Chapter 2

Nanomaterials: Revolutionizing Agriculture and Its Applications

Deepa K

Post Graduate & Research Department of Chemistry

Korambayil Ahamed Haji Memorial Unity Women's College, Manjeri

Email : deepakarat08@gmail.com

The field of synthesizing, characterizing, and applying nanoscale materials has seen remarkable technological advancements. Nanotechnology, with its interdisciplinary approach, has transformed science into a more application-oriented discipline. Nanomaterials, defined as materials with at least one dimension falling within the size range of 1 to 100 nm, exhibit distinct physico-chemical properties compared to bulk materials.

The imperative to address climate change, cope with population explosion, and meet the escalating demand for quality food and health necessitates the development of more advanced, dependable, and environmentally friendly technologies. This underscores the significance of the remarkable characteristics exhibited by materials at the nanoscale, where their properties are primarily determined by size and shape. The complexity of these materials' properties and their applications is further heightened by a multitude of surface functionalization opportunities. Consequently, nanomaterials have found applications in virtually every facet of life, including but not limited to medical fields, water and air purification, food production and enhancement, cosmetics, clothing, and various household products.

Nanotechnology and Agriculture

Agricultural products play a crucial role in our daily lives, serving as essential components in food, fuel, furniture, textiles, and feedstock. However, the productivity of agriculture faces significant challenges such as limited space, diseases, and shifts in agro-climatic conditions. The utilization of fertilizers and pesticides to improve crop yield has demonstrated adverse effects, some of which are severe and life-threatening. Consequently, there is an urgent need to modernize agricultural practices and methods, leveraging insights from cutting-edge technologies. This is where the relevance of applying nanotechnology in agriculture becomes evident. Emerging nanotechnological approaches show promise in enhancing agricultural productivity. These include the development of nano-formulations for agrochemicals to protect crops, the identification of toxicity using nanobiosensors, genetic manipulation of plants facilitated by nanodevices, and efficient diagnosis of plant diseases. Utilizing nanoarrays for the delivery of genetic material and proteins proves beneficial in crop engineering, drug delivery, and environmental monitoring. As we embrace these advancements, we pave the way for a more sustainable and effective future in agriculture. Nanotechnological methods have demonstrated significant applications in agriculture, encompassing fertilizer delivery, macronutrient supply, and insect pest management. Advances in nanoinsecticides, nanofungicides, and nanoherbicides further underscore its tremendous impact. Nanotechnology spans a wide spectrum in agriculture, ranging from biomass conversion technology and precision farming to alternative fertilizers. Its versatile applications extend from field-to-table processing of agricultural products, owing to the physiological influence of nanomaterials on plants, their role in pesticide bioremediation, smart packaging, and product tracking. Nanotechnology offers diverse agricultural solutions, including nano-sized nutrients, micronutrient fertilizers coated with zinc oxide nanoparticles, and nanoemulsions. The entry of harmful pesticides and herbicides into the food chain has heightened health concerns. Nanomaterial-based bioremediation presents a promising avenue to either completely degrade these compounds or convert them into non-toxic by-products. With a focus on health and environmental safety, nanotechnology emerges as a pivotal force in mitigating the adverse effects of current agricultural practices. The progress in bioremediation, encompassing substances like uranium, hydrocarbons, and soil contaminants, showcases its potential impact on soil remediation and groundwater safety. While the plant cell wall serves to impede the entry of external agents, nanoparticles possess the capacity to traverse through the pores. Engineered nanoparticles have been observed to induce the enlargement of existing pores or the formation of new pores during their uptake. Additionally, upon contact with the leaf surface, nanoparticles demonstrate absorption through stomata and trichome bases, subsequently undergoing translocation across the plant. Once internalized by the cells, the nanoparticles mediate their effect on the plant as a whole. Its functions can be determined by the particle size, shape, chemistry and surface functionalization.

Precision Farming and Nanotechnology

The application of nanotechnology in precision farming is anticipated to enhance agricultural yield while minimizing the use of chemical inputs. This approach aims to reduce the heavy accumulation of agrochemicals in soil and water. This involves the use of nanomaterials for the slow release of agrochemicals and managing plant diseases. Precision farming can be finely tuned by exploring the growth-regulating effects of nanomaterials, their application in soil water retention, and their role in delivering nutrients, thereby improving the quality of agricultural products. Nanotechnological methods, such as enhancing photosynthesis, food and biofuel production, and resistance to crop diseases, as well as nanobionics, show highly promising applications in agriculture. Exciting developments in plant nanobionics highlight the potential of biomimetic materials for light harvesting and biochemical detection. This approach holds promise for augmenting photosynthesis and biochemical sensing through the use of single-walled carbon nanotube–chloroplast assemblies. Advancements in nanofabrication and characterization methods have improved our understanding of the mechanisms of pathogenesis and enhanced strategies for disease treatment. Nanofabricated xylem vessels, mimicking capillary action, provide insights into the colonization, film development, and subsequent movement and recolonization at new sites by xylem-inhabiting bacteria. Intelligent nanosystems offer various advantages in agriculture, including the prevention of nutrient release into the soil, minimal leaching, improved uptake by plants, and mitigation of eutrophication.

Control Release Formulations

The process of nanoencapsulation involves coating the pesticide or active component with another material of varying size. This technique is employed for the controlled release of active ingredients, ensuring sustained activity over an extended period. Researchers have explored the potential of nanotechnology in mitigating the indiscriminate use of pesticides and promoting their safe application through nanoencapsulation. This approach facilitates a multistage delivery of pesticides, with slow release preventing premature degradation and enhancing efficacy for an extended duration. Consequently, it diminishes the quantitative need for pesticides, reduces human exposure, and proves to be more environmentally friendly compared to traditional applications.

Nanoagrochemicals

The enhancement of agricultural production through nanotechnology encompasses the utilization of nano-agrochemicals, the advancement of crop protection methods, and the effective post-harvest management of agricultural products. The production of polymeric nanoparticles that encapsulate herbicides provides an environmentally friendly approach to weed management. Additionally, the targeted application of herbicide-loaded nanoparticles directly to the roots of weeds facilitates effective weed removal. Various metal nanoparticles have also been employed as herbicides in commercial vegetable crops.

Nanopesticides

Nanoemulsions have been documented for their ability to encapsulate functional groups within droplets, thereby diminishing the quantity of necessary chemicals. The utilization of nano-sized materials enhances the stability of active compounds, concurrently reducing foliar leaching. Colloidal formulations of nanoinsecticides and pesticides exhibit noteworthy potential, notably diminishing chemical doses, frequency of applications, and, consequently, human exposure risk. To further enhance the environmental safety of nanoformulations, the incorporation of biocompatible and biodegradable polymers is recommended. Whether derived from petroleum or microbial sources, these biopolymers are environmentally degradable. Upon degradation, they release encapsulated active components.

Nanofungicides

The potential effectiveness of silver, carbon, silica, and alumino-silicate nanoparticles as antifungal agents has been investigated. Studies have reported the inhibition of various plant pathogens by silver and TiO_2 nanoparticles. Treatment with nanosilica has additionally demonstrated an increase in plant phenolic compounds, suggesting an enhancement in resistance.

Nanofertilizers

Various slow-release fertilizers (SRFs) and controlled-release fertilizers have been developed using synthetic or biopolymer materials. Additionally, polymeric nanoparticles have been employed as coatings for biofertilizers to enhance resistance to desiccation. Numerous nanomaterials have undergone extensive examination due to their properties as nanofertilizers. These encompass carbon-based nanoparticles, TiO_2, iron oxide, zinc oxide, and urea hydroxyapatite. The suggested benefits of their usage include improved nutrient mobilization, the preservation of soil health, and the promotion of microbial diversity, ultimately resulting in increased yields, nutrient-enriched food, and sustainability. Nano-sized materials have exhibited superior properties for promoting plant growth compared to bulk materials. This has been observed in the germination rate and germination vigor index of various plants, such as spinach. Additionally, applications of nanomaterials have been reported to enhance the photosynthetic rate, chlorophyll levels, plant dry weight, and seed stress resistance.

The integration of nanotechnology into agriculture encompasses several phases, including the synthesis of nanomaterials/nanofertilizers, nanoparticle delivery, the uptake and translocation of nanomaterials within plants, and their distribution. Although various methods of applying nanomaterials to plants have been demonstrated, foliar application has proven to exhibit superior performance. In the context of Vigna unguiculata, the positive impact of iron and magnesium nanomaterials on plant growth has been evident through foliar applications. Addressing the challenge of feeding a growing population necessitates enhancing agricultural productivity. The agriculture sector increasingly exploits the size and shape-based properties of nanomaterials. Despite being in its initial stages, the application of nanotechnology to agriculture holds the potential for the next agricultural revolution based on ongoing developments in this field.

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