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Plant Mediated Green Synthesis of Metal Nanoparticles for Sustainable Applications

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ABSTRACT

The use of biological resources including plants, bacteria, fungus, yeast, and algae in green synthesis has become a popular and eco-friendly method for producing metal and metal oxide nanoparticles. Because plant extracts contain a wide variety of phytochemicals—such as alkaloids, terpenoids, flavonoids, polysaccharides, proteins, and amino acids—plant-mediated synthesis has become one of the most popular methods. This study delves into the fundamentals and relevance of green nanoparticle synthesis, focusing on biological synthesis from plants and the part played by phytochemicals in the process. The size, shape, stability, dispersion, and yield of the nanoparticles are affected by critical synthesis parameters such as temperature, pH, reaction duration, and extract concentration. Nanoparticle manufacturing is explored via the use of various biological resources, such as plants, algae, fungus, yeast, and bacteria. Among the many benefits of plant-mediated synthesis are its ease of use, cheap cost, decreased chemical needs, friendliness with the environment, and possibility of sustainable production.

Keywords: *Green Synthesis, Metal, Biological Synthesis, Sustainable Nanotechnology, Nanoparticle.*

I. INTRODUCTION

When compared to other techniques of synthesis, the green production of metallic nanoparticles utilising biological pathways—especially through live cells—yields a larger quantity. For the production of environmentally friendly nanoparticles, plants are an excellent resource due to the abundance of biochemicals and components that may act as both reductants and stabilisers. Compared to other physical, chemical, and biological approaches, this one is more popular because to its less impact on the environment, lack of toxicity, low cost, and increased stability. There are three primary approaches to the green production of nanoparticles: phytochemical, intracellular, and extracellular. One major benefit of using plant extracts in nanoparticle synthesis is the high concentration of phytochemicals. These phytochemicals operate as excellent reducing and stabilising agents, allowing metal ions to be converted into G-MNPs, or green-synthesized metal nanoparticles. When compared to other ways, this one yields a larger yield for less money. Diagnostics, wound healing, immunotherapy, regenerative medicine, dentistry, biosensing platforms, and metal oxide and metal nanoparticles produced in a greener way are just a few of the many biomedical areas where these nanoparticles are making waves. Much research has focused on their biotoxicological, antibacterial, antifungal, and antiviral characteristics. Environmental remediation, photocatalysis, catalytic reduction, sensing, energy storage, and various organic transformations like coupling, reduction, and multicomponent reactions are just a few of the many biological activities shown by copper oxide nanoparticles synthesised plant-mediated from different plant extracts.

In addition to being a non-toxic, cost-effective, and environmentally acceptable option, green nanoparticle manufacturing improves nanoparticles' active performance in removing antibiotics, metal ions, and dyes, surpassing existing physical and chemical approaches. As stated in the study of Osman et al. (2024).

Because it maximises stability, decreases toxicity, and is environmentally friendly, this process is considered the best way to prepare nanoparticles. Because of their abundance of phytochemicals—such as phenolics, terpenoids, polysaccharides, and flavonoids—which have oxidation-reduction capabilities, plants are ideal for green synthesis. Nanoparticle stability during production is greatly aided by these phytochemical substances. Since plant secondary metabolites, especially polyphenols, play a large role in green synthesis, it is crucial to know the precise phytochemical composition in order to produce stabilised nanoparticles.

Compared to other biological approaches that include bacteria, fungus, actinomycetes, or algae, the green synthesis of nanoparticles is superior in terms of advancement, safety, cost-effectiveness, reproducibility, and stability. Because of their high phytochemical content, green nanoparticles are synthesised using a variety of plant parts, such as roots, stems, leaves, seeds, and fruits. To extract nanoparticles from plants, one must first wash the plant material, then remove phytochemicals, filter, and add certain metal salts. Many different types of metallic nanoparticles may be synthesised using this process. The personal care, medical, culinary, aquaculture, agricultural, and nanoenabled device industries are some of the many that make use of green nanoparticles. They are well-suited for the mass manufacturing of G-MNPs, or metal nanoparticles synthesised in an environmentally responsible way, because of their low environmental impact. In order to promote environmentally friendly and sustainable development and minimise hazardous by-products, the biosynthesis strategy is essential. This technique involves a variety of biological entities, including plant extracts, bacteria, yeast, seaweeds, and algae.

II. FACTORS INFLUENCING THE GREEN SYNTHESIS OF VARIOUS NANOPARTICLES

Various parameters, including pH, temperature, reaction time, and reactant concentration, may be adjusted to characterise the shape of nanoparticles during their green production. The significance of environmental influences on nanoparticle synthesis has been highlighted by these parameters, and these aspects may be crucial in optimising metallic nanoparticle production.

Temperature

A variety of research studies are being prepared on a global scale to gain a better understanding of how to manage the temperature of nanoparticles. When it comes to changing the size, shape, and production level of nanoparticles, temperature is the single most critical factor. Depending on the temperature, nanoparticles can take on a variety of forms, including triangles, octahedral platelets, spherical, and rod. Their size can also be customised. The creation of nucleation centers is bolstered by a rise in both the temperature level and the reaction response rate. Reaction time is the single most essential parameter in green nanoparticle synthesis for controlling the final product's size, shape, and yield.

pH

In terms of nanoparticle structure, the response pH is crucial. Nucleation centers are regulated by a number of environmental factors, including pH and temperature. The most critical factor in enhancing the production of metal nanoparticles is a rise in the pH level, as this results in an automatically increased number of nucleation sites. It is well-known that pH plays a crucial role in determining the nanoparticles' size and structural shape. One of the most important steps in making nanoparticles is the medium pH reaction.

Reaction Time

When it comes to controlling the structural morphology of nanoparticles, the reaction time is the most critical factor, along with temperature and pH.

III. ROLE OF BIOMATERIAL IN SYNTHESIS OF NANOPARTICLES

It is commonly known as "green chemistry," which means making nanoparticles using creatures that already exist in the environment, such as plants, actinomycetes, bacteria, and fungus. Biosynthesis using the aforementioned species to produce nanoparticles with desirable characteristics is one green alternative. The ability for single-celled and multicellular organisms to communicate has been achieved through this synthesis. A large portion of society holds the view that plants provide nature with the most cost-effective and environmentally friendly biochemicals.

Maytenus founier, Acanthopanax sciadophylloides, Arabidopsis helleri, Sesbania drummondii, Clethra barbinervis, Thlaspicaerulescens, and Brassica juncea are some of the plants that are included in this group. Currently, these plants are being used to extract heavy metals from water solutions because to their remarkable capacity to remove pollutants and toxins from waste in an ecologically friendly manner. Nanoparticles with a range of elements, such as iron, zinc, gold, and silver, have been effectively produced by an environmentally friendly process. Metal ions can be bioreduced by phytoconstituents such as polyphenols, terpenes, and polyols, which are present in plant extracts.

Bacteria

Phytoremediation, bioextraction, and bioengineering are just a few of the many uses for bacteria. In order to make NPs, you need certain microorganisms that can break down metal ions. Metal or metal oxide NPs are often manufactured using actinobacteria and prokaryotic microbes.

Yeast

Yeast, a unicellular bacteria, is found inside eukaryotic cells. Just 1,500 yeast species have been identified thus far. Multiple research groups have now come out to announce that they successfully synthesised nanomaterials using yeast. A wide range of materials may be used to create metal nanoparticles. There have been reports of a yeast strain that can biosynthesise silver and gold nanoparticles using Saccharomyces cerevisiae broth.

Fungus

However, fungus-mediated biosynthesis of metal/oxide NPs is particularly successful for producing NPs with suitable morphologies and in a highly distributed form. They are suggested for the production of metal and metal oxide nanoparticles (NPs) because of the abundance of internal enzymes. Fungi are more capable than bacteria in producing nanoparticles. The abundance of proteins, enzymes, and reducing agents in their cells also gives them an advantage over other microbes. The most probable process for the production of metal nanoparticles is a biochemical reduction enzyme either in the cell wall or inside the fungal cell. One major advantage of utilising fungi in nanoparticle synthesis is their adaptability to large-scale production, as shown by methods like thin solid substrate fermentation. Rhizopus nigricans is one of the fungi that can produce nanoparticles of metals and metal oxides, including silver.

Algae

An emerging field in nanoscience, "phyco-nanotechnology" focuses on creating nanoparticles using algae. This area of nanoscience is still in its infancy. Because they can grow at room temperature, gather metal well, are easy to work with and care for, and are becoming less harmful to the environment, algae are used to make nanoparticles. Phaeophyceae, cyanophyceae, chlorophyceae, and rhodophyceae are the four most common types of algae used to make silver nanoparticles.

Plants

Metals may accumulate in several parts of a plant, including its leaves, stem, roots, fruits, flowers, and more. As a result, there has been a rise in interest in synthesis using plant extracts as a practical, inexpensive, efficient, and fundamental method to create nanoparticles. Functional groups, which are biologically active compounds found in plants, may decrease metal ions substantially more rapidly than bacteria or fungus, allowing a broad variety of plants to be used to reduce and stabilise metal nanoparticles during synthesis.

Essential phytochemicals involved in NP bioreduction include thiamins, terpenoids, polyphenols, vitamin C, alkaloids, oxalic acids, glycosides, and flavonoids. Making gold and silver nanopartcles is a common practice, and a few plants are often utilised for this purpose. Two of these plants are aloe vera and lemon.

IV. GREEN METAL NANOPARTICLES PRODUCED BY PLANTS SPECIES & THEIR BIOLOGICAL APPLICATIONS

Plants are considered inexpensive and low-maintenance nanofactories for MNPs. Since plant extracts are abundant in phytochemicals, which may function as reducing and stabilising agents during MNP formation, a variety of plant components have been utilised for MNPs manufacture. To make nanoparticles from plants, the chosen plant material is cooked in distilled water after being carefully cleansed. Following a series of pressing and filtering processes, the plant extract is combined with the precursor solution needed to synthesise the MNPs. The plant extract starts to change colour after adding the MNP precursor solution, which means that MNPs are starting to develop.

Plant biomass contains phytochemicals that can reduce and cap metal nanoparticles. The phytochemicals' functional moieties—such as hydroxyl, carboxyl, and ketones—serve as bio-reducers for phyto-MNPs, while the amino acids and proteins contained in plants serve as caps. A number of compounds, including phenolic acids, tannins, terpenoids, alkaloids, and flavonoids, have strong reducing and stabilising properties. Capped with proteins and amino acids, MNPs reveal advantageous stability profiles and physiochemical characteristics, and they are less likely to aggregate.

Silver and gold salt solutions can be reduced to nanoforms by means of the isoprene-based terpenoids and flavonoids. Clove extract, which is high in eugenol, was able to convert AuCl4 and AgNO3 to Ag and Au-NPs by using hydroxyl groups attached to benzene rings and powerful electron-withdrawing groups at the ortho and para positions, methoxy and allyl groups. A highly effective reducing agent, eugenol's capacity to liberate protons was amplified by the presence of the powerful electron withdrawing groups, methoxy and allyl, that surround the hydroxyl group. Eugenol also has a resonant anionic form that stabilises its proton release. Both AuCl4 and AgNO3 absorb the electrons, resulting in the formation of the reduced forms Au0 and Ag0, respectively. The opposite was true for the flavonoid-rich leaf extracts of Ocimum basilicum and Mangifera indica; these plants released protons in their tautomeric state, reducing silver salts and producing AgNPs. After reducing an aqueous HAuCl4 solution with ketones, alcohols, amines, aldehydes, and carboxylic acids, gold nanoparticles were extracted from Diopyros kaki and Magnolia kobus extracts. After being dried and calcined into CaO nanoparticles, the calcium ion is reduced to Ca(OH)2 by the hydroxyl group of quercetin in broccoli extract. The oxidation of hydroxyl to carbonyl groups is believed to involve dihydromyricetin in the formation of AuNPs. Due to their abundance of capping, reducing/stabilizing, and chelating compounds (such as ginerol, luteolin, quercetin, rutin, etc.), aqueous ginger/cardamom extracts have recently gained recognition as potential phyto-MNPs producers. Iron nitrate, cobalt nitrate, and water-based ginger and cardamom extracts can be used to effectively produce 100 nm-sized crystalline cobalt ferrite.

The morphological and physiochemical properties of MNPs are affected by changes in the plant extract content that occur during the formation of phyto-MNPs. Smaller, more uniformly distributed phyto-MNPs are produced by lower amounts of plant extract, whereas larger, more uniformly distributed MNPs are the result of higher concentrations of plant extract. Lin et al. found that at high concentrations of Morinda lucida leaf extract, spherical AuNPs with a diameter less than 15 nm appeared, in contrast to the hexagonally produced AuNPs of more than 100 nm at low extract concentrations. This is attributed to the fact that larger quantities of plant extracts, which are required for MNPs capping and aggregation prevention, have comparatively high phytochemical contents. Since the plant's chemical make-up differs from one part to another, the specific plant part used for phytosynthesis will have an impact on the characteristics of MNPs. According to Appapalam and Panchamoorthy, the Aerva lanata flower extract had bigger AgNPs, but the Aerva lanata foliage extract had normal sized AgNPs (<15 nm). The saponins, polyphenols (gallic acid and ellagic acid), and flavonoids (kaempferol, rutin, and quercetin) found in abundance in the A. lanata extracts were responsible for the decrease of AgNO3. The size and distribution of phyto-MNPs are also affected by the circumstances under which plant extracts are stored. Both the bio-reduction process and the stability of the phytochemicals that regulate it are impacted by storage conditions, as are the capping of biogenic MNPs. The phytochemicals in plant extracts become unstable and the ageing time increases as storage temperatures are raised. Big, distributed phyto-MNPs are linked to this.

V. CONCLUSION

In recent years, nanoparticles have gained attention as a potentially useful and adaptable material class due to their exceptional characteristics. Improving procedures, reducing environmental harm, and meeting the rising demand for these nanostructures' applications is an ongoing field of study in green synthesis, which uses biologically active substances and natural resources to create nanoparticles. By making use of biological resources, nanoparticle production may be accomplished more quickly, with less expense, and with the same or improved physical and chemical characteristics. Because of its great potential and the sustainable and efficient production of nanoparticles, this method is attractive for the synthesis of nanostructures and other compounds due to the wide range of sizes and shapes that can be achieved.

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