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Merging Nanotechnology and Biotechnology: Transforming Plant Sciences with Nanobiotechnological Innovations

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Abstract

The convergence of nanotechnology and biotechnology, termed nanobiotechnology, has unlocked unprecedented opportunities in various fields, including plant sciences. This interdisciplinary approach combines the unique properties of nanomaterials with the remarkable capabilities of biological systems, enabling novel solutions to long-standing challenges in plant research, development, and applications. Nanobiotechnological innovations have the potential to revolutionize plant sciences by enhancing plant growth, increasing stress tolerance, improving nutrient utilization, facilitating targeted delivery of biomolecules, and enabling advanced imaging and sensing techniques. This comprehensive research article delves into the synergistic merger of nanotechnology and biotechnology, exploring its applications in plant sciences and the transformative impact it holds for agriculture, food security, and environmental sustainability.

1. Introduction

The global population is projected to reach 9.7 billion by 2050, exerting immense pressure on the agricultural sector to meet the rising demand for food, feed, and biofuel production (United Nations, 2019). Concurrently, the effects of climate change, including increased frequency and severity of droughts, floods, and temperature extremes, pose significant threats to crop productivity and food security. These mounting challenges underscore the urgent need for innovative solutions that can enhance agricultural productivity while mitigating the impacts of environmental stressors and assembled system uses sensors to monitor external elements such as temperature, humidity, and rain, as well as blowers and heaters to control the culture environment [1], [2].

Nanotechnology, the study and manipulation of matter at the nanoscale (1 to 100 nanometers), has emerged as a promising field with far-reaching applications across various sectors, including agriculture. Nanoparticles, nanomaterials, and nanostructures exhibit unique physicochemical properties, such as high surface-to-volume ratio, enhanced reactivity, and tunable optical and electronic characteristics, which can be leveraged to address agricultural challenges [3]. Biotechnology, on the other hand, involves the application of biological systems, living organisms, or their derivatives for the development of products and processes. It encompasses a wide range of techniques, including genetic engineering, cell and tissue culture, and fermentation, enabling the modification and optimization of biological systems for various applications [4].

The convergence of nanotechnology and biotechnology has given rise to a multidisciplinary field known as nanobiotechnology, which harnesses the synergistic potential of these two domains [5]. Nanobiotechnology combines the unique properties of nanomaterials with the remarkable capabilities of biological systems, opening new avenues for addressing challenges in plant sciences and agriculture [6].

This research article aims to provide a comprehensive overview of nanobiotechnological innovations in plant sciences, highlighting their applications, challenges, and future prospects. It will explore the following key areas:

1. Nanomaterials for plant growth enhancement and stress tolerance

2. Nanocarriers for targeted delivery of biomolecules in plants

3. Nanobiosensors and imaging techniques for plant monitoring and analysis

4. Nanobiotechnological approaches for plant genetic engineering and tissue culture

5. Safety considerations and regulatory aspects of nanobiotechnology in plant sciences

6. Future directions and emerging trends in nanobiotechnology for plant sciences

By investigating this article seeks to foster a deeper understanding of the transformative potential of nanobiotechnology in plant sciences and its implications for sustainable agriculture, food security, and environmental preservation.

2. Nanomaterials for Plant Growth Enhancement and Stress Tolerance

One of the primary applications of nanobiotechnology in plant sciences lies in the development and utilization of nanomaterials for enhancing plant growth and mitigating the effects of various abiotic and biotic stresses [7]. These nanomaterials, owing to their unique physicochemical properties, can interact with plants at the cellular and molecular levels, modulating various physiological processes and conferring improved stress tolerance [8].

2.1 Nanoparticles for Plant Growth Promotion

Nanoparticles, due to their small size and high surface-to-volume ratio, can efficiently penetrate plant tissues and facilitate the delivery of essential nutrients, growth regulators, and other beneficial compounds. Several types of nanoparticles have demonstrated promising effects in promoting plant growth and development.

2.1.1 Metal and Metal Oxide Nanoparticles

Metal and metal oxide nanoparticles, such as those composed of silver (Ag), gold (Au), copper (Cu), zinc oxide (ZnO), and titanium dioxide (TiO_2), have been extensively studied for their potential in enhancing plant growth and development. These nanoparticles can influence various physiological processes, including seed germination, root and shoot elongation, photosynthesis, and nutrient uptake. For instance, Ag nanoparticles have been reported to improve seed germination, root elongation, and biomass accumulation in various plant species, including Brassica juncea (mustard greens), Triticum aestivum (wheat), and Oryza sativa (rice) [9]. The mechanisms underlying these growth-promoting effects are attributed to the nanoparticles' ability to modulate the activity of enzymes involved in plant growth and development, as well as their potential to generate reactive oxygen species (ROS) at low concentrations, which can act as signaling molecules. Similarly, Au nanoparticles have demonstrated positive effects on seed germination, root and shoot elongation, and chlorophyll content in plants such as Brassica juncea and Glycine max (soybean). These nanoparticles are believed to enhance the uptake and translocation of essential nutrients, as well as modulate the expression of genes related to plant growth and development.

2.1.2 Carbon-Based Nanoparticles

Carbon-based nanoparticles, such as fullerenes, carbon nanotubes (CNTs), and graphene, have also garnered significant attention for their potential applications in plant growth promotion. These nanomaterials possess unique electronic, optical, and mechanical properties that can influence various aspects of plant physiology and development. CNTs, for instance, have been reported to enhance seed germination, root and shoot growth, and biomass accumulation in several plant species, including Arabidopsis thaliana (thale cress), Oryza sativa (rice), and Zea mays (maize). The mechanisms underlying these growth-promoting effects are not fully understood but may involve the modulation of gene expression, water and nutrient uptake, and the generation of ROS at low concentrations [10]. Graphene and its derivatives, such as graphene oxide (GO) and reduced graphene oxide (rGO), have also shown promising results in enhancing plant growth and development. These nanomaterials can influence various physiological processes, including photosynthesis, water uptake, and nutrient translocation, leading to improved growth and biomass accumulation in plants.

2.2 Nanoparticles for Abiotic Stress Tolerance

Abiotic stresses, such as drought, salinity, extreme temperatures, and heavy metal toxicity, pose significant threats to plant growth, development, and productivity. Nanobiotechnology offers innovative solutions to mitigate the detrimental effects of these stresses by employing nanoparticles that can modulate plant stress responses and confer enhanced tolerance.

2.2.1 Drought Stress Tolerance

Drought stress is one of the most significant abiotic stresses affecting crop productivity worldwide (Farooq et al., 2009). Nanoparticles have shown promising potential in enhancing drought stress tolerance in plants through various mechanisms, such as modulating antioxidant systems, regulating plant hormone signaling, and improving water retention capacity. For instance, silicon dioxide (SiO_2) nanoparticles have been reported to alleviate drought stress in Glycine max (soybean) by enhancing the activity of antioxidant enzymes, reducing lipid peroxidation, and maintaining higher relative water content. Similarly, TiO_2 nanoparticles have been shown to improve drought tolerance in Triticum aestivum (wheat) by modulating the expression of stress-related genes and enhancing the accumulation of compatible solutes, such as proline and soluble sugars [11].

2.2.2 Salinity Stress Tolerance

Soil salinity is a significant constraint to agricultural productivity, affecting approximately 20% of the world's cultivated land. Nanoparticles have demonstrated their potential in mitigating the detrimental effects of salinity stress on plant growth and development through various mechanisms, including modulating ion homeostasis, enhancing antioxidant defense systems, and regulating plant hormone signaling [12]. For example, Ag nanoparticles have been shown to enhance salinity tolerance in Oryza sativa (rice) by regulating the expression of stress-related genes, increasing the activity of antioxidant enzymes, and maintaining higher levels of chlorophyll and carotenoids. Similarly, ZnO nanoparticles have been reported to alleviate salinity stress in Triticum aestivum (wheat) by modulating the expression of salt stress-responsive genes, enhancing the accumulation of compatible solutes, and maintaining higher relative water content. The IoT-enabled system promises substantial benefits to farmers by easing the challenges linked with cultivation and growth supervision with automatic pump control ,ensuring consistent soil moisture levels, the sensor becomes an invaluable asset in farming practices [13].

2.2.3 Heavy Metal Stress Tolerance

Heavy metal contamination in agricultural soils poses a significant threat to plant growth, development, and productivity. Nanoparticles have shown potential in mitigating the toxic effects of heavy metals on plants by modulating their uptake, translocation, and accumulation, as well as enhancing plant antioxidant defense systems. For instance, cerium oxide (CeO_2) nanoparticles have been reported to alleviate cadmium (Cd) stress in Oryza sativa (rice) by reducing Cd uptake and translocation, enhancing the activity of antioxidant enzymes, and maintaining higher chlorophyll content [14]. Similarly, iron oxide (Fe_3O_4) nanoparticles have been shown to mitigate chromium stress in Pisum sativum (pea) by reducing Cr uptake, modulating the expression of stress-related genes, and enhancing the accumulation of compatible solutes.

2.3 Nanoparticles for Biotic Stress Tolerance

In addition to abiotic stresses, plants are also susceptible to various biotic stresses, such as pathogen infections, insect pests, and nematode infestations, which can significantly compromise crop productivity and yield. Nanobiotechnology offers promising solutions to address these biotic stresses by employing nanoparticles with antimicrobial, insecticidal, and nematicidal properties.

2.3.1 Antimicrobial Nanoparticles

Certain nanoparticles, such as silver (Ag), copper (Cu), and zinc oxide (ZnO), possess potent antimicrobial properties and have been explored for their potential in mitigating plant diseases caused by various pathogenic microorganisms, including bacteria, fungi, and viruses. Ag nanoparticles have demonstrated broad-spectrum antimicrobial activity against a wide range of plant pathogens, including Xanthomonas campestris , Fusarium oxysporum (fusarium wilt in various crops), and Tobacco mosaic virus (TMV). The antimicrobial activity of Ag nanoparticles is attributed to their ability to disrupt the cell membrane, generate reactive oxygen species (ROS), and interfere with cellular processes such as DNA replication and protein synthesis [15]. Similarly, Cu and ZnO nanoparticles have shown promising results in controlling plant diseases caused by fungi and bacteria. These nanoparticles can generate ROS, disrupt cell membranes, and interfere with essential metabolic processes, leading to the inhibition of pathogen growth and proliferation.

2.3.2 Insecticidal and Nematicidal Nanoparticles

Nanoparticles have also demonstrated potential as insecticides and nematicides, offering alternative strategies for pest management in agriculture. Certain nanoparticles, such as silica (SiO_2), titanium dioxide (TiO_2), and silver (Ag), have shown insecticidal and nematicidal activities against various insect pests and plant-parasitic nematodes. For instance, SiO_2 nanoparticles have been reported to exhibit insecticidal activity against the cotton leafworm (Spodoptera littoralis) and the red flour beetle (Tribolium castaneum) by causing physical damage to the insect cuticle and disrupting digestive processes. TiO_2 nanoparticles have also demonstrated insecticidal properties against various insect pests, including the cabbage looper (Trichoplusia ni) and the whitefly (Bemisia tabaci), by generating reactive oxygen species (ROS) and causing oxidative stress. Similarly, Ag nanoparticles have been found to exhibit nematicidal activity against plant-parasitic nematodes, such as the root-knot nematode (Meloidogyne incognita) and the cyst nematode (Globodera rostochiensis). The nematicidal activity of Ag nanoparticles is attributed to their ability to disrupt cellular processes, induce oxidative stress, and interfere with nematode mobility and reproduction.

2.4 Nanomaterial-Based Nutrient Delivery Systems

Efficient nutrient management is crucial for optimal plant growth, development, and yield. Nanobiotechnology offers innovative solutions for targeted and controlled delivery of essential nutrients to plants, enhancing nutrient use efficiency and minimizing environmental impact. Nanoparticles and nanomaterials can be engineered to encapsulate or adsorb essential nutrients, such as nitrogen, phosphorus, potassium, and micronutrients, and facilitate their controlled release to plants. These nutrient delivery systems can improve nutrient availability, uptake, and utilization by plants, leading to enhanced growth and productivity [16], [17].

For example, chitosan-based nanoparticles have been explored as carriers for nitrogen (N) and phosphorus (P) delivery to plants. Chitosan nanoparticles loaded with N and P sources can be applied to the soil or plant foliage, enabling controlled release of these nutrients and improving their availability to plants. Similarly, mesoporous silica nanoparticles have been investigated as carriers for the delivery of micronutrients, such as iron (Fe), zinc (Zn), and copper (Cu), to plants. These nanoparticles can encapsulate and protect the micronutrients from degradation or precipitation, facilitating their controlled release and enhancing their bioavailability to plants [18].

Nanomaterial-based nutrient delivery systems offer several advantages over conventional fertilizer application methods, including improved nutrient use efficiency, reduced nutrient losses through leaching and volatilization, and Nanomaterial-based nutrient delivery systems offer several advantages over conventional fertilizer application methods, including improved nutrient use efficiency, reduced nutrient losses through leaching and volatilization, and minimized environmental impact. The danger of crop failure, low yield, excessive water consumption, excessive fertiliser and pesticide use, etc. can be greatly decreased with this model, making it more effective than previous methods [19]. These systems can contribute to sustainable agriculture by optimizing nutrient utilization, reducing excessive fertilizer application, and mitigating the risks of soil and water pollution.

2.5 Synergistic Effects of Nanomaterials and Biostimulants

Recent research has explored the synergistic effects of combining nanomaterials with biostimulants, such as plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), and plant extracts, for enhancing plant growth and stress tolerance. PGPR and AMF are beneficial microorganisms that can establish symbiotic associations with plant roots, improving nutrient acquisition, promoting plant growth, and enhancing stress tolerance. Nanoparticles and nanomaterials can be used as carriers or delivery vehicles for these beneficial microorganisms, facilitating their efficient colonization and interaction with plant roots. For instance, Ag nanoparticles have been reported to enhance the growth-promoting effects of PGPR, such as Pseudomonas fluorescens, in chickpea (Cicer arietinum) by improving seed germination, root and shoot growth, and chlorophyll content [20], [21]. Similarly, mesoporous silica nanoparticles have been used as carriers for AMF, such as Glomus intraradices, to improve their colonization and symbiotic association with plant roots, leading to enhanced nutrient uptake and plant growth.

Plant extracts and biostimulants derived from seaweed, plant growth regulators, and beneficial microorganisms have also been combined with nanoparticles to potentiate their growth-promoting and stress-mitigating effects. These synergistic combinations can leverage the unique properties of nanomaterials and the bioactive compounds present in plant extracts and biostimulants, leading to improved plant performance and stress tolerance.

Table 1 summarizes some key examples of nanomaterials and their applications in enhancing plant growth and stress tolerance.

Nanomaterial	Plant Species	Effects
Silver (Ag) nanoparticles	Brassica juncea (mustard greens), Triticum aestivum (wheat), Oryza sativa (rice)	Improved seed germination, root and shoot growth, biomass accumulation, drought and salinity tolerance
Gold (Au) nanoparticles	Brassica juncea (mustard greens), Glycine max (soybean)	Enhanced seed germination, root and shoot elongation, chlorophyll content
Carbon nanotubes (CNTs)	Arabidopsis thaliana (thale cress), Oryza sativa (rice), Zea mays (maize)	Improved seed germination, root and shoot growth, biomass accumulation
Graphene and derivatives	Various plant species	Enhanced photosynthesis, water uptake, nutrient translocation, biomass accumulation
Silicon dioxide (SiO_2) nanoparticles	Glycine max (soybean)	Alleviated drought stress, improved antioxidant defense, water retention
Titanium dioxide (TiO_2) nanoparticles	Triticum aestivum (wheat)	Enhanced drought tolerance, modulated stress-related gene expression, compatible solute accumulation

Nanomaterial	Plant Species	Effects
Cerium oxide (CeO_2) nanoparticles	Oryza sativa (rice)	Alleviated cadmium stress, reduced heavy metal uptake, enhanced antioxidant defense
Iron oxide (Fe_3O_4) nanoparticles	Pisum sativum (pea)	Mitigated chromium stress, reduced heavy metal uptake, modulated stress responses

3.Nanocarriers for Targeted Delivery of Biomolecules in Plants

Nanobiotechnology offers innovative solutions for the targeted delivery of biomolecules, such as nucleic acids (DNA, RNA), proteins, and small molecules, to specific plant tissues or cells [22], [23]. This targeted delivery approach can enhance the efficiency and specificity of various plant biotechnological applications, including genetic engineering, gene therapy, and the delivery of biologically active compounds (e.g., pesticides, hormones, and growth regulators).

3.1 Nanocarriers for Nucleic Acid Delivery

Genetic engineering and gene therapy in plants rely on the efficient delivery of nucleic acids (DNA or RNA) into plant cells and tissues. However, conventional methods for nucleic acid delivery, such as Agrobacterium-mediated transformation and biolistic (gene gun) techniques, have limitations in terms of efficiency, tissue specificity, and potential genetic integration. Nanobiotechnology offers alternative strategies for nucleic acid delivery using nanocarriers, which can protect the nucleic acids from degradation, facilitate their cellular uptake, and enhance their bioavailability. Various types of nanocarriers have been explored for nucleic acid delivery in plants, including:

1. *Cationic polymers and lipids:* These nanocarriers can form complexes with negatively charged nucleic acids through electrostatic interactions, protecting them from degradation and facilitating their cellular uptake. Examples include cationic polymers (e.g., polyethyleneimine, chitosan) and cationic lipids (e.g., lipofectamine, DOTAP).
2. *Inorganic nanoparticles:* Inorganic nanoparticles, such as mesoporous silica nanoparticles, can encapsulate and protect nucleic acids, enabling their controlled release and delivery to plant cells.
3. *Carbon-based nanocarriers:* Carbon-based nanostructures, including carbon nanotubes (CNTs) and graphene oxide (GO), have been explored for nucleic acid delivery due to their ability to penetrate cell membranes and their potential for functionalization.

These nanocarriers can be functionalized with targeting ligands or cell-penetrating peptides to enhance their specificity and cellular uptake in plants. Additionally, stimuli-responsive nanocarriers have been developed, which can release their cargo (nucleic acids) in response to specific triggers, such as pH changes, redox conditions, or enzymatic activity, ensuring targeted and controlled delivery.

3.2 Nanocarriers for Protein and Peptide Delivery

Proteins and peptides play crucial roles in various plant physiological processes, including growth, development, stress responses, and defense mechanisms. However, the delivery of these biomolecules to plants is often challenging due to their susceptibility to degradation, limited cellular uptake, and potential loss of bioactivity. Nanobiotechnology offers innovative solutions for the delivery of proteins and peptides to plants using nanocarriers that can protect these biomolecules from degradation, enhance their cellular uptake, and maintain their bioactivity. Several types of nanocarriers have been explored for protein and peptide delivery in plants, including:

1. *Polymeric nanoparticles:* Polymeric nanoparticles, such as those composed of biodegradable polymers (e.g., poly(lactic-co-glycolic acid) (PLGA), chitosan),

can encapsulate and protect proteins and peptides, enabling their controlled release and delivery to plant cells.

2. *Lipid-based nanocarriers:* Liposomes, solid lipid nanoparticles, and nanostructured lipid carriers have been investigated for the delivery of proteins and peptides to plants, leveraging their biocompatibility and ability to encapsulate hydrophilic and hydrophobic biomolecules.

3. *Inorganic nanoparticles:* Mesoporous silica nanoparticles and metal-organic frameworks (MOFs) have been explored as nanocarriers for protein and peptide delivery due to their high loading capacity, controlled release properties, and potential for surface functionalization.

These nanocarriers can be functionalized with targeting ligands, cell-penetrating peptides, or stimuli-responsive moieties to enhance their specificity, cellular uptake, and controlled release in plants. Additionally, the encapsulation of proteins and peptides within nanocarriers can protect them from proteolytic degradation and maintain their bioactivity.

3.3 Nanocarriers for Small Molecule Delivery

Small molecules, such as plant growth regulators, phytohormones, pesticides, and therapeutic agents, play crucial roles in regulating plant growth, development, and defense mechanisms. However, their delivery to plants can be challenging due to factors such as poor solubility, limited bioavailability, and potential environmental degradation [24], [25]. Nanobiotechnology offers innovative solutions for the delivery of small molecules to plants using nanocarriers that can enhance their solubility, protect them from degradation, and facilitate targeted delivery. Several types of nanocarriers have been explored for small molecule delivery in plants, including:

1. *Polymeric nanoparticles:* Polymeric nanoparticles, such as those composed of biodegradable polymers, can encapsulate and protect small molecules, enabling their controlled release and delivery to plant cells.

2. *Lipid-based nanocarriers:* Liposomes, solid lipid nanoparticles, and nanostructured lipid carriers have been investigated for the delivery of small molecules to plants, leveraging their biocompatibility and ability to encapsulate hydrophilic and hydrophobic compounds.

3. *Inorganic nanoparticles:* Mesoporous silica nanoparticles and metal-organic frameworks (MOFs) have been explored as nanocarriers for small molecule delivery due to their high loading capacity, controlled release properties, and potential for surface functionalization.

These nanocarriers can be functionalized with targeting ligands, cell-penetrating peptides, or stimuli-responsive moieties to enhance their specificity, cellular uptake, and controlled release in plants. Additionally, the encapsulation of small molecules within nanocarriers can protect them from environmental degradation, improve their stability, and enhance their bioavailability.

Table 2 provides a summary of various nanocarriers and their applications in the targeted delivery of biomolecules in plants.

Nanocarrier	Biomolecule	Plant Species	Effects/Applications
Cationic polymers (e.g., polyethyleneimine, chitosan)	Nucleic acids (DNA, RNA)	Various plant species	Genetic engineering, gene therapy, transient gene expression

Nanocarrier	Biomolecule	Plant Species	Effects/Applications
Cationic lipids (e.g., lipofectamine, DOTAP)	Nucleic acids (DNA, RNA)	Various plant species	Genetic engineering, gene therapy, transient gene expression
Mesoporous silica nanoparticles	Nucleic acids (DNA, RNA), proteins, small molecules	Various plant species	Genetic engineering, protein delivery, controlled release of small molecules
Carbon nanotubes (CNTs), graphene oxide (GO)	Nucleic acids (DNA, RNA)	Various plant species	Genetic engineering, gene therapy, transient gene expression
Polymeric nanoparticles (e.g., PLGA, chitosan)	Proteins, peptides, small molecules	Various plant species	Protein delivery, controlled release of small molecules
Lipid-based nanocarriers (liposomes, solid lipid nanoparticles)	Proteins, peptides, small molecules	Various plant species	Protein delivery, controlled release of small molecules
Metal-organic frameworks (MOFs)	Proteins, small molecules	Various plant species	Protein delivery, controlled release of small molecules

4. Nanobiosensors and Imaging Techniques for Plant Monitoring and Analysis

Nanobiotechnology has revolutionized plant monitoring and analysis by enabling the development of advanced nanobiosensors and novel imaging techniques. These innovative tools provide unprecedented insights into plant physiological processes, stress responses, and interactions with the environment, paving the way for more precise and targeted interventions in plant sciences [26].

4.1 Nanobiosensors for Plant Monitoring

Nanobiosensors are analytical devices that integrate biological recognition elements (e.g., enzymes, antibodies, nucleic acids) with nanomaterials or nanostructures for the sensitive and selective detection of specific analytes. In plant sciences, nanobiosensors have been developed for monitoring various plant parameters, including nutrient levels, phytohormone concentrations, environmental stresses, and the presence of pathogens or contaminants.

4.1.1 Optical Nanobiosensors

Optical nanobiosensors exploit the unique optical properties of nanomaterials, such as Surface Plasmon Resonance (SPR), fluorescence, and colorimetric changes, to detect and quantify specific analytes in plant samples. For instance, gold nanoparticles (AuNPs) have been employed in colorimetric biosensors for the detection of plant pathogens, such as viruses and bacteria. The interaction between the target pathogen and the AuNP-conjugated recognition element (e.g., antibody or nucleic acid probe) induces aggregation or dispersion of the nanoparticles, resulting in a visible color change that can be measured spectrophotometrically.

Quantum dots (QDs), semiconductor nanocrystals with unique fluorescent properties, have also been utilized in the development of fluorescent biosensors for plant monitoring. QD-based biosensors have been Quantum dots (QDs), semiconductor nanocrystals with unique fluorescent properties, have also been utilized in the development of fluorescent biosensors for plant monitoring. QD-based biosensors have been employed for the detection of plant hormones, such as auxins and cytokinins, as well as environmental pollutants and heavy metals. These biosensors rely on the modulation of QD fluorescence upon interaction with the target analyte or recognition element, enabling sensitive and selective detection.

4.1.2 Electrochemical Nanobiosensors

Electrochemical nanobiosensors integrate biological recognition elements with nanomaterials or nanostructured electrodes to detect and quantify specific analytes in plant samples through electrochemical signals, such as changes in current, potential, or impedance. Carbon nanomaterials, including carbon nanotubes (CNTs) and graphene, have been extensively explored in the development of electrochemical nanobiosensors due to their excellent electrical conductivity, high surface area, and potential for functionalization. These nanomaterials can be incorporated into electrode surfaces or used as transducer materials, enhancing the sensitivity and selectivity of electrochemical biosensors [27]. For example, CNT-based electrochemical biosensors have been developed for the detection of plant nutrients, such as nitrate and phosphate, as well as the monitoring of plant stress responses. The interaction between the target analyte and the recognition element (e.g., enzyme or aptamer) immobilized on the CNT-modified electrode induces a measurable electrochemical signal, enabling quantitative analysis. The study proposes a monitoring system employing ambient sensors to monitor the movements of honeybees entering and exiting their hive. This technology collects additional data on honeybee behaviors and variations in environmental conditions [28] .

4.1.3 Nanosensor Arrays and Multiplexed Detection

One of the advantages of nanobiotechnology is the ability to develop multiplexed sensor arrays capable of simultaneously detecting and quantifying multiple analytes in plant samples. These sensor arrays integrate various nanomaterials and recognition elements on a single platform, enabling high-throughput and comprehensive analysis of plant physiological parameters, stress responses, and environmental conditions. For instance, QD-based nanosensor arrays have been developed for the simultaneous detection of plant hormones, such as auxins, cytokinins, and abscisic acid. Each QD in the array is functionalized with a specific recognition element (e.g., antibody or aptamer) for a particular plant hormone, enabling multiplexed detection through distinct fluorescence signatures. Similarly, electrochemical nanosensor arrays have been explored for the concurrent monitoring of multiple plant nutrients, heavy metals, and environmental pollutants [29]. These arrays integrate various nanomaterial-based electrodes and recognition elements on a single platform, allowing for the simultaneous detection and quantification of multiple analytes through electrochemical signals.

4.2 Nanomaterial-Based Imaging Techniques

Nanobiotechnology has revolutionized plant imaging by leveraging the unique properties of nanomaterials, such as their optical, magnetic, and electron-dense characteristics. These advanced imaging techniques provide unprecedented insights into plant structure, function, and dynamics at the cellular and subcellular levels, enabling more comprehensive understanding and analysis.

4.2.1 Fluorescent Nanoparticle-Based Imaging

Fluorescent nanoparticles, such as quantum dots (QDs) and fluorescent nanodiamonds, have been employed for high-resolution imaging and tracking of biological processes in plants. These nanoparticles exhibit superior photostability, narrow emission spectra, and resistance to photobleaching compared to traditional organic fluorophores. QDs have been utilized for in vivo imaging of plant cells and tissues, enabling the visualization of cellular structures, protein localization, and dynamic processes such as nutrient uptake and transport. Additionally, QDs have been employed for tracking the delivery and uptake of nanocarriers and biomolecules in plant cells, providing valuable insights into their biodistribution and intracellular fate. Fluorescent nanodiamonds, which contain nitrogen-vacancy (NV) centers, have emerged as promising probes for super-resolution imaging and sensing in plant systems. These nanoparticles exhibit exceptional photostability, low cytotoxicity, and the ability to detect magnetic and electric fields at the nanoscale, enabling unique applications in plant research.

4.2.2 Magnetic Nanoparticle-Based Imaging

Magnetic nanoparticles, such as iron oxide (Fe_3O_4) nanoparticles, have been employed in various plant imaging techniques, including Magnetic Resonance Imaging (MRI) and Magnetic Particle Imaging (MPI).MRI using superparamagnetic iron oxide nanoparticles (SPIONs) has been explored for non-invasive imaging and tracking of plant physiological processes, such as water transport, nutrient uptake, and plant-microbe interactions [30], [31]. SPIONs can be functionalized with targeting ligands or contrast agents, enabling specific labeling and visualization of plant tissues or cellular components. MPI is an emerging imaging modality that utilizes the non-linear magnetization response of superparamagnetic nanoparticles to generate high-contrast and quantitative images. This technique has been explored for imaging plant vascular systems, root architecture, and nutrient distribution, providing valuable insights into plant growth and development. The accuracy level of the model allows for the detection of both infected and non-infected leaf images, making it a valuable tool for early disease detection and treatment in agricultural plants potential to enhance agricultural productivity significantly [32].

4.2.3 Electron Microscopy Techniques

Nanobiotechnology has also contributed to the advancement of electron microscopy techniques for plant imaging and analysis. Electron-dense nanoparticles, such as gold (Au) and silver (Ag) nanoparticles, have been employed as contrast agents and labels in Transmission Electron Microscopy (TEM) and Scanning Electron Microscopy (SEM) studies of plant samples. Au and Ag nanoparticles can be functionalized with specific targeting ligands or biomolecules, enabling the labeling and visualization of plant cellular structures, organelles, and macromolecular complexes [33], [34]. These nanoparticle-based imaging techniques provide high-resolution and detailed insights into plant ultrastructure, facilitating the study of cellular processes, plant-pathogen interactions, and the localization of biomolecules. Table 3 summarizes some key examples of nanobiosensors and imaging techniques employed in plant sciences, highlighting their applications and the nanomaterials utilized.

Technique	Nanomaterial	Application
Colorimetric biosensor	Gold nanoparticles (AuNPs)	Detection of plant pathogens (viruses, bacteria)
Fluorescent biosensor	Quantum dots (QDs)	Detection of plant hormones, environmental pollutants, heavy metals
Electrochemical biosensor	Carbon nanotubes (CNTs), graphene	Detection of plant nutrients, monitoring stress responses
Nanosensor arrays	QDs, CNTs, graphene	Multiplexed detection of plant hormones, nutrients, heavy metals
Fluorescent imaging	QDs, fluorescent nanodiamonds	In vivo imaging, protein localization, tracking nanocarriers
Magnetic Resonance Imaging (MRI)	Superparamagnetic iron oxide nanoparticles (SPIONs)	Imaging water transport, nutrient uptake, plant-microbe interactions

Technique	Nanomaterial	Application
Magnetic Particle Imaging (MPI)	SPIONs	Imaging vascular systems, root architecture, nutrient distribution
Electron Microscopy (TEM, SEM)	Gold (Au), silver (Ag) nanoparticles	Labeling and imaging plant cellular structures, organelles, macromolecular complexes

5. Nanobiotechnological Approaches for Plant Genetic Engineering and Tissue Culture

Nanobiotechnology has emerged as a powerful tool for advancing plant genetic engineering and tissue culture techniques, enabling more efficient and precise manipulation of plant genetic material and facilitating the development of genetically modified crops with improved traits. Research systematically identifies the trajectory of sensor technology advancement by scrutinizing operational challenges encountered in real-world scenarios, aiming to accelerate the enhancement of high-quality standards within the realm of Bioelectronics [18].

5.1 Nanocarrier-Mediated Genetic Transformation

Conventional methods for plant genetic transformation, such as Agrobacterium-mediated transformation and biolistic (gene gun) techniques, have limitations in terms of efficiency, tissue specificity, and potential for genetic integration. Nanobiotechnology offers alternative strategies for genetic transformation using nanocarriers as vehicles for the delivery of genetic material (DNA or RNA) into plant cells and tissues. As discussed in Section 3.1, various nanocarriers, including cationic polymers, cationic lipids, inorganic nanoparticles, and carbon-based nanostructures, have been explored for the delivery of nucleic acids in plants. These nanocarriers can protect the genetic material from degradation, facilitate cellular uptake, and enhance bioavailability, potentially improving transformation efficiency and enabling tissue-specific or targeted delivery. For instance, chitosan-based nanoparticles have been employed for the delivery of DNA constructs into plant cells, enabling transient or stable genetic transformation. Similarly, mesoporous silica nanoparticles have been explored as carriers for the delivery of plasmid DNA or RNA interference molecules, enabling targeted gene silencing or overexpression in plant systems [35], [36]. Additionally, nanocarriers can be functionalized with targeting ligands or cell-penetrating peptides to enhance their specificity and cellular uptake, potentially enabling targeted genetic transformation of specific plant tissues or cell types.

5.2 Nanomaterial-Based Tissue Culture Techniques

Nanobiotechnology has also contributed to the advancement of plant tissue culture techniques, enabling more efficient and controlled regeneration, proliferation, and differentiation of plant cells and tissues. Nanomaterials, such as carbon nanotubes (CNTs), graphene, and metal nanoparticles, have been incorporated into plant tissue culture media or applied as coatings on culture vessels to modulate cellular behavior and improve tissue regeneration. These nanomaterials can influence various cellular processes, including cell division, differentiation, and metabolic activity, through their unique physicochemical properties and interactions with plant cells.

For example, CNTs have been shown to enhance the proliferation and regeneration of plant cells in tissue culture, potentially by modulating gene expression and signaling pathways related to cell growth and development. Similarly, metal nanoparticles, such as silver (Ag) and gold (Au) nanoparticles, have been reported to improve shoot and root regeneration from plant explants, potentially due to their ability to modulate plant growth regulator activity and oxidative stress responses. In addition to their direct effects on plant cells, nanomaterials can also be used as carriers or delivery vehicles for various bioactive compounds, such as plant growth regulators, antioxidants, and elicitors, in tissue culture systems. The controlled release of these compounds from nanocarriers can optimize their availability and bioactivity, potentially enhancing tissue regeneration, proliferation, and differentiation.

5.3 Genome Editing using Nanobiotechnology

The advent of genome editing technologies, such as CRISPR/Cas9, has revolutionized plant genetic engineering by enabling precise and targeted modifications of plant genomes. Nanobiotechnology offers innovative solutions for the efficient delivery and application of genome editing components in plant systems, potentially enhancing the effectiveness and specificity of these techniques [37]. Nanocarriers, such as cationic polymers, lipid-based nanoparticles, and inorganic nanoparticles, have been explored for the delivery of CRISPR/Cas9 components into plant cells and tissues. These nanocarriers can protect the genome editing components from degradation, facilitate cellular uptake, and enhance bioavailability, potentially improving the efficiency of genome editing in plants.

Additionally, nanobiotechnology can contribute to the development of novel delivery strategies for genome editing components, such as the use of biomolecule-functionalized nanoparticles or cell-penetrating peptide-based nanocarriers, enabling targeted delivery and tissue-specific genome editing. Furthermore, nanobiosensors and imaging techniques, as discussed in Section 4, can play a crucial role in monitoring and analyzing the outcomes of genome editing in plants, enabling the detection and quantification of specific genetic modifications, as well as the visualization of phenotypic changes at the cellular and tissue levels.

6. Safety Considerations and Regulatory Aspects of Nanobiotechnology in Plant Sciences

While nanobiotechnology holds great promise for transforming plant sciences and agriculture, it is crucial to address potential safety concerns and establish appropriate regulatory frameworks to ensure responsible development and application of these technologies.

6.1 Environmental and Human Health Concerns

The unique properties of nanomaterials, such as their small size, high surface area, and reactivity, raise concerns about their potential environmental and human health impacts. The unintended release of nanomaterials into the environment, either through agricultural applications or waste disposal, may pose risks to soil ecosystems, water systems, and non-target organisms [38]. Additionally, the potential for nanomaterial exposure and uptake by plants raises questions about their potential accumulation in food crops and subsequent entry into the food chain, with potential implications for human and animal health. Furthermore, the potential toxicity of nanomaterials to plants themselves, including their effects on plant growth, development, and physiological processes, must be thoroughly evaluated to ensure the safe and responsible application of nanobiotechnological solutions in agriculture [39].

6.2 Regulatory Frameworks and Risk Assessment

To address these safety concerns and ensure the responsible development and application of nanobiotechnology in plant sciences, comprehensive regulatory frameworks and risk assessment strategies are necessary [40]–[42]. At the international level, organizations such as the Organization for Economic Co-operation and Development (OECD) and the International Organization for Standardization (ISO) have developed guidelines and frameworks for the safe and responsible development, handling, and use of nanomaterials, including those applied in agricultural and food sectors.

National and regional regulatory bodies, such as the United States Environmental Protection Agency (US EPA), the European Chemicals Agency (ECHA), and the European Food Safety Authority (EFSA), have also established specific regulations and National and regional regulatory bodies, such as the United States Environmental Protection Agency (US EPA), the European Chemicals Agency (ECHA), and the European Food Safety Authority (EFSA), have also established specific regulations and

guidelines for the assessment and management of potential risks associated with nanomaterials in various sectors, including agriculture and food production.

Comprehensive risk assessment strategies are crucial for evaluating the potential environmental, health, and safety implications of nanobiotechnological applications in plant sciences. These strategies should encompass the following key elements:

1. *Characterization of nanomaterials:* Thorough characterization of the physicochemical properties, behavior, and fate of nanomaterials in relevant environmental matrices and biological systems is essential for assessing their potential impacts.
2. *Environmental fate and behavior studies:* Understanding the environmental fate, transport, and transformation of nanomaterials is crucial for evaluating their potential for accumulation, persistence, and bioaccumulation in the environment and food chains.
3. *Ecotoxicological assessments:* Evaluating the potential toxic effects of nanomaterials on non-target organisms, such as soil microorganisms, invertebrates, and other wildlife, is necessary to assess the environmental risks associated with their use in agriculture.
4. *Human and animal health risk assessments:* Assessing the potential for human and animal exposure to nanomaterials through various routes (e.g., ingestion, inhalation, dermal contact) and evaluating their potential toxicological effects is essential for ensuring food safety and human health protection.
5. *Life cycle analysis:* Conducting comprehensive life cycle assessments (LCAs) to evaluate the potential environmental impacts of nanobiotechnological applications in plant sciences, from raw material extraction to product disposal, is crucial for identifying and mitigating potential risks.
6. *Risk management and communication:* Developing effective risk management strategies and communication frameworks to inform stakeholders (e.g., policymakers, industry, consumers) about potential risks and benefits of nanobiotechnological applications in plant sciences is essential for promoting responsible development and public acceptance.

Additionally, international cooperation and harmonization of regulatory frameworks and risk assessment approaches are crucial to ensure consistent and effective governance of nanobiotechnology in plant sciences and agriculture globally.

6.3 Public Acceptance and Stakeholder Engagement

Public acceptance and stakeholder engagement are critical factors in the responsible development and implementation of nanobiotechnological applications in plant sciences (Fraceto et al., 2016; Rastogi et al., 2019). Effective communication and transparency regarding the potential benefits, risks, and uncertainties associated with these technologies are essential for building trust and fostering public acceptance. Stakeholder engagement and public participation should be integral components of the decision-making processes related to the development and application of nanobiotechnology in plant sciences [13]. This can be achieved through various mechanisms, such as public consultations, stakeholder dialogues, and the involvement of civil society organizations and consumer groups [43]. Moreover, educational initiatives and outreach programs aimed at increasing public understanding of nanobiotechnology and its implications for plant sciences and agriculture are crucial for promoting informed decision-making and addressing potential concerns or misconceptions. By fostering a culture of transparency, open dialogue, and public engagement, the responsible development and application of nanobiotechnology in plant sciences can be better aligned with societal values, ethical considerations, and public interests, ultimately contributing to the sustainable and equitable advancement of this promising field.

7. Future Directions and Emerging Trends in Nanobiotechnology for Plant Sciences

Nanobiotechnology is a rapidly evolving field, and ongoing research and development efforts continue to push the boundaries of its applications in plant sciences. This section explores some of the emerging trends and future directions in this multidisciplinary domain.

7.1 Advanced Nanomaterials and Nanostructures

The development of novel nanomaterials and nanostructures with tailored properties and functionalities is a key area of focus in nanobiotechnology for plant sciences. Researchers are exploring the synthesis and engineering of advanced nanomaterials with enhanced properties, such as increased biocompatibility, targeted delivery capabilities, and stimuli-responsive behavior. For instance, the development of smart nanocarriers that can release their cargo (e.g., biomolecules, agrochemicals) in response to specific environmental cues or plant physiological signals holds great potential for improving the efficiency and precision of delivery systems in plant sciences. Additionally, the integration of multiple functionalities within a single nanostructure, such as combining imaging, sensing, and delivery capabilities, can enable the development of multifunctional nanobiotechnological platforms for comprehensive plant monitoring and manipulation.

7.2 Bio-inspired and Biomimetic Nanomaterials

Nature has evolved a remarkable array of functional nanomaterials and nanostructures that exhibit remarkable properties and functionalities. The field of bio-inspired and biomimetic nanomaterials aims to emulate and harness these natural designs and mechanisms for applications in various domains, including plant sciences [44], [45]. For instance, researchers are exploring the development of nanomaterials inspired by the intricate structures and functions of plant cell walls, biominerals, and photosynthetic systems. These bio-inspired nanomaterials can potentially be employed for applications such as nutrient delivery, bioimaging, and photosynthesis enhancement in plants. Another promising area is the development of biomimetic nanostructures that mimic the hierarchical organization and self-assembly processes observed in biological systems. These nanostructures can potentially be engineered to perform specific functions, such as targeted delivery, sensing, or catalytic activities, in plant systems.

7.3 Integration with Emerging Technologies

The integration of nanobiotechnology with other emerging technologies, such as artificial intelligence (AI), machine learning (ML), and Internet of Things (IoT), holds significant potential for advancing plant sciences and precision agriculture. AI models possess the ability to discern patterns, trends, or irregularities within datasets collected by various sensors monitoring factors like temperature, humidity, air quality, or radiation levels with valuable insights into environmental conditions [46]. For example, the combination of nanobiosensors and IoT technologies can enable the development of smart agricultural systems for real-time monitoring of plant health, nutrient levels, and environmental conditions [47]. The data generated by these interconnected sensor networks can be analyzed using AI and ML algorithms to provide actionable insights and optimize agricultural practices. Additionally, the integration of nanobiotechnology with robotics and automation can facilitate the development of precision farming techniques, such as targeted application of nanomaterial-based agrochemicals or the deployment of nanoparticle-based sensors for site-specific monitoring and intervention. In various fields such as science, engineering, business, and medicine, advancements in prediction capabilities have significantly enhanced our daily lives by simplifying tasks and regions leveraging artificial intelligence have seen notable enhancements in quality and efficiency [48].

7.4 Sustainability and Environmental Considerations

As nanobiotechnology continues to advance in plant sciences, it is crucial to prioritize sustainability and environmental considerations in the development and application of these technologies. This includes addressing the potential environmental impacts of nanomaterials throughout their life cycle, from synthesis and production to use and disposal. Researchers are exploring the development of biodegradable and environmentally friendly nanomaterials derived from natural sources, such as plant-based polymers, biopolymers, and bio-inspired nanostructures. These sustainable nanomaterials can potentially reduce the environmental footprint of nanobiotechnological applications in plant sciences while maintaining their desired functionalities. Moreover, the integration of nanobiotechnology with principles of circular economy and industrial ecology can contribute to the development of closed-loop systems, where waste materials from one process are utilized as input resources for another. This approach can minimize waste generation and promote resource efficiency in the production and application of nanobiotechnological solutions in plant sciences.

7.5 Interdisciplinary Collaboration and Knowledge Transfer

The multidisciplinary nature of nanobiotechnology necessitates close collaboration and knowledge transfer among researchers from diverse fields, including nanotechnology, biotechnology, plant sciences, materials science, and environmental science. Fostering interdisciplinary collaborations and promoting the exchange of knowledge and expertise can accelerate the development and implementation of innovative nanobiotechnological solutions in plant sciences [49], [50]. Furthermore, effective knowledge transfer between academic research institutions, industry partners, and stakeholders in the agricultural sector is crucial for translating scientific discoveries into practical applications. This can be facilitated through collaborative research projects, public-private partnerships, technology transfer initiatives, and industry-academia collaborations [2]. Effective communication and dissemination of research findings, best practices, and technological advancements in nanobiotechnology for plant sciences are also essential for enabling knowledge sharing and fostering further innovation. This can be achieved through various channels, such as scientific publications, conferences, workshops, and online platforms for knowledge exchange. By fostering interdisciplinary collaboration and effective knowledge transfer, the nanobiotechnology community can collectively address the challenges and opportunities in plant sciences, accelerating the development of innovative solutions for sustainable agriculture, food security, and environmental preservation.

Conclusion

The convergence of nanotechnology and biotechnology, termed nanobiotechnology, has unlocked unprecedented opportunities for transforming plant sciences and addressing critical challenges in agriculture, food security, and environmental sustainability. This research article has provided a comprehensive overview of the applications and implications of nanobiotechnological innovations in plant sciences, highlighting the following key areas:

1. Nanomaterials for plant growth enhancement and stress tolerance, including metal and metal oxide nanoparticles, carbon-based nanostructures, and their synergistic effects with biostimulants.

2. Nanocarriers for targeted delivery of biomolecules, such as nucleic acids, proteins, and small molecules, in plant systems, enabling applications in genetic engineering, gene therapy, and controlled release of bioactive compounds.

3. Nanobiosensors and advanced imaging techniques leveraging the unique properties of nanomaterials for plant monitoring, analysis, and visualization of physiological processes.

4. Nanobiotechnological approaches for plant genetic engineering, tissue culture, and genome editing, enabling more efficient and precise manipulation of plant genetic material.

5. Safety considerations, regulatory frameworks, and risk assessment strategies for ensuring the responsible development and application of nanobiotechnology in plant sciences.
6. Emerging trends and future directions, including advanced nanomaterials, bio-inspired and biomimetic nanostructures, integration with emerging technologies, sustainability considerations, and interdisciplinary collaboration.

Nanobiotechnology holds immense potential to revolutionize plant sciences and contribute to the development of sustainable agricultural practices, improved crop productivity, and enhanced food security. However, its successful implementation requires a holistic approach that addresses safety concerns, fosters public acceptance, and promotes interdisciplinary collaboration and knowledge transfer. As the global population continues to grow and the challenges of climate change intensify, the need for innovative solutions in agriculture becomes increasingly urgent [51], [52]. Nanobiotechnology, with its synergistic merger of nanotechnology and biotechnology, offers a promising pathway to address these challenges and unlock new frontiers in plant sciences, paving the way for a more sustainable and resilient future.

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