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A REVIEW ON GREEN SYNTHESIS OF METALLIC NANOPARTICLES: ADVANCEMENTS AND APPLICATIONS IN SUSTAINABLE TECHNOLOGY

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ABSTRACT

It provides a comprehensive overview of the latest advancements and applications in the field of green synthesis of metallic nanoparticles, with a particular focus on sustainable technology. Metallic nanoparticles possess unique properties that make them highly desirable for various applications, ranging from biomedical to environmental fields. Green synthesis methods, including plant-mediated, have emerged as environmentally friendly alternatives to conventional synthesis routes. These methods offer advantages such as reduced environmental impact and biocompatibility. The abstract delves into the wide-ranging applications of green-synthesized metallic nanoparticles. Biomedical applications and environmental applications are highlighted. Additionally, the role of metallic nanoparticles in optoelectronics, sensing technologies, and food safety is examined. Throughout the discussion, the importance of sustainability is underscored, emphasizing the need to address environmental concerns and promote eco-friendly technologies. Overall, this abstract provides valuable insights into the potential of sustainable technology in shaping the future of nanoparticle synthesis and applications.

Keywords: Metallic Nanoparticles, Introduction, Synthesis, Characterization, Applications.

RASĀYAN *J. Chem.*, Vol. 17, No.4, 2024

INTRODUCTION

Richard Feynman first introduced the concept of nanotechnology in his 1959 lecture, "There's Plenty of Room at the Bottom," envisioning a field of scientific exploration focused on manipulating materials at the atomic scale. Japanese scientist Norio Taniguchi later defined nanotechnology in 1974, emphasizing manipulation at the level of individual atoms or molecules, with a precision of around 1 nanometer. This field involves the control, assembly, and modification of materials at the nanoscale to achieve new or enhanced properties. The advent of advanced computer technology and electron microscopes has propelled nanotechnology research. Carbon nanotubes, discovered in 1991, exemplify nanomaterials with remarkable strength and lightweight properties. Nanoscience has rapidly evolved, influencing diverse fields such as engineering, pharmacy, and environmental science, with a growing number of publications reflecting its expanding significance.[1-2] This review provides a comprehensive overview of the advancements and applications in the field of green synthesis of metallic nanoparticles, with a particular focus on sustainable technology. Metallic nanoparticles possess unique properties that make them highly desirable for various applications, ranging from biomedical to environmental fields. Green synthesis methods, including plant-mediated, have emerged as environmentally friendly alternatives to conventional synthesis routes.

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Vol. 17 | No. 4 |1766-1772| October - December | 2024

The Significance of Nano Size

Nanoparticles, sized between 1-100 nm, are materials where at least one dimension is in the nanoscale. Unlike bulk materials, nanoparticles exhibit distinct properties due to their size. Reducing material dimensions to the nanoscale alters their physical and chemical properties, making them unique compared to their macroscopic counterparts.[3]

The improvised size-dependent characteristic properties that might be changed at the nano range are:

- Chemical properties (Solubility, Catalysis, Reactivity, etc.)
- Physical properties (Mobility etc.)
- Thermal properties (Melting point etc.)
- Optical properties (Color or Luminescence etc.)
- Mechanical properties (Mechanical strength, elastic modulus, adhesion, capillary forces)
- Electrical properties (electronic conductivity etc.) and Magnetic properties (magnetic strength, permeability, etc.)

At the nanoscale, materials exhibit unique properties due to increased surface area-to-volume ratios and quantum effects. The higher surface area enhances reactivity, influencing chemical, physical, and optical characteristics, as seen in gold's lower melting points and improved catalytic activity. Quantum effects and negligible gravitational forces lead to distinctive properties, with random molecular motion and enhanced features in nanocomposites, like core-shell structures that merge electrical and magnetic properties.[4-5]

Methods of Synthesis for Nano Material

Nanotechnology focuses on creating specialized nanomaterials, which can be naturally occurring or synthetically produced. Synthesis methods include:

1. Top-down approach: Breaking down bulk materials into nanoscale particles.
2. Bottom-up approach: Building nanoparticles from atoms or molecules.

Methods for synthesis are physical (e.g., grinding, laser ablation), chemical (e.g., chemical vapor deposition), and biological (e.g., using plant or microbial extracts).[6] Figure-1 gives a flow chart expressing various synthetic methods for nanomaterials, including green synthesis.

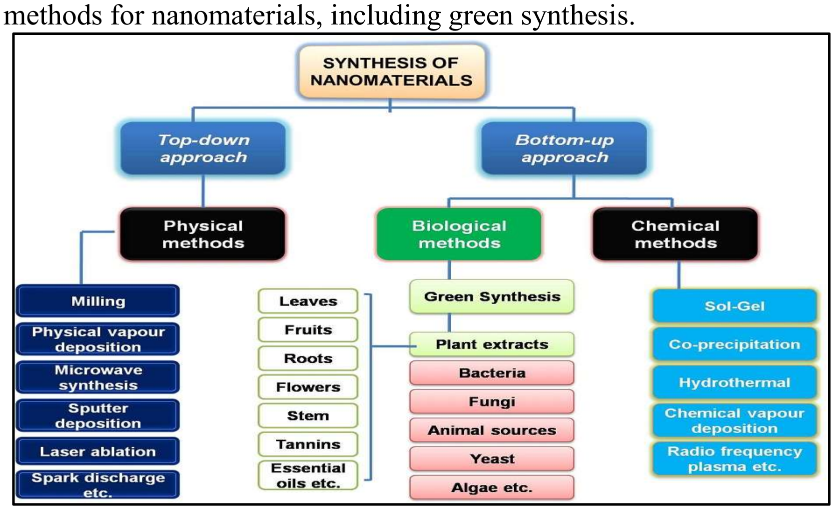

Fig.-1: A Flow Chart of Various Synthesis Methods of Nanomaterials, Including Green Synthesis

Chemical methods for synthesizing nanomaterials involve reducing metal precursors and preventing aggregation using agents like sodium borohydride, citrate, and ascorbate.[7-8] Stabilizing agents, such as surfactants, polymers (e.g., polyvinyl alcohol, polyethylene glycol), or ligands, are used to avoid aggregation. Microbial synthesis employs peptides and enzymes from fungi and bacteria, such as Fusarium oxysporum, Penicillium sp, and Bacillus subtilis, to assist in the reduction process and nanomaterial formation.[9-11]

Factors Affecting Nanomaterials Synthesis

Selecting appropriate synthetic methods for metallic nanoparticles is crucial as it affects their chemical and physical properties, including size, shape, surface chemistry, and charge. Key factors influencing nanoparticle synthesis include pH, concentration, temperature, reaction time, and plant extract composition. For instance, extended reaction times can initially increase particle numbers but may lead to agglomeration, forming larger particles with random shapes. This aggregation can alter the nanoparticles' chemical, physical, and optical properties, making it difficult to restore monodispersity. Temperature is another critical factor; higher temperatures generally accelerate reaction rates and increase nucleation centers, which can reduce particle size up to a threshold temperature but might increase sizes beyond that point. pH levels impact the reaction kinetics, with alkaline conditions typically promoting faster and more uniform particle formation, while acidic conditions slow down the process and lead to larger particles. Additionally, different plant extracts introduce various phytochemicals that affect particle size and morphology. Higher concentrations of plant extracts often lead to smaller nanoparticles due to increased nucleation rates.Effective control over these variables ensures the desired nanoparticle properties for specific applications.[12-15]

Significance of Green Synthesis

Green chemistry focuses on designing chemical processes to minimize environmental and health hazards throughout a product's lifecycle. In response to the environmental damage caused by urbanization and industrialization, green synthesis using natural sources has gained attention. Biological molecules from plants are particularly valuable in nanomaterial synthesis due to their unique properties. Biological synthesis, a bottom-up approach involving reduction or oxidation reactions, is increasingly significant in nanotechnology for producing nanoparticles. This method offers several advantages over traditional physical and chemical methods, which often require complex, costly, and hazardous processes. Green synthesis procedures generally involve three key steps: selecting eco-friendly solvents, non-toxic stabilizing agents, and environmentally benign reducing agents. Plant extracts, which naturally contain stabilizing agents, are preferred due to their cost-effectiveness and simplicity. They provide a single-step, safe, and efficient alternative to methods requiring high temperatures, pressures, or sophisticated equipment. Plant parts such as leaves stems, and fruits can produce well-distributed, stable nanoparticles with controlled size and shape. Phytochemical compounds in plants, including polysaccharides and flavonoids, play a crucial role in reducing metal ions and stabilizing nanoparticles.[16-20]

Preparation of Plant Extract

Several studies exist to optimize phytochemical molecules such as plant drying techniques, temperature, and solvent used. Before synthesizing nanoparticles, plant extracts with active phytochemical molecules can be prepared using various parts of plants. In general, here we provide the common procedure followed for the preparation of plant extras in the Fig.-2.

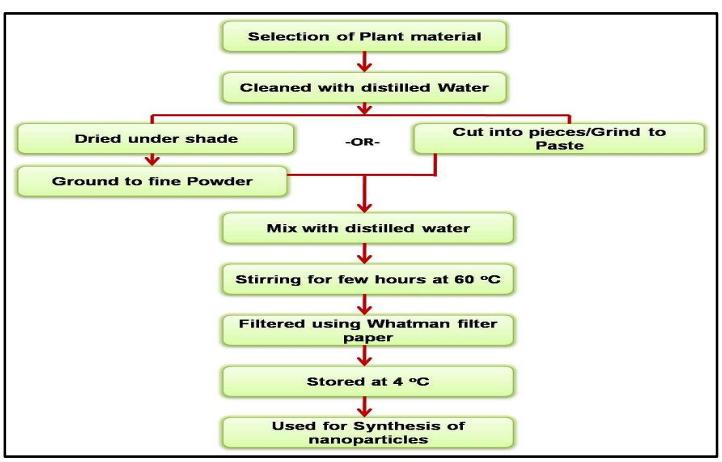

Fig.-2: A Flow Chart of the Common Procedure Followed for the Preparation of Aqueous Plant Extracts

Green Synthesis of Nanomaterials

The various nanoparticles are synthesized using different plant extracts previously. The common procedure for the green synthesis of nanoparticles, different characterization techniques, and performed applications are provided as a flow chart shown in Fig.-3.

Characterization Techniques

Visual Observations

Nanoparticles exhibit various colors due to Surface Plasmon Resonance (SPR), where electron clouds vibrate in response to specific wavelengths of light. This optical property is common in metallic nanoparticles, allowing their detection and analysis using UV-Vis spectroscopy.

UV-Visible Spectrophotometry

UV-Visible spectrophotometry, based on Beer's and Lambert's laws, is a cost-effective method for monitoring metal nanoparticle formation. It measures light absorption and transmission through a sample, providing insights into nanoparticle size, shape, and concentration. The various nanomaterials between the size range 2-100 nm are characterized by UV-Vis spectroscopy using the light wavelength in the 200-800 nm range.[21]

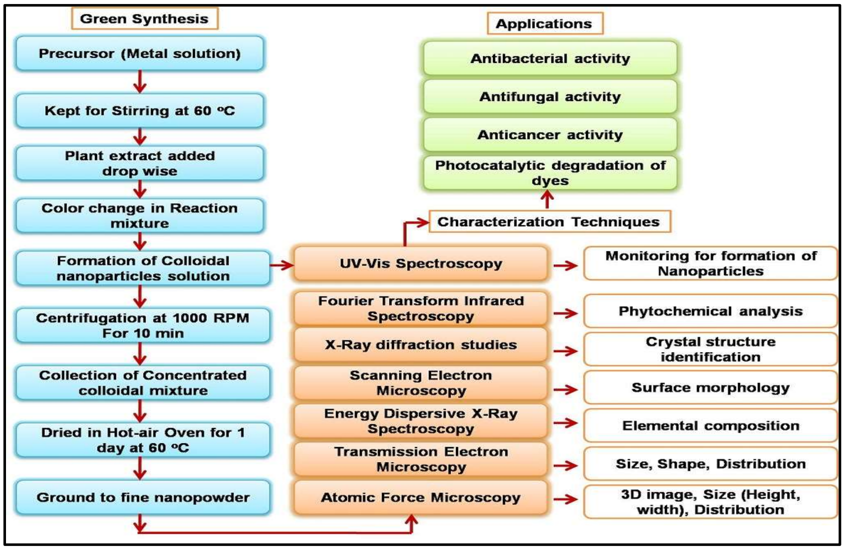

Fig.-3: A Flowchart for the Green Synthesis of Various Nanoparticles, Characterization Techniques and Applications

Fourier Transform Infra-Red Spectrophotometry (FTIR) Analysis

It identifies organic molecules by their characteristic vibrational frequencies in the IR region (4000-400 cm-1). Stretching and bending vibrations reflect bond lengths and angles, with double and triple bonds exhibiting higher frequencies compared to single bonds.

X-Ray Diffractometry (XRD) Analysis

X-ray diffraction (XRD) uses X-rays (0.01–10 nm wavelength) to analyze the crystal structure of materials. By measuring the angle (2θ) between incident and diffracted X-rays, XRD determines crystallite size, orientation, and lattice parameters. The Bragg condition, $2d\sin\theta = \lambda$, helps identify interplanar spacings in crystals.[22]

Scanning Electron Microscopy-Energy Dispersive Spectroscopy (SEM-EDS)

SEM-EDS/EDX is a powerful technique for analyzing nanomaterials. SEM provides high-resolution, 2D topographical images of surfaces, while EDX, integrated with SEM, analyzes elemental composition by measuring characteristic X-ray emissions. EDX plots X-ray energy versus counts to identify elements based on unique peak positions.

Transmission Electron Microscopy (TEM) Analysis

Transmission Electron Microscopy (TEM) is used in material science, nanotechnology, and other fields to analyze nanoparticles' size, shape, and structure. TEM transmits electrons through thin samples to produce high-resolution images, with sizing accuracy. It distinguishes between grain size and aggregate size, crucial for accurate measurements.

Vol. 17 | No. 4 |1766-1772| October - December | 2024

Selected Area Electron Diffraction (SAED)

Selected Area Electron Diffraction (SAED) is used to determine the crystal structure of materials in a Transmission Electron Microscope (TEM). In SAED, electrons interact with atoms in the sample, creating a diffraction pattern. Diffused backgrounds indicate lattice distortion or amorphous states, while distinct bright spots on a dark background reveal crystalline structures. Single bright spots suggest a monocrystalline material, while concentric ring patterns indicate a polycrystalline nature.

Atomic Force Microscopy (AFM) Analysis

AFM is essential in nanotechnology for non-destructive nanoparticle analysis. It uses a sharp tip on a flexible cantilever to scan the surface, measuring topography, friction, and other properties. AFM produces high-resolution 3D images of surface features, revealing particle height, roughness, and clustering.

Applications

Nanoparticles have found diverse applications across various fields in recent years. In nano biosensors, they help diagnose diseases like multiple sclerosis and tuberculosis and detect cancer and flu viruses. Nanoplasmonics is used for personalized medicine, early cancer detection, and photonic applications like light-activated cancer treatments. Nanoelectronics includes advancements like 7 nm transistors, energy-efficient devices, and wearable sensors for health monitoring. In food and agriculture, nanomaterials improve pesticide delivery, pathogen detection, and nutrient dispersion. Nanobiotechnology and nanomedicine are used in drug delivery, disease diagnostics, and advanced treatments such as artificial retinas and self-healing materials. Energy applications involve enhancing batteries, fuel cells, and renewable energy technologies. Space technology utilizes nanoparticles for radiation shielding and improved electronics. In cosmetics, nanoparticles enhance UV protection and ingredient delivery. Nanosensors are employed for gas detection and medical diagnostics. Construction benefits from improved materials for durability and energy efficiency. In the automobile industry, nanoparticles are used for scratch-resistant paints and fuel additives. Disaster management uses nanomaterials for protective coatings and filters. Lastly, in HIV/AIDS treatment, nanoparticles are explored for drug delivery and diagnostic tools. Various types of metal nanoparticles and their applications in the biological field are shown in Fig.-4.

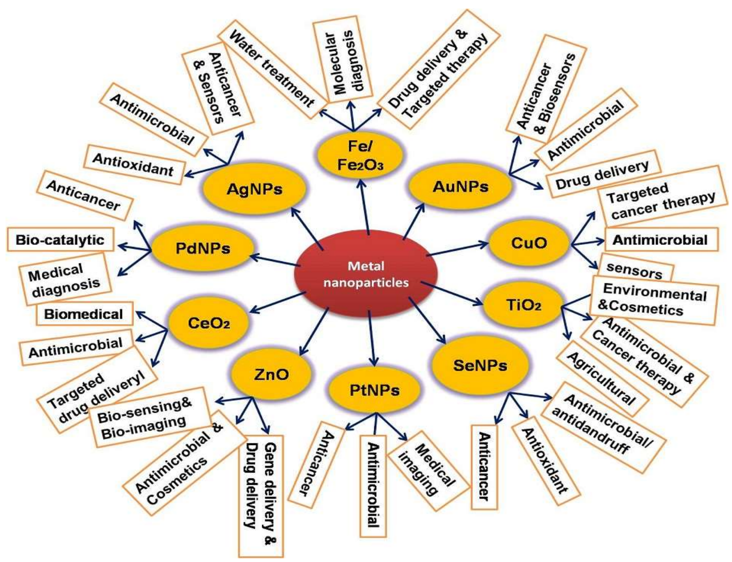

Fig.-4: Various Types of Metal Nanoparticles and their Applications

CONCLUSION

In conclusion, the green synthesis of metallic nanoparticles represents a significant advancement in sustainable technology. By utilizing environmentally friendly methods such as plant-mediated synthesis, we reduce ecological impact while enhancing biocompatibility. These nanoparticles show promise across diverse fields, including biomedicine, environmental protection, optoelectronics, and food safety. Emphasizing sustainability in nanoparticle production not only addresses environmental concerns but also paves the way for future innovations in eco-friendly technologies. This approach is crucial for advancing both science and sustainability.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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[RJC- 9035/2024]