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Application of Nanotechnology in Agricultural Systems: Improving Efficiency and Sustainability

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Abstract: Nanotechnology is the field that studies how to manipulate matter on an atomic scale. The discipline of managing the smallest particles possible has the possibility of enhancing agricultural productivity in the face of obstacles that cannot be handled using conventional approaches. Improving the fertility of the soil by releasing stored nutrients is a primary goal of management, and nano clays and zeolites are used to improve fertilizer efficiency. Using nano biosensors and a satellite network, farmers can calculate the precise inputs their crops need and have them delivered to them at the perfect time and place. The development and research of nanoherbicides are being driven by the difficulties of controlling perennial weeds and decreasing the supply of weed seeds. Mechanisms such as targeted distribution, slow/controlled release mechanisms, and conditional release might allow the active components of a nanostructured formulation to be released with more precision in response to environmental signals and biological demands. Nanofertilizers have been demonstrated to improve nutrient usage efficiency, reduce soil toxicity, and buffer against the potentially disastrous effects of overdose, all while reducing the number of times they need to be applied. As a result, nanotechnology has a lot of potential for helping developing countries adopt sustainable agricultural methods.

Keywords: *Nanotechnology, sustainable agriculture, Nano fertilizer, Nano herbicide*

1. Introduction

The world's food supply and environmental stability depend on maintaining this equilibrium. Soil deterioration, water contamination, and a drain on scarce natural resources have all been linked to the conventional agricultural methods of using pesticides and fertilizers excessively and with little regard for their intended targets[1-3]. In order to combat these threats, new strategies to improve agricultural productivity, lessen waste, and protect natural resources are required. One such development is the incorporation of nanotechnology (the study of matter on a scale of 1 to 100 nanometers) into agricultural practices. Agriculture stands to benefit greatly from the use of nanotechnology due to the unique qualities and capabilities it offers at the nanoscale. The capacity to modify the characteristics of nanomaterials to suit a variety of agricultural uses is at the core of this revolution. By putting nanotechnology to use, we can improve upon conventional agricultural practices in terms of both efficiency and environmental impact, while also breaking ground in such areas as resource management, crop protection, and more. This study delves at the many ways in which nanotechnology has been used to enhance the effectiveness and longevity of agricultural systems[4]. Topics covered include the creation of nanopesticides and nano-fertilizers, the use of nanomaterials for soil remediation, the use of nanosensors to enable precision agriculture, the application of nanocoatings to seeds to improve crop yields, and the purification of water supplies that are essential to agricultural production. We also discuss the difficulties and moral questions raised by using nanotechnology to farming. Nanotechnology's use in farming is more than just a scientific advance; it's a sea change that might resuscitate farming while reducing its environmental effect[5]. Insights into the existing status, potential, and consequences of nanotechnology in agriculture for the future of global food production, sustainability, and environmental stewardship are the goals of this article. Most poor nations' economies have traditionally relied heavily on agriculture. It not only feeds people, but also keeps the economy going. Censuses taken between 2014 and 2015 put India's total population at 1.27 billion. The need to feed such a massive population necessitates the development of cutting-edge farming techniques that provide greater results in less time. Because of the complexity of the natural world, there will always be imbalances that have an impact on agriculture and, by

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extension, on animal and human health[6-8]. According to this, additional variables that have an impact on farming include insufficient supplies of macro and micronutrients, a growing population, more industrialisation, a shrinking water supply, varying soil conditions, and erosion of the top layer of soil. Fertilizer is used in farming primarily to supplement the soil's natural supply of macro and micronutrients. Some fertilizer has no effect on plant development at all, while the other 35-40% is dependent on it. Nanotechnology is one potential solution for overcoming these disadvantages. Since fertilizers are of primary importance, a breakthrough in this area of technology would be the creation of nano-based fertilizer[9]. There are a variety of methods for applying fertilizer, including spraying it on the ground, on the leaves, or even in water. Nitrogen, phosphorus, and potassium are the three major components, and these inorganic fertilizers provide them in equal amounts [10]. The NUE is improved by a factor of three when using nano fertilizers, and the plants are better able to withstand stress. No matter the crop, nanotechnology enhances soil aggregation, increases carbon absorption, and reduces the crop's environmental impact. These nano fertilizers will have a delayed and efficient release due to the nutrients and growth promoters being encased in nano size polymers[11]. The study of atoms on a nanoscale, taking into account their physical, catalytic, magnetic, and optical capabilities, is what nanotechnology is all about. Plants and soil microorganisms are exposed to a potentially dangerous degree of chemical reactivity due to the high frequency and intensity of use. Nano fertilizers are more cost-effective and may be used with less resources than chemical fertilizers. Farmers have known for a long time that excessive nitrogen uptake is the primary cause of poor crop output. There has been a recent uptick in the production of sensing devices. There are assays that provide correct results when testing a specific analyte from soil that has caused a disturbance in the field, but these assays are time- and labor-intensive and hence not ideal. The findings that sensors provide are superior since they are based on real-time data collected from the field[12]. When it comes to toxicity research, sensors can keep a continual eye on the toxicity generated in the field by tracking changes in the soil's pH, moisture level, and the growing circumstances of the crop's stem, fruit, or root. Because it is designed with people in mind, the sensor immediately begins detecting and alerting the farmer, giving him the chance to take preventative steps. By installing a certain number of nodes, a person using wireless technology may keep tabs on events in the field and manage all of the nodes simultaneously using cloud computing or in-the-air programming. In order to elevate nanotechnology to the pinnacle, a variety of cutting-edge sensors and fertilizers are briefly discussed. In this context, fertilizer represents cutting-edge technology. There are a variety of methods for applying fertilizer, including spraying it on the ground, on the leaves, or even in water. These inorganic fertilizers are provided so that the plant may have an adequate supply of nitrogen, phosphorus, and potassium. The NUE of crops is multiplied by three when treated with nanofertilizers, and the plants' stress resistance is much improved[13]. No matter the crop, nanotechnology enhances soil aggregation, increases carbon absorption, and reduces the crop's environmental impact. These nano fertilizers will have a delayed and efficient release due to the nutrients and growth promoters being encased in nano size polymers. 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When it comes to toxicity research, sensors can keep a continual eye on the toxicity generated in the field by tracking changes in the soil's pH, moisture level, and the growing circumstances of the crop's stem, fruit, or root[16]. Because it is designed with people in mind, the sensor immediately begins detecting and alerting the farmer, giving him the chance to take preventative steps. By installing a certain number of nodes, a person using wireless technology may keep tabs on events in the field and manage all of the nodes simultaneously using cloud computing or in-the-air programming[17-18]. To put nanotechnology at the pinnacle, we take a quick look at a wide range of innovative sensors and fertilizers.

2. Properties of the Nanoparticles

Nanoparticles have several unique properties that make them valuable in various agricultural applications. These properties can help improve agricultural efficiency, crop production, and environmental sustainability. Here are some of the key properties of nanoparticles relevant to agriculture:

Enhanced Nutrient Delivery: Nanoparticles can encapsulate and deliver nutrients (such as fertilizers or micronutrients) to plants more efficiently. Their high surface area-to-volume ratio allows for controlled and targeted release, optimizing nutrient uptake by crops.

Improved Pesticide and Herbicide Delivery: Nanoparticles can enhance the delivery of pesticides and herbicides to crops. Nanoencapsulation of these chemicals improves their solubility and stability, reducing the amount needed and minimizing environmental contamination.

Selective Adsorption: Nanoparticles can selectively adsorb pollutants, heavy metals, or contaminants from soil and water, helping to remediate contaminated agricultural sites and maintain soil health.

Enhanced Seed Coatings: Nanocoatings on seeds can improve germination rates and protect seeds from pests and diseases. These coatings can also provide a controlled release of nutrients to support early plant growth.

Crop Protection: Nanostructured materials can be used to create protective barriers or films on crops. These barriers shield plants from environmental stressors such as UV radiation, extreme temperatures, and pathogens.

Soil Health: Nanoparticles can improve soil structure and nutrient availability by enhancing nutrient retention and reducing nutrient leaching. This promotes healthier soils for crop growth.

Water Purification: Nanotechnology can be used to develop nanofilters and nanomembranes for water purification, ensuring a clean and safe water supply for agricultural use.

Environmental Sustainability: By reducing the need for excessive chemical inputs, nanoparticles contribute to environmentally sustainable agriculture. They help minimize soil and water pollution while conserving resources.

Customizability: Nanoparticles can be tailored for specific agricultural applications by adjusting their size, shape, surface chemistry, and composition. This customizability allows for optimization according to crop and soil requirements.

Reduced Environmental Impact: The precise targeting and controlled release of nutrients, pesticides, and herbicides through nanoparticles can reduce their overall environmental impact and minimize unintended harm to non-target organisms.

Disease and Pest Management: Nanoparticles can be used in the development of novel disease and pest management strategies, offering a more environmentally friendly approach to crop protection.

3. Nano-Agriculture

Since the beginning of the last century, scientists have used molecular modification to experiment with many aspects of food production and agriculture. The holes that exist in the industrial food chain are filled up by the agro-nano sector. Plants that have been exposed to cutting-edge nano-scale gene-mixing and gene-harnessing techniques are referred to as atomically modified plants. These plants have been transformed genetically. The eradication of target pests is made possible by the precise packaging of pesticides, which also makes it possible to include synthetic flavorings and natural nutrients that have been formulated to satisfy the taste. Automated, centralized, and industrial agriculture are moving closer and closer to becoming a reality because to the development of molecular sensors, molecular delivery systems, and low-cost labor. The European Union (EU) is working toward the aim of becoming a "knowledge-based economy," and one of its objectives is to maximize the potential of biotechnology to enhance all aspects of the economy of the area, society, and ecology. New challenges are emerging for the sector, including the rising cost of food and the requirement to guarantee that it is safe to consume, the proliferation of infectious diseases, and the possibility that climate change may result in the loss of agricultural and fishery production. Nevertheless, the development of a the bioeconomy is a challenging endeavor with a myriad of facets that calls for collaboration across a wide range of scientific fields. Because of nanotechnology, new approaches to the treatment of diseases at the molecular level, rapid disease detection, increasing plants' ability to absorb nutrients, and other similar developments may totally transform both the farming and food sectors.

A. Precision farming

Monitoring the many environmental elements and acting in a targeted manner are the two main components of precision farming. Because of this, farmers are able to boost their output (crop yields) while simultaneously reducing their input (including fertilizers, pesticides, herbicides, and so on). Precision farming makes utilization of computers, global positioning satellites systems, and remote sensing equipment to analyze extremely localized environmental factors in order to decide whether crops are growing at ideal efficiency or to properly identify the kind and location of difficulties. This is done in order figure out whether crops are growing at their best or to accurately pinpoint the type and location of issues. Through the use of consolidated data on the soil's conditions and plant development, farmers may be able to save money and increase yields. This data may be used for optimal planting, the application of fertilizer and pesticides, as well as the amount of water needed. It is discussed in the Erosion, also Technology, and Concentration (ETC) subgroup how precision farming may help to mitigate the adverse impacts of agriculture on the natural environment by reducing the amount of food that is thrown away. Even if they are not yet used to a large extent, the miniature sensors and monitoring systems that are made feasible by nanoscale will have a substantial impact on the development of future precision agricultural methods. Autonomous sensors that are connected to a GPS (global positioning system) in order to perform real-time monitoring will play an important role in the development of future devices that are enabled by nanotechnology. This nanotechnology might be scattered around the field in order to monitor the many environmental conditions that influence the growth of the crop. When biotechnology and nanotechnology are combined, sensors get a higher level of sensitivity, which enables them to respond more quickly to changes in their surrounding environment.

B. Nano Sensors

Soil fertility and agricultural yield may also be increased with the help of nanotechnology applications now under development. Magnetic nanoparticles might eliminate soil toxins, and nano sensors could track plant and animal health. Significant changes may also occur in underdeveloped countries as a result of "lab on a chip" research. Nanoparticles for soil conservation or remediation, and nanosensors for plant disease and pesticide detection are only two examples of how nanotechnology is improving agriculture. High-value, low-volume enzyme applications are required for nanobiosensor immobilization with nanomaterials.

C. Nanotechnology and food systems

Because food systems comprise food availability, food access, and food use, applications of nanotechnology that aim to increase food security should target every aspect of the agricultural production and consumption system. In addition, in an economy that is rapidly globalizing, increased earnings in rural areas will be the key driver driving improvements in food availability and consumption.

The process of adding value across the whole agricultural production-to-consumption cycle is often regarded as the most important factor in boosting rural incomes. These links are between farms and the inputs they use, production techniques, post-harvest processing, and the people who buy their produce.

Nanotechnology has to be implemented at every stage of the agricultural value chain, not only at the farm level, if it is to have any chance of enhancing agricultural productivity, as well as the quality of commodities, the degree of customer acceptability, and the amount of efficiency with which resources are used. While farm expenditures will go down, the value of output will go up, rural incomes will go up, and so on and so forth, the quality of the natural resource base that agricultural production systems draw upon will increase. Nanotechnology need to be seen as an assisting hand that is capable of working in conjunction with more established sciences such as chemistry and biology.

D.Field application of nano pesticides and fertilizers

The effectiveness and environmental impact of pesticides and fertilizers are affected by how they are applied. Pesticides are often sprayed using either knapsacks, which provide big droplets (9-66 m), which are linked with splash loss, or ultra light volume sprayers, which apply controlled droplets of smaller sizes (3-28 m), which cause spray drift. The use of NP-encapsulated or nanosized pesticides may help alleviate some of the difficulties associated with spraying owing to the size of the droplets, leading to greater efficiency and less spray drift and splash losses [17].

In addition, the nano-small of this fungicide meant that it remained stable in water for up to a year, while fungicides with bigger particle size components usually needed to be agitated every two hours to avoid clogging in the tank. Applying the right amount of fertilizer in the right way increased nutrient absorption and decreased pollution.

Soil type, crop type, irrigation system, and applied nutrient all play a role in determining the best fertilizer application technique. Runoff is an issue with conventional application methods including broadcasting, banding, side dressing, and dusting since these methods dissolve in wet soil and are washed away.

Salt damage was created by reducing soil moisture and putting a lot of fertilizer near the seedlings. Both laboratory and field tests were conducted to determine how various nitrogen fertilizer delivery techniques affected the algal flora and biological nitrogen fixing in wetland rice soil. Nitrogen fixing was suppressed and green algae growth was stimulated when urea was applied by broadcast.

The development of nitrogen-fixing blue-green algae was not inhibited by the addition of urea granules to depths of 1-2 g. NP coatings on fertilizers have the potential to slow down the fertilizer's release rate, reducing its environmental impact.

Table 1: Top ten applications of nanotechnologies

Rank	Applications	Examples
1	Energy storage, production and conversion	CNT storage of H
2	Agricultural productivity Enhancement	Herbicide delivery
3	Water treatment and remediation	Nano-membranes
4	Disease diagnosis and screening	Lab-on-Chip
5	Drug delivery systems	Nano-capsules
6	Food processing and storage	Coating/packaging
7	Air pollution and remediation	Nano-catalysts
8	Construction	Durability
9	Health monitoring	Sensors
10	Vector and pest detection/control	Sensors and pesticides

E. Nanotechnology in crop nutrition

During the time of the green revolution, high-yielding and fertilizer-responsive crop varieties were developed. As a result, fertilizers were an essential component in the process of boosting India's food grain supply. Although grain yields have grown considerably, yields of many other crops have leveled out as a consequence of uneven fertilization and a decline in the amount of organic matter contained in the soil. In addition to playing a role in the process of eutrophication that occurs in aquatic ecosystems, the excessive use of nitrogenous fertilizers has an effect on the groundwater. It is discouraging to learn that nitrogen fertilizer is only used effectively at a rate of 20-50 percent, while phosphorus fertilizer is only utilized effectively at a rate of 10-25 percent. It is possible that the introduction of nano-fertilizers as an alternative to conventional fertilizers may put a stop to the process of nutrient accumulation in soils, and therefore, eutrophication and water pollution. In point of fact, the use of nanotechnology has made it feasible to lessen the financial burden associated with environmental preservation while concurrently raising the level of effectiveness with which nutrients are utilized.

4. Conclusion

As a result of their widespread usage, agrochemicals have contaminated not just the soil, but also the water supply, the food supply, and the environment. Increasing agricultural output is important, but new methods should be sought to reduce their impact on the environment. The agriculture industry increasingly relies on nanotechnology. Pesticides, biopesticides, fertilizers, and genetic material for plant transformation are only few of the areas where promising findings and applications are currently being produced. It is anticipated that using nanomaterials to transport pesticides and fertilizers would allow for lower doses and more gradual transport. Using nanoparticles to stabilize biocontrol preparations is expected to make a significant contribution toward mitigating environmental risk. Nanotechnology has enabled the development of Nano sensors that can detect infections at ppb levels by taking use of the unique features of nanomaterials. Nanotechnology has applications beyond detection, including the degradation of persistent compounds into harmless and even beneficial components. Nanotechnology's tools can be used to help solve some of the world's most pressing environmental problems. Environmental detection, sensing, and cleanup technologies may benefit from nanotechnology's potential to deliver and fundamentally simplify these tools..

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