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RESEARCH TITLE

Green Methods for Gold Nanoparticle Synthesis: Properties, Characterization, and Diverse Applications – Review Article

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Abstract

This paper presents a review on the environmentally friendly methods for the synthesis of gold nanoparticles. It explains the green synthesis methods, particle properties, and potential biological applications. This study demonstrates that gold nanoparticles have remarkable light absorption, good chemical stability, and multiple interactions with biological systems. Since conventionally synthesized nanoparticles are equipped with toxic chemicals, alternative, safer methods must be discovered. The paper discusses the synthesis of gold nanoparticles through different "green" methods, using natural sources such as plants and microorganisms—fungi and bacteria—as reducing and catalyzing agents.These green methods generally result in the production of nanoparticles with high purity to avoid contamination, long-term stability to ensure durability, and low toxicity for biomedical safety. Technically, the paper discusses the characterization techniques of different produced nanoparticles by UV–Vis spectroscopy and scanning electron microscopy. The research results show that the particle properties, such as size, dimensions, morphology, distribution, and crystallinity, are essential features that directly affect the performance of the particles under actual working conditions for most applications. This research proves the importance, feasibility, and usefulness of further research on the synthesis methods of gold nanoparticles. Expanding their application areas, especially in the future biotechnology and medical engineering sectors, is very necessary.

Key Words: Green Synthesis, Gold Nanoparticles (AuNPs), Biosynthesis, Nanotechnology, Biomedical Applications.

عنوان البحث

الطرق الخضراء لتخليق جسيمات الذهب النانوية الخصائص والتوصيف والتطبيقات – مقالة مراجعة

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المستخلص

تقدم هذه الورقة مراجعة للطرق الصديقة للبيئة لتخليق جسيمات النانو الذهبية. وتشرح طرق التخليق الخضراء وخصائص الجسيمات والتطبيقات البيولوجية المحتملة. وتوضح هذه الدراسة أن جسيمات النانو الذهبية تتمتع بامتصاص ضوئي رائع واستقرار كيميائي جيد وتفاعلات متعددة مع الأنظمة البيولوجية. ونظرًا لأن الجسيمات النانوية المصنعة تقليديًا مزودة بمواد كيميائية سامة، فيجب اكتشاف طرق بديلة أكثر أمانًا. وتناقش الورقة تخليق جسيمات النانو الذهبية من خلال طرق "خضراء" مختلفة، باستخدام مصادر طبيعية مثل النباتات والكائنات الحية الدقيقة – الفطريات والبكتيريا – كعوامل اختزال وتحفيز. وتؤدي هذه الطرق الخضراء عمومًا إلى إنتاج جسيمات نانوية عالية النقاء لتجنب التلوث، واستقرار طويل الأمد لضمان المتانة، وسمية منخفضة للسلامة الطبية الحيوية. من الناحية الفنية، تناقش الورقة تقنيات توصيف الجسيمات النانوية المختلفة المنتجة بواسطة مطيافية الأشعة فوق البنفسجية والمرئية والمجهر الإلكتروني الماسح. وتظهر نتائج البحث أن خصائص الجسيمات، مثل الحجم والأبعاد والشكل والتوزيع والبلورية، هي سمات أساسية تؤثر بشكل مباشر على أداء الجسيمات في ظل ظروف العمل الفعلية لمعظم التطبيقات. ويثبت هذا البحث أهمية وجدوى وفائدة إجراء المزيد من البحوث حول طرق تخليق جسيمات النانو الذهبية. وتوسيع مجالات تطبيقها، وخاصة في قطاعات التكنولوجيا الحيوية والهندسة الطبية في المستقبل، أمر ضروري للغاية.

الكلمات المفتاحية: التخليق الأخضر، جسيمات الذهب النانوية (*AuNPs*)، التخليق الحيوي، تكنولوجيا النانو، التطبيقات الطبية الحيوية.

1. Introduction

Nanoparticles have a long history in medicine since in ancient times they were used for therapeutic purposes such as colloidal gold. Modern applications of nanoparticles, however, did attract serious attention until the late 20th century when nanotechnology was relatively well advanced [1]. They are now extensively used for specific drug delivery systems, imaging and diagnostics, and cancer therapy. In most cases, nanoparticles are used to increase the accuracy of treatments due to enhanced solubility, stability, and focus of actions as well as side effects. Indeed, their applications cut across oncology, regenerative medicine, and vaccine development [2]. Nanoparticles have several physical and chemical properties because of their much larger surface area. Among several nanoparticles, metal nanoparticles of gold, silver, platinum, and palladium have gained prominent attention because of their catalytic activities, biological activities, optical activities, electrochemical applications, biotechnology, and electronic properties [3]. Further, they have plenty of applications in the field of analytical and electroanalytical fields since their properties are quite different compared with other metallic nanoparticles [4]. Apart from these, interest in AuNPs is quite strong for chemical stability and size with electronic structure-related electronic, optical, and spectroscopic properties used in research work. Moreover, the activities of AuNPs are also reported against animal and food pathogens [5]. The applications of AuNPs continue to broaden in studies related to pharmacokinetics, the environment, the space industry, as well as the analytical sector, which encompasses separation science. The stationary phases in separation techniques are ever-evolving to meet the regular demand in the field of the analytical sector [6].

2. Green Synthesis of Gold Nanoparticles

An elementary scientific consideration is the synthesis of nanoscale gold in the controlled phase or morphologies. The preparation of colloidal gold was described by Michael Faraday almost 150 years back using phosphorous for the reduction of $AuCl_4$ ions [17]. Over the last few years, several methodologies based on biological, physical, or chemical approaches have been developed for the synthesis of GNPs used in the fields of electrical, biotechnological, industrial, pharmaceutical, agricultural, or medical sectors. This method is used for the synthesis of well-defined compositions of gold nanostructures as colloids, clusters, wires, powders, tubes, rods, and thin films [18]. Physical and chemical approaches used for the synthesis of GNPs have been illustrated previously according to Figure 1. A few limitations were noticed in these synthesis approaches despite extensive research: they involved the use of harsh chemicals, highly stringent synthesis conditions, and high energy or capital requirements with less productivity [19]. The as-synthesized mix-shaped NPs need high-cost purification processes, such as the usage of a method of differential centrifugation. Further, these also led to more sludge and hazardous environmental risks due to the harmful solvents or additives [20]. Due to this, there has been an increased need for clean, nontoxic, ecologically friendly long-term synthesis methods. The major challenge is in developing high-yield, low-cost NPs production technologies. NPs have, in fact, attracted a wide variety of applications because of application diversity [21].

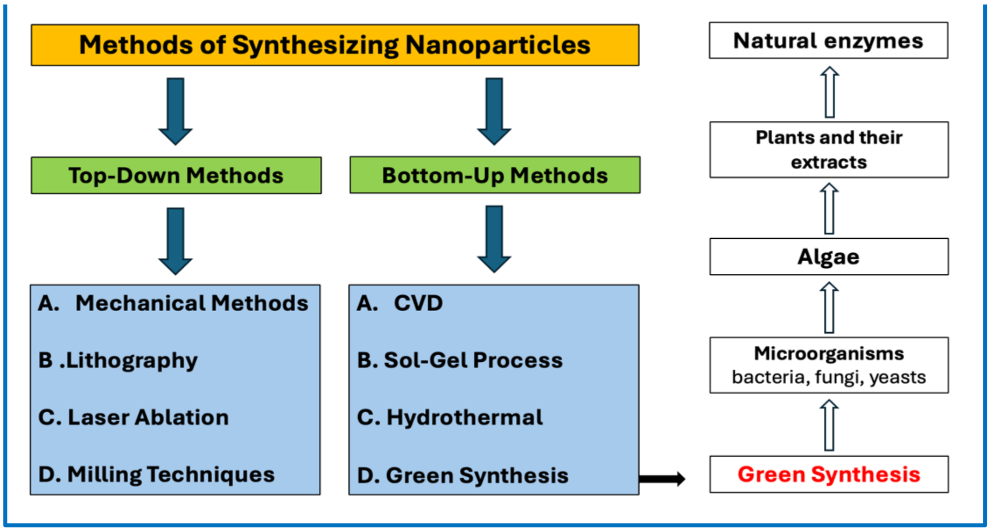

Figure 1: Schematic showing the methods for the synthesis of gold nanoparticles (AuNPs) [22]**.**

2.1 Plant-mediated synthesis

This is a process that depends on the natural compound of phenols and flavonoids found in the plants, which reduce the gold ions with no hazard or complexity of chemicals and thus need to be reduced to their nanometer size [23]. A solution of gold ions has to be brought into contact with the plant extract. It then catalyzes the reaction reduction, and nanoparticles are formed. This method is very simple and environmentally friendly because it uses plant resources that are abundant and easily accessible and does not require much energy or hazardous chemicals [24]. The particles obtained can be applied to medical fields such as drug carriers as well as in biosensor technology, hence a very promising and effective way of nanomaterial production [25].

Table 1: Biosynthesis of gold nanoparticles using different plant-reducing agents (leaves, fruits, flowers, seeds, bark, oils).

No.	Plant species	Part used	Shape	Analytical Techniques	Size (nm)	Applications	Ref.
1.	C. auriculata	Leaves	• Triangular • Spherical	• UV–VIS • FTIR • XRD • TEM • SEM • EDAX	15 - 25	• Antidiabetic activity	[27]
2.	D. kotschyi	Leaves	• Spherical	• TEM-SEAD • SEM-EDAX • XRD • ZP • DLS • FTIR	11	• Anticancer activity • Antibacterial activity	[28]
3.	C. papaya	Leaves	• Spherical • Triangular	• HRTEM • XRD • SEM • FTIR	2 - 20	• Antibacterial activity	[29]
4.	N.	Leaves	• Spherical	• HRTEM	2 - 10	• Antioxidant	[30]

	oleander			• SEM • XRD, FTIR, EDX		activity	
5.	P. dactylifera	Leaves	• Spherical	• UV–VIS • TEM • FTIR	32 - 45	• Catalytic activity	[31]
6.	P. benghalensis	Leaves	• Cubic	• UV–VIS • TEM • XRD • FTIR	13.07	• Photocatalytic activity	[32]
7.	Z. mauritiana	Leaves	• Spherical	• UV–VIS • SEM • XRD • FTIR	20 - 40	• Antibacterial activity	[33]
8.	S. nigrum	Leaves	• Spherical	• UV–VIS • TEM • XRD • FTIR • ZP • DLS	50	• Antioxidant activity • Antibacterial activity	[34]
9.	V. negundo	Leaves	• Spherical	• UV • FESEM • particle size analysis • ZP • SAED • HRTEM	98.65 - 71.86	• Drug delivery	[35]
10.	T. decandra	Leaves	• Spherical, hexagonal, cubical	• UV • FTIR • SEM • EDX	37.7 - 79.9	• Antimicrobial activity	[36]

2.2 Bacterial synthesis

Synthesis of gold nanoparticles using bacteria, this process involves the reduction of gold ions by bacteria through completely biological chemical reactions and the formation of gold nanoparticles. Because the bacteria secrete enzymes or some kind of natural compounds that react with the gold ions [77]. This method is described as environmentally friendly because it avoids the use of chemicals, and it is also economical. The size and geometric shape of the nanoparticles can be controlled by modifying the environmental conditions of the synthesis. [78].

Table 2: Biosynthesis of gold nanoparticles using different bacterial reducing agents.

No.	Scientific name	Category	Shape	Analytical Techniques	Size (nm)	Applications	Ref.
1.	Streptomyces sp.	Bacteria	Spherical	• UV-VIS • XRD • FTIR • SEM • EDXA • TEM	40	• Medicine	[79]
2.	Brevibacterium casei	Bacteria	Spherical	• UV-VIS • TEM • XRD • FTIR	10 - 50	• Biological activities	[80]
3.	Geobacillus stearothermophilus	Bacteria	Spherical	• UV-VIS • FTIR • TEM • XRD	12 - 14	• Heat transfer	[81]
4.	Bacillus stearothermophilus	Bacteria	Spherical, triangular	• TEM • SOE	5 - 30	• Biosensor • Biological Probes • Enzyme Catalysts	[82]
5.	Shewanella oneidensis	Bacteria	Spherical	• UV-VIS • FTIR • XRD • EDXA • TEM	2 - 50	• Antibacterial activity	[83]
6.	staphylococcus epidermidis	Bacteria	Spherical	• UV-VIS • TEM • FTIR	20 - 25	• Catalytic activity	[84]
7.	Lactobacillus sp.	Bacteria	Hexagonal	• TEM • SEM • EDXA • XRD	60 - 30	• Analytical chemistry • Nanotechnology • Medicine • Metal ion recovery	[85]
8.	pseudomonas veronii	Bacteria	Variable	• UV-VIS • FTIR • XRD • TEM	5 - 25	• Synthesis only	[86]
9.	Paracoccus haeundaensis BC74171 T	Bacteria	Spherical	• UV-VIS • FTIR • TEM • DLS	3.46±20.93	• Antioxidant activity	[87]
10.	Bacillus cereus	Bacteria	Spherical	• TEM • SEM • XPS • XRD	10 - 30	• Bionanocatalyst	[88]

2.3 Fungal synthesis

Fungi-mediated synthesis involves the ability of the fungi to secrete enzymes, which further reduce the gold ions into nanoparticles. This acts as a completely natural process without the enforcement of any sort of harmful chemicals, with fungi acting as biocatalysts [89]. The methodology is user-friendly and productive, whereby the nanoparticles thus formed find a great lot of applications in the field of medicinal and biotechnological purposes [90].

Table 3: Biosynthesis of gold nanoparticles using different fungal reducing agents.

No.	Scientific name	Category	Shape	Analytical Techniques	Size (nm)	Applications	Ref.
1.	Trichoderma viride and Hypocrea lixii	Fungi	Spherical, irregular	•UV-VIS •FTIR •TEM •XRD	20 - 30	•Biocatalytic activity •Antimicrobial activity	[91]
2.	Volvariella volvacea	Fungi	Triangular, spherical, hexagonal	•UV-VIS •SAED •XRD •FTIR	20 - 150	•Therapeutic	[92]
3.	Inonotus obliquus	Fungi	Spherical, triangle, hexagonal	•UV-VIS •TEM •FTIR	23	•Antibacterial activity •Antioxidant activity •Cytotoxicity activity	[93]
4.	Candida albicans	Fungi	Spherical	•UV-VIS •FTIR •TEM •AFM •Fluorescence spectroscopy	20 - 40	•Liver cancer screening	[94]
5.	Helminthosporium solani	Fungi	Variable	•UV-VIS •FTIR •XRD •TEM	3 - 80	•Anti-cancer activity	[95]
6.	Colletotrichum sp.	Fungi	Decahedral	•UV-VIS •FTIR •TEM	30 - 50	•Synthesis only	[96]
7.	Neurospora crassa	Fungi	Spherical	•TEM •SEM •EDS	3 - 80	•Synthesis only	[97]
8.	Penicillium brevicompactum	Fungi	Spherical	•TEM •XRD •FTIR •UV-VIS	20 - 60	•Cytotoxic activity	[98]
9.	Phanerochaete chrysosporium	Fungi	Spherical	•UV-VIS •XRD •FTIR •SEM •AFM	20 - 110	•Synthesis only	[99]
10.	Cylindrocladium floridanum	Fungi	Spherical	•UV-VIS •XRD •SEM •EDXA •HRTEM	19.05	•Synthesis only	[100]

2.4 Algal synthesis

The biosynthesis of gold nanoparticles is generally referred to as the reduction of gold ions to nanoparticles by algae using their natural biological property [101]. The choice of the algae species, extraction of biologically active molecules like proteins and sugars, which assist in this reduction, immobilization of the nanoparticles into aqueous extracts, and finally their stabilization into an ionic state is carried out in this process [102].

Table 4: Biosynthesis of gold nanoparticles using different algal reducing agents.

No.	Scientific name	Category	Shape	Analytical Techniques	Size (nm)	Applications	Ref.
1.	Sargassum muticum	Algae	Spherical	•UV–VIS •TEM •XRD •ZP	1.18 ±5.42	•Synthesis only	[105]
2.	Prasiola crispa	Algae	Spherical	•UV–VIS •TEM •XRD •FTIR •DLS	9.8	•Just synthesis	[106]
3.	Stylidium tenerrimum	Algae	Anisotropic	•UV–VIS •DLS •TEM •DLS •ZP •FTIR	5 - 45	•Catalytic activity	[107]
4.	Stoechospermum marginatum	Algae	Spherical	•FTIR •SEM •TEM •XRD •XRF •UV-VIS •PL	18.7 - 93.7	•antibacterial activity	[108]
5.	Sargassum swartzii	Algae	Spherical	•UV-VIS •Zeta Potential •TEM	35	•cytotoxicity activity	[109]
6.	Galaxaura Elongate	Algae	Spherical	•TEM •Zeta Potential •FTIR	3.85 - 77.13	•antibacterial activity	[110]
7.	Prasiola crispa	Algae	Spherical	•UV-VIS •XRD •TEM •FTIR •DLS	5 - 25	•Synthesis only	[111]
8.	Padina gymnospora	Algae	Spherical	•UV-VIS •SEM •FTIR •AFM •XRD	53 - 67	•Synthesis only	[112]
9.	Lemanea fluviatilis (L.)	Algae	face-centered	•UV-VIS •XRD	5.9	•Antioxidant activity	[113]

	C.Ag.		cubic	• TEM • FTIR • DLS • PL			
10.	Kappaphycus alvarezii	Algae	Spherical	• UV-VIS • FTIR • SEM • TEM • XRD	10 - 40	• Synthesis only	[114]

3. Gold Nanoparticles Characterization Techniques

Characterization of block stabilized gold nanoparticle samples by various techniques is expected to lead to homogeneity and orientation of the metal particles [115]. These techniques include surface characterization microscopy, spectrophotometry, X-ray spectroscopy, and flux properties.

3.1 UV-Visible Spectroscopy (UV-Vis)

The Ultraviolet-Visible (UV-Vis) spectroscopy technique is used to study the core chemistries of gold nanoparticles (AuNPs) via their interaction and absorption of UV and visible light rays. This can be explained by Gold Nanoparticles because AuNPs show what is known as Localized Surface Plasmon Resonance (LSPR), where there is vigorous oscillation of electrons on the surface of the nanoparticle upon interaction with incoming light [116]. Hence, there is a very intense peak of absorption noticed [117].

3.2 Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform Infrared (FTIR) spectroscopy determines chemical composition and surface functional groups of AuNPs; therefore, it is a valuable technique to know how molecules or functional groups are attached to the surface of the nanoparticles. The Fourier-transform infrared spectrometer measures the absorption of infrared light by the molecules at different wavelengths; the absorbed light excites vibration (stretching or bending) of the bonds between atoms in a molecule. The laboratory collects the vibrational spectra as peaks on an infrared spectrum to give a "fingerprint" of the chemical bonds and functional groups present [120].

3.3 X-ray diffraction (XRD) analysis

X-ray diffraction is one of the important procedures that can be used to study the structural features of gold nanoparticles synthesized by environmentally friendly methods. The crystalline structure of the particles is viewed using this technique by recording the angles of diffraction from the sample with X-rays incident upon it. X-rays are directed onto a sample of gold nanoparticles, after which angles at which the rays are reflected off and scattered by the atoms constituting the particles are measured; in the end, peaks appear on the spectrum, with each corresponding to a set of crystalline grains [122].

3.4 Transmission Electron Microscopy (TEM)

TEM is an advanced method of study for the structural and optical properties of green-synthesized gold nanoparticles [125]. An accurate view of the particles at the nanoscale can be obtained by TEM; hence, the shape, size, and distribution may be understood in detail. In TEM, the sample is bombarded by a beam of electrons if it is scanned with electrons penetrating the particles, generating an image based on how these electrons interact with the atoms inside the particles. Such images give the exact dimensions of the particles, thus helping in understanding size and shape distributions. The TEM will also show the crystal structure of the particles that way if the particles are of regular or random crystal structure [126].

3.5 Atomic Force Microscopy (AFM)

In this view, atomic force microscopy (AFM) ascertains the structural properties of gold nanoparticles in a diversity of applications. The exquisiteness of three-dimensional images of nanoparticles for size, shape, and surface distribution made possible by AFM is of much value [128]. Since the chemical and physical properties of gold nanoparticles are hugely dependent on their surface properties and size, size control became crucial and a study of its application in various fields [129]

4. Discussion

The size values of gold nanoparticles in Table 1 indicate that there is a large variation in the particle sizes, indicating that the type of plant extract is responsible for the synthesis of particles with different sizes, perhaps due to some chemical and biological factors present in the plant extract, which may induce the size of the nanoparticles. Therefore, it is necessary to choose the appropriate plant extract to synthesize the desired nanoparticles. Similarly, for the nanoparticles synthesized using fungal or bacterial extracts in Tables 2, 3 and 4. For the nanoparticles synthesized using bacterial extract, a relative stability was observed among most of the nanoparticle size distributions, with the majority of particles being between 10 and 40 nm. The more uniform distribution here compared to the plant extract indicates the fact that the bacterial extract can provide a more controlled environment for the production of nanoparticles with similar sizes. For the plant extract, a large variation in the sizes of the nanoparticles should be observed, with some particles being very large while others being small in size. This difference can be attributed to the various phytochemicals and enzymes; hence, nanoparticles of different sizes are generated, depending on the effects of these compounds on particle growth and synthesis.

Hence, the disparity in the size of the nanoparticles synthesized by each extract is due to the chemical and biological composition present in each organism, that is, fungi and algae. Different organic compounds and enzymes are contained in those two respective organisms, which then influence the speed or rather rate of nanoparticle formation and their sizes in different ways.

5. Conclusions

The present work deals with environmentally acceptable protocols available for the synthesis of gold nanoparticles, and it deals with their properties, characterization techniques, and applications. The green methods of synthesis consider non-toxic and natural materials rather than utilizing hazardous chemical reagents that cause severe effects on the environment. Several methods for the synthesis of gold nanoparticles using plants and microorganisms, bacteria, and fungi are established in this paper as safer and more economical substitutes. The methods produce nanoparticles of required physical and chemical properties, which are as effective as the traditional ones. Antioxidant and antibacterial properties in gold nanoparticles produced through green synthesis suggest their potential application in newer fields of biomedicine for the fabrication of biosensors, targeted therapies for the treatment of cancer by attacking cancer cells, and drug delivery systems. In addition, the techniques employed in the characterization of nanoparticles using electron microscopy and spectroscopy are reviewed. This helps in the study of structure and properties. The paper concludes by underlining the need for environmentally friendly techniques in nanomaterial synthesis and encouraging their extension to reduce effects on the environment and increase sustainability, with further research into uses in medicine, industry, and biotechnology.

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