

NANOTECHNOLOGY IN AGRICULTURE: EMERGING TRENDS AND TRANSFORMATIVE APPLICATIONS

Abstract

Nanotechnology is rapidly emerging as a crucial tool in modern agriculture and is expected to have a significant impact on the economy in the near future. By utilizing various chemical agents and innovative delivery systems, nanotechnology has the potential to enhance crop productivity and reduce the reliance on large quantities of agrochemicals. Furthermore, nanotechnology offers promising solutions to the existing challenges faced by the agricultural sector, such as climate change, inefficient resource utilization, and excessive chemical fertilizer usage. Nanotechnology in agriculture offers various practical uses, including the efficient delivery of agrochemicals and nutrients, the advancement of nano-scale carriers, smart packaging, nanosensors, veterinary care, and applications in fisheries, aquaculture, and nutrient deficiency detection. Despite significant public funding invested in this field over the last decade, its progress has been relatively limited. This can be attributed to the distinctive characteristics of farm production, operating as an open system with the free exchange of energy and matter, and the substantial scale of input materials needed compared to industrial nanoproducts. These factors have posed challenges to the widespread implementation of nanotechnology in agriculture.

Keywords: Nanotechnology, Nanomaterials, Farming, Fertilizers, Crop Breeding

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I. INTRODUCTION

It is becoming clear that nanotechnology is one of the most important instruments in modern agriculture and that it will soon be a major economic force. In addition to increasing crop yield and having the ability to reduce the use of bulk agrochemicals, nanotechnology also has the potential to provide more effective solutions for the present issues facing the agricultural industry. Nano-fertilizers are now being utilized more frequently as alternatives to bulk fertilizers and to lessen the impact of various agrochemicals on soil and water pollution. Nano-fertilizers make it easier for nutrients to be released gradually and steadily, which lowers nutrient loss and increases nutrient use efficiency. Slow-release fertilizers are a great replacement for soluble fertilizers because they are a good way for nanotechnology to increase the efficacy of nutrient utilization and lower preservation of the environment expenses.

Over 60 percent of the population depends on agriculture for a living, making it the foundation of the majority of emerging nations. The agricultural sector is currently faced with a number of issues, including climate change, the unjustified use of resources, and an excess of synthetic fertilizer [1]. The design, characterization, manufacture, and use of a structure, device, or system by managing shape and size at the nanoscale is known as nanotechnology, which is defined as "the art and science of manipulating matter at the nanoscale" [2]. The current era's sixth revolutionary technology is emerging as nanotechnology. It is regarded as a developing discipline of science that is heavily influenced by many other scientific subjects and is expected to play a major role in the field of agriculture and food science in the future, although there haven't been any recent studies about how it applies to agriculture globally [3]. About 40% to 60% of the world's food supply depends on the use of fertilizers, which are essential for plant nutrition and crop quality. [4]. By confronting issues that cannot be solved conventionally, nanotechnology increases hopes for improving agricultural productivity. Nanotechnology applications have the potential to change agricultural production by enabling better management and conservation of inputs for plant and animal production. Because nanoparticles have unique physicochemical properties, such as high surface area, high reactivity, and controllable pore size, they provide a wide range of novel uses in the plant nutrition disciplines to meet future demands of the growing population.

II. WHAT IS NANOTECHNOLOGY?

Nanotechnology revolutionizes scientific exploration by harnessing the physical and chemical properties of substances at the molecular level. It delves into the nanometer-scale realm, enabling investigations and applications in fields ranging from medicine to agriculture [5]. Nanotechnology focuses on materials smaller than 100 nm, where one nanometer measures 10^{-9} meters. This multidisciplinary field integrates disciplines such as solid-state physics, chemistry, chemical engineering, biochemistry, biophysics, and materials science.

III. THE ADVENT OF NANOTECHNOLOGY IN AGRICULTURE: ENHANCING FARMING THROUGH INNOVATIVE SCIENCE

The US Environmental Protection Agency [6] defines nanotechnology as the scientific pursuit focused on comprehending and manipulating matter within the range of approximately 1–100 nm. This definition, while informative, may be considered somewhat

inflexible when it comes to size dimensions. It could benefit from a stronger emphasis on the problem-solving potential of nanomaterials. Other definitions, particularly within the agricultural context, propose that nanoparticles are particulates with size dimensions ranging from 10 to 1,000 nm, which also possess colloidal properties. These alternative definitions highlight the importance of both size dimensions and the colloidal nature of nanoparticles.

In essence, nanotechnology can be described as the scientific discipline focused on the precise design and construction of machines where every atom and chemical bond is meticulously specified. It encompasses a wide range of capabilities that will push our technology to the limits dictated by atomic physics. Nanotechnology aspires to achieve the same level of control over matter that computers have provided us with information. A key objective within this field is the development of the "assembler," a Nano machine engineered to manipulate matter at the atomic level [7]. As nanotechnology finds growing applications in agriculture, the emphasis on problem-solving materials remains crucial, and the strict adherence to the upper limit of 100 nm may not be necessary. The challenges faced in applying nanotechnology to agriculture are rooted in the inherent imperfections and complexities of large-scale farm production systems, where input use efficiency can be low. This calls for nanomaterials with adaptable dimensions that can effectively operate within agricultural production systems, in contrast to nanomaterials designed for precise control in factory-based settings. Meeting these demands is crucial to harnessing the full potential of nanotechnology in the agricultural domain.



Figure 1: Improvement of Plant Responses by Nano-Biofertilizer

1. Limits of Conventional Farming: The Green Revolution has significantly boosted the world's food supply in recent years, but it has unintentionally caused detrimental effects on the environment and ecosystem services. This underscores the urgent need for more sustainable agricultural approaches [8]. Extensive research findings highlight the adverse consequences arising from the excessive and improper use of fertilizers and pesticides in agriculture. This overuse has resulted in elevated nutrient and toxin levels in both

groundwater and surface waters, leading to increased costs for health and water purification efforts. Moreover, it has triggered a decline in fish populations and recreational opportunities. Agricultural practices that degrade soil quality further exacerbate the problem, contributing to eutrophication in aquatic habitats and necessitating higher fertilization, irrigation, and energy inputs to sustain productivity on degraded soils. Additionally, these practices negatively impact beneficial insects and other wildlife. In regions where irrigation surpasses natural rainfall replenishment, there has been a concerning decline in groundwater levels. Surprisingly, though only 16% of agricultural fields worldwide are irrigated, they account for a significant 40% of crop production. However, the long-term consequences of irrigation and drainage practices have accelerated soil mineral weathering, resulting in soil acidity, salt accumulation, and the abandonment of once-fertile farmland. Intensive tillage, excessive irrigation, and the misuse of fertilizers have also caused more substantial damage to soil carbon profiles compared to early agrarian practices. These issues underscore the pressing need for sustainable agricultural approaches to preserve both our natural resources and agricultural productivity for the future. The limitations of conventional technologies become evident when considering alternative farming approaches like "conservation agriculture"[11]. Advocates of conservation agriculture propose methods that are not necessarily new or practical, as traditional farming operates within an open system where conservation practices face thermodynamic challenges. Conservation principles typically apply to isolated systems rather than the complex dynamics of farming. Likewise, "organic farming" acknowledges the negative impacts of Green Revolution technologies but falls short in achieving both high productivity and ensuring a superior environment and food quality. Similarly, rainfed or dry land farming struggles to match the productivity levels achievable through irrigated farming.

Ecosystem degradation poses a substantial threat to human well-being and society at large, with the extent of degradation closely linked to the ecosystem's capacity to retain carbon and prevent the release of various forms of nitrogen into water bodies and the atmosphere. Despite efforts during the Green Revolution to increase crop yields and incorporate crop residues to enhance soil organic matter, long-term carbon retention and nitrogen pollution control remained challenging. Adding to the complexity, rising soil temperatures in ecosystems have worsened the situation. Many soils worldwide, particularly those intensely cultivated in the latter half of the previous century, now suffer from contamination by hazardous trace metals and pesticide residues. The daunting task of cleaning up such lands through bioremediation, including methods like phytoremediation, becomes practically infeasible without relocating farmers and disrupting their livelihoods. Addressing ecosystem degradation calls for innovative and sustainable solutions to mitigate the impact on both the environment and human communities. However, there are opportunities to genetically modify plants through reengineering, and Nano biotechnology holds promise in this regard.

- 2. The Superiority of Nanomaterials Compared to Bulk Materials: Benefits and Advantages:** When materials are reduced to the nanoscale, they exhibit exceptional properties that are not observed in bulk materials. For instance, clays possess functions such as surface area, cation exchange capacity, ion adsorption, and complexation, which are significantly amplified when they are transformed into nanoparticles. A key distinction between nanoparticles and bulk materials is that a substantial proportion of

atoms in nanoparticles reside on their surfaces [12]. This disparity leads to differences in surface compositions, types and densities of sites, as well as reactivity when compared to larger particles. These unique surface characteristics enable nanoparticles to engage in various processes, including adsorption and redox reactions, which can be effectively utilized in the synthesis of nanomaterials for agricultural applications.

IV. NANOTECHNOLOGY IN AGRICULTURE: SAFEGUARDING LIVELIHOODS AND ENSURING FOOD SECURITY

Nanotechnology has garnered widespread acknowledgment for its potential to uplift the livelihoods of impoverished populations, particularly in developing countries. As the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS), a significant component of the 1994 trade agreements under the World Trade Organization, gains traction, more developing nations are adopting intellectual property rights regulations. This has resulted in a surge in international and US patents for various nanotechnologies worldwide [13]. However, the majority of these patents originate from technologically advanced countries such as the USA, Western European nations, Japan, South Korea, and Australia. Among developing nations, only major emerging economies like the People's Republic of China have managed to develop patented nanotechnologies. Unfortunately, this trend of strengthening intellectual property rights is likely to deepen the knowledge divide between developed and economically disadvantaged countries.

Agricultural nanotechnology holds immense promise in addressing critical challenges faced by impoverished nations, such as poor input use efficiency, water scarcity, unsanitary conditions, and other pressing issues. Nevertheless, to fully harness the advantages of nanotechnology, it is crucial for these nations to consider the long-term cost implications of importing farm technology versus developing it domestically in a sustainable manner. By investing in indigenous research and development, these countries can unlock the full potential of nanotechnology in agriculture and reap its rewards for securing their livelihoods.

V. NANOMATERIALS AND AGRICULTURE

Nanomaterials exhibit distinct chemical, physical, and biological properties compared to their larger counterparts, leading to unique safety considerations. The agricultural and food sectors have witnessed significant interest in utilizing nanotechnology due to its immense potential to enhance product quality. With the rapid progress of nanotechnology in recent decades, the controlled synthesis of nanomaterials with specific morphology and size, along with emerging concepts and methodologies, have provided a solid foundation for addressing unresolved questions related to nutrient uptake.

The application of nanotechnology in agriculture encompasses various areas, including targeted delivery of agrochemicals, the exploration of plant disease mechanisms, and the improvement of genomes [14]. Nanomaterials have demonstrated numerous positive effects in agriculture, particularly when operating on a nanoscale. At sizes smaller than 100 nanometers, materials exhibit behavior governed by the principles of quantum mechanics, fundamentally different from the rules that govern our familiar macroscopic world. This paradigm shift opens up new possibilities and transformative changes in agricultural

practices. There are several factors that contribute to the advantages of nanoparticles in agriculture:

- Nanoparticles exhibit higher solubility when suspended in a liquid medium.
- The larger surface area and particle size of nanoparticles enable easier penetration of seed coats, promoting the emergence of roots.
- Nanoparticles enhance the bioavailability of molecules to seed radicals, facilitating their uptake and utilization.

1. The Properties of Nanomaterial for Agricultural Applications: Nanotechnology offers various advantages in agriculture, including:

- Precise delivery and controlled release of fertilizers or pesticides based on specific conditions. For example, the use of titanium dioxide nanoparticles as a plant fertilizer for Mung beans has shown potential in enhancing crop production .
- Enhanced targeted activity, allowing for more effective and efficient application of agricultural inputs .
- Reduced environmental harm and safer transportation methods, providing a more sustainable approach to farming practices.

2. Nanomaterials Usage in Agriculture: Nanomaterials find diverse applications across all stages of agricultural production, encompassing a wide range of forms and procedures. These applications include:

- Nano-fertilizers for achieving balanced crop nutrition .
- Crop improvement through the use of zinc nanoparticles as a fertilizer to enhance the production of *Pennisetum americanum* .
- Plant protection ingredients, such as nano-based pesticides, fungicides, and weedicides .
- Weed management strategies.
- Nano-based pesticides designed for effective pest control .
- Nano sensors for monitoring various agricultural parameters .
- Post-harvest technology applications [15].
- Bioprocessing involving the use of bio-synthesized nanoparticles for agricultural purposes .
- Biosensors for aquaculture applications.
- Nano biotechnology for gene expression analysis and regulation .
- Monitoring the identity and quality of agricultural produce .
- Precision agriculture techniques that aim to increase crop yields while minimizing soil and water damage, reducing nutrient loss through leaching and emissions, and promoting long-term nutrient incorporation by soil microorganisms.
- Seed technology advancements.
- Water management strategies.
- Use of nano-based plant growth regulators.
- Soil management practices
- Integration of nanotechnology in agricultural engineering aspects
- Applications of nanotechnology in food technology

These various applications demonstrate the broad scope of nanomaterial utilization in agriculture.

VI. VARIOUS APPLICATIONS OF NANOTECHNOLOGY IN AGRICULTURE

Nanotechnology has contributed to several areas of crop improvement and agricultural practices, including:

1. Enhancement of crop yields through improved fertilizers and pesticides that promote efficient nutrient utilization and pest management.
2. Advancements in soil management techniques to optimize soil health, nutrient availability, and water retention.
3. Detection and early diagnosis of plant diseases using Nano sensors and Nano devices for more accurate and timely intervention.
4. Water management strategies employing nanotechnology for efficient water usage, irrigation systems, and conservation practices.
5. Analysis of gene expression and regulation, enabling a deeper understanding of plant genetics and facilitating targeted crop improvement.
6. Post-harvest technology applications incorporating nanomaterials to prolong shelf life, reduce spoilage, and maintain product quality.
7. These advancements in nanotechnology have significantly contributed to crop improvement, sustainable agricultural practices, and the overall efficiency and productivity of the agricultural sector.

VII. POTENTIAL HAZARDS OF NANOTECHNOLOGY

The utilization of nanomaterials in agriculture has raised concerns regarding potential negative effects on biological systems and the environment. For instance, the application of high concentrations of Nano Silver on edible plants can pose chemical hazards. Additionally, in certain situations, nanomaterials have been found to generate free radicals in living tissues, which can result in DNA damage. As a result, it is crucial to exercise caution and conduct thorough evaluations before widespread implementation of nanotechnology in agro-materials. This approach ensures the proper assessment of potential risks and the development of appropriate safety measures to mitigate any adverse effects.

- 1. Nanotechnology in Genetic Engineering and Crop Breeding:** Crop breeding is a recognized technology for improving the genetic traits of crops, aiming to develop high-yield and high-quality varieties [16]. Traditional and molecular methods have been employed in crop breeding, including functional genomic tools, genetic selection, mutagenic breeding, physical maps, soma clonal variations, and whole-genome sequencing approaches. Nanotechnology emerges as an innovative approach to enhance the efficiency and precision of crop breeding. Nano biotechnology plays a crucial role in improving crop breeding efficacy by facilitating the delivery of exogenous biochemical or nucleotides into plant cells. Overcoming the challenges of transporting molecules across the cell wall and the limitations posed by the size of genetic material inserted into crop cells, the combination of biotechnology and nanotechnology offers promising avenues for biomolecule transport through the cell wall. Notably, a nanomaterial-mediated gene delivery system has been developed, demonstrating high transformation efficiency in

plant cells without the need for external physical or chemical methods, thus exhibiting significant potential for plant genetic engineering. For instance, Torney et al. conducted a groundbreaking study by delivering target genes into the leaves of tobacco (*Nicotiana benthamiana* L.) using mesoporous silica nanoparticles (MSNs). Moreover, silicon dioxide nanoparticles (SiO₂ NPs) have been successfully employed for DNA delivery to crops such as tobacco and maize (*Zea mays* L.) without adverse effects. The technique of particle bombardment, known as the gene-gun, has been utilized for plant transformation since the early 1980s, utilizing tungsten or gold particles as carriers for DNA. The current system is adapted to allow NPs delivery, which most likely decreases the cell damage caused by microprojectile hits during the bombardment and thus improves the expression efficiency of the transgenes. The DNA-coated NPs are utilized as bullets in the gene-gun technology to bombard the tissues or cells to deliver the desired genes into the target crops. Silicon carbide-participated plant transformation has been found to transfer the sequences or fragments of DNA in various calli [maize, tobacco, rice, soybean (*Glycine max* L.), and cotton (*Gossypium hirsutum* L.)] as an effective method. The complex of MNPs and β -glucuronidase target gene was permeated to the pollens of cotton by magnetic force, with no negative effects on the viability of pollens. By pollinating with magnetofected pollens, the transgenic cotton plants were effectively selected and exogenous genetic information was steadily inherited into offspring achieved by selfing, successfully combined into the genome, and finally expressed. The scaffolds of carbon nanotubes were applied to deliver linear or plasmid DNA, in cotton, tobacco, and wheat (*Triticum aestivum* L.) leaves, causing a strong transient expression of GFP. In addition to the above-mentioned DNA delivery, NPs are also used to deliver RNA into plant cells. Chitosan NPs-embedded small interfering RNA (siRNA) delivery systems have offered a novel strategy for crop improvement by permitting the unique dominance of the target pest as chitosan has the capability to validly bind with RNA and the ability to penetrate cell membranes. The double-stranded RNAs (dsRNAs) carried on non-toxic and degradable clay nanosheets offer defense against cauliflower mosaic virus in leaves of tobacco. The siRNA was transferred to tobacco seedlings constitutively expressing the GFP gene, resulting in a high percentage silencing of the target gene. The carbon nanotubes-mediated platform realized effective RNA transfer into intact crop cells and protected RNA from nuclease degradation, enabling gene silencing of endogenous GFP in mutants.

- 2. Nanotechnology and Food Systems:** The application of nanotechnology in enhancing food security must consider the entire agricultural production-consumption system, as food systems involve the availability, access, and utilization of food. In an increasingly globalized economy, access to food and its utilization in rural areas relies on the growth of rural incomes. Value addition across different stages of the agricultural production-consumption chain has been recognized as the primary means of increasing rural incomes. This chain includes farm inputs, production systems, post-harvest management, processing, markets, and consumers. To address food security comprehensively, the application of nanotechnology should extend beyond the farm production level and encompass all links of the agricultural value chain. This broader implementation can enhance agricultural productivity, product quality, consumer acceptance, and resource utilization efficiency. The result is a reduction in farm costs, increased production value, higher rural incomes, and improved quality of natural resources in agricultural production systems [17]. It is important to perceive nanotechnology as an enabling technology that

can complement conventional technologies and biotechnology, rather than viewing it as a standalone solution. Considering the concerns surrounding biosafety and consumer acceptance that have emerged with the introduction of agribiotechnology-based products in the market over the past two decades, it is essential to thoroughly understand the societal and environmental implications before integrating and deploying new technologies like nanotechnology in agricultural and food systems.

- 3. Nanotechnology in Crop Nutrition:** The introduction of high-yielding and fertilizer-responsive crop varieties during the green revolution era played a crucial role in enhancing food grain production in India. However, despite the initial success in increasing yields, many crops have started to experience stagnation in productivity due to imbalanced fertilization practices and declining organic matter content in soils. The excessive use of nitrogenous fertilizers not only impacts groundwater quality but also leads to eutrophication in aquatic ecosystems. It is concerning that the fertilizer use efficiency for nitrogen ranges from 20% to 50%, and for phosphorus, it ranges from 10% to 25%. In this context, nano-fertilizers have emerged as potential alternatives to conventional fertilizers, offering the opportunity to address nutrient buildup in soils, mitigate eutrophication, and prevent contamination of drinking water. The advent of nanotechnology presents new avenues to improve nutrient use efficiency while minimizing the costs associated with environmental protection.

VIII. CONCLUSION

Nanotechnology holds great potential as a transformative tool to enhance agricultural production by improving nutrient efficiency and plant protection practices. It offers promising solutions to address various challenges in agriculture, including the development of improved crop varieties, effective plant protection measures, disease detection, and plant growth monitoring. The advanced applications of nanotechnology in agriculture present a wealth of opportunities to increase global crop production and meet the food demands of the growing world population in the coming decades. Already, there are encouraging results and ongoing developments in areas such as nano nutrients for enhanced plant productivity, the implementation of crop productivity strategies, the use of nanotechnology in plant protection through herbicides and pesticides, nano-packaging, and the use of nano sensors to monitor agricultural processes.

Nanotechnology is rapidly emerging as a crucial tool in modern agriculture and is expected to have a significant impact on the economy in the near future. By utilizing various chemical agents and innovative delivery systems, nanotechnology has the potential to enhance crop productivity and reduce the reliance on large quantities of agrochemicals. Furthermore, nanotechnology offers promising solutions to the existing challenges faced by the agricultural sector, such as climate change, inefficient resource utilization, and excessive chemical fertilizer usage. The direct applications of nanotechnology in agriculture encompass the delivery of agrochemicals and nutrients, development of nano-scale carriers, smart packaging, nanosensors, veterinary care, fisheries, aquaculture, and detection of nutrient deficiencies. While nanotechnology in agriculture has received substantial public funding over the past decade, its development has been relatively modest. This can be attributed to the unique nature of farm production, functioning as an open system with the free exchange of

energy and matter, as well as the immense scale of input material requirements compared to industrial nanoproducts.

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