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Review Article

Nanotechnology Applications in the Production of Sustainable Agricultural Products: A Comprehensive Review

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ABSTRACT

Nanotechnology has emerged as a promising field with immense potential for various scientific disciplines, including plant sciences. In recent years, nanotechnology has revolutionized the way we study and manipulate plants, providing new tools and strategies to enhance crop productivity, improve disease resistance, and address environmental challenges. This review aims to provide a comprehensive overview of the applications of nanotechnology in plant sciences, highlighting its impact on plant growth, development, and stress tolerance. Furthermore, the article explores various nanomaterials and nanotechniques employed in plant science research, along with their advantages and limitations. Additionally, the potential risks associated with the use of nanomaterials in plants are discussed, emphasizing the need for responsible and sustainable nanotechnology practices. Overall, this review underscores the transformative potential of nanotechnology in addressing the global challenges of food security and sustainable agriculture.

Keywords: *Nanotechnology*, CNTs, AgNPs, ZnONPs

INTRODUCTION

Today, using advanced science to improve food health, especially medicinal plants, is one of the most essential issues. As we know, knowing the goals in the field of biological systems can create a more correct path in product management (Ahandani et al., 2013; & Alinia-Ahandani et al., 2019).

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Nanotechnology, manipulating and controlling materials at the nanoscale (1-100 nanometers), has emerged as a promising field with significant implications for various scientific disciplines, including plant sciences. Nanotechnology enables scientists to engineer and utilize nanomaterials with unique properties and interactions at the molecular level, opening up new avenues for research and innovation (Gupta et al., 2019). In recent years, nanotechnology has revolutionized the way we study and manipulate plants, providing new tools and strategies to enhance crop productivity, improve disease resistance, and address environmental challenges (Tripathi et al., 2020). The unique characteristics exhibited by nanomaterials, such as large surface area-to-volume ratio, high reactivity, and unique optical and magnetic properties, have made them attractive for various applications in plant research (Gogos et al., 2021).

Nanotechnology has brought about significant advancements in plant science research by facilitating a deeper understanding of plant biology, physiology, and molecular processes. By manipulating materials at the nanoscale, researchers can precisely control the delivery of nutrients, hormones, and genetic materials to plants, leading to improved growth, development, and overall performance (Khodakovskaya et al., 2019). Additionally, nanotechnology has enabled the development of innovative strategies for plant disease management, including the targeted delivery of antimicrobial agents, the detection of plant pathogens, and the development of more efficient and eco-friendly pesticides (Tiwari et al., 2021) Moreover, nanotechnology has demonstrated potential in enhancing plant tolerance to various abiotic stresses, such as drought, salinity, and heavy metal contamination, by improving water and nutrient uptake, reducing oxidative damage, and facilitating stress signalling mechanisms (Li et al., 2020).

The importance of nanotechnology in plant research is evident in its ability to address critical challenges in agriculture and contribute to global food security. With the world's population expected to exceed 9 billion by 2050, there is a pressing need to develop sustainable agricultural practices that can meet the increasing demand for food while minimizing environmental impacts (DeRosa et al., 2020). Nanotechnology offers innovative solutions to these challenges by improving crop yields, reducing pesticide usage, and promoting resource-efficient farming practices. Furthermore, nanotechnology enables the production of smart delivery systems for agrochemicals, enhancing their efficacy while reducing their negative effects on the environment (Yang et al., 2021).

In conclusion, nanotechnology has emerged as a transformative field in plant sciences, offering a wide range of applications and solutions to address the challenges faced by modern agriculture. By harnessing the unique properties of nanomaterials and leveraging nanotechniques, researchers can gain a deeper understanding of plant biology, improve crop productivity, and develop sustainable agricultural practices. However, it is crucial to consider the potential environmental risks and ensure the responsible and sustainable use of nanotechnology in plant research and agricultural applications.

2. Nanomaterials in Plant Sciences

2.1 Carbon-based nanomaterials

Carbon-based nanomaterials, such as carbon nanotubes (CNTs), graphene, and graphene oxide, have gained significant attention in plant science research due to their unique properties and potential applications.

Carbon nanotubes (CNTs) are cylindrical structures made of rolled-up graphene sheets. They possess exceptional mechanical, electrical, and thermal properties, making them ideal for various applications in plant sciences (Kumar et al., 2020). CNTs have been explored for their role in improving plant growth, nutrient uptake, and stress tolerance. Studies have shown that the application of CNTs can enhance seed germination, promote root growth, and improve overall plant biomass (Rizwan et al., 2021). Additionally, CNTs have been utilized as carriers for the controlled release of nutrients and agrochemicals, enabling targeted delivery to plant roots and improving nutrient use efficiency (Lin et al., 2020). However, it is important to note that the potential toxicity of CNTs on plant systems and the environment requires further investigation to ensure safe and responsible use.

Graphene, a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice, exhibits exceptional mechanical, electrical, and thermal properties. In plant sciences, graphene has been explored for its potential in enhancing plant growth, photosynthesis, and stress tolerance. Studies have demonstrated that the application of graphene-based materials can improve seed germination rates, root elongation, and chlorophyll content, leading to enhanced plant growth and development (Gurunathan et al., 2020). Moreover, graphene-based materials have been utilized as nanocarriers for the targeted delivery of plant growth regulators and agrochemicals, allowing precise control over their release and improving their efficacy (Tripathi et al., 2019). However, the long-term environmental impact and potential toxicity of graphene-based nanomaterials on plants and ecosystems require further investigation.

Graphene oxide (GO), an oxidized form of graphene, has also shown promise in plant sciences. GO has unique physicochemical properties, including a high surface area and abundant functional groups, making it suitable for various applications. Studies have reported that the application of GO can enhance seed germination, root elongation, and nutrient uptake in plants (Mukherjee et al., 2020). Additionally, GO has been explored as a nanocarrier for the targeted delivery of genetic materials to plant cells, including DNA and RNA, enabling efficient genetic transformation and gene expression modulation (Zhang et al., 2020). However, the potential cytotoxicity and environmental impact of GO on plants and ecosystems necessitate careful evaluation and risk assessment.

The utilization of carbon-based nanomaterials, including CNTs, graphene, and graphene oxide, holds great potential for various applications in plant sciences. Their unique properties and versatility make them suitable for improving plant growth, nutrient delivery, and stress tolerance. However, it is essential to conduct further research to fully understand the potential risks and ensure the safe and responsible use of these nanomaterials in plant systems.

2.2 Metal-based nanomaterials

Metal-based nanomaterials, including silver nanoparticles (AgNPs), gold nanoparticles (AuNPs), and zinc oxide nanoparticles (ZnONPs), have attracted significant attention in plant science research due to their unique physicochemical properties and potential applications.

Silver nanoparticles (AgNPs) have shown remarkable antimicrobial activity against a wide range of plant pathogens, including bacteria, fungi, and viruses. AgNPs have been investigated for their potential in plant disease management, acting as nanopesticides and fungicides (Singh et al., 2021). Studies have reported the efficacy of AgNPs in inhibiting the growth of plant pathogens, protecting crops from diseases, and improving overall plant health (Ma et al., 2020). Moreover, AgNPs have been explored for their role in enhancing plant growth and development. They have shown the ability to promote seed germination, stimulate root elongation, and increase photosynthetic activity (Kim et al., 2019). However, the potential cytotoxicity of AgNPs on plants and the environment requires careful consideration, and further research is needed to understand their long-term effects.

Gold nanoparticles (AuNPs) exhibit unique physicochemical properties, including high stability and biocompatibility, making them suitable for various applications in plant sciences. AuNPs have been explored for their potential in improving plant growth, enhancing nutrient uptake, and mitigating abiotic stresses. Studies have demonstrated that the application of AuNPs can promote seed germination, enhance root development, and improve overall plant biomass (Choudhury et al., 2020). Furthermore, AuNPs have been utilized as nanocarriers for the targeted delivery of plant growth regulators and genetic materials, facilitating efficient delivery and enhancing their bioavailability (Tripathi et al., 2018). However, the environmental impact and long-term effects of AuNPs on plant systems and ecosystems require further investigation.

Zinc oxide nanoparticles (ZnONPs) have gained attention for their potential in plant nutrition and crop enhancement. ZnONPs possess unique physicochemical properties, such as high surface area and reactivity, which make them suitable for delivering zinc, an essential micronutrient, to plants. Studies have shown that the application of ZnONPs can enhance zinc uptake and improve plant growth and development (Kumar et al., 2019). Additionally, ZnONPs have demonstrated the potential to mitigate abiotic stresses, such as drought and heavy metal toxicity, by improving antioxidant defences and reducing oxidative damage in plants (Kumari et al., 2020). However, the potential phytotoxicity and accumulation of ZnONPs in the environment should be carefully evaluated to ensure their safe and sustainable use.

2.3 Other nanomaterials

In addition to carbon-based and metal-based nanomaterials, several other types of nanomaterials have been explored for their applications in plant sciences. This section will discuss metal oxide nanoparticles, quantum dots, and lipid-based nanoparticles.

Metal oxide nanoparticles, such as titanium dioxide nanoparticles (TiO_2NPs) and iron oxide nanoparticles (Fe_3O_4NPs), have attracted attention in plant research due to their unique properties and potential applications. TiO_2NPs have been investigated for their role in plant growth and development. Studies have shown that the application of TiO_2NPs can enhance seed germination, promote root elongation, and improve overall plant biomass (Khodakovskaya et al., 2018). Fe_3O_4NPs, on the other hand, have been explored for their potential in plant nutrient delivery and magnetic targeting. Fe_3O_4NPs can serve as carriers for the controlled release of fertilizers and micronutrients, enabling targeted delivery to plant roots and improving nutrient use efficiency (Tripathi et al., 2021). However, the potential toxicity of metal oxide nanoparticles on plants and the environment should be carefully evaluated to ensure safe and responsible use.

Quantum dots (QDs) are semiconductor nanocrystals with unique optical and electrical properties. QDs have been utilized for imaging and sensing applications in plant sciences. They have been used as fluorescent probes to study plant processes, including cellular uptake, transport, and localization of nanoparticles (Li et al., 2021). QDs offer advantages over traditional fluorescent dyes, such as high brightness, photostability, and tunable emission spectra, enabling precise and sensitive detection in plants. However, the potential cytotoxicity and environmental impact of QDs should be considered when using them in plant systems.

Lipid-based nanoparticles, including liposomes and solid lipid nanoparticles (SLNs), have gained attention as delivery systems for various compounds in plant sciences. Lipid-based nanoparticles provide a stable and biocompatible platform for encapsulating and delivering plant growth regulators, agrochemicals, and genetic materials. They offer protection, controlled release, and targeted delivery to plant cells (Mitter et al., 2020). Liposomes and SLNs have been explored for the targeted delivery of RNA interference (RNAi) molecules, enabling efficient gene silencing and modulation of gene expression in plants (Tahir et al., 2020). Furthermore, lipid-based nanoparticles can enhance the stability and bioavailability of bioactive compounds, such as antioxidants and plant extracts, leading to improved plant stress tolerance and growth (Mishra et al., 2021). However, the potential effects of lipid-based nanoparticles on plant physiology and the environment should be carefully evaluated.

The utilization of other nanomaterials, including metal oxide nanoparticles, quantum dots, and lipid-based nanoparticles, offers exciting opportunities for various applications in plant sciences. These nanomaterials provide unique functionalities, such as nutrient delivery, imaging, sensing, and targeted delivery, which can contribute to plant growth, disease management, and genetic manipulation. However, assessing their potential toxicity and environmental impact is crucial to ensure safe and sustainable utilization in plant systems.

The utilization of metal-based nanomaterials, including AgNPs, AuNPs, and ZnONPs, offers exciting opportunities for various applications in plant sciences. Their unique properties enable them to improve plant health, enhance nutrient uptake, and mitigate environmental stresses. However, assessing their potential toxicity and environmental impact is crucial to ensure responsible and sustainable utilization in plant systems.

3. Nanotechnology Applications in Plant Sciences

Plants, as one of the main sources of food in the world, must have sufficient standards to check health and improve its position in human societies. More clearly, using new methods of health assessment, raising the level of resistance in plants and having healthier medicinal plants can guarantee the correctness of better food and reduce all kinds of diseases, especially cancers (Alinia-Ahandani et al., 2021; Sheydaei & Alinia-Ahandani, 2021; & Selamoglu et al., 2023). Nanotechnology, with its unique properties and versatile applications, has emerged as a promising field in plant sciences. This section will provide an overview of the diverse applications of nanotechnology in plant sciences, including nanomaterials for enhanced plant growth, nanosensors for plant monitoring, nanodelivery systems for genetic modification, and nanoremediation for environmental restoration.

3.1. Nanomaterials for Enhanced Plant Growth and Development

Nanomaterials have shown great potential in improving plant growth and development through various mechanisms. They can enhance seed germination, stimulate root growth, improve nutrient uptake, and mitigate abiotic stresses. For instance, nanoparticles such as silicon nanoparticles (SiNPs) have been found to improve seed germination rates, enhance root elongation, and enhance stress tolerance in various plant species (Pandey et al., 2019) Similarly, carbon-based nanomaterials like carbon nanotubes (CNTs) and graphene oxide (GO) have demonstrated the ability to enhance plant growth, nutrient absorption, and photosynthetic efficiency (Tripathi et al., 2020). These nanomaterials offer unique physicochemical properties that can improve plant physiological processes, ultimately leading to enhanced growth and yield.

3.2. Nanosensors for Plant Monitoring

Nanosensors play a crucial role in monitoring and diagnosing plant health, nutrient status, and stress responses. Nanoscale sensors can be integrated into plants to provide real-time monitoring of various parameters. For example, carbon nanotube-based sensors have been used to detect changes in pH, temperature, moisture, and nutrient levels within plant tissues (de la Escosura-Muñiz et al., 2020). These sensors enable precise and non-destructive monitoring of plant physiological processes, facilitating timely interventions and optimized resource management.

3.3. Nanodelivery Systems for Genetic Modification

Nanotechnology offers advanced delivery systems for genetic modification in plants. Nanoparticles can serve as carriers for delivering genetic materials, such as DNA, RNA, and proteins, into plant cells. This enables efficient gene transfer, targeted gene expression, and modulation of plant traits. For example, lipid-based nanoparticles, such as cationic liposomes and solid lipid nanoparticles, have been used for the delivery of RNA interference (RNAi) molecules in plants, enabling effective gene silencing and targeted gene regulation (Nguyen et al., 2021). These nanodelivery systems offer improved efficiency, stability, and specificity in genetic modification, opening new avenues for crop improvement and plant biotechnology.

3.4. Nanoremediation for Environmental Restoration

Nanotechnology-based approaches have shown promise in environmental restoration and remediation of contaminated soils and water. Nanomaterials can efficiently remove pollutants, degrade toxic compounds, and improve soil quality. For instance, nanoparticles such as iron oxide nanoparticles (IONPs) have been used for the remediation of heavy metal-contaminated soils (Tripathi et al., 2022, & Alinia-Ahandani et al., 2021). These nanoparticles facilitate the immobilization and/or removal of heavy metals, reducing their bioavailability and potential ecological risks. Nanoremediation offers a sustainable and efficient approach for restoring contaminated environments, protecting ecosystems, and improving soil health.

In conclusion, nanotechnology has revolutionized the field of plant sciences by offering innovative solutions for enhanced plant growth, monitoring plant health, genetic modification, and environmental restoration. The applications of nanomaterials, nanosensors, nanodelivery systems, and nanoremediation hold great promise in addressing key challenges in agriculture, crop productivity, and environmental sustainability.

3.5. Nanomaterials for Enhanced Plant Growth and Development

Nanomaterials have shown immense potential in improving plant growth and development through various mechanisms. This section will discuss their applications in seed germination and seedling growth, nutrient delivery systems, and controlled-release systems for agrochemicals.

Seed germination and seedling growth are crucial stages in plant development. Nanomaterials have been employed to enhance these processes by providing favorable conditions and promoting seedling vigor. For instance, the application of nanomaterials such as silicon nanoparticles (SiNPs) has been shown to enhance seed germination rates, increase root length, and improve seedling growth in several plant species (Pandey et al., 2019). SiNPs can facilitate nutrient uptake, improve water absorption, and enhance antioxidant activity, leading to improved seedling establishment and growth.

Nanomaterials have also been utilized as nutrient delivery systems to enhance plant nutrition. Nano-sized carriers, such as nanoclays, nanohydrogels, and nanoporous materials, have encapsulated and delivered essential nutrients to plants (de Oliveira et al., 2019). These nanocarriers protect the nutrients from leaching or degradation, improve their stability, and provide controlled release, ensuring a sustained supply of nutrients to the plants. This approach has shown promise in enhancing nutrient availability, uptake, and utilization efficiency, leading to improved plant growth and yield.

Furthermore, nanomaterials have been employed as controlled-release systems for agrochemicals, including pesticides, herbicides, and plant growth regulators. Nanocarriers, such as mesoporous silica nanoparticles (MSNPs) and polymer-based nanoparticles, can encapsulate and release these active compounds in a controlled manner (Pérez-de-Luque et al., 2019). Controlled-release systems offer several advantages, including reduced agrochemical usage, targeted delivery, enhanced efficacy, and minimized environmental impact. They can provide a sustained release of agrochemicals over an extended period, ensuring their availability to the plants while minimizing off-target effects and reducing environmental contamination.

Overall, nanomaterials offer promising strategies for enhancing plant growth and development. Their applications in seed germination and seedling growth, nutrient delivery systems, and controlled-release systems for agrochemicals provide opportunities to improve crop productivity while minimizing the environmental impact of conventional agricultural practices.

3.6. Nanotechnology for Plant Disease Management

Nanotechnology has shown promising applications in plant disease management by offering innovative strategies for the development of effective and sustainable control measures. This section will discuss the use of nanopesticides and fungicides, nanobiosensors for disease detection, and nanocarriers for targeted delivery of antimicrobial agents.

3.6.1. Nanopesticides and Fungicides

Nanotechnology-based formulations of pesticides and fungicides, known as nanopesticides and nanofungicides, have gained attention as potential alternatives to conventional chemical control methods. These formulations utilize nanomaterials as carriers for active ingredients, enhancing their efficacy, stability, and targeted delivery. For instance, nanoparticles such as silver nanoparticles (AgNPs) and copper nanoparticles (CuNPs) have shown potent antimicrobial properties against various plant pathogens (Ali et al., 2019). These nanomaterials can inhibit the growth and development of fungal and bacterial pathogens, offering effective disease management. Nanopesticides and nanofungicides provide advantages such as reduced environmental impact, lower application rates, and enhanced control efficiency, making them promising tools for sustainable disease management.

3.6.2 Nanobiosensors for Disease Detection

Nanotechnology-based biosensors offer sensitive and rapid detection methods for plant pathogens, enabling early disease diagnosis and timely intervention. Nanobiosensors utilize nanomaterials as sensing elements to detect specific pathogen-related molecules or biomarkers. For example, quantum dot-based biosensors have been developed for the detection of plant viruses, bacteria, and fungi (Debode et al., 2020). These nanobiosensors provide high sensitivity, specificity, and real-time monitoring capabilities, facilitating early disease detection and accurate pathogen identification. Rapid and precise disease diagnosis using nanobiosensors allows for targeted disease management strategies, reducing the need for broad-spectrum treatments and minimizing economic losses.

3.6.3. Nanocarriers for Targeted Delivery of Antimicrobial Agents

Nanotechnology-based delivery systems offer targeted and controlled release of antimicrobial agents, enhancing their efficacy and reducing off-target effects. Nanocarriers, such as liposomes, solid lipid nanoparticles, and polymer-based nanoparticles, can encapsulate antimicrobial compounds, including antibiotics, antifungal agents, and plant-derived bioactive compounds. These nanocarriers protect the antimicrobial agents from degradation, improve their stability, and enable controlled release at the site of infection. For instance, liposome-based formulations have been used to deliver antifungal agents for effective management of fungal diseases (Zhang et al., 2020). Nanocarriers provide localized and sustained release of antimicrobial agents, maximizing their bioavailability, reducing the required dosage, and minimizing the development of resistance.

The utilization of nanotechnology in plant disease management through nanopesticides and fungicides, nanobiosensors for disease detection, and nanocarriers for targeted delivery of antimicrobial agents offers exciting prospects for more efficient, sustainable, and precise control of plant diseases. These nanotechnology-based approaches provide innovative solutions to address challenges in disease management, including pathogen resistance, environmental impact, and accurate diagnosis.

3.6.4. Nanomaterials for Abiotic Stress Tolerance

Nanotechnology has emerged as a promising approach for enhancing plant tolerance to abiotic stresses, such as drought, salinity, heavy metal toxicity, and temperature extremes. This section will discuss the applications of nanomaterials in improving plant tolerance to drought and salinity stress, facilitating heavy metal detoxification, and mitigating temperature stress.

Drought and salinity stress are major challenges in agriculture, leading to reduced crop productivity and quality. Nanomaterials have shown potential in alleviating the detrimental effects of these stresses by improving water uptake, water retention, and osmotic regulation in plants. For example, the application of silica nanoparticles (SiNPs) has been reported to enhance water availability, mitigate oxidative damage, and improve drought and salinity tolerance in plants (Hasanuzzaman et al., 2021). SiNPs can promote water uptake and distribution, enhance antioxidant defenses, and regulate stomatal behavior, enabling plants to withstand water scarcity and salt stress.

Heavy metal contamination in soils significantly threatens plant growth and human health. Nanomaterials have been explored for their potential in detoxifying heavy metals and reducing their phytotoxicity. Nanoparticles, such as zero-valent iron nanoparticles (nZVI) and titanium dioxide nanoparticles (TiO_2NPs), have been used for the immobilization, sequestration, and transformation of heavy metals in contaminated soils (Tripathi et al., 2017). These nanomaterials can adsorb heavy metals, facilitate their precipitation or immobilization, and enhance soil remediation efforts. The use of nanomaterials for heavy metal detoxification offers a sustainable approach to mitigate the adverse effects of heavy metal contamination on plants and ecosystems.

Temperature, heat, and cold stress negatively impact plant growth, development, and yield. Nanomaterials have been investigated for their potential in mitigating temperature stress by improving plant thermotolerance and cold tolerance. For instance, carbon-based nanomaterials, such as carbon nanotubes (CNTs) and graphene oxide (GO), have been shown to enhance the heat and cold tolerance of plants (Tripathi et al., 2020). These nanomaterials can improve cellular stability, modulate stress-responsive gene expression, and enhance antioxidant defenses, enabling plants to cope with temperature extremes.

The application of nanomaterials in improving plant tolerance to abiotic stresses offers innovative solutions to enhance crop productivity, improve stress resilience, and ensure food security. By addressing the challenges associated with drought and salinity stress, facilitating heavy metal detoxification, and mitigating temperature stress, nanotechnology holds great promise in sustainable agriculture and the cultivation of stress-tolerant crops.

4. Nanotechniques in Plant Sciences

4.1 Nanosensors and Imaging Techniques

Nanotechnology has revolutionized the field of plant sciences by providing advanced nanosensors and imaging techniques that enable precise and detailed analysis of plant structures, processes, and interactions at the nanoscale. This section will discuss the applications of nanosensors and imaging techniques, including fluorescent probes and quantum dots for molecular imaging, as well as scanning electron microscopy (SEM) and transmission electron microscopy (TEM) for high-resolution imaging.

Fluorescent probes and quantum dots have emerged as powerful tools for molecular imaging and sensing in plant sciences. These nanoscale materials exhibit unique optical properties, including high brightness, photostability, and tunable emission spectra, making them ideal for visualizing specific molecules and processes within plant cells and tissues. For example, fluorescent probes can be designed to target specific cellular components, such as organelles or biomolecules, allowing researchers to track and visualize dynamic processes, such as cellular signaling or gene expression (Gambhir, 2018). Quantum dots, on the other hand, offer long-lasting fluorescence and narrow emission spectra, enabling multiplexing and simultaneous detection of multiple targets within plant samples (Courty et al., 2019). These nanosensors and imaging techniques provide valuable insights into cellular dynamics, subcellular localization, and molecular interactions, advancing our understanding of plant biology.

Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are widely used imaging techniques that have been enhanced by nanotechnology. SEM provides high-resolution surface imaging, allowing researchers to examine plant samples' surface structures and morphology. It offers detailed information about plant cells, tissues, and structures' shape, size, and surface features. In combination with nanotechnology, SEM can utilize specialized detectors and sample preparation techniques to enhance contrast and resolution, enabling detailed imaging of nanoscale features (Tripathi et al., 2021). Conversely, TEM offers higher resolution and allows researchers to investigate the internal structures of plant samples at the nanoscale. It utilizes a focused electron beam to transmit through ultra-thin sections of plant tissues, revealing detailed information about cellular and subcellular structures, such as organelles, membranes, and nanoparticles (Yin et al., 2018). Nanotechnology has further expanded TEM's capabilities by enabling nanomaterials as contrast agents or labels, enhancing imaging and enabling the visualization of specific targets within plant samples.

Nanosensors and imaging techniques in plant sciences provide powerful tools for studying plant structures, molecular processes, and interactions at the nanoscale. The use of fluorescent probes and quantum dots enables real-time visualization and tracking of specific molecules, while SEM and TEM offer high-resolution imaging of plant samples, providing valuable insights into their morphology and internal structures. These nanotechniques contribute to a deeper understanding of plant biology, facilitating advancements in plant research, crop improvement, and biotechnological applications.

5. Nanomanipulation and Genetic Engineering

Nanotechnology has revolutionized the field of genetic engineering by providing innovative tools and techniques for precise manipulation and modification of genetic material. This section will discuss the applications of nanotechnology in genetic engineering, including CRISPR-Cas9 nanodelivery systems and nanobiosensors for gene expression analysis.

5.1. CRISPR-Cas9 Nanodelivery Systems

The CRISPR-Cas9 system has emerged as a powerful tool for targeted gene editing, allowing scientists to make precise modifications in the genetic material of organisms. Nanotechnology has contributed to the development of efficient and precise delivery systems for CRISPR-Cas9 components, enhancing their delivery into plant cells. Nanoparticles, such as liposomes, polymeric nanoparticles, and carbon-based nanomaterials, have been explored as carriers for CRISPR-Cas9 components, including the guide RNA and the Cas9 nuclease (Wang et al., 2020). These nanodelivery systems protect the CRISPR-Cas9 components from degradation, facilitate their cellular uptake, and enable targeted delivery to the desired genomic sites. Nanotechnology-based delivery systems have shown improved efficiency and precision in gene editing, offering new possibilities for crop improvement, trait modification, and disease resistance in plants.

5.2. Nanobiosensors for Gene Expression

Nanobiosensors have emerged as powerful tools for monitoring and analyzing gene expression in plant cells. These nanoscale sensors can detect and quantify specific gene transcripts or proteins, providing insights into the regulation of gene expression and cellular processes. Nanobiosensors utilize nanomaterials, such as carbon nanotubes, quantum dots, or gold nanoparticles, as sensing elements that interact with the target molecules and generate measurable signals.

For example, fluorescent nanobiosensors have been developed to monitor the expression of specific genes in real-time, enabling the study of gene regulatory networks, stress responses, and developmental processes in plants (Debode et al., 2019). Nanobiosensors offer high sensitivity, specificity, and real-time monitoring capabilities, facilitating the understanding of gene expression dynamics and the development of genetic engineering strategies in plants.

The application of nanotechnology in genetic engineering through CRISPR-Cas9 nanodelivery systems and nanobiosensors for gene expression analysis offers exciting prospects for precise and efficient manipulation of plant genomes. These nanotechnological approaches provide innovative solutions for targeted gene editing, gene expression analysis, and the development of genetically modified crops with desired traits. By harnessing the power of nanotechnology, genetic engineering can contribute to the sustainable improvement of crop productivity, nutritional quality, and environmental resilience.

6. Environmental Implications and Safety Concerns

The application of nanotechnology in plant sciences offers numerous benefits, but it is crucial to assess the potential environmental implications and safety concerns associated with the use of nanomaterials. This section will discuss the uptake and translocation of nanomaterials in plants, their ecotoxicological effects on non-target organisms, and the importance of risk assessment and regulation in the field of nanotechnology in plant sciences.

6.1. Uptake and Translocation of Nanomaterials in Plants

Nanomaterials can enter plant systems through various routes, including uptake by roots, foliar uptake, or through their interaction with pollen or seeds. Once inside the plant, nanomaterials can be translocated and distributed to different plant tissues and organs, including the shoots, leaves, and even reproductive organs. The uptake and translocation of nanomaterials depend on various factors, including their physicochemical properties, size, surface charge, surface chemistry, and plant-specific factors such as plant species, root characteristics, and physiological processes. Understanding the mechanisms of nanomaterial uptake and translocation in plants is essential for assessing their potential impacts on plant growth, development, and overall plant health (Huang et al., 2019).

6.2. Ecotoxicological Effects and Impact on Non-Target Organisms

Nanomaterials may have potential ecotoxicological effects on non-target organisms, including soil microorganisms, beneficial insects, aquatic organisms, and even humans. Assessing the potential adverse effects of nanomaterials on ecosystem health and the functioning of natural systems is crucial. Studies have shown that certain nanomaterials can affect soil microbial communities, disrupt the activity of soil enzymes, and impact nutrient cycling processes (Gogos et al., 2016; & Alinia-ahandani et al., 2019). In aquatic environments, nanomaterials may accumulate in sediments, affect aquatic organisms' growth and reproduction, and alter the overall ecosystem dynamics. Additionally, there is a need to evaluate the potential risks associated with the release of nanomaterials into the environment, including their persistence, bioaccumulation, and potential long-term effects on ecosystems.

6.3. Risk Assessment and Regulation of Nanotechnology in Plant Sciences

Risk assessment and regulation play a critical role in ensuring the safe and responsible use of nanotechnology in plant sciences. It involves systematically evaluating potential risks, including identifying hazards, exposure assessment, and risk characterization. Risk assessment helps in understanding the potential adverse effects of nanomaterials on human health, environment, and non-target organisms, allowing for the development of appropriate risk management strategies. Regulatory frameworks and guidelines are important in establishing safety standards, labeling requirements, and risk management practices for the use of nanomaterials in agriculture and plant sciences. Plants can play a very important role in improving health, so the need to use new methods of product improvement is one of the most vital issues. It should also be noted that there are many reports on increasing the daily use of plants in different ways around the world and the use of herbal medicine is increasing (Alinia-Ahandani, 2018; Hajipour et al., 2023; & Mohammadi & Alinia-Ahandani, 2020)

Various organizations and regulatory bodies have been actively working on developing guidelines and regulations for nanotechnology in agriculture and plant sciences. For instance, the Organization for Economic Cooperation and Development (OECD) has published guidelines for the testing of nanomaterials, including their environmental fate and effects (OECD, 2017). These guidelines provide standardized approaches for evaluating the potential risks associated with nanomaterials in different environmental compartments. Additionally, national regulatory agencies, such as the U.S. Environmental Protection Agency (EPA) and the European Food Safety Authority (EFSA), are involved in assessing and regulating nanotechnology products in agriculture, ensuring their safety and minimizing potential risks.

In summary, understanding the environmental implications and ensuring the safety of nanomaterials in plant sciences is crucial. Assessing the uptake and translocation of nanomaterials in plants, evaluating their ecotoxicological effects on non-target organisms, and implementing effective risk assessment and regulatory frameworks are essential for the responsible and sustainable use of nanotechnology in plant sciences.

7. Future Perspectives and Challenges

The field of nanotechnology in plant sciences holds immense potential for addressing various challenges in agriculture and crop production (Alinia-Ahandani 2018; & Selamoglu et al., 2023). However, there are certain future perspectives and challenges that need to be considered. This section will discuss the integration of nanotechnology with other emerging technologies, the commercialization and scaling up of nanotechnology applications, and the ethical and societal considerations associated with its implementation.

7.1. Integration of Nanotechnology with Other Emerging Technologies

Nanotechnology can be integrated with other emerging technologies to further enhance its capabilities and applications in plant sciences. For instance, the combination of nanotechnology with biotechnology, such as genetic engineering and genome editing, can lead to the development of novel plant varieties with improved traits, disease resistance, and enhanced nutritional value. The integration of nanotechnology with precision agriculture and digital farming techniques, including remote sensing, big data analytics, and artificial intelligence, can enable real-time monitoring and precise management of crops for optimal resource utilization and yield optimization. Exploring the synergies between nanotechnology and other emerging technologies will open new avenues for sustainable agriculture and food production.

7.2. Commercialization and Scaling Up of Nanotechnology Applications

One of the key challenges in the field of nanotechnology in plant sciences is the successful commercialization and scaling up of nanotechnology-based applications. While promising research findings have demonstrated the potential of nanomaterials and nanodevices in enhancing plant growth, disease management, and stress tolerance, there is a need to bridge the gap between laboratory research and practical implementation in agricultural settings. The development of cost-effective and scalable manufacturing processes for nanomaterials and the establishment of efficient delivery systems and application methods is crucial for the widespread adoption of nanotechnology in agriculture. Collaboration between researchers, industry partners, and regulatory agencies is essential to navigate the regulatory and commercial landscape and ensure nanotechnology's safe and efficient implementation in plant sciences.

7.3. Ethical and Societal Considerations

The ethical and societal implications of nanotechnology in plant sciences should be carefully considered. As with any emerging technology, there may be concerns regarding the potential environmental impact, health and safety risks, and socio-economic implications. It is essential to conduct comprehensive risk assessments and ensure the responsible use of nanomaterials to mitigate any potential adverse effects on the environment and human health. Additionally, there is a need for transparent communication and public engagement to address concerns, gain public trust, and foster informed decision-making regarding the adoption and regulation of nanotechnology in agriculture. Ethical considerations related to intellectual property rights, equitable access to technology, and potential disparities in the adoption of nanotechnology-based solutions should also be taken into account.

In conclusion, the integration of nanotechnology with other emerging technologies, the commercialization and scaling up of nanotechnology applications, and the ethical and societal considerations are crucial aspects that need to be addressed for the successful implementation of nanotechnology in plant sciences. By navigating these challenges and embracing responsible and sustainable practices, nanotechnology has the potential to revolutionize agriculture, contribute to global food security, and address pressing challenges in the field of plant sciences.

CONCLUSION

Nanotechnology has emerged as a promising field in plant sciences, offering innovative solutions to enhance plant growth, improve disease management, and increase stress tolerance. Using various nanomaterials and nanotechniques has made significant advancements in understanding plant physiology, optimizing nutrient delivery, and developing targeted delivery systems for agrochemicals. Nanotechnology applications have the potential to revolutionize agriculture, contributing to sustainable and efficient crop production.

In conclusion, nanotechnology holds great promise in revolutionizing plant sciences, offering new avenues for sustainable agriculture and improved crop production. However, continuing research and development in this field is essential, considering the environmental implications, ensuring safety, and addressing societal concerns. With careful implementation and responsible practices, nanotechnology has the potential to transform plant sciences and contribute to a more sustainable and resilient agricultural future.

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Author Contribution

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