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Nano-AgriTech: Pioneering Growth and Challenges in Agriculture

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Nanotechnology has garnered significant attention in recent years due to its wide-ranging applications in fields such as medicine, pharmaceuticals, catalysis, energy, and materials science. Nanoparticles, characterized by their small size and large surface area (1–100 nm), offer numerous potential functions. In today's world, sustainable agriculture is crucial, and the development of nanochemicals has emerged as a promising approach to enhance plant growth, fertilizers, and pesticides. Recently, nanomaterials have been explored as alternative means of controlling plant pests, including insects, fungi, and weeds. Various nanomaterials are also employed as antimicrobial agents in food packaging, with silver nanoparticles being particularly noteworthy. Nanoparticles such as Ag, Fe, Cu, Si, Al, Zn, ZnO, TiO_2, CeO_2, $Al2O_3$, and carbon nanotubes have been reported to adversely affect plant growth and development. In the food industry, nanoparticles play a vital role in producing high-quality food with excellent nutritional value.

Introduction

Nanotechnology in agriculture has advanced significantly over the past decade, driven by substantial public funding. The field shows promise, particularly due to the open system nature of farm production, which allows free exchange of energy and matter. The demand for agricultural nanomaterials is high compared to industrial nanoproducts, though control over these inputs is less stringent (Huang, et al., 2015). Nanotechnology offers innovative agrochemical agents and advanced delivery mechanisms to boost crop productivity and reduce pesticide use. Precision farming techniques can further enhance yields while preserving soil and water quality, reducing nitrogen loss, and protecting soil microorganisms.

Applications include nanoparticle-mediated gene transfer for developing insect-resistant plants, improving food processing and storage, and extending shelf life. Nanotechnology also holds potential for advancing biomass-to-fuel production. Experts emphasize weighing the benefits of nanotechnology in agriculture, food, fisheries, and aquaculture against potential concerns for soil, water, environmental health, and worker safety. Current research and testing are exploring the use of nanomaterials, valued for their unique properties. Agricultural waste is also being considered as a renewable source for nanomaterial production. Insecticide resistance exemplifies rapid evolutionary change, posing challenges for agriculture and public health. Nanotechnology applications, such as nanocapsules and nanoparticles for disease detection and treatment, aim to reduce plant protection product use and increase yields (Ghidan, et al., 2018).

Nanotechnology-derived devices are being explored for plant breeding and genetic transformation. Despite its potential, issues like risk assessment remain crucial, with some nanoparticles derived from biopolymers posing minimal health and environmental risks. Nanotechnology promises to revolutionize agriculture and the food industry by improving farming techniques, nutrient absorption, disease detection, and pest control (Chinnamuthu, C.R. and Murugesa, 2009).

Use of Nanotechnology in Agriculture

The use of nanotechnology in agriculture offers numerous benefits, including efficient disease detection and management, precision farming with nano-sensors, enhanced productivity through nano-fertilizers and pesticides, and improved food quality and safety via innovative packaging materials. Agriculture can leverage nanotechnology in several transformative ways, fundamentally altering traditional farming practices (Mukhopadhyay, 2014).

One of the primary applications is the development of nanoformulations of agrochemicals. These nanoformulations enable the precise application of pesticides and fertilizers, ensuring that crops receive the exact amount needed for optimal growth. This not only boosts crop yield but also minimizes the environmental impact by reducing chemical runoff into the soil and water systems. Additionally, nano-sensors can be deployed throughout agricultural fields to monitor plant health in real-time, detect diseases early, and track soil conditions. These sensors provide farmers with critical data, allowing for timely interventions and better resource management.

Nanotechnology also facilitates the genetic modification of crops through advanced nanodevices. These devices can deliver DNA or RNA sequences directly into plant cells, promoting the development of insect-resistant or drought-tolerant crop varieties. This technology promises to significantly enhance crop resilience and sustainability, particularly in regions prone to extreme weather conditions or pest infestations.

The utilization of nanoparticles in agriculture has led to the creation of new materials that improve nutrient utilization and reduce abiotic stressors such as extreme temperatures, salinity, and drought. These nanoparticles can be engineered to release nutrients slowly and steadily, ensuring that plants receive a consistent supply over time. This controlled release mechanism enhances plant growth and reduces the need for frequent fertilizer applications.

Smart delivery systems for fertilizers and pesticides are another significant advancement brought about by nanotechnology. These systems can target specific parts of the plant or soil, releasing their contents only when needed. Such precision ensures that resources are used efficiently, reducing waste and environmental impact. For instance, encapsulating pesticides in nanoparticles can protect them from degradation by sunlight or rain, ensuring they remain effective for longer periods (Ghidan, et al., 2016).

In crop establishment, nanotechnology aids in the germination and early growth stages of plants. Nano-enhanced seed coatings can protect seeds from pests and diseases, while also providing essential nutrients that promote vigorous growth. For weed management, nanoparticles can be used to develop herbicides that are more effective at lower doses, reducing the overall chemical load on the environment (Lin, and Xing, 2007).

Stress reduction is another critical area where nanotechnology can make a substantial difference. Plants often face various stresses, including drought, salinity, and heavy metal contamination. Nanoparticles can help mitigate these stresses by enhancing the plant's natural defense mechanisms and improving its overall health and resilience.

Irrigation control is also enhanced through the use of nanotechnology. Nano-sensors can monitor soil moisture levels accurately, ensuring that water is used efficiently. This is particularly important in arid regions where water is a scarce resource. By providing precise data on when and how much to irrigate, these sensors help conserve water and promote sustainable farming practices.

Furthermore, nanotechnology has the potential to revolutionize food packaging, improving food quality and safety. Innovative packaging materials embedded with nanoparticles can extend the shelf life of food products by preventing microbial contamination and spoilage. These materials can also indicate the freshness of the food, providing consumers with more reliable information. In summary, nanotechnology plays a crucial role in modern agriculture, offering a range of benefits from enhanced crop productivity and resilience to improved resource management and environmental protection. Its applications in disease detection, nutrient delivery, genetic modification, and stress management are transforming traditional farming practices, paving the way for a more sustainable and efficient agricultural future (Sekhon, 2014). The nanotechnological aspects pioneering in growth of plant for development of sustainable agriculture in presented in the figure.

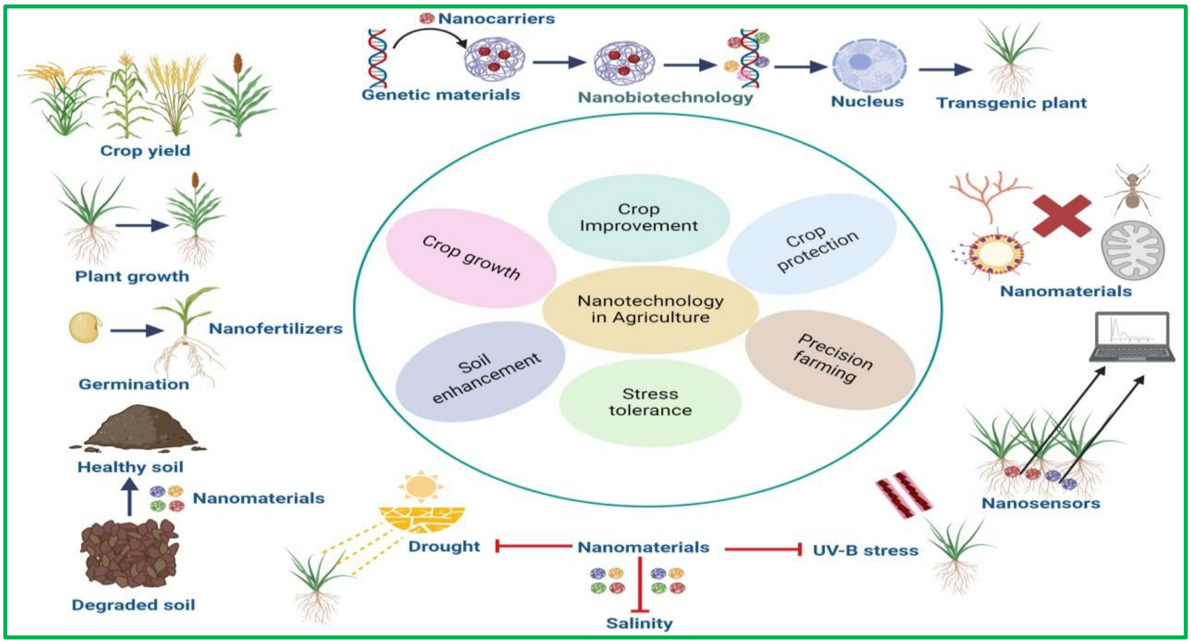

Figure: Nanotechnological aspects pioneering agricultural development

Nanotechnology in pesticides and fertilizers

Long-term experiments are essential to demonstrate the effects of various agricultural practices on soil properties for sustainability. In the U.S., federal agencies recognize nano-chemicals as promising agents for plant growth and pest control. Nanomaterials used as fertilizers can improve crops while reducing eco-toxicity and may bioaccumulate in the food chain. Recent advancements in agriculture include nanoparticles (NPs) for more efficient chemical use (Mohan, et al., 2015). Studies report varied effects of NPs like magnetite, alumina, zinc, and zinc oxide on plant growth and phytotoxicity. For instance, silver nanoparticles enhance wheat growth and yield, while zinc nanoparticles aid in crucial metabolic activities, impacting crop yield and quality. The development of insecticide resistance in pests remains a challenge for agriculture and public health. Magnesium oxide (MgO) nanoparticles have applications in adsorbents, fire retardants, ceramics, waste remediation, and photoelectronic materials, with green synthesis methods using non-toxic plant extracts being developed.

Nanotechnology in Plant Pests Control

Researchers have successfully synthesized magnesium oxide (MgO) nanoparticles and evaluated their impact on the green peach aphid (GPA) under greenhouse conditions.

Additionally, nanomaterials such as copper oxide (CuO), zinc oxide (ZnO), and magnesium hydroxide (MgOH) have been synthesized using aqueous extracts from Punica granatum peels, Olea europaea leaves, and Chamaemelum nobile flowers. These bio-nanoparticles have demonstrated efficacy in increasing GPA mortality rates. Following greenhouse experiments, the accumulation of metal oxide nanoparticles in the fruits and leaves of green sweet pepper was analyzed, revealing no detectable metal accumulation in the plant fruits. Foliar spraying of green pepper leaves with MgOH nanoparticles at concentrations ranging from 100 to 800 ppm significantly benefited plant growth, resulting in healthier plants with greener leaves and higher fruit quality compared to untreated controls (Sutradhar, et al., 2016).

Substantial strides have been made in nanoparticle synthesis using various methods, including physical, chemical, and biological approaches. Green synthesis methods utilizing plant extracts offer distinct advantages: they are simple, convenient, environmentally friendly, and require shorter reaction times. Nanomaterials prepared through eco-friendly processes hold the potential to enhance agricultural practices by improving fertilization, promoting plant growth, and reducing reliance on environmentally harmful pesticides. The green peach aphid is recognized as a key pest of peach and is globally significant in arable and horticultural crops, including in regions like Jordan, where it is considered one of the most economically impactful agricultural pests worldwide.

Nanoinsicticidal potential

Copper oxide nanoparticles (CuONP) are synthesized using various methods, including precipitation and chemical reduction. Plant aqueous extracts, such as Citrus lemon juice and carob leaves, have been utilized in these processes. Similarly, zinc oxide nanoparticles (ZnONP) are synthesized through chemical routes, precipitation methods, hydrolysis in polar organic solvents, and microwave synthesis, with plant extracts like *Olea europaea*, *Solanum nigrum* leaves, and *Azadirachta indica* employed in the green synthesis of ZnONP.

Methods for synthesizing magnesium oxide hydroxide nanoparticles (MgOH NP) and magnesium oxide nanoparticles (MgONP) include hydrothermal routes, water-in-oil microemulsion, and microwave reactions. MgOH is synthesized using eco-friendly methods involving non-toxic materials, such as neem leaf extract, Citrus lemon leaf extract, acacia gum, Brassica oleracea, and Punica granatum peels.

In the agricultural sector, nanotechnology offers various applications, including nanotech-based pesticides and fertilizers that effectively enhance plant growth. Molecular farming using nanovectors shows promise as an alternative to viral vectors for delivering genetic materials, potentially revolutionizing agricultural practices.

Role of nanomaterials in antimicrobial activity

Several nanomaterials are widely used as antimicrobial agents in food packaging, with silver nanoparticles being particularly prominent due to their extensive application. Other nanoparticles currently employed include titanium dioxide (TiO_2), zinc oxide (ZnO), silicon oxide (SiO_2), magnesium oxide (MgO), and gold. Each of these materials possesses specific characteristics and functions; for instance, zinc nanocrystals exhibit both antimicrobial and antifungal properties (Vermeiren, et al, 2002).

Silver has a long history as a disinfectant and sterilizing agent, used by NASA and the Russian Space Station for water treatment, and continues to garner significant attention. Gold nanoparticles are noted for their high temperature stability, low volatility, and broad-spectrum effectiveness against bacteria, with FDA-approved applications for commercial water disinfection since 2009. Nanosilver particles, particularly those coated with cellulose acetate phthalate, demonstrate effective antimicrobial properties against bacteria such as *E. coli*, *L*. monocytogenes, and Staphylococcus aureus.

Various nanoparticles have also exhibited antifungal activity, targeting fungi such as Candida albicans, Aspergillus niger, and yeast. Silver nanoparticles (AgNPs) have shown efficacy against methicillin-resistant Staphylococcus aureus (MRSA). Additionally, titanium dioxide (TiO_2) nanoparticles are recognized for their antimicrobial activity under UV light, while zinc oxide (ZnO) nanoparticles exhibit antimicrobial properties in packaging materials (Kumar, and Munstedt, 2005).

Nanotechnology application as nanofungicides

Recent studies have focused on nanosilver's efficacy against the phytopathogen Colletotrichum gloeosporioides. However, various nanoparticles like Fe, Cu, Si, Al, Zn, ZnO, TiO_2, CeO_2, $Al2O_3$, and carbon nanotubes can potentially harm plant growth despite their antimicrobial properties (Ehlert, et al., 2014). Nanoparticles may also affect beneficial soil bacteria like Pseudomonas putida KT2440. Research groups are exploring eco-friendly pesticides, with nanoparticle-based formulations showing promise as alternatives to traditional chemicals. These nanoparticles act as antimicrobial agents to protect crops from diseases, potentially reducing reliance on intensive pesticide use. Nanoparticles' inherent antifungal properties make them suitable for developing pesticide formulations. Silver nanoparticles have garnered significant research attention due to their advantages over other inorganic nanoparticles such as copper, zinc, gold, ZnO, $Al2O_3$, and TiO_2 in antimicrobial applications.

Nanotechnology for controlling plant virus

Plant viruses, particularly spherical viruses, are considered naturally occurring nanomaterials. The smallest known plant virus to date is the satellite tobacco necrosis virus, measuring a mere 18 nm in diameter. These viruses typically consist of single or double-stranded RNA/DNA genomes encapsulated within a protein coat. Their unique ability to infect host cells, deliver their nucleic acid genomes to specific sites within these cells, replicate, package the nucleic acid, and exit the host cell in a controlled manner has made them highly valuable in nanotechnology applications (Wilson, 1993).

Recently, Young et al. conducted a comprehensive review on the use of plant viruses as bio templates for nanomaterials and their various applications. Plant viruses serve as excellent templates due to their structural uniformity and the precision with which they can assemble into ordered structures at the nanoscale. Researchers have explored their potential in fields such as nanoelectronics, nanomedicine, and environmental sensing, leveraging their natural ability to self-assemble into functional nanomaterials.

The utilization of plant viruses in nanotechnology not only capitalizes on their innate properties but also opens up innovative avenues for the development of novel nanomaterials with tailored functionalities. As research progresses, plant viruses continue to play a pivotal role in advancing nanotechnology applications through their unique biological properties and structural versatility.

Nanotechnology in food packaging

The food industry plays a crucial role in improving the nutritional quality of food products. Advanced nanomaterials are employed in high-barrier packaging to protect food from UV radiation and environmental factors, thereby extending shelf life and ensuring food safety. These nanomaterials also enhance the strength of packaging materials, maintaining the integrity of their contents.

Nanosensors represent another breakthrough in food technology, enabling the detection of chemicals, gases, and pathogens in food products. This capability is essential for smart packaging, where materials actively monitor and respond to changes in their environment (Duncan, 2011). Despite these advancements, concerns persist among consumers and researchers regarding the direct use of nanoparticles in food, citing potential risks. Addressing these concerns requires rigorous safety measures to mitigate risks to human health and ensure consumer safety. Regulatory frameworks and guidelines are essential for overseeing the safe application of nanomaterials in food packaging and processing.

Current research focuses on safely harnessing nanotechnology in the food industry, aiming to balance innovation with safety considerations. By addressing consumer concerns and implementing robust safety protocols, the food industry can leverage the advantages of nanotechnology while maintaining the integrity and safety of food products globally.

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