**Nanotechnology in Agriculture: Opportunity and Challenges**

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**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 potential risks of nanoparticles to human health, the environment, and regulatory challenges are among the difficulties. 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.

1. **INTRODUCTION**

 According to Chinnamuthu and Boopathi (2009), nanotechnology is a potent technology with the capacity to bring about significant changes in farming. 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 works with materials with at least one dimension between 1 and 100 nm. Nanotechnology is used in agriculture to improve food production while maintaining or even improving nutritional content, quality, and safety. The most crucial strategies to increase agricultural production are using fertilizers, insecticides, herbicides and plant growth regulators efficiently. In order to minimize the usage of pesticides and antibiotics, nanotechnology is a clever and intelligent system that distributes the appropriate amount of nutrients and other agrochemicals needed by plants. In the development of controlled release fertilizer, a technical challenge using nano-structured or nano-scale materials, such as fertilizer carriers or controlled-release, has shown the immense potential of nanotechnology (Rawat *et al*., 2018).

The development of slow-release nano fertilizers for plant fertilization, nanoparticle-encapsulated pesticides for controlled and on-demand release, site-specific drug and nutrient delivery in fisheries and livestock, nanoparticles, nanobrushes, and nanomembranes for water and soil treatment, and nanosensors for assessing plant health and soil quality are all possible outcomes of the use of nanotechnology in agriculture. According to a study by Salamanca-Buentella *et al.* (2005), there are several ways that nanotechnology can increase agricultural output in underdeveloped countries. 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

**2. OPPORTUNITIES**

**2.1 Crop improvement**

***Seed germination*:** Carbon nanotubes (CNTs) operate as new holes for water permeation by penetrating the seed coat and as a channel for water to flow into the seeds from the substrate. These procedures promote germination, which the rainfed agricultural system can use. Other nano particles which helps in germination are given in Table 1.

Table 1. Nano particles which improve seed germination

|  |  |
| --- | --- |
| **Nano particles** | **Crops** |
| nano-TiO2 and nano-SiO2 | Soybean seeds |
| Ag, Cu and Fe nanoparticles | Wheat seeds |
| carbon nano-tubes (CNTs) | Tomato seeds |
| nanoscale zinc oxide | Peanut seeds |
| nano SiO2 | Maize seeds |

 (Source: Rawat et al., 2018)

When applied to pearl millet, zinc nano fertilizer increased root length, shoot length, root area, chlorophyll content, plant dry biomass, and grain yield, whereas nano titanium dioxide increased grain number/spike. CNTs also boosted root elongation.

***Nutrient management****:* It has been unequivocally proven that fertilizer accounts for between 35 and 40 percent of any crop's productivity. Given its significance, the Indian government extensively subsidizes the price of fertilizers, notably urea. This has led to uneven fertilization and, in some places, nitrate contamination of ground waters as a result of excessive nitrogen application. The use efficiency of N, P, and K fertilizers has remained stable over the past few decades at 30–35%, 18–20%, and 35–40%, respectively. This means that the majority of additional fertilizers are left to build up in the soil or enter aquatic systems, where they cause eutrophication. It is crucial to develop a nano-based fertilizer in order to address problems with low fertilizer usage efficiency, uneven fertilization, multi-nutrient deficits, and declining 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 ≤ 100 nm) on fertilizers is particularly beneficial for slow-release fertilization, especially in soils that lack sufficient sulfur content. The stability of the coating reduced the rate of dissolution of the fertilizer and allowed slow sustained release of sulphur coated fertilizer. In addition to sulphur nano coatings or encapsulation of urea and phosphate and their release will be beneficial to meet the soil and crop demands. Other nanomaterials with the potential application include kaolin and polymeric biocompatible NPs used biodegradable, polymeric chitosan NPs (~ 78 nm) for controlled release of the NPK fertilizer sources such as urea, calcium phosphate and potassium chloride (Manjunatha *et al*., 2016)

Commercialized nano fertilizers are mainly the micro-nutrients at the nanoscale viz. Mn, Cu, Fe, Zn, Mo, N, B, (Table 2). It is noted that the use of other nanomaterials (instead of the typical conventional crop fertilizers), such as carbon nano-onions and chitosan NPs, could also increase crop growth and quality. It is anticipated that the novel nano fertilizers will motivate and transform current fertilizer production industries in 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)

New nutrient delivery systems that exploit the porous nanoscale parts of plants could reduce nitrogen loss by increasing plant uptake (Table 3). Fertilizers encapsulated in nanoparticles will increase the uptake of nutrients. Nutrient release can be initiated by an environmental factor or precisely timed for a specific desired moment.

**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)

**2.2 Weed management**

When a plant community is repeatedly exposed to a herbicide in one season and a different herbicide in another season, resistance eventually develops and the plants are unable to be controlled by chemicals. 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 development of a target-specific herbicide molecule enclosed in a nanoparticle is directed at a particular receptor in the roots of the target weeds; this receptor allows the herbicide to penetrate the root system and translocate to areas that hinder the hydrolysis of food reserves in the root system. As a result, the weed plant will starve to death and die (Chinnamuthu and Kokiladevi, 2007). Manjunatha *et al*. (2016) reported that the combination of paraquat with alginate/chitosan nanoparticles changes the herbicide's release profile and its interaction with the soil, suggesting that this system may be a useful tool for minimizing the harmful effects of paraquat. Tests revealed that the amount of organic matter in the soil affected the sorption of paraquat, whether it was free 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. Broadleaf and grassy weeds are controlled before and after their emergence with the s-triazine-ring pesticide atrazine, which has a high persistence (half life of 125 days) and mobility in some soil types. 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. In a controlled environment, the use of silver modified with magnetite nanoparticles stabilized with Carboxy Methyl Cellulose (CMC) nanoparticles resulted in 88% breakdown of the herbicide atrazine residue (Manjunatha *et al*., 2016).

Herbicides can also be released under regulated conditions by using nanocarriers. As an atrazine herbicide carrier, poly (epsilon-caprolactone) nanocapsules have recently been developed. To increase the herbicidal activity compared to commercial atrazine, poly (epsilon-caprolactone) nanocapsules containing atrazine were applied to mustard plants (*Brassica juncea*). This resulted in a sharp decline in net photosynthetic rates and stomatal conductance, a significant increase in oxidative stresses, and ultimately weight loss and reduced growth in the tested plants. 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 demonstrated to make glyphosate-resistant plants susceptible to the herbicide when combined with other nano surfactants.

**2.3 Water management**

Nanotechnology provides the promise of cutting-edge nanomaterials for the treatment of surface water, groundwater, and wastewater contaminated by hazardous metal ions, organic and inorganic solutes, and bacteria. Water filtration may be aided by nanofiber membranes and nano biocides, both of which show promise. Drinkable water is contaminated by biofilms, which are mats of bacteria wrapped in organic polymers and difficult to eradicate using antimicrobials or other chemicals. They can only be removed mechanically, 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. To store water and liquid agrochemicals in soil for their later delayed release to plants, nanomaterials like zeolites and nanoclays are utilized. Toxic compounds are filtered and bound with the use of nanomaterials like carbon nanotubes (CNTs) and nZVI nanoclays, which are then removed from the environment.

**2.4 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. By protecting the active ingredient from unfavorable environmental conditions and promoting persistence, a nanotechnology technique known as "nano-encapsulation" can be used to boost the insecticidal value. It is possible to nano-encapsulate insecticides, fungicides, and nematicides to produce formulations that effectively eradicate pests while minimizing the building of residues in the soil. To increase the efficacy of the formulation, a nanotechnology approach of "controlled release of the active ingredient" may be utilized, which may greatly reduce the amount of pesticide input and related environmental dangers. Through this approach, the active component is designed to exhibit increased durability and safeguarded against degradation. Nano-pesticides will decrease the rate of application because the quantity of substance that is genuinely effective is at least 10–15 times less than that applied with traditional formulations. In order to accomplish considerably better and longer-lasting management, a lot smaller amount might be required (NAAS, 2013). Clay nanotubes (halloysite) have been made as pesticide carriers at a low cost for longer release and better contact with plants. By reducing the number of pesticides by 70–80%, they will lower the price of pesticides that have the least negative effects on water streams. Nanocarriers such as silica NPs and polymeric NPs have been developed as modified release systems to disperse pesticides in a controlled manner. Nanoparticle-mediated gene or DNA transfer has also been used to create insect-resistant plant cultivars in addition to nanocarriers. As pesticides with heightened toxicity and sensitivity, some nanomaterials themselves may also have this capability (He et al., 2019). Other nanomaterials for increasing the stability of biopesticides and pesticides enclosed in nanomaterials for controlled release are listed in Table 4.

**Table 4: Delivery of nanocides for pest management**

|  |  |
| --- | --- |
| **Pesticide delivery** | **Nano particles** |
| 1. **Chemicals**
 |  |
| Avermectin | Porous hollow silica (15 nm) |
| Tebucanazole/chlorothalonil | Polyvi nylpyridine andpolyvinylpyridine-co-styrene (100 nm) |
| 1. **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 was found to be particularly effective in preventing bacterial diseases such as 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 created for use as a plant growth regulator and to protect plants from both abiotic and biotic challenges such as plant diseases. Many other products, such as 'Nano-Gro' (Agro Nano Technology Corporation, Florida) and 'Nano-5,' with fungicidal potentialities against many 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 so on, (Gopa et al., 2011). NANOCU® is a fungicide and bactericide manufactured by Bio Nano Technology in Giza, Egypt (He et al., 2019).

Nano-based viral diagnostics, such as the development of multiplexed **diagnostics kits**, have gained traction in order to detect the specific virus strain and stage of application of a specific medicine to halt the sickness. The identification and deployment of biomarkers, which consistently identify illness phases, is another emerging subject of study in bio-nanotechnology. By assessing differential protein production in both healthy and ill states, it is possible to discover several proteins that are produced during 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)

**2.4 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. With the passage of a certain gas, their resistance modifies, causing a change in electrical signal that creates the 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, known for their exceptional performance, can also be applied to detect contaminants in food and environmental substances. They provide high specificity and sensitivity, quick response, simple use, and small size at a reasonable price (Amine et al., 2006). Because of their very specific adherence to specific biomolecules, enzymes can operate as sensing components. The electronic nose (E-nose) recognizes diverse odour types by using a pattern of reaction across a number of gas sensors. It can recognize the odorant, measure its concentration, and uncover its distinctive qualities in the same way that the human nose can sense an odour. It is largely made up of nanoparticle-based gas sensors, such as ZnO nanowires.

**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 may close, and a thin, toxic barrier layer may form on the stigma, blocking pollen tubes from entering. They might also penetrate the vascular tissue and obstruct the flow 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. Risk assessment is necessary to comprehend potential dangers, likelihoods of exposure, and related risks to people and other animals as a result of nanomaterials.
6. The development of standardized risk assessment techniques is hampered by the wide variety of nanoparticles and the paucity of information on their toxicity under varied circumstances.
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.

**CONCLUSION**

The potential application of nanomaterials in different agricultural applications needs further research investigation with respect to synthesis, toxicology, and its effective application at field level. In 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 success in agriculture is primarily claimed by academic sector. Public opinion and proper regulatory mechanism are very much required for its success at field level. V

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