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Eco-Friendly Nanoparticle Synthesis: A Green Chemistry Approach

Aditi Gharat[1], Komal Patil[2], Aditya Salunkhe[3], Gurumeet C. Wadhwa[4], Smita M. Tandale[5], Asmita A. Tupe[6]

Student P. G. Department of Chemistry, Veer Wajekar ASC Collage Phunde, Uran, Raigad[1-4]
Assistant Professor Department of Chemistry, Veer Wajekar ASC Collage Phunde, Uran, Raigad[5]
Ph.D Research Scholar, Department of Home Science, NIILM University, Kaithal, Haryana[6]

Abstract: *Nanotechnology and biomedical sciences offer a vast potential for research and medical applications at the molecular and cellular levels. In recent years, biosynthesis of nanoparticles has gained significant attention as an eco-friendly and cost-effective alternative to conventional chemical and physical methods. The use of plant-mediated synthesis in nanoparticle production represents a sustainable approach, bridging the gap between nanotechnology and green chemistry. This method enables the synthesis of nanoparticles under ambient conditions, at neutral pH, and with minimal environmental impact.*

Plants, often referred to as nature's "chemical factories," provide an efficient and sustainable platform for nanoparticle synthesis. They require minimal maintenance and offer a wide range of bioactive compounds that facilitate nanoparticle formation. This study explores the evolution of nanotechnology, the properties of nanoparticles, diverse synthesis strategies, and the comparative advantages and limitations of different approaches. Additionally, it highlights the broad spectrum of applications that green-synthesized nanoparticles can offer in various fields..

Keywords: Green Synthesis, Nanoparticles, Sustainable Approach, Eco-friendly, Plant-Mediated Synthesis

I. INTRODUCTION

Nanoparticles (NPs), with at least one dimension ranging between 1 and 100 nm, serve as an intermediate between bulk materials and atomic or molecular structures. Their extremely small size, high surface area, and free reactive bonds contribute to their unique properties and enhanced reactivity. Although scientists have recognized the potential of biological systems in reducing metal precursors since the 19th century, the underlying mechanisms remain largely unexplored.

The growing interest in green synthesis has been driven by the need for eco-friendly, cost-effective methods that eliminate the use of hazardous chemicals and excessive energy consumption. Unlike conventional physicochemical approaches, biological synthesis utilizes natural reducing, stabilizing, and capping agents, making it a sustainable alternative. The rapid pace of industrialization, urbanization, and population growth has led to environmental degradation, with increasing amounts of toxic substances being released into the atmosphere. This pressing issue underscores the importance of exploring nature's vast resources, which can inspire advancements in nanoparticle synthesis.

Given that nanoparticles are extensively used in applications involving direct human contact, there is an urgent need to develop synthesis methods that avoid toxic reagents. While conventional physical and chemical methods can produce nanoparticles, they often require significant financial investment and present challenges such as the use of harmful solvents, the generation of hazardous byproducts, and inconsistencies in surface structure. Chemical synthesis, in particular, may involve multiple reactive species, leading to unpredictable particle behavior and potential risks to both human health and the environment. In contrast, green synthesis offers a safer, more sustainable alternative, aligning with the principles of environmentally responsible nanotechnology.

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II. REVIEW OF LITERATURE

Recent research has demonstrated that plant extracts serve as effective precursors for synthesizing nanomaterials in an environmentally friendly manner. Various plant-based approaches have been successfully employed to produce nanoparticles of metals such as cobalt, copper, silver, gold, palladium, platinum, zinc oxide, and magnetite. Over the past decade, it has been observed that numerous biological systems—including plants, algae, diatoms, bacteria, yeast, fungi, and even human cells—are capable of converting inorganic metal ions into metal nanoparticles. This transformation occurs due to the reductive properties of proteins and metabolites present within these organisms.

The biological synthesis of metallic nanoparticles is of significant interest due to their distinctive optical and chemical characteristics. Several plant species have been effectively utilized for the rapid extracellular synthesis of gold and silver nanoparticles. For instance, extracts from Geranium (Pelargonium graveolens), lemongrass (Cymbopogon flexuosus), camphor (Cinnamomum camphora), neem (Azadirachta indica), Aloe vera, tamarind (Tamarindus indica), and Indian gooseberry (Emblica officinalis) have been shown to reduce Au(III) ions into gold nanoparticles (Au^0) and silver nitrate into silver nanoparticles (Ag^0).

Additionally, plant-derived biomasses such as wheat (Triticum aestivum), oat (Avena sativa), and alfalfa (Medicago sativa), along with modified hop biomass and water remnants from soaked Bengal gram beans (Cicer arietinum), have been successfully utilized for gold nanoparticle synthesis. Interestingly, gold nanoparticles have also been synthesized within living plant tissues of Medicago sativa, Chilopsis linearis, and Sesbania seedlings. Furthermore, alfalfa sprouts and germinating seeds of Brassica juncea have been used for the biological synthesis of silver nanoparticles. These eco-friendly methods align with the principles of green chemistry, demonstrating the potential of biological entities—including bacteria, fungi, and plants—as sustainable alternatives for nanoparticle production.HISTORY:

The emergence of materials at the nanoscale has sparked great interest among researchers, with the potential to revolutionize material science in the 21st century and beyond. The term "Nano" originates from the Greek word for "dwarf" and signifies "a billionth." A nanometer (nm) is one-billionth of a meter, approximately 250 millionths of an inch, or about 1/80,000th the diameter of a human hair. It is also roughly ten times the size of a hydrogen atom. The concept of "Nanotechnology" was first introduced by Prof. Norio Taniguchi from Tokyo Science University in 1974 to describe the precise fabrication of materials at the nanometer scale. Later, Eric Drexler popularized the term in his 1986 book Engines of Creation: The Coming Era of Nanotechnology.

Although nanoparticles are often regarded as a modern scientific advancement, their use dates back centuries. Artisans in Mesopotamia as early as the ninth century utilized nanoparticles to create a shimmering effect on pottery. Even today, medieval and Renaissance ceramics often display a metallic gold or copper-like shine. This luster effect results from a thin metallic film applied over a transparent glaze. The brilliance remains visible if the layer has withstood oxidation and environmental wear over time.

The luster effect was achieved by dispersing silver and copper nanoparticles within the glassy structure of ceramic glazes. Ancient artisans created these nanoparticles by applying a mixture of silver and copper salts, oxides, vinegar, ochre, and clay onto pre-glazed pottery. The objects were then placed in a kiln and heated to approximately 600°C in a reducing atmosphere. At high temperatures, the softened glaze allowed metal ions to migrate toward the outer surface, where they were reduced to their metallic state and assembled into nanoparticles. These nanoparticles produced the unique color and optical effects seen in lusterware.

NANO-SCIENCE:

It has been well established that plants have the ability to reduce metal ions both on their surfaces and within various tissues and organs, even those distant from the site of ion penetration. Nanotechnology, an interdisciplinary field integrating biology, physics, chemistry, and materials science, plays a crucial role in developing innovative nanoscale materials for biomedical and pharmaceutical applications. Nanoparticles possess multifunctional properties and hold significant potential in diverse sectors, including medicine, nutrition, and energy.

One of the key challenges in biomaterial science is the biogenic synthesis of monodispersed nanoparticles with controlled sizes and shapes. However, advancements in this field have significantly contributed to the pharmaceutical industry, aiding in the treatment of bacterial and viral infections. Nanomedicine has revolutionized healthcare by

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providing novel solutions for managing chronic diseases. As a result, the eco-friendly synthesis of nanoparticles is being recognized as a fundamental approach for future generations to combat various health conditions.

Beyond medicine, nanoparticles have extensive applications in agriculture and plant sciences. For example, bio-processing technologies utilizing nanoparticles can convert agricultural and food waste into energy and valuable by-products. This review focuses on the biosynthesis of metallic nanoparticles derived from plants and their applications across medical and commercial industries, including wastewater treatment, cosmetics, and the food sector. Additionally, it examines the benefits and limitations of nanoparticle use across various fields.

Despite their numerous advantages, a significant challenge in translating nanoparticle-based diagnostic and therapeutic approaches into mainstream medicine is the concern over their potential toxicity. Some nanoparticles, particularly unmodified copper or silver nanoparticles, may accumulate in bodily tissues and pose health risks. However, surface modification of nanoparticles can alter their chemical and biological properties, reducing toxicity while enhancing their effectiveness for specific applications.

GREEN SYNTHESIS:

Nature has developed various mechanisms for producing nano- and microscale inorganic materials, leading to the emergence of a relatively new and largely untapped research area focused on the biosynthesis of nanomaterials. Utilizing biological organisms for synthesis aligns with the principles of green chemistry, ensuring an environmentally friendly, non-toxic, and safe approach. The "green synthesis" of nanoparticles employs sustainable methods that eliminate the need for hazardous chemicals.

Nanoparticles produced through biological techniques or green technology exhibit diverse characteristics, enhanced stability, and optimal size control due to their one-step synthesis process. A wide range of methods can be used to generate nanoparticles, including chemical, physical, biological, and hybrid techniques. Some advanced fabrication methods include laser desorption, lithography, sputter deposition, molecular beam epitaxy, and layer-by-layer growth. Additionally, chemical techniques such as electro-deposition, sol–gel processing, chemical solution deposition, chemical vapor deposition, the Langmuir-Blodgett method, catalytic synthesis, hydrolysis, co-precipitation, and wet chemical approaches are frequently employed.

However, conventional chemical and physical synthesis methods often rely on high-energy radiation, concentrated reducing agents, and stabilizers that pose risks to both human health and the environment. In contrast, biological synthesis offers a sustainable alternative, utilizing a single-step bio-reduction process that requires minimal energy while producing eco-friendly nanoparticles.

Green nano-biotechnology involves the synthesis of nanoparticles and nanomaterials through biological processes using microorganisms, plants, viruses, or their byproducts, such as proteins and lipids, with the aid of biotechnological tools. Nanoparticles produced through green technology offer several advantages over those synthesized using conventional physical and chemical methods. These eco-friendly approaches eliminate the need for costly chemicals, require less energy, and generate non-toxic products and byproducts.

The 12 principles of green chemistry serve as a global framework for researchers, scientists, and chemical technologists to develop safer chemical processes and materials. In this context, green nanobiotechnology provides a sustainable alternative for producing biocompatible and stable nanoparticles. A common method for plant-based synthesis of metallic nanoparticles involves using dried plant biomass as a natural reducing agent and metallic salts as precursors.

Silver, known for its medicinal and preservative properties for over 2,000 years, is often used in nanoparticle synthesis. Biological synthesis follows a bottom-up approach, where nanoparticles are formed with the help of natural reducing and stabilizing agents. This process typically includes three essential steps: selecting a suitable solvent medium, choosing an environmentally safe reducing agent, and using a non-toxic capping agent to stabilize the nanoparticles.

Physical properties of nanoparticles:

Nanoparticles exhibit unique properties due to their large surface area, which significantly influences their behavior compared to bulk materials. They come in various colors, such as yellow, gold, and gray, with gold nanoparticles displaying significantly lower melting points (~300°C for 2.5 nm particles) compared to bulk gold (1064°C). Silver nanoparticles, in particular, possess remarkable physicochemical characteristics, including high electrical and thermal conductivity, surface-enhanced Raman scattering, catalytic activity, chemical stability, and nonlinear optical properties.

In photovoltaic applications, nanoparticles absorb solar radiation more efficiently than bulk materials or thin films, enhancing energy conversion. Their small size provides significant advantages in drug delivery systems. First, they can penetrate tiny capillaries and be absorbed by cells, ensuring efficient drug accumulation at the target site. Second, the use of biodegradable materials in nanoparticle formulations allows for controlled and sustained drug release over days or even weeks.

Beyond medicine, nanotechnology has the potential to revolutionize various industries. In electronics, it contributes to advancements in nano-diodes, nano-transistors, OLEDs, plasma displays, and quantum computing. The energy sector also benefits, as nanotechnology enhances batteries, fuel cells, and solar cells, making them more compact and efficient. Additionally, manufacturing industries utilize nanomaterials such as aerogels, nanotubes, and nanoparticles to develop stronger, lighter, and more durable products.

Nanoparticles offer several advantages in drug delivery, including precise size control and effective encapsulation for drug protection. They improve therapeutic efficiency and bioavailability while reducing variability due to food intake and enhancing drug stability. Moreover, nanoparticle-based drug formulations offer prolonged retention at target sites and avoid toxicity issues associated with traditional carriers. Large-scale production and sterilization of nanoparticles pose no significant challenges, apart from the need to minimize organic solvent use.

Despite these benefits, nanotechnology also has drawbacks. One major concern is the potential loss of jobs in traditional manufacturing and agriculture due to automation and material advancements. Additionally, it raises security risks, as the technology could lead to the development of more accessible and powerful atomic weapons. Health risks are another issue, as inhaling nanoparticles can cause respiratory problems and other serious conditions, given their ability to penetrate lung tissues. Furthermore, the high cost of nanotechnology research and development makes it an expensive field, and manufacturing nanomaterials remains complex, contributing to the higher cost of nanotechnology-based products.

III. CONCLUSION

While nanotechnology has significantly improved the standard of living, it has also contributed to environmental pollution, including contamination of air and water. This specific type of pollution, referred to as nano pollution, poses serious risks to living organisms. Despite the rapid advancements in nanotechnology, the potential negative impacts of nanoparticles remain underexplored, particularly concerning their role in drug delivery systems.

One concern in nanoparticle-based drug delivery is the widespread use of polyvinyl alcohol as a stabilizing agent, which may raise toxicity issues. Additionally, nanoparticles have limited targeting capabilities, making continuous therapy challenging. Their application in drug delivery has been associated with cytotoxic effects, inflammation in lung tissues, and disruption of autonomic balance, which can directly affect cardiovascular function. Furthermore, nanoparticles may exhibit unpredictable behaviors, such as uncontrolled particle growth, unexpected gelation, instability in polymeric transitions, and sudden burst release of drugs, posing challenges in medical applications.

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