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Advances in Green Synthesis of Metal Nanoparticles using Extracts from Different Parts of Plants and their Biological Applications: A Review

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ABSTRACT: Green synthesis has emerged as a transformative approach in sustainable chemistry, focusing on minimizing environmental impact while maximizing efficiency. This review paper provides an in-depth examination of green synthesis with a specific focus on nanoparticles synthesized from leaf extracts. It explores recent advancements, methodologies, and the biological applications of these nanoparticles. The review highlights the synthesis techniques, the role of leaf extract nanoparticles in various biological fields, and addresses the associated challenges and future research directions.

I. INTRODUCTION

The recent period has seen significant advancements in nanomaterials across various research fields due to their outstanding physical, chemical, and electronic properties.[1] These properties are crucial in several scientific disciplines, including catalysis, electronics, targeted drug delivery, water sensing and treatment, corrosion prevention, oil recovery, and many others..[2–4] The term "nanoparticles" typically refers to particles that range in size from 1 to 100 nanometers; however, in biotechnology, this definition often extends to include particles as large as 500 nanometers..[5] "Size" is the defining characteristic that distinguishes nanoparticles from other materials, commonly referred to as "bulk materials," and enables them to exhibit specific and significant physicochemical properties..[5,6] Usually, fabricated nanoparticles are metallic in nature and display an effect commonly known as “Surface Plasmon Resonance”, This plays a crucial role in the quantum mechanical interactions of light in the UV-Visible spectrum, resulting in distinctive optronic and optoelectronic properties..[7] Significantly, any alteration in the size or shape of a nanoparticle impacts its inter-particle interactions and absorption characteristics..[8] Because of their remarkable properties, nanoparticles are widely used in a range of biomedical applications..[9–11] The many advancements in nanoscale science have led to the creation of a wide array of nano-sized materials to support related research, resulting in the commercial production of various valuable nanomaterials..[12] It is expected that, in the future, nano-sized materials and their associated products will play a significant role in everyday life. Additionally, it is crucial for these nano-sized materials to have a strong capacity to interact with various biological molecules, both within and on the surface of cells. Their ability to penetrate cells allows these materials to influence various cellular physicochemical and biochemical processes..[13] Due to their small size, nanoparticles can be rapidly and easily absorbed into cellular compartments and organelles. Additionally, nano-sized particles can effortlessly cross the placenta and the blood-brain barrier..[12,14] This accounts for the presence of nanosized materials in approximately 45 different drug formulations, as discussed in detail by Weissig et al..[15] For example, $TiO2$ and ZnO nanoparticles can withstand UV radiation, leading to their incorporation into various cosmetic products, particularly sunscreens. When applied to the skin, these nanoparticles remain transparent to visible light and offer superior protection against UV rays compared to conventional sunscreens..[16] Additionally, a range of nanoparticles based on single-walled carbon nanotubes (SWCNT) has recently been introduced to the Russian market..[17] In the food industry, nano-sized materials are already being utilized to extend the shelf life of edible products and manage spoilage rates..[18] Vance et al. conducted a comprehensive evaluation of nanotechnology-based products on the market and reported that approximately 1,814 products containing nano-sized materials have been introduced by around 622 companies across approximately 32 countries globally. They noted that about 435 silver-based nano-sized materials are readily available, including in items such as veils, toothpaste, detergents, humidifiers, and shampoo. Currently, there is a strong demand for nanomaterials, estimated to range from 300,000 to 1.6 million tonnes worldwide. The Asia-Pacific region holds the largest market share at 34%, followed by North America at 31% and Europe at 30%.[19] The synthesis of nano-sized materials is a crucial chemical process. Currently, both chemical and physical methods are used to prepare these materials; however, these methods may not be optimal due to their high costs and potential environmental pollution. As a result, there is a need to develop alternative methods that are environmentally friendly (green synthesis)

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throughout the entire production process, which has garnered significant interest from researchers worldwide..[19,20] Traditional synthesis methods (both physical and chemical) typically require extremely harsh conditions. In contrast, biological synthesis methods are usually performed at ambient temperature and pressure, offering simplicity, energy savings, and lower toxicity or harm to both humans and the environment. Considering these advantages, a variety of biological resources, such as bacteria, fungi, yeast, plants, and algae, are being utilized to synthesize both intracellular and extracellular materials with nano-sized dimensions..[21] Although nanoparticles are synthesized using biological methods (biosynthesis), understanding the mechanisms behind their synthesis remains a complex challenge..[22] Nonetheless, these methods are well-established and frequently used for synthesizing nano-sized materials, as they are more cost-effective and environmentally friendly than conventional methods. Biological methods utilize renewable resources like plants and microorganisms, which serve as reducing agents to stabilize and cap nanomaterials, thereby eliminating the need for chemical additives..[23,24] A standardized method for synthesizing nanoparticles using plant extracts follows a systematic approach. First, a specific plant material is carefully selected and taxonomically identified to obtain the desired plant extract. After selecting the plant parts, an extraction process is performed using suitable solvents, followed by filtration or chromatography to remove any impurities. Concurrently, a solution of the chosen metal salt is prepared as the nanoparticle precursor. The prepared plant extract is then added to the metal salt solution while maintaining the appropriate temperature and pH for the reaction, initiating a process that results in the formation of nanoparticles.[25] In various methods reported in previous studies, continuous stirring of the reaction mixture yields better results in the form of uniformly sized nanoparticles, which is visually indicated by a noticeable color change. Additionally, ultrasonic treatment can be applied to ensure uniform dispersion. Afterward, the nanoparticles are separated from the solution using centrifugation and then washed to remove any residual impurities. Optionally, the nanoparticle precipitate can be dried to eliminate any further contaminants..[26] Finally, the synthesized nanoparticles are thoroughly characterized using various analytical techniques to verify their composition and physicochemical properties. After synthesis, different spectroscopic and microscopic methods are essential for characterizing the nanoparticles. For example, UV-Vis spectrophotometry is used to evaluate their optical properties, while FTIR spectroscopy helps identify the functional groups present on the nanoparticle surface. Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) are employed for a detailed analysis of their size, shape, and structure. Additionally, Dynamic Light Scattering (DLS) and Zeta potential measurements are utilized to determine the size and surface charge of the nanoparticles. These techniques provide valuable insights into the properties and behavior of the synthesized nanoparticles.

II. PRINCIPLES OF GREEN CHEMISTRY

Green chemistry is guided by twelve principles designed to foster sustainable chemical practices. These principles include waste prevention, atom economy, safer chemical synthesis, and energy efficiency. Nanoparticles synthesized from leaf extracts adhere to these principles by reducing the need for toxic chemicals and minimizing environmental impact. The use of natural leaf extracts for nanoparticle synthesis aligns with the principle of using renewable feedstocks and designing safer chemicals. The green synthesis methods are often more energy-efficient and produce fewer by-products, which contributes to their overall sustainability.

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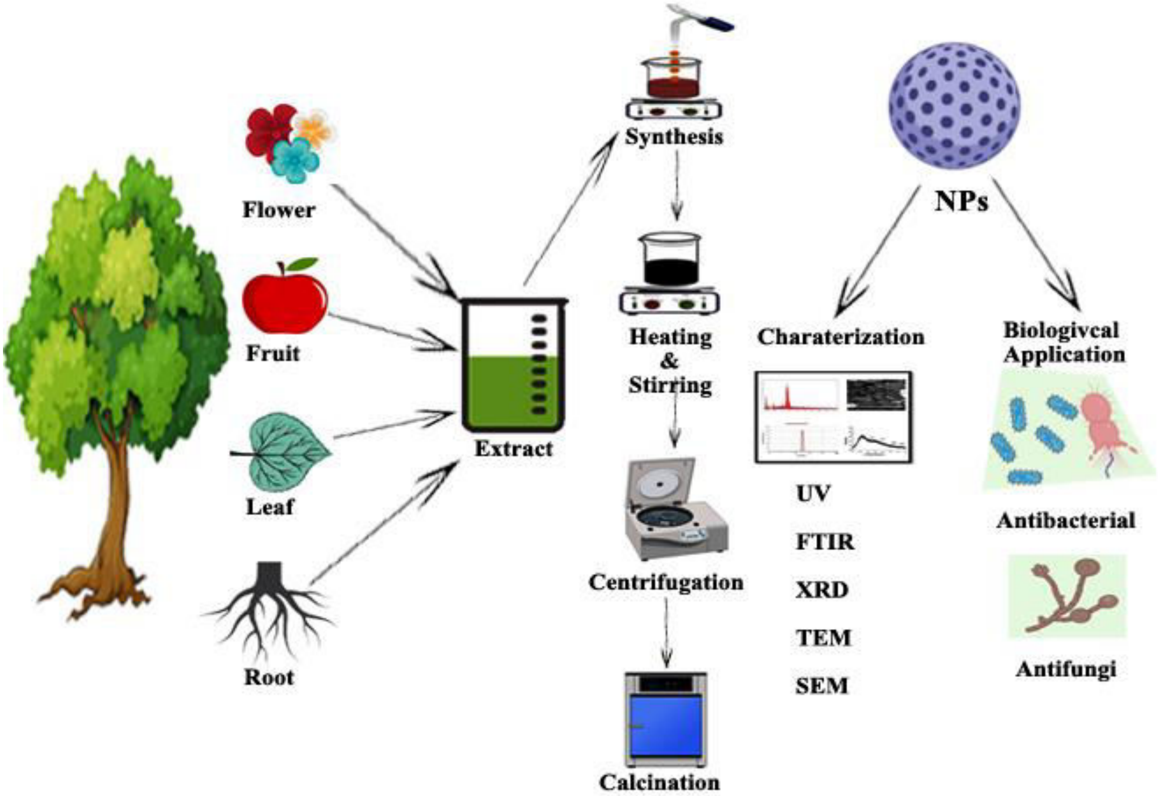

Fig:1 Synthesis of nanoscale metals using extracts from different parts of plants.

III. SYNTHESIS OF NANOPARTICLES USING LEAF EXTRACTS

The synthesis of nanoparticles using leaf extracts is a promising green chemistry approach. The process typically involves preparing a leaf extract by boiling or soaking leaves in a solvent to extract the phytochemicals. These extracts are then used to reduce metal salts to form nanoparticles. For instance, silver nanoparticles can be synthesized using extracts from neem, mint, and tea leaves. The phytochemicals in the leaf extracts, such as flavonoids and polyphenols, act as reducing and stabilizing agents. This method is advantageous because it avoids the use of harmful chemicals and high-energy processes, making it an eco-friendly alternative to conventional synthesis methods.

Plant	Source of Nanoparticles	Metal Oxide	Size	Application	Reference
Ficus carica	Leaf	Fe_3O_4	43–57 nm	Antioxidant activity	[27]
Azadirachta indica	Leaf	CuO	NA	Anticancer property	[28]
Peltophorum pterocarpum	Leaf	Fe_3O_4	85 nm	Rhodomine degradation	[29]
Terminalia chebula	Seed	Fe_3O_4	NA	Methylene blue degradation	[30]
Punica granatum	Peel	ZnO	118.6 nm	Antibacterial property	[31]
Lactuca serriols	Seed	NiO	NA	Degradation of dye	[32]
Vitis rotundifolia	Fruit	CoO	NA	Degradation of acid blue dye	[33]

Fig: 2 List of nanoparticles synthesized by different algae and their size and shape.

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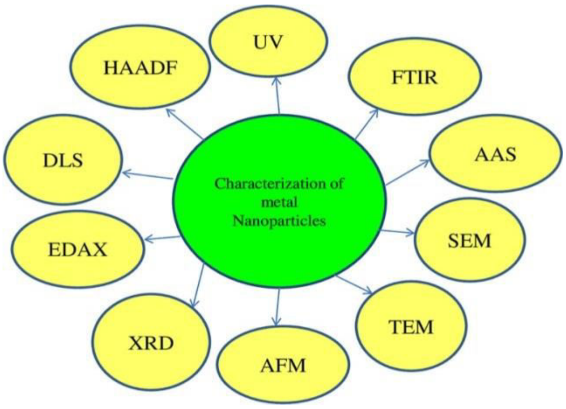
IV. CHARACTERIZATION OF LEAF EXTRACT NANOPARTICLES

Characterizing nanoparticles synthesized from leaf extracts is crucial for understanding their properties and potential applications. Common techniques include transmission electron microscopy (TEM) and scanning electron microscopy (SEM) to visualize nanoparticle size and morphology. X-ray diffraction (XRD) and energy-dispersive X-ray spectroscopy (EDX) provide information about the crystal structure and elemental composition. Dynamic light scattering (DLS) measures the size distribution and stability of the nanoparticles in solution. These characterization techniques help in optimizing synthesis conditions and tailoring nanoparticles for specific applications.



V. BIOLOGICAL APPLICATIONS OF LEAF EXTRACT NANOPARTICLES

Leaf extract nanoparticles have shown promising applications in various biological fields due to their unique properties and biocompatibility. Their applications include:

a. Antimicrobial Activity
Nanoparticles synthesized from leaf extracts exhibit significant antimicrobial properties. Silver nanoparticles, for example, have been extensively studied for their ability to inhibit the growth of bacteria and fungi. The antimicrobial action is attributed to the release of silver ions, which interact with microbial cell membranes and cause cellular damage. Leaf extract-based silver nanoparticles have been effective against a wide range of pathogens, including antibiotic-resistant strains. Similarly, gold and zinc oxide nanoparticles derived from leaf extracts have shown potential in combating microbial infections.

b. Drug Delivery Systems
Leaf extract nanoparticles are increasingly being explored for use in drug delivery systems. Their small size and high surface area make them ideal carriers for delivering therapeutic agents to targeted sites. For example, nanoparticles can be engineered to encapsulate drugs and release them in a controlled manner, improving the efficacy and reducing side effects. Leaf extract-based nanoparticles, such as those from pomegranate or ginger, have been investigated for their potential to enhance the bioavailability and stability of drugs. These nanoparticles can also be functionalized to target specific cells or tissues, further improving drug delivery.

c. Cancer Therapy
In cancer therapy, leaf extract nanoparticles are used for targeted treatment and imaging. Gold nanoparticles, synthesized from leaf extracts like those of pomegranate or mint, have been employed in photothermal therapy, where they absorb light and generate heat to destroy cancer cells. Additionally, these nanoparticles can be conjugated with therapeutic agents or imaging dyes to enhance diagnostic accuracy and treatment specificity. The biocompatibility and functionalization of leaf extract nanoparticles make them suitable candidates for developing advanced cancer therapies.

d. Antioxidant and Anti-inflammatory Effects
Nanoparticles derived from leaf extracts also exhibit significant antioxidant and anti-inflammatory activities. The phytochemicals in the leaf extracts, such as polyphenols and flavonoids, contribute to these effects. Antioxidant nanoparticles can neutralize free radicals, thereby reducing oxidative stress and preventing cellular damage. Anti-inflammatory nanoparticles can modulate inflammatory pathways, offering potential therapeutic benefits for conditions

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such as arthritis and cardiovascular diseases. Research into these applications continues to expand, highlighting the versatility of leaf extract nanoparticles in biological applications.

VI. CHALLENGES AND LIMITATIONS

While leaf extract nanoparticles offer numerous benefits, several challenges and limitations must be addressed. The variability in leaf extract composition can lead to inconsistencies in nanoparticle synthesis, affecting their quality and performance. Scalability is another significant challenge, as processes that are effective at the laboratory scale may not easily translate to industrial production. Additionally, the potential toxicity of nanoparticles and their long-term environmental impact need thorough investigation. Ensuring the safety and efficacy of these nanoparticles is crucial for their successful application in biological and medical fields.

VII. FUTURE DIRECTIONS

Future research in leaf extract nanoparticles should focus on optimizing synthesis methods to improve reproducibility and scalability. Investigating new leaf sources and their phytochemical profiles can lead to the development of nanoparticles with enhanced properties and applications. Integrating leaf extract nanoparticles with advanced technologies, such as nanotechnology and bioengineering, holds promise for creating innovative solutions in medicine and environmental management. Furthermore, exploring the principles of circular economy, such as recycling and reusing nanoparticles, can contribute to their sustainability and long-term viability.

VIII. CONCLUSION

Nanoparticles synthesized from leaf extracts represent a significant advancement in green synthesis, offering a sustainable and environmentally friendly alternative to traditional methods. Their unique properties, coupled with their applications in antimicrobial activity, drug delivery, cancer therapy, and antioxidant effects, underscore their potential in various biological fields. By addressing existing challenges and focusing on future research directions, the field of leaf extract nanoparticles can continue to evolve and contribute to advancements in green chemistry and biotechnology.

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