake by target pests. By creating nanopesticide, nanofungicide, nanoherbicide, nanobiocide, nanosensor, slow or controlled release fertilizer, nanotube clay, etc., nanotechnology improves agriculture and lessens environmental issues. The challenges encompass concerns regarding the potential hazards of nanoparticles on human health and the environment, as well as the regulatory hurdles that need to be addressed. Regulation and market uptake are hampered by scientific knowledge gaps in environmental safety and application expertise. In this chapter, opportunities and problems are discussed in more detail.

Keywords: Chemical fertilizers, Agriculture, Nanotechnology

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I. INTRODUCTION

As per the findings of Chinnamuthu and Boopathi (2009), nanotechnology holds considerable promise for effecting substantial transformations in the field of agriculture. Today, the field of nanotechnology is expanding quickly transdisciplinary scientific field that integrates using physics, chemistry, and engineering biology and does away with the conventional borders separating them (Ray *et al*., 2009). Nanotechnology deals with materials that have at least one dimension falling within the range of 1 to 100 nm. In the realm of agriculture, nanotechnology serves the purpose of enhancing food production while simultaneously upholding or even elevating nutritional value, quality, and safety standards. A pivotal approach to augment agricultural output involves the efficient utilization of fertilizers, insecticides, herbicides, and plant growth regulators. To curtail the use of pesticides and antibiotics, nanotechnology offers a sophisticated and intelligent system for precisely dispensing the requisite quantities of nutrients and other agrochemicals required by plants. The development of controlled-release fertilizers, which presents a technical challenge employing nano-structured or nano-scale materials like fertilizer carriers, underscores the immense potential of nanotechnology. (Rawat *et al*., 2018).

The utilization of nanotechnology in agriculture has the potential to lead to various advancements, including the creation of slow-release nano fertilizers for gradual plant nourishment, the encapsulation of pesticides within nanoparticles for controlled and on-demand release, precise delivery of drugs and nutrients in fisheries and livestock, the deployment of nanoparticles, nanobrushes, and nanomembranes for treating water and soil, and the development of nanosensors to evaluate plant health and soil conditions. According to a study by Salamanca-Buentella *et al.* (2005), there exist multiple pathways through which nanotechnology can enhance agricultural productivity in less developed nations. These include: (i) The use of nanoforms of zeolites in the delivery of pesticides, plant fertilizers, and pharmaceuticals for livestock in addition to effective water dosing and progressive release nanosensors for pest detection, soil quality monitoring, and plant health (ii) and soil pollution removal with nanomagnets

II. OPPORTUNITIES

1. Crop Improvement

- ***Seed germination*:** Carbon nanotubes (CNTs) function as novel pathways for water infiltration, penetrating the seed coat and facilitating water flow into the seeds from the substrate. These mechanisms support the germination process, which can be beneficial for rainfed agricultural systems. Additional nanoparticles that contribute to germination are listed in Table 1.

Table 1: Nano particles which improve seed germination

Nano particles	Crops
nano-TiO_2 and nano-SiO_2	Soybean seeds
Ag, Cu, Fe nanoparticles	Wheat seeds
carbon nano-tubes (CNTs)	Tomato seeds
nanoscale zinc oxide	Peanut seeds
nano SiO_2	Maize seeds

(**Source:** Rawat et al., 2018)

The application of zinc nano fertilizer to pearl millet resulted in the augmentation of root length, shoot length, root area, chlorophyll content, plant dry biomass, and grain yield, while nano titanium dioxide enhanced the grain number per spike. Additionally, carbon nanotubes (CNTs) promoted root elongation.

- **Nutrient Management**: It has been unequivocally proven that fertilizer accounts for between 35 and 40 percent of any crop's productivity. Due to its significance, the Indian government provides extensive subsidies for fertilizers, particularly urea. However, this policy has resulted in imbalanced fertilization practices, leading to nitrate contamination of groundwater in certain areas due to excessive nitrogen application. The efficiency of N, P, and K fertilizers has remained relatively constant over the past few decades, with rates at around 30-35%, 18-20%, and 35-40%, respectively. Consequently, the majority of additional fertilizers accumulate in the soil or find their way into aquatic systems, where they contribute to eutrophication. It is imperative to develop nano-based fertilizers to address issues related to low fertilizer utilization efficiency, imbalanced fertilization, deficiencies in multiple nutrients, and the decline in soil organic matter.

  Nanomaterials offer promising advantages for the gradual release of fertilizers. When nanomaterials are used to coat or create surface layers on fertilizer particles, they enhance the adhesion of the fertilizer to plants because of their higher surface tension compared to traditional surfaces. Additionally, these nano coatings serve as a protective shield for larger particles. Utilizing sulfur nanocoating (with a layer thickness of $\leq$ 100 nm) on fertilizers is particularly beneficial for slow-release fertilization, especially in soils that lack sufficient sulfur content. The durability of the coating led to a decrease in the fertilizer's dissolution rate, enabling a gradual and consistent release of sulfur-coated fertilizer. Moreover, applying sulfur nano-coatings or encapsulating urea and phosphate for controlled release can be advantageous in meeting the specific requirements of soil and crops. Other nanomaterials with potential applications include substances like kaolin and biocompatible polymeric nanoparticles. For instance, biodegradable polymeric chitosan nanoparticles, with an average size of approximately 78 nanometers, can be employed for the controlled release of NPK fertilizer sources like urea, calcium phosphate, and potassium chloride (Manjunatha *et al*., 2016)

  The nano fertilizers available in the commercial market primarily consist of micronutrients in nanoscale form, including elements like Mn, Cu, Fe, Zn, Mo, N, and B, as indicated in Table 2. Notably, the utilization of alternative nanomaterials, such as carbon nano-onions and chitosan nanoparticles, in place of the traditional conventional crop fertilizers, has the potential to enhance both crop growth and quality. Anticipations suggest that these innovative nano fertilizers will serve as a catalyst for and reshape the landscape of the current fertilizer production industry over the next decade.

Table 2: Comemercial Nanofertilizer for nutrient management

Commercial names	Manufacturer
Nano-Ag Answer®	Urth Agriculture
NanoPro™, NanoRise™, NanoGro™, NanoPhos™, NanoK™, NanoPack™, NanoStress™, NanoZn™.	Aqua-Yield® Operations, LLC
pH5®	Aqua-Yield® Operations, LLC
Saula Drip, Saula Solocross, Saula Motawazen	Bio Nano Technology, Giza, Egypt
Ready to Use Spray	Green Earth-Nano Plant, FL, USA

(**Source:** He *et al*., 2019)

Innovative nutrient delivery methods that leverage the porous nanoscale components of plants have the potential to mitigate nitrogen loss by enhancing plant nutrient absorption, as outlined in Table 3. When fertilizers are encapsulated within nanoparticles, it can boost nutrient uptake. This encapsulation allows for nutrient release to be triggered by environmental factors or precisely scheduled for a specific desired timing.

Table 3: Fertilizer delivery for plant

Fertilizer delivery	Nano particles
NPK controlled delivery	Nano-coating of sulfur (100 nm layer)
	Chitosan (78 nm)
Genetic material delivery DNA	Gold (10-15 nm) Gold (5-25 nm)
	Starch (50-100 nm)
Double stranded RNA	Chitosan (100 nm)

(**Source:** Manjunatha *et al*., 2016)

2. **Weed Management:** When a plant community is subjected to a specific herbicide in one growing season and then a different herbicide in another season, resistance gradually emerges, making it challenging to manage these plants using chemical means. Lower yields than where weeds are controlled are likely to result from weed infestations and weed seeds. Crop productivity may increase if nanotechnology is used to increase the effectiveness of herbicides. The encapsulated nano-herbicides are important considering the requirement to create a nano-herbicide with natural environment protection that only works when there is a period of precipitation that closely resembles the rainfed system.

   The creation of a herbicide molecule, designed to be specific to a target, and encapsulated within a nanoparticle, is aimed at a particular receptor found in the roots of the targeted weeds. This receptor facilitates the entry of the herbicide into the root system and its movement to locations that impede the breakdown of food reserves in the roots. Consequently, the weed plant will ultimately succumb to starvation and perish (Chinnamuthu and Kokiladevi, 2007). Manjunatha *et al*. (2016) reported that when paraquat is combined with alginate/chitosan nanoparticles, it alters the herbicide's release pattern and its interaction with the soil. This implies that this approach could serve as an effective method for reducing the adverse impacts of paraquat. Experiments demonstrated that the quantity of organic matter present in the soil influenced the adsorption of paraquat, whether it was in its free form or bound to the nanoparticles.

Herbicides that are used in excess leave behind residue in the soil and harm subsequent crops. Herbicide-resistant weed species evolve as a result of repeated application, and the weed flora changes. Both broadleaf and grassy weeds are effectively managed using the s-triazine-ring pesticide atrazine, which exhibits significant durability with a half-life of 125 days and can move through certain soil types. This control occurs both before and after the emergence of these weeds. Herbicide use is at risk of becoming widely used due to residual issues caused using atrazine, which also restricts the types of crops that can be rotated. Recent research from TNAU in India gives reason for optimism regarding the possibility of quickly removing atrazine residue from soil. Under controlled conditions, the employment of silver particles modified with magnetite nanoparticles, which were stabilized by Carboxy Methyl Cellulose (CMC) nanoparticles, led to an 88% degradation of the herbicide atrazine residue (Manjunatha *et al*., 2016).

Herbicides can also be released under regulated conditions by using nanocarriers. Poly (epsilon-caprolactone) nanocapsules have recently been formulated as carriers for the atrazine herbicide. When these nanocapsules, loaded with atrazine, were used on mustard plants (*Brassica juncea*), there was a substantial reduction in net photosynthetic rates and stomatal conductance. This caused a notable increase in oxidative stress and, consequently, a decrease in plant weight and growth, surpassing the herbicidal activity of commercial atrazine. The use of nanoencapsulation, in particular, enables you to use less herbicide without sacrificing effectiveness, which is beneficial for the environment (He *et al*., 2019).

Currently, adjuvants for spraying herbicides exist; these adjuvants incorporate nanoparticles. One "nanotechnology-derived surfactant," created from soybean micelles, has been shown that when combined with other nano surfactants, it can render glyphosate-resistant plants vulnerable to the herbicide.

3. **Water Management:** Nanotechnology holds the potential to offer advanced nanomaterials for addressing the contamination of surface water, groundwater, and wastewater caused by hazardous metal ions, organic and inorganic solutes, as well as bacteria. The potential applications in water filtration include nanofiber membranes and nano biocides, both of which display significant promise. Biofilms, which are collections of bacteria enveloped in organic polymers and pose a challenge to eliminate with traditional antimicrobial agents or chemicals, are known to pollute potable water sources. Their removal is possible only through mechanical means, which involves a significant amount of work and downtime. These biofilms may be dissolved by enzyme treatments, which are currently being explored. When compared to soil that hasn't been modified with biodegradable hydrogel, the enhanced soil moisture from these substances is up to 400% higher. Nanomaterials such as zeolites and nanoclays are employed to retain water and liquid agrochemicals within the soil for subsequent gradual release to plants. Harmful substances are filtered and captured using nanomaterials like carbon nanotubes (CNTs)

and nZVI nanoclays, and subsequently, these contaminants are eliminated from the environment.

4. **Plant Protection:** Using active substances on the surface that is being treated is one of the most practical and cost-effective ways to manage insect pests because pest populations can be decreased to the point at which management is no longer effective. "Nano-encapsulation," a nanotechnology method, is employed to enhance the insecticidal effectiveness by shielding the active ingredient from adverse environmental conditions and extending its persistence. This approach is used to nano-encapsulate insecticides, fungicides, and nematicides, resulting in formulations that effectively eliminate pests while minimizing residue buildup in the soil. The "controlled release of the active ingredient," another nanotechnology approach, is employed to enhance the formulation's efficacy, significantly reducing pesticide usage and associated environmental risks. Through this method, the active component gains increased durability and protection against degradation. Nano-pesticides can reduce application rates, as the effective substance quantity needed is at least 10-15 times less than that of traditional formulations, potentially leading to significantly improved and longer-lasting pest control (NAAS, 2013).

Low-cost clay nanotubes (halloysite) have been developed as pesticide carriers, enabling extended release and improved plant contact. These innovations have the potential to reduce pesticide use by 70-80%, thus mitigating adverse effects on water bodies. Moreover, modified release systems, such as silica nanoparticles and polymeric nanoparticles, have been created to control the dispersion of pesticides. Additionally, nanoparticle-mediated gene or DNA transfer has been harnessed to develop insect-resistant plant varieties, complementing the use of nanocarriers. Certain nanomaterials, due to their increased toxicity and sensitivity, may possess the potential to act as pesticides themselves (He *et al*., 2019). Other nanomaterials for increasing the stability of biopesticides and pesticides enclosed in nanomaterials for controlled release are found in Table 4.

Table 4: Delivery of Nanocides for Pest Management

Pesticide delivery	**Nano particles**
A. Chemicals	
Avermectin	Porous hollow silica (15 nm)
Tebucanazole/chlorothalonil	Polyvi nylpyridine andpolyvinylpyridine -co-styrene (100 nm)
B. Biopesticides	
Plant origin: nanosilica for insectcontrol	Nanosilica (3-5 nm)
Microganisms: Lagenidiumgiganteum cells in emulsion	Silica (7-14 nm)
Microbial product: absorption of Myrothrecium verrucaria enzyme	Chitosan/kaolin (250-350 nm)

(**Source:** Manjunatha et al., 2016)

Nano-copper demonstrated notable efficacy in averting bacterial diseases like rice blight (*Xanthomonas oryzae* pv. *oryzae*) and mung leaf spot (*Xanthomonas campestris* pv. *phseoli)*. Fluconazole, a triazole fungicide, had its antifungal activity increased by employing biologically generated AgNPs to target fungal diseases and pollutants such as *Candida albicans*, *Phoma glomerata*, and Trichoderma. Syngenta has created nano formulations of propiconazole and fludioxonil, which are sold as seed treatment chemicals under the brand names Banner MAXX and Aoron MAXX, respectively. Primo MAXX, a cyclopropyl derivative of cyclohexenone, was also developed to serve as a plant growth regulator and offer protection to plants against both abiotic and biotic challenges, including plant diseases. There are several other products, like 'Nano-Gro' from Agro Nano Technology Corporation in Florida, and 'Nano-5,' which exhibit fungicidal potential against a wide range of diseases, such as grey mold, rice blast, early and late blight, southern blight, bacterial wilt, powdery mildews, mosaic, tristeza virus, exocortis viroid, cyst nematodes, spiral nematodes, and more., (Gopa *et al*., 2011). NANOCU® is a fungicide and bactericide produced by Bio Nano Technology in Giza, Egypt (He *et al*., 2019).

The utilization of nanotechnology in viral diagnostics, including the creation of multiplexed diagnostic kits, has gained momentum in the identification of precise virus strains and determining the appropriate medicine to combat the illness. The identification and deployment of biomarkers, which consistently identify illness phases, is another emerging subject of study in bio-nanotechnology. By comparing the production of proteins in both states of health and illness, it becomes feasible to identify a number of proteins that are generated throughout the infection cycle. Also, by measuring the various oxygen requirements of soil-dwelling bacteria, **Nano sensors** can be utilized to identify diseases that are spread through soil and excess pesticide (Table 5).

Table 5: Pesticide sensor for pesticides

Pesticide Sensor	Nanoparticles
Carbofuran /Triazophos	Gold (40 nm)
DDT	Gold (30 nm)
Organophosphate	Zirconium oxide (50 nm)
Paraoxon	Silica (100-500 nm) Carbon nanotubes
Imidacloprid	Titanium oxide (30 nm)

(**Source:** Manjunatha *et al*., 2016)

5. **Soil management:** Rapid, sensitive, and precise molecular detection of contaminants and pathogens is necessary for environmental and soil health protection. For in-field real-time monitoring of vast areas, precise sensors are required for remote sensing, small portable devices, and in situ detection. These tools can shorten the time needed for protracted immunoassays and microbiological testing. These instruments are used for a variety of purposes, including the detection of pollutants in various bodies, including water supplies. When a specific gas flows through them, their resistance changes, leading to an alteration in the electrical signal, which then generates the distinctive fingerprint pattern for gas identification (NAAS, 2013). Leveraging nanotechnology in agriculture enables the production of nanoparticles, nanobrushes, and nanomembranes for tasks such as treating water and soil, as well as managing and preserving aquatic ecosystems. Moreover, nanosensors can be employed to assess both plant health and soil conditions.

Biosensors, renowned for their outstanding capabilities, can be employed for the detection of impurities in food and environmental substances as well. They offer remarkable specificity and sensitivity, rapid responsiveness, ease of use, and compact dimensions, all at an affordable cost (Amine *et al*., 2006). Because of their very specific adherence to specific biomolecules, enzymes can operate as sensing components. The electronic nose (E-nose) identifies various odor varieties through a pattern of responses from multiple gas sensors. It has the ability to detect the odor, gauge its concentration, and unveil its unique characteristics in a manner akin to how the human nose perceives odours. It is largely made up of nanoparticle-based gas sensors, such as ZnO nanowires.

III. CHALLENGES

1. Nanoparticles from pesticides, fertilizers, or other formulations that are airborne may land on a plant's above-ground parts and eventually settle there. Stomata have the potential to shut, leading to the development of a delicate and toxic barrier layer on the stigma, preventing pollen tubes from entering. Additionally, they can infiltrate the vascular tissue, impeding the movement of water, minerals, and photosynthate.
2. Nanoparticles could cause lung infections if they were ingested, breathed, or absorbed via the skin.
3. They cause inflammation, impair immunological function, and mess with enzyme and protein regulatory processes.
4. Nanoparticles may build up in water, plants, and soil.
5. Assessing risks is essential in order to understand the potential hazards, probabilities of exposure, and associated risks to humans and other animals due to nanomaterials.
6. The diverseness of nanoparticles and the limited data regarding their toxicity in various conditions hinder the establishment of standardized risk assessment methods.
7. Because of their size-related characteristics, which may differ from their bulk counterpart, it can be difficult to create regulatory frameworks that effectively address NT. However, this is further challenging by the absence of a globally accepted, practical definition of NT [14],[24]. To encourage nations to exchange knowledge, trade in goods containing nanoparticles, and reduce associated dangers, it is necessary to adopt regulations specifically for nanotechnology and to create a standard definition.

IV. CONCLUSION

Further research is required to explore the potential use of nanomaterials in various agricultural applications, focusing on their synthesis, toxicological aspects, and practical implementation in field settings. In the realm of agriculture, there remain numerous unexplored opportunities for the development of new nanoproducts and methodologies. However, despite the potential benefits that nanotechnology offers, its implementation in agricultural contexts lags behind that in other industrial sectors. The academic sector primarily attributes success in agriculture. However, the endorsement of public opinion and the establishment of effective regulatory mechanisms are crucial for its success at the practical field level.

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