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THE ROLE OF NANOTECHNOLOGY IN AGRICULTURE: A PATH TO SUSTAINABLE FARMING

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This abstract explores the transformative potential of nanotechnology in agriculture, presenting it as a pathway towards sustainable farming practices. With global food security facing unprecedented challenges due to population growth, climate change, and unsustainable agricultural practices, the integration of nanotechnology offers innovative solutions to enhance crop productivity, resource efficiency, and environmental stewardship. By leveraging nano-enabled formulations for precision farming, targeted nutrient delivery, and eco-friendly pest management, stakeholders can mitigate the adverse effects of chemical inputs, reduce resource wastage, and improve overall agricultural sustainability. This abstract highlights the pivotal role of nanotechnology in reshaping the agricultural landscape, driving towards a future where food production is not only sufficient but also environmentally responsible and resilient.

Scientists and farmers have been concentrating on enhancing the quality and yield of crops by harnessing cutting-edge technologies like nanotechnology to overcome challenges to sustainable and resilient agriculture. Given the rising global population and the increasing prevalence of monoculture, it is imperative to urgently tackle the issue of food shortages that impact around 800 million people each year (Shukla et al, 2019). According to predictions, the global population is expected to reach 9 billion by 2050, which means that food production would need to grow by 50% (Roberts, 2011). Nanotechnology, ranked as the 6th most groundbreaking technology, has the potential to make a substantial contribution towards the United Nations' objective of eradicating hunger completely. The green revolution that took place in the 1960s had a substantial impact on increasing agricultural output, sustainability, and stability (Conway and Barbie, 1988). Nanotechnology is currently transforming the agricultural industry by providing remedies for issues such as overdependence on chemical fertilizers, resistance to pesticides, and the impact of climate change. The unsustainability of mono-cropping and the extensive utilization of pesticides on a global scale emphasize the necessity for improved resource management and creative alternatives. Agri-nanotechnology is becoming increasingly important for researchers and agriculturists as it helps improve the overall status of the worldwide agri-food sector. Ensuring food security relies heavily on maintaining stability in agriculture. Nano agrochemicals, which include nano pesticides, insecticides, fertilizers, fungicides, and herbicides, provide researchers and agriculturist's additional ecologically sustainable options to consider (Singh et al, 2021). By adopting nanotechnology in agriculture, stakeholders may tackle the issues presented by unsustainable farming methods, climate change, and food shortages, ultimately making a significant contribution to a more secure and sustainable global food system.

Types of Nanoparticle

Nanoparticles, with sizes typically ranging from 1 to 100 nm, display unique characteristics as a result of their extremely small dimensions (Khan et al., 2019). Natural occurrences of these substances include hemoglobin and milk lipoproteins, whereas controlled laboratory settings are used to artificially produce substances like carbon nanotubes for various applications. Engineered nanoparticles (ENPs), often referred to as manufactured or industrial NPs, have become notable because of their distinct physiological and chemical characteristics (Prajitha et al., 2019). These nanoparticles possess attributes such as a significant ratio of surface area to weight, a variety of shapes and sizes, the ability to penetrate cells, and a high capacity for adsorption. Their unique characteristics arise from the significant surface area-to-volume ratio at the nanoscale, resulting in unusual behaviors compared to larger materials. Engineered nanoparticles (ENPs) possess a diverse set of characteristics such as catalytic, antibacterial, optical, mechanical, electrical, magnetic, and sterical capabilities. These traits make ENPs highly attractive for a wide range of applications in agriculture and associated industries. ENPs, which are classified into five types based on their composition, have a wide range of applications in various fields.

Potential of Nanotechnology in Agriculture

Nanotechnology has the potential to greatly transform agriculture by tackling important issues encountered by the agri-food industry. Nanomaterials, regarded as the foremost particles of the current period, are being employed in diverse agricultural applications including crop protection, crop enhancement, pathological analysis, precision farming, and stress resilience. Salinity stress is a significant abiotic factor that negatively impacts worldwide crop yield, resulting in decreased production and stagnant yield. Wahid et al., (2020), conducted a study on wheat plants and found that treatment with silver nanoparticles (Ag NPs) resulted in a decrease in oxidative stress when the plants were exposed to salt stress. Salinity stress is caused by reactive oxygen species (ROS), which consist of hydrogen peroxide (H2O2), superoxide anion radical (O2-), hydroxyl radicals (OH), and oxygen (O2). The nanobiotechnological method seeks to control the balance of reactive oxygen species (ROS) and increase the ability of plants to tolerate salt, providing a hopeful path for enhancing agriculture. Nanoparticles function as effective carriers for agricultural inputs such as fertilizers, insecticides, synthetic hormones, and genetic material (An et al., 2022). Nanotechnology has become a transformative force in agricultural fields, fundamentally changing the way we package and preserve food. Conventional ways of packing food have restrictions in terms of their capacity to break down naturally, ensure safety, and minimize the danger of infection. To address these issues, nanotechnology provides a hopeful solution by creating polymer nanocomposites (PNCs) that include different nanomaterials (Adhikari, 2021). These PNCs, which can be in the shape of nanotubes, nanosheets, nanoplatelets, nanorods, and nano whiskers, are regarded as innovative materials for packaging food. Clay and silica nanoparticles, carbon nanotubes, titanium dioxide, and zinc oxide are frequently employed as fillers in polymer matrices. Researchers and enterprises are using nanotechnology to improve the quality, safety, and shelf life of packaged food goods by combining it with standard packaging methods. Nanotechnology has not only resulted in the enhancement of packaging materials, but it has also facilitated the creation of active packaging solutions. These involve the use of biopolymer matrices containing nanoparticles, namely silver nanoparticles (Ag NPs), which are embedded in materials such as cellulose, chitosan, agar/banana, and gelatin (Kumar et al, 2021). The nanocomposite films possess antibacterial characteristics, efficiently battling pathogens such as *Escherichia coli*, *Pseudomonas aeruginosa*, *Bacillus cereus*, and *Salmonella* (Tian et al, 2022). In addition, nanofillers such as titanium dioxide (TiO2) nanoparticles (NPs), zinc oxide (ZnO) NPs, and silicon dioxide (SiO_2) NPs are used in biopolymer nanocomposites to achieve antibacterial properties, remove oxygen, and prevent oxidation.

Nano Fertilizers Offer Several Advantages Over Traditional Fertilizers, Including

High Nutrient Use Efficiency: Nano fertilizers provide better nutrient uptake and utilization by plants, leading to increased efficiency in nutrient delivery (Mahanta et al, 2019).

Increased Nutritional Value: Nano fertilizers can enhance the nutritional content of crops by ensuring optimal nutrient absorption (Elemike et al, 2019).

High Yields: The targeted delivery of nutrients through nano fertilizers can promote plant growth and increase crop yields (Solanki et al., 2015).

Reduced Production Cost: Nano fertilizers can be used in smaller amounts compared to traditional fertilizers while maintaining effectiveness, thus reducing production costs (Seleiman et al., 2020).

Environmental Benefits: Nano fertilizers have less environmental impact due to their controlled release mechanisms and high solubility, minimizing nutrient leaching and runoff. Studies have shown that nano fertilizers, such as those based on silicon dioxide (SiO_2), zinc oxide (ZnO), and iron (Fe), have positive effects on seed germination, plant growth, and nutrient absorption in various crops like tomatoes, rice, soybeans, and wheatgrass. These nano fertilizers offer a promising alternative to conventional fertilizers by providing targeted and efficient nutrient delivery to plants (Fig.1) (Iqbal, 2019).

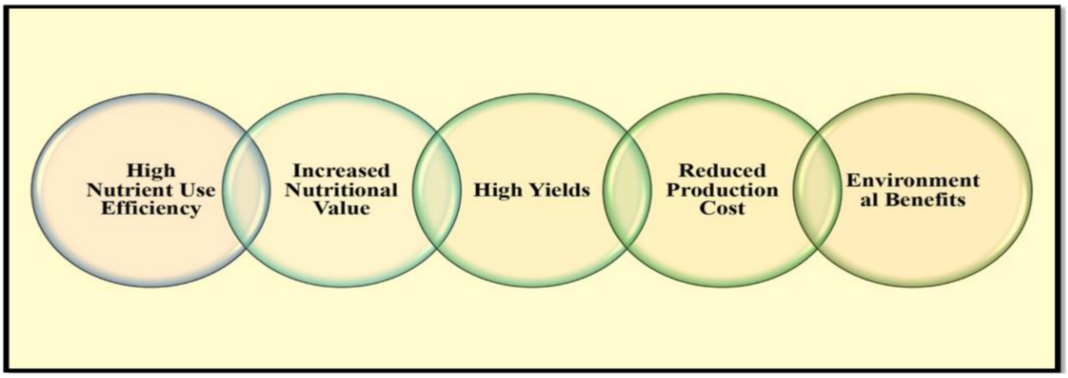

Fig.1 Advantages of nano fertilizers over traditional fertilizers

Here Are Some Ways in Which Nanotechnology Is Utilized for Disease and Pest Management in Agriculture

Nano Herbicides: Nano herbicides are designed to target specific weeds while minimizing the impact on non-target plants and the environment. Nanoparticles can enhance the efficacy of herbicides by improving their delivery and absorption, leading to better weed control (Muchhadiya et al., 2022).

Nano Fungicides: Nano fungicides are developed to combat fungal diseases in crops. These nanomaterials can penetrate plant tissues more effectively, providing enhanced protection against pathogens and reducing the need for frequent fungicide applications (Siddhartha et al., 2022).

Nanoemulsions: Nanoemulsions are nano-sized formulations that can encapsulate active ingredients such as pesticides or fungicides. These nanoemulsions improve the stability and efficacy of the active compounds, allowing for targeted delivery and controlled release on plant surfaces (Gupta et al., 2016).

Targeted Delivery: Nanoparticles enable targeted delivery of pesticides or fungicides to specific plant tissues or pests, reducing the amount of chemicals needed and minimizing off-target effects (Fig.2) (Santana et al, 2020).

Fig.2 Various methods utilized for employing nanotechnology in the pests and diseases management

Conclusion

By harnessing the unique properties of nanomaterials, such as their small size, high surface area, and controlled release capabilities, nanotechnology offers more precise and sustainable solutions for disease and pest management in agriculture. These advancements contribute to safer and more effective pest control strategies while minimizing the negative impacts on ecosystems and human health. Nano fertilizers are an advanced method in agriculture that provide sustainable solutions for enhancing crop yield, nutrient use, and environmental sustainability in current farming systems. Nanotechnology plays a crucial role in disease and pest management in agriculture by providing inventive alternatives to address the constraints of conventional pesticides. Nano agrochemicals, such as nano herbicides, nano fungicides, and nanoemulsions, have proven to be highly efficient in managing crop diseases and pests. Nanotechnology provides accurate and sustainable solutions for disease and pest management in agriculture by utilizing the distinctive characteristics of nanoparticles, including their small size, large surface area, and controlled release capabilities. These technological breakthroughs enhance the safety and efficacy of pest management methods, while reducing their adverse effects on ecosystems and human health.

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