Editorial

The Transformative Role of Phytonanotechnology in Medicinal and Pharmaceutical Research

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ABSTRACT

Phytonanotechnology, the marriage of plant biology and nanotechnology, is a rapidly expanding research domain with exceptional potential to revolutionize numerous industries and address critical global challenges. Harnessing the applications of phytonanoparticles has broad-ranging impacts and solutions to some of the most pressing issues the human race is facing today. Phytonanoparticles or plant-based nanoparticles are employed in diverse fields, from healthcare to agriculture and environmental remediation. The development of phytonanoparticles highlights the potential of bio-inspired solutions for sustainable development. For example, phytonanoparticles can be engineered to encapsulate therapeutic agents, rendering them more stable and bioavailable. From cancer therapy to wound healing, they are set to usher in personalized medicine and improve patient outcomes. Nanoparticles derived from plant sources possess low cytotoxicity, biocompatibility, and biodegradability, rendering them suitable for medical and pharmaceutical applications. They hold promises to develop innovative therapies and clinical treatments that address some of the most dreaded disorders. In this editorial, we shed light on the game-changing potential of phytonanotechnology and its implications for sustainable development.

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Introduction

The concept of nanotechnology was introduced in 1959 when physicist Richard Feynman gave a talk entitled "there's plenty of room at the bottom," where he foresaw the manipulation of single atoms and molecules [1, 2]. Significant breakthroughs occurred in the 1980s and 1990s by developing scanning tunneling microscopy and atomic force microscopy, enabling scientists to see and handle materials on the nanometer scale. Nanotechnology has been used to develop new materials with unusual properties at nanolevels, such as quantum dots, carbon nanotubes and nanoparticles [3]. Nanotechnology fosters innovation in electronics (e.g. nanoscale transistors) and renewable energy applications (e.g. nanostructured solar cells and energy storage devices). Healthcare will be transformed entirely with advances such as targeted drug delivery systems and personalized medicines using molecular imaging at the nanometre resolution. Targeted drug delivery systems, diagnostic tools, and tissue engineering approaches are examples of how nanotechnology is changing medicine [4]. Technology continues to shrink electronic devices while developing new computing paradigms such as quantum computing. Water purification, pollution control, and sustainable energy solutions are some environmental challenges that can be addressed if we use nanotechnologies properly [5, 6]. Most studies investigated sustainable and environmentally friendly nanoparticle synthesis methods using plants rich in phytochemicals and characterizing their physicochemical properties, including the so-called "phytonanochemistry." In recent years, green synthesis of plant-based nanoparticles has been investigated for drug delivery, imaging, and disease diagnosis [7, 8]. In addition, phytonanochemistry has also contributed to sustainable agriculture by developing nanopesticides, nutrient delivery systems, and soil remediation strategies [9-11].

Further research will yield advanced nanomaterials with finely tuned properties for specific applications. Collaborations between botanists, chemists, material scientists, and biomedical researchers are required to generate discoveries and applications. The next phase of this research will explore the biocompatibility and safety of plant-derived nanoparticles for various applications. In the constantly changing field of medicine and pharmaceutical research, phytonanotechnology will be a game-changer due to its potential to provide novel, unprecedented solutions in healthcare. Our viewpoint will discuss the transformative potential for healthcare represented by phytonanotechnology, from drug delivery and diagnostics to regenerative medicine and many other aspects.

Applications of phytonanotechnology

Phytonanotechnology involves the application of nanotechnology to modify the properties and functions of plant-based materials. Using nanomaterials and nanotechniques, plant structures can be manipulated at the nanoscale to enhance performance, stability, and efficiency. Examples of common applications of phytonanotechnology are listed below.

Nanoparticles and nanocomposites generated via plant extracts

The most popular application of phytonanotechnology is the generation of nanoparticles and nanocomposites using plant-derived materials, such as plant extracts, essential oils, and phytochemicals. Using plants provides several benefits, such as cost-effectiveness and environmental friendliness. Various plants are rich in bioactive compounds that are required for the green synthesis of various nanoparticles such as silver nanoparticles (AgNPs) [12, 13], gold nanoparticles (AuNPs) [14, 15], selenium nanoparticles (SeNPs) [16, 17], zinc oxide (ZnO) nanoparticles [18, 19], copper oxide (CuO) nanoparticles [20, 21], quantum dots [22, 23] and different nanocomposites such as, magnetic $Fe_3O_4/SiO_2/ZnO-Pr_6O_{11}$ [24], $MnFe_2O_4@SiO_2@Au$ [25] and $Fe_3O_4/SiO_2/Cu_2O-Ag$ [26]. The bioactive compounds act as reducing and stabilizing agents in the synthesis process, yielding nanoparticles with unique properties suitable for different applications. Nanoparticles derived from plant extracts exhibit lower cytotoxicity, biocompatibility, and biodegradability, making them preferable for medical and pharmaceutical applications [27, 28]. In addition, green nanocomposites often exhibit enhanced biological activity due to incorporating nanoparticles and bioactive compounds from plant extracts. Due to their unique properties, these nanocomposites find applications in various fields, especially in biomedicine (antimicrobial, anticancer, anti-inflammatory, antioxidant, antiviral and so on).

Nanocarriers developed from plant materials for drug delivery

Nanotechnology techniques have been used to fabricate nanocarriers from plant-derived materials to deliver a drug specifically to the organ or tissue. Plant-based nanoparticles or nanovesicles are used to load drugs or therapeutic compounds and are shown to enhance their solubility, stability and bioavailability [23, 29, 30]. The use of plant-based nanoparticles has gained extensive consideration in drug delivery systems. Phytonanoparticles are used to transport drugs directly to tissues, cells, or organs, thereby reducing systemic side effects and increasing therapeutic efficacy [31]. From the chemotherapy of cancer cells to the treatment of various infectious diseases, phytonanotechnology helps enhance the effectiveness of pharmaceutical interventions.

Bioimaging and biosensing

Besides drug delivery, phytonanotechnology has been employed to create bioimaging and sensing platforms based on plant-derived nanomaterials [32]. Nanoparticles produced from plant-derived resources, such as gold nanoparticles and quantum dots, display exclusive optical behaviors that render them ideal candidates for imaging and sensing applications. These nanoparticles can be connected with targeted molecules or fluorescent tags for bioimaging. Alternatively, nanoparticles may be incorporated into biodetectors to identify biomolecules or microbes [33]. Considering their sensitivity and specificity profiles, phytonanoparticles are poised to reorganize medical diagnostics and enhance disease detection.

Environmental remediation

Plants have long been known for their ability to uptake and detoxify pollutants in soil, water and air; phytonanotechnology takes advantage of this natural ability to further engineer plant-based nanomaterials with enhanced adsorptive, catalytic, and degradative properties. These "green" nanoparticles offer effective and environmentally friendly approaches for environmental cleanups and pollution remediation [34, 35]. Organic dyes are used in various industries, such as pharmaceuticals and rubber. One of the most economical ways to degrade various dyes is using green nanoparticles' photocatalytic decomposition under UV light radiation [36].

Nanobiotechnology in agriculture

The application of nanotechnology in agriculture exploits plant-based nanomaterials for crop protection, nutrient delivery, or soil remediation. Nanomaterials obtained from plant extracts can be used to deliver agrochemicals in a controlled manner (known as smart farming), which means targeted delivery of nutrients and pesticides to improve plant growth, reduce environmental impact, and enhance agricultural productivity [37, 38].

Phytotherapy and nanomedicine

Integrating nanotechnology with phytotherapy involves enhancing the therapeutic effects of plant-based medicines. Nanoformulating natural plant compounds includes incorporating them into nanocarriers like nanoparticles, liposomes, or nanoemulsions to increase their stability, solubility and bioavailability. Nanoformulations of natural plant chemicals can improve their absorption, distribution, and targeting within the body to treat various diseases, including cancer, infections, and inflammatory disorders. This method can overcome limitations like poor water solubility and rapid degradation, thereby improving the efficacy and delivery of plant-based treatments. Nanoformulated plant compounds have the potential for different applications, including drug delivery, cosmetics and agricultural products. They provide targeted delivery and controlled release with improved therapeutic outcomes, making them a promising research area for pioneering efficient treatments [39-41].

Plant nanobionics

Plant nanobionics embeds nanomaterials into plants to amplify their intrinsic physiological functions or introduce novel ones [42]. Nanosensors built in plants can monitor environmental factors or detect contaminants, providing vital real-time information for precision agriculture or environmental monitoring [43, 44].

Regenerative medicine and tissue engineering

Phytonanotechnology could promote regenerative medicine and tissue engineering, opening new opportunities to repair and regenerate tissues. Phytonanoparticles incorporated into tissue engineering constructs can increase cell adhesion, proliferation and differentiation, resulting in better tissue integration and function [45]. Nanocellulose from plant cell walls presents a promising scaffold material readily grown in vitro to yield tissues and organs [46, 47]. Whether it is a skin graft or organ transplant, phytonanotechnology facilitates regeneration.

Challenges and future directions

It can be concluded that phytonanotechnology is a promising and emerging interdisciplinary field that uses the unique characteristics of plants and nanomaterials to meet the various challenges in medicine, agriculture, and environmental science. This new field might offer relatively safe, sustainable and innovative approaches to meet the demands of its own and related disciplines by using the natural diversity and properties of plant-derived materials at the nanoscale. However, it faces numerous challenges regarding safety, regulatory approval, and implementation.

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Conclusion

When facing intricate issues like food security, environmental decline, and public health, the merging of plant biology and nanotechnology presents a promising solution. In general, phytonanotechnology is a paradigm shift in sustainable development that combines the powers of nature and nanoscience to develop revolutionary solutions that will benefit society and the Earth. More specifically, it signifies a shift in medical and pharmaceutical research that provides innovative solutions to some of the most demanding problems in the healthcare sector. From improving drug delivery systems to enabling advanced diagnostics and regenerative therapies, phytonanotechnology holds promise for revolutionizing patient care and shaping the future of medicine.

The future of nanotechnology and phytonanochemistry holds immense promises, driven by interdisciplinary collaborations, technological advancements, and a focus on addressing societal challenges while ensuring ethical and sustainable practices. As these fields continue to evolve, they will undoubtedly shape the future of science, technology and innovation.

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