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Microwave assisted synthesis of nanopartical: A green chemistry

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Abstract
This review critically examines microwave-assisted synthesis (MAS) as a sustainable strategy for nanomaterial fabrication, addressing the environmental limitations of conventional synthetic approaches. MAS offers substantial advantages through rapid and uniform heating, which significantly reduces energy consumption, reaction time, and hazardous waste generation. By systematically comparing MAS and traditional methods in terms of energy efficiency, reaction performance, waste minimization, selectivity, product uniformity, and scalability, this review establishes a comprehensive framework for sustainable nanomaterial production. Green chemistry metrics and sustainability assessment tools are employed to evaluate the environmental impact and industrial feasibility of diverse MAS protocols. Furthermore, the integration of MAS with eco-friendly precursors—such as plant extracts, biomolecules, and ionic liquids—for synthesizing key nanomaterial classes, including metal nanoparticles, carbon quantum dots (CQDs), and hybrid nanocomposites, is discussed in depth. The review also explores practical applications in catalysis, environmental remediation, energy storage, and biomedical technologies, emphasizing how MAS-derived nanomaterials contribute to addressing current sustainability challenges. Finally, it outlines existing limitations and future research directions for scaling MAS to industrial applications, underscoring its potential to revolutionize nanomaterial manufacturing in alignment with circular economy principles.

Keywords: Microwave assisted green synthesis, silver nanoparticle

Introduction

Metal nanoparticles (MNPs) have attracted considerable research attention due to their remarkable electronic, optical, and chemical properties. Nanotechnology involves the synthesis of materials with controlled shapes, sizes, and compositions within the nanoscale range of 1–100 nm. In recent decades, the synthesis and characterization of MNPs have gained significant interest because of their unique properties compared to their bulk counterparts. These distinctive characteristics primarily arise from their exceptionally high surface area-to-volume ratio.

Nanoparticles composed of metals such as silver, gold, copper, platinum, iridium, osmium, and palladium have been extensively explored for various biomedical applications. Among these, silver nanoparticles (AgNPs) are particularly important, with an estimated global production of around 500 tonnes annually. AgNPs exhibit strong antimicrobial activity, effectively inhibiting the growth of pathogenic microorganisms responsible for diseases in humans and animals. In addition, AgNPs serve as nanocarriers for the targeted delivery of bioactive molecules and are widely applied in diagnostics, medical imaging, and pharmaceutical formulations. Beyond biomedical uses, AgNPs also find applications as sensors, conductive materials, and catalytic substrates, as well as in antimicrobial, antiviral, and anticancer therapies. A variety of synthesis methods, including both top-down and bottom-up approaches, are utilized for the fabrication of metal nanoparticles (MNPs). In the bottom-up approach, atoms or molecules self-assemble through chemical or biological processes to form nuclei that subsequently grow into nanoscale particles. Conversely, the top-down approach involves breaking down bulk materials into smaller particles using techniques such as pulse wire discharge, evaporation–condensation, ball milling, and pulsed laser ablation Among these, the evaporation–condensation method is the most widely employed for MNP synthesis via the top-down route.

Regardless of the approach, physical methods are generally regarded as the primary routes for nanoparticle generation. Within the bottom-up strategies, chemical reduction remains the most common technique for synthesizing silver nanoparticles (AgNPs), where capping agents are employed to stabilize particle size and prevent agglomeration. One of the major advantages of this technique is its ability to produce large quantities of nanoparticles efficiently. However, many chemical synthesis methods—such as chemical precipitation, pyrolysis, hydrothermal processing, and chemical vapor deposition—can lead to the adsorption of toxic substances on the nanoparticle surface, which poses potential risks in biomedical applications. Furthermore, conventional physical and chemical methods often involve high energy consumption, expensive equipment, and the use of hazardous reagents, making them less suitable for large-scale or environmentally sustainable production.

In response, green nanotechnology has emerged as an eco-friendly alternative, offering sustainable pathways for nanoparticle synthesis. Agricultural waste and plant-based materials rich in phytochemicals such as antioxidants, phenolic acids, and flavonoids can be repurposed as natural reducing and stabilizing agents. These plant extracts contain functional groups—such as hydroxyl, carboxyl, carbonyl, and phenolic moieties—that play a crucial role in reducing metal ions, including silver, gold, zinc, and copper, into their corresponding nanoparticles. This approach not only minimizes environmental impact but also enhances biocompatibility and cost-effectiveness. Biological synthesis of silver nanoparticles (AgNPs) has been achieved using a wide range of organisms, including plants, bacteria, fungi, yeast, algae, and other biological systems. This approach offers several advantages over conventional physical and chemical methods. Among these biological routes, plant-mediated synthesis is particularly preferred due to its simplicity, cost-effectiveness, and environmental compatibility.

In contrast, nanoparticle synthesis using microorganisms such as bacteria, fungi, yeast, and viruses tends to be relatively slow and often limited in terms of the diversity of particle shapes and sizes that can be produced. Moreover, the process typically requires advanced laboratory equipment and stringent conditions to obtain clear filtrates from colloidal broths before nanoparticle recovery. In the case of viruses, nanoparticle formation depends on the presence of a suitable microbial host, making large-scale production complex and time-consuming. Consequently, plant-based green synthesis has emerged as a more practical and sustainable alternative for metal nanoparticle fabrication. Most silver nanoparticles (AgNPs) synthesized using plant extracts have traditionally relied on conventional heating methods, which are energy-intensive, time-consuming, and environmentally unsustainable. In contrast, microwaveassisted green synthesis accelerates the nucleation process responsible for nanoparticle formation through precisely controlled and uniform heating. According to Abboud *et al*. (2013), microwave irradiation produces nanoparticles with enhanced crystallinity, narrower size distribution, and improved control over morphological characteristics compared to conventional thermal methods.

Previous studies conducted under similar temperature and reaction time conditions have demonstrated that microwave-assisted synthesis yields more efficient reactions and superior nanoparticle quality than traditional heating techniques. Numerous reports highlight the simplicity, reproducibility, and effectiveness of nanoparticle synthesis under microwave conditions, establishing it as a competitive and sustainable alternative.

Microwave-assisted green synthesis offers several distinct advantages — including reduced reaction time, lower energy consumption, minimal use of toxic reagents, and improved control over particle size and dispersion. The technique enhances reaction kinetics by delivering energy directly to reactants through the interaction of microwave radiation with the solvent medium. As a result, it provides a rapid, economical, non-toxic, and environmentally friendly route for nanoparticle production, yielding smaller, more uniform particles while preventing agglomeration. Several studies have further detailed the microwave-assisted green synthesis of AgNPs using diverse plant extracts, along with their comprehensive characterization through standard analytical techniques such as UV–Vis spectroscopy, DLS, FTIR, SEM, TEM, EDX, and XRD. The Mitragyna parvifolia tree, commonly known as kadamb or kaim, is a medium- to large-sized species belonging to the Rubiaceae family. It grows abundantly in the arid and semi-arid regions of India, Pakistan, and Sri Lanka. The aerial parts of the plant—such as leaves, stems, bark, and roots—contain a variety of indolic and oxindolic alkaloids, including tetrahydroalstonine, akuammigine, and hirsuteine. Traditionally, different parts of this tree, including the stem bark, leaves, and fruit juice, have been used in indigenous healthcare systems by local and tribal communities for centuries.

As discussed earlier, different plants possess distinct phytochemical compositions that influence the synthesis of silver nanoparticles (AgNPs), affecting their size, shape, physicochemical properties, and biological activities. A comprehensive review of existing literature revealed that M. parvifolia has not yet been utilized for AgNP synthesis. The phytochemicals present in this plant are expected to serve as natural reducing, capping, and stabilizing agents, thereby enhancing the biological potential of the resulting nanoparticles.

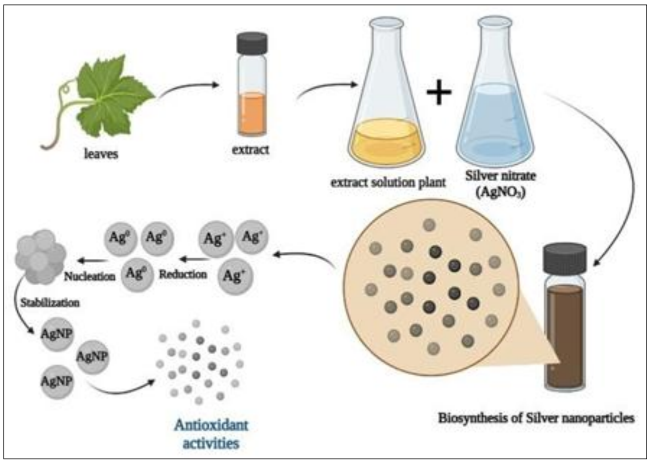
In the present study, M. parvifolia bark extract was employed for the microwave-assisted green synthesis of AgNPs, functioning simultaneously as a reducing, capping, and stabilizing medium. The synthesized AgNPs were characterized using UV–Vis spectroscopy, XRD, FTIR, TEM, SEM, EDX, SAED, particle size, and surface charge analyses. Their biological activities were further evaluated through *in vitro* antimicrobial assays (turbidimetric and plating methods), antioxidant tests (DPPH and ABTS radical scavenging assays), and cytotoxicity studies against human breast cancer cell lines (MCF-7 and MDA-MB-231) using the MTT assay. Additionally, antinociceptive and sedative activities of the synthesized AgNPs were examined in Swiss albino mice.

Fundamental Principle of MAS

The underlying principle of microwave-assisted synthesis distain -guises' itself through electromagnetic energy delivery within the 0.3–300 GHz spectrum, creating internal heat generation rather than relying on surface-to-core thermal transfer characteristics of traditional methodologies.22Conventional heating strategies necessitate sequential energy migration through conductive and convective pathways, inherently producing thermal gradients and extended processing durations.23The mechanism involved in MAS of Nano materials is depicted in. Polar molecules orison absorbs microwave radiation in the reaction mixture in microwave-assisted synthesis. Due to this absorption, localized heating occurs at the molecular scale and allows for breaking of chemical bonds and chemical reactions to begin.24This selective heating of reaction components provides a means of controlling reaction conditions, specificaly temperature, pressure, and reaction kinetics, with a degree of precision.25Microwave technology promotes simultaneous molecular agitation via dipole oscillation and charged particle migration throughout the entire reaction volume. While this internal energy deposition theoretically achieves homogeneous temperature paroles and accelerated kinetics, practical impel-mentation reveals challenges.25The vessel conjugration, reaction scale, and material dielectric characteristic introduce heterogeneous energy absorption patterns that compromise the uniformity assumption, raising concerns bout process reproducibility and commercial scalability potential. If uniform heating, a primary claimed advantage of MAS, cannot be reliably achieved, then comparative advantage saver conventional methods require reconsideration.

Synthesis of silver nanoparticles by hot plate heating

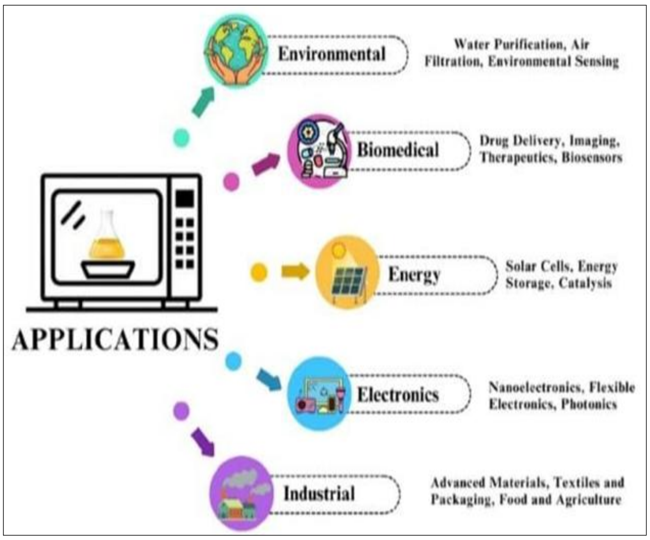
Silver nanoparticles (AgNPs) were synthesized by heating the reaction mixture on a hot plate, and the power consumption, cost, and CO_2 emissions associated with this method were compared to those of microwave-assisted synthesis. For this process, 35 mL of silver nitrate ($AgNO_3$) solution (2 mM) was mixed with 15 mL of Mitragyna parvifolia aqueous extract (MPAE) in a conical flask. The mixture was then heated on a hot plate magnetic stirrer (Tarsons Digital Spinot) maintained at 60 °C. A 7:3 ratio ($AgNO_3$: MPAE) was selected based on previous optimization, which produced the most uniform nanoparticles under microwave irradiation under similar conditions (Citation40). The heating was continued until the color of the reaction mixture changed to a deep brown, indicating the successful.



Applications

Nanomaterials, owing to their unique physicochemical properties at the nanoscale, have attracted significant attention across various disciplines for their potential to revolutionize industries and address critical societal challenges. The advantages of microwave-assisted synthesis (MAS) include rapid reaction kinetics, scalability, and the ability to produce nanomaterials with high purity and uniformity, making it highly suitable for applications in electronics, catalysis, and biomedical engineering.

These nanomaterials have demonstrated remarkable versatility, exhibiting enhanced performance and novel functionalities in fields such as biomedical applications, environmental remediation, and energy storage. Moreover, they play a vital role in advancing electronics, optoelectronics, and industrial miniaturization, contributing to improved power efficiency, multifunctionality, and sustainable technological development.



Conclusion

In summary, the comprehensive findings indicate that the green synthesis of silver nanoparticles (AgNPs) using M. parvifolia bark extract represents a highly promising and sustainable approach for the production of nanoparticles with potential applications in industrial and biomedical fields. The study revealed that the bark extract of M. parvifolia contains a wide spectrum of phytoconstituents—such as flavonoids, polyphenols, and tannins—which act as natural reducing, capping, and stabilizing agents during nanoparticle formation.

The synthesized AgNPs were thoroughly characterized using multiple analytical techniques, including UV–Vis spectroscopy, X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), energy-dispersive X-ray (EDX), transmission electron microscopy (TEM), and selected area electron diffraction (SAED). These analyses confirmed the successful formation of welldispersed, small-sized AgNPs with a negative surface charge.

The M. parvifolia-derived AgNPs (MPAgNPs) exhibited significant antimicrobial activity against various pathogenic strains such as Escherichia coli and Staphylococcus aureus. In addition, they demonstrated potent antioxidant and anticancer properties, likely attributed to the presence of phenolic and flavonoid compounds in the bark extract. The biosynthesized nanoparticles also showed notable antinociceptive and mild sedative effects, suggesting their potential utility across biomedical, pharmaceutical, and industrial applications. Overall, this study concludes that microwave-assisted green synthesis of AgNPs using M. parvifolia bark extract provides a cost-effective, eco-friendly, and efficient route for nanoparticle production. These nanoparticles exhibit multifunctional biological activities, making them promising candidates for applications in antimicrobial therapy, cancer treatment, pain management, antioxidant formulations, and drug delivery systems. Nonetheless, further mechanistic studies and in-depth clinical evaluations are required to elucidate their precise biological pathways and therapeutic efficacy.

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