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A review of the green syntheses and anti-microbial applications of gold nanoparticles

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ABSTRACT

Nanotechnology has emerged as a promising multidisciplinary field. It has shown several applications including diagnostics, imaging and structural design. Nanoparticles can be synthesized via chemical and physical approaches, carrying many threats to the ecosystem. To overcome these threats, sustainable routes for the synthesis of nanoparticles were implemented. Green synthesis is the most fascinating and attractive alternative to chemical synthesis as it offers more advantages. Nontoxic and eco-friendly secondary metabolites from plants are used as reducing and capping agents. This process is comparatively simple and cost-effective. A gold salt is simply reduced by biomolecules (phenols, alkaloids, proteins, etc.) present in the extracts of these plants. In this review, we have emphasized the synthesis and antimicrobial potential of gold nanoparticles using various plant extracts and their proposed mechanisms.

Abbreviation: Au: aurum; gold; DLS: dynamic light scattering; EDAX: energy-dispersive X-ray analysis; EDS: energy-dispersive spectroscopy; FTIR: Fourier transform infrared spectroscopy; HRTEM: high-resolution transmission electron microscopy; NPs: nanoparticles; UV-VIS: ultra violet-visible spectroscopy; SEM: scanning electron microscopy; XRD: X-ray Diffraction

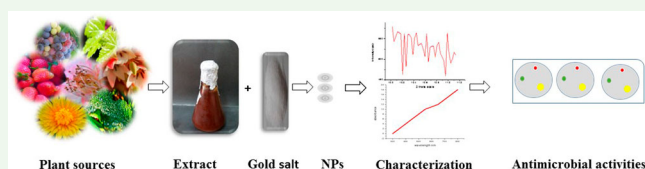
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Gold nanoparticles; green synthesis; biomedical applications; plants; antimicrobial; characterization



Introduction

The word “nano” is used as a prefix for one billionth part, i.e. 10^{-9} . Metallic nanoparticle sizes range from 1 to 100 nm (1,2). Due to their distinctive physical and chemical properties, metallic nanoparticles have been used in several fields, such as synthetic biology, health care, cellular transportations, food and optical devices (3). Among nanoparticles, gold nanoparticles (Au NPs) have unique surface morphologies, stable nature and controlled geometry (4). Most Au NPs are used in sensing, electronics, data packing, molecular switches and light-harvesting assemblies (5–8). Au NPs are also used in detection, diagnosis and treatments of several diseases (2,9). Recently, different methods have been used to synthesize NPs such as physical (sonication, laser ablation and radiation), chemical (condensation, sol gel method and reduction)

and biological methods (Figure 1). The conventional approaches have many challenges and encouraged researchers to find alternative approaches (9). The biological synthesis of nanoparticles is safe, dynamic and energy efficient (10,11). This method uses various biological resources ranging from prokaryotes to eukaryotes for *in vivo* production of NPs (12). Metabolites (proteins, fatty acids, sugars, enzymes, phenolic, etc.) in these sources are strongly involved in both bio reduction of metallic ions to NPs and their stabilization (Figure 2) (11). Furthermore, functional groups such as polyols and carboxylic acid have also been supposed to be responsible for the synthesis of NPs (13,14). The proposed mechanism of conversion is Au^{+3} into metallic Au^0 NPs by these bio reductants is emphasized in Figure 2 (15,16). Until now, the chemically synthesized

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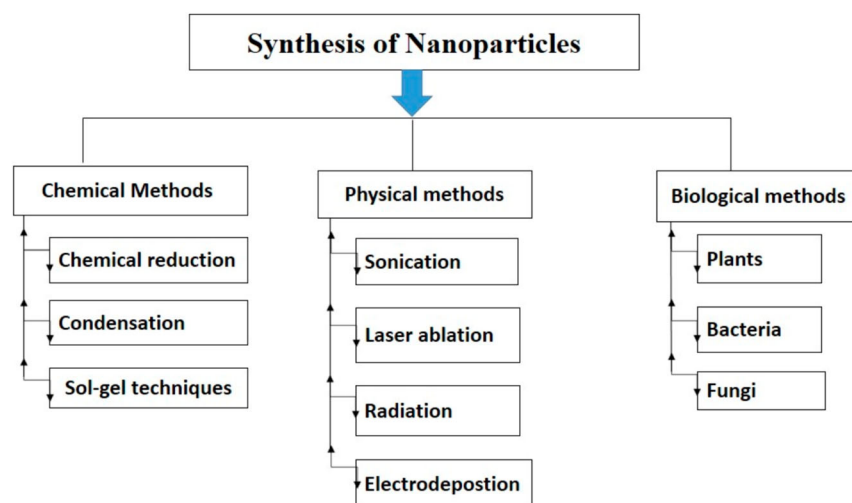


Figure 1. Various methods for making nanoparticles.

NPs have been used for these activities, but according to current reports, NPs synthesized via biological methods are more stable than others methods (17). This review mainly focuses on the synthesis of Au NPs using diverse biotic resources such as plants and microbes, with an emphasis on their applications, particularly their antimicrobial activities.

Plant green synthesis

Nanoparticles are synthesized through many physio-chemical processes which have posed numerous pressures on the environment. Plant-based synthesis of nanoparticles is a simple process, a metal salt is mixed with plant extract and the reaction completes in minutes to few hours at ordinary room temperature.

The metallic salt solution is reduced into respective nanoparticles (Figure 3) (18). This fashion of simplicity have got considerable attention during the last decade, especially gold nanoparticles (Au NPs), which are safer compared to other metallic NPs (19). Furthermore, their synthesis is quick, cost-effective, eco-friendly and can be scaled up easily.

Au NPs from leaf decoction of Indian borage (*Coleus amboinicus*) was reported by Narayanan and Sakthivel (20). FTIR results confirmed the existence of aromatic amines, amide groups and secondary alcohols that were claimed to be responsible for the stabilization and reduction of NPs. Elephant apple (*Dillenia indica*) fruit extract has been used to synthesize Au NPs of various morphologies. Phenolic compounds in the fruit extract were found accountable for the reduction of

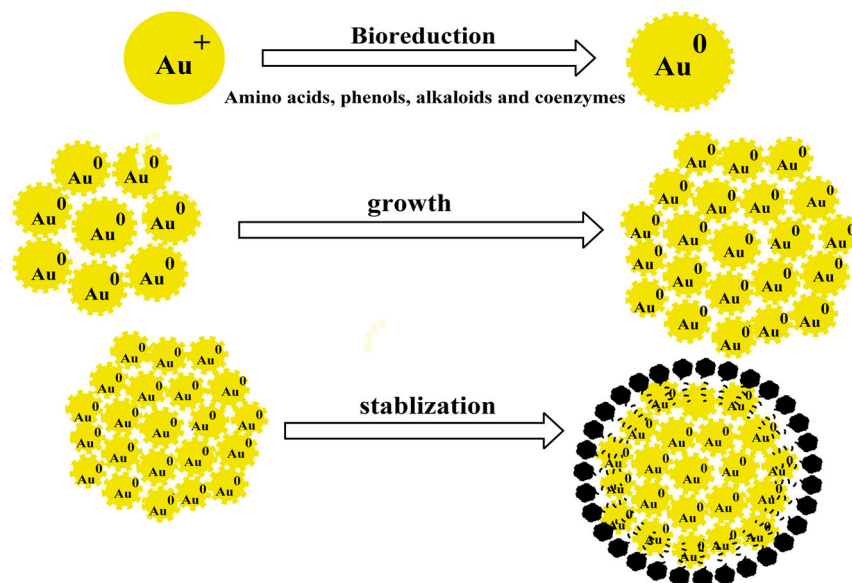


Figure 2. Mechanistic approach for green synthesis of Gold nanoparticles (Au NPs).

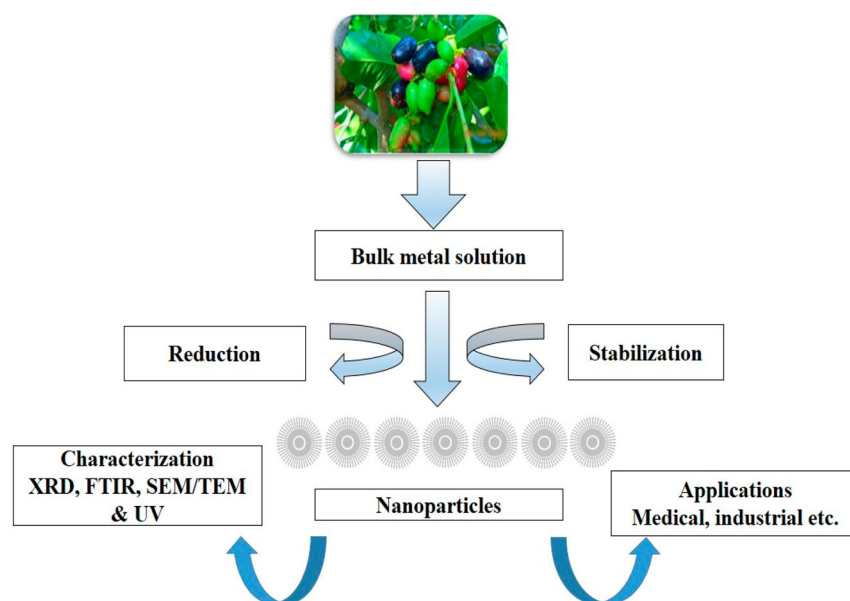


Figure 3. Green synthesis of nanoparticles from bulk metal solution.

the Au^{+3} to Au NPs (21). Triangular-shaped Au NPs were synthesized using tuber extract of *Dioscorea bulbifera*, commonly known as “air potato.” Complete reduction occurred after 5 h, leading to synthesis of NPs (22). Au NPs synthesized from leaf extract of medicinally important herb *Euphorbia hirta* had shown good antimicrobial potential (23). *Butea monosperma*, also known as “flame of forest”, leaf extract derived Au NPs conjugated with doxorubicin showed excellent anticancer potential (24). Leaf extract of coriander (*Coriandrum sativum*) was used to synthesize Au NPs, and depicted diversity in shapes and sizes (7–58 nm) (25). Au NPs synthesized from *Terminalia arjuna* leaf extract improved cell division and pollen development in *Allium cepa* and *Gloriosa superba* (26). Au NPs synthesized from ginger (*Zingiber officinale*), had been used as carrier for drug and gene transport (27). Au NPs synthesized using mint (*Mentha piperita*) leaf extract were documented to have

antimicrobial activity against gram-positive and gram-negative strains (28). Au NPs made from *Maytenus royleanus* indicated antileishmanial activity (29). Stable Au NPs using leaf extract of banana (*Musa paradisiaca*) have been reported. The extract contained carboxyl, amine and hydroxyl groups were ascribed to reduce Au^{+3} to Au NPs. The peel extract mediated AuNPs synthesis displayed efficient anti-fungal activity (30).

Gold nanoparticles were synthesized from medicinal shrub *Memecylon edule* leaves (10–45 nm). Saponins in the extracts were credited for higher yield of AuNPs (31). *Garcinia mangostana*, commonly known as mangosteen, fruit extract has been used to make Au NPs. The phenols, flavonoids, benzophenones and anthocyanins were used as reducing agents (32). Au NPs were synthesized using *Citrus reticulata*, *Citrus aurantium*, *Citrus sinensis* and *Citrus grandis* fruit extracts possessed considerable antimicrobial activity (33). Highly stable crystalline Au NPs were observed at pH 10, 100°C and 100 ppm aurochlorate, from *Momordica charantia* (34). Several other plants extract from different parts have been used for the synthesis of Au NPs as shown in Table 1.

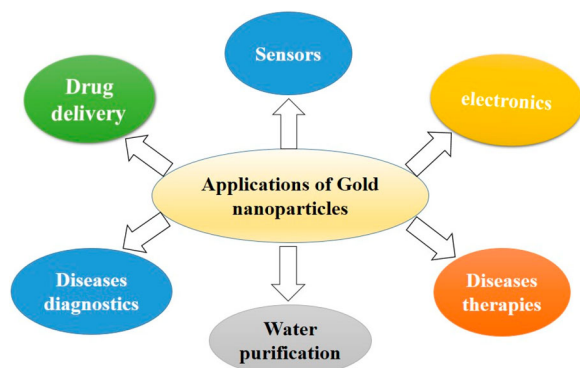


Figure 4. Various applications of Au NPs.

Applications of gold nanoparticles

In recent years, a dramatic surge has occurred in the field of nanotechnology, its applications ranging from medicine to engineering (101). The biocompatible nature of Au NPs makes them suitable for medical applications. Au NP conjugates are mostly used in the treatment of cancer, arthritis and antimicrobial therapies. When cancer cells are treated with green synthesized Au NPs

Table 1. Green synthesis of gold nanoparticles from different plants extracts.

References	Plant species	Common name	Part used	Shape	Characterization	Size (nm)
Alvarez et al. (9)	<i>Opuntia ficus-indica</i>	Barbary fig	Leaves	Diverse	TEM, UV	10–20
Rajan et al. (35)	<i>Areca catechu</i>	Palm	Nuts	Spherical	UV–VIS, TEM, XRD, and FTIR	13.7
Ganesan and Prabu (36)	<i>Acorus calamus</i>	Sweet flag	Rhizome	Spherical	SPR, UV–VIS, XRD and FTIR	<100
Chandran et al. (37)	<i>Aloe vera</i>	Indian Alces	Leaves	Spherical	UV–VIS–NIR TEM	15.2
Sheny et al. (13)	<i>Anacardium occidentale</i>	Cashew tree	Leaves	Spherical	UV–VIS, FTIR, XRD, HRTEM and SAED	6–17
Sheny et al. (38)	<i>Anacardium occidentale</i>	Cashew tree	Oils	Hexagonal	UV–VIS, TEM and FTIR	36
Bindhu and Umadevi (39)	<i>Ananas comosus</i>	Pineapples	Fruit	Tetrahedral	UV–VIS, TEM, and XRD	16
Venkatachalam et al. (40)	<i>Cassia auriculata</i>	Matura tea	Flower	Spherical	UV–VIS, XRD, GC–MS, FTIR, TEM and SEM with EDAX	12–41
Mukundan et al. (41)	<i>Bauhinia tomentosa</i>	Yellow bauhinia	Leaves	Spherical	SPR, EDAX, FESEM, and HRTEM	31.32
Shankar et al. (42)	<i>Azadirachta indica</i>	Neem	Leaves	Planar	UV–VIS, TEM and XRD	
Babu et al. (43)	<i>Bacopa monnieri</i>	Waterhyssop	Leaves	Spherical	TGA, UV–VIS, TEM and XRD	3–45
Geetha et al. (44)	<i>Couroupita guianensis</i>	Cannonball tree	Fruit	Diverse	UV–VIS, FTIR, XRD, SEM and TEM	7–48
Vilchis-Nestor et al. (45)	<i>Camellia sinensis</i>	Green tea	Leaves	Irregular	UV–VIS–NIR, TEM	40
Kumar et al. (46)	<i>Cassia auriculata</i>	Matura tea tree	Leaves	Triangular and spherical	TEM, SEM-EDAX, FTIR, UV–VIS, XRD	15–25
Dwivedi and Gopal (47)	<i>Chenopodium album</i>	Goosefoot	Leaves	Spherical	EDX, FTIR, TEM and XRD	10–30,
Huang and et al. (14)	<i>Cinnamomum camphora</i>	Camphor tree	Leaves	Triangular and spherical	SPR, EDX, FTIR and XRD	55–80
Naraginti and Sivakumar (48)	<i>Coleus forskohlii</i>	Indian Coleus	Root	Triangular	UV–VIS, XRD, FTIR and TEM	25–40
Sreekanth et al. (49)	<i>Dioscorea batatas</i> <i>Diospyros ferrea</i>	Chinese yam Black ebony or sea ebony	Rhizome Whole plant	Diverse	XRD, FTIR, UV–VIS and TEM SEM, UV and FTIR	18.48–56.18 70–90
Dorosti and Jamshidi (50)	<i>Dracocephalum kotschy</i>		Leaves	Spherical	TEM-SEAD, SEM-EDAX, XRD, ZP, DLS and FTIR	11
Pattanayak and Nayak (51)	<i>Elettaria cardamomum</i>	Cardamom	Seed		SPR, XRD and UV–VIS	
Ankamwar et al. (52)	<i>Embolia Officinalis</i>	Amla	Fruit	Spherical	UV–VIS–NIR and TEM	16.8
Guo et al. (53)	<i>Eucommia ulmoides</i>	Hardy rubber tree	Bark	Spherical	ZP, EDX, ZP, DLS and XRD	16.4
Raghunandan et al. (54)	<i>Psidium guajava</i>	Guava	Leaves		EDAX, UV–VIS, XRD and FESEM, AFM and TEM	27
Tamuly et al. (55)	<i>Gymnocladus assamicus</i>		Pod	Diverse	UV–VIS, XRD and HRTEM	4–22
Philip (56)	<i>Hibiscus rosa-sinensis</i>	Shoeblack plant	Leaves	Spherical	XRD, TEM, UV–VIS and FTIR	13
Bindhu et al. (57)	<i>Hibiscus cannabinus</i>	Kenaf	Stem	Spherical	XRD, TEM and FTIR, EDX and SPR	13
Kumar et al. (27)	<i>Zingiber officinale</i>	Ginger	Rhizome		DLS, TEM and FTIR	5–15
Basavegowda et al. (58)	<i>Hovenia dulcis</i>	Japanese Raisin	Fruit	Spherical and hexagonal	TEM, XRD, EDX and FTIR	20
Lokina et al. (59)	<i>Punica granatum</i>	Pomegranate	Fruit	Spherical and triangular	HRTEM, XRD, TGA and FTIR	5–17
Aromal et al. (60)	<i>Macrotyloma uniflorum</i>	Horse gram			TEM, XRD and FTIR	14–17
Song et al. (61)	<i>Magnolia kobus</i>	Mango	Leaves	Diverse	ICP, SEM, EDX, XPS and FTIR	5–300
Song et al. (61)	<i>Diospyros kaki</i>	Persimmon, kaki	Leaves	Diverse	ICP, SEM, EDX, XPS and FTIR	5–300
Yang et al. (62)	<i>Magnolia kobus</i>	Mango	Peel	Spherical	UV–VIS, TEM, XRD and FTIR	6.03–18
Suman et al. (63)	<i>Morinda citrifolia</i>	Indian mulberry, beach mulberry	Root	Spherical	UV–VIS, XRD, FTIR, FESEM, EDX and TEM	12.17–38.26
Philip et al. (64)	<i>Murraya koenigii</i>	Curry tree	Leaves	Diverse	UV–VIS, TEM, XRD and FTIR	~20,
Muthukumar et al. (65)	<i>Carica papaya</i>	Papaw	Leaves	Spherical and triangular	HRTEM, XRD, SEM and FTIR	2–20
Muthukumar et al. (65)	<i>Catharanthus roseus</i>	Madagascar periwinkle	Leaves	Spherical and triangular	HRTEM, XRD, SEM and FTIR	3.5–9
Tahir et al. (66)	<i>Nerium oleander</i>	Oleander	Leaves	Spherical	HRTEM, SEM, XRD, FTIR and EDX	2–10
Philip and Unni (67)	<i>Ocimum sanctum</i>	Tulsi, basil	Seed	Hexagonal	UV–VIS, TEM, XRD and FTIR	30
Khalil et al. (68)	<i>Olea europaea</i>	Olive	Leaves	Triangle	UV–VIS, TEM, XRD and FTIR	50–100
Parida et al. (69)	<i>Allium cepa</i>	Onion		Spherical and cubic	UV–VIS, TEM, SEM, and XRD	~100
Zayed and Eisa (70)	<i>Phoenix dactylifera</i>	Date	Leaves	Spherical	UV–VIS, TEM and FTIR	32–45
Islam et al. (71)	<i>Pistacia integerrima</i>	Chakarangi	Galls		UV–VIS, SEM and FTIR	20–200
Mata et al. (72)	<i>Plumeria alba</i>	White frangipani, Champa	Flower	Spherical	UV–VIS, TEM, and XRD and FTIR	28 ± 5.6–15.6 ± 3.4
Paul et al. (73)	<i>Pogostemon benghalensis</i>	Pangala	Leaves	Cubic	UV–VIS, TEM, XRD and FTIR	13.07

(Continued)

Table 1. Continued.

References	Plant species	Common name	Part used	Shape	Characterization	Size (nm)
Byranvand and Kharat (74)	<i>Pomegranate</i>	Pomegranate	Juice	Spherical	TEM, SAED, XRD, EDX and UV-VIS	5–15
Dubey et al. (75)	<i>Rosa rugosa</i>	Rosa rugosa	Leaves	Triangular and hexagonal	UV-VIS, TEM, XRD, FTIR, Zetasizer and EDX	11
Ahmed et al. (76)	<i>Salicornia brachiata</i>				XRD, TEM, FFT and FESEM	22–35
Islam et al. (33)	<i>Salix alba</i>	White willow	Leaves	Spherical	UV-VIS, AFM, SEM, and XRD and FTIR	50–80
Dhas et al. (77)	<i>Sargassum myriocystum</i>		Leaves	Triangular and spherical	UV-VIS, FTIR, TEM, SEM-EDAX, and XRD	15
Namvar et al. (78)	<i>Sargassum muticum</i>	Japanese wire weed,	Leaves	Spherical	UV-VIS, TEM, XRD and ZP	5.42 ± 1.18
Das and Velusamy (79)	<i>Sesbania grandiflora</i> L	Vegetable hummingbird		Triangular	FESEM, TEM, UV-VIS, TEM, XRD, EDX and FTIR	7–34.
Sharma et al. (80)	<i>Prasiola crispa</i>		Whole plant	Spherical	UV-VIS, TEM, XRD FTIR and DLS	9.8
Muthuvel et al. (81)	<i>Solanum nigrum</i>	Black nightshade	Leaves	Spherical	UV-VIS, TEM, XRD FTIR, ZP and DLS	50
Khademi-Azandehi and Moghaddam (82)	<i>Stachys lavandulifolia</i> Vahl	Betony	Aerial parts	Spherical and triangular	UV-VIS, TEM, FTIR and DLS	56.3
Sadeghi et al. (83)	<i>Stevia rebaudiana</i>	Sweet Leaf	Leaves	Spherical	UV-VIS, TEM, SEM, FTIR and XRD	5–20
Rajathi et al. (84)	<i>Stoechospermum marginatum</i>		Whole plant	Hexagonal and triangle	TEM, SEM, FTIR and XRD	18.7–93.7
Dubey et al. (85)	<i>Tanacetum vulgare</i>	Tansy	Fruit	Triangular, hexagonal and spherical	TEM, XRD, EDX and FTIR	10–40
Ramakrishna et al. (86)	<i>Turbinaria conoides</i>	Agar-agar lesong	Whole plant	Diverse	UV-VIS, DLS, TEM, DLS, ZP and FTIR	12–57
Ramakrishna et al. (86)	<i>Stylidium tenerrimum</i>		Whole plant	Anisotropic	UV-VIS, DLS, TEM, DLS, ZP and FTIR	5–45
Sadeghi (87)	<i>Zizyphus mauritiana</i>	Indian jujube	Leaves	Spherical	UV-VIS, SEM, XRD and FTIR	20–40
Devi et al. (88)	<i>Vitex negundo</i>	Sambhalu, Nirgundi	Leaves	Spherical	UV, FESEM, particle size analysis, ZP, SAED and HRTEM	98.65–71.86
Geethalakshmi and Sarada (89)	<i>Trianthema decandra</i>	Black Pigweed	Leaves	Spherical, hexagonal and cubical	UV, FTIR, SEM and EDX	37.7–79.9
Bindhu and Umadevi (90)	<i>Solanum lycopersicum</i>	Tomato	Fruit	Diverse	UV-VIS, TEM, EDS, XRD and FTIR	14
Sujitha and Kannan (91)	<i>Citrus limon</i>	Lemon	Fruit	Spherical	UV-VIS, TEM and XRD	32.2
	<i>Citrus reticulata</i>	Mandarin orange	Fruit	Spherical	UV-VIS, TEM and XRD	43.4
	<i>Citrus sinensis</i>	Sweet orange	Fruit	Spherical	UV-VIS, TEM and XRD	56.7
Vankar and Bajpai (92)	<i>Mirabilis jalapa</i>	Marvel of Peru	Flowers		UV-VIS, FTIR, TEM, XRD, EDAX and AFM	60–70
Godipurge et al. (93)	<i>Rivea hypocrateriformis</i>	Night Glory	Aerial parts	Spherical	UV-VIS, XRD, FTIR, FESEM/TEM, TGA and EDAX	10–50
Baharara et al. (94)	<i>Zataria multiflora</i>	Avishan-E-Shirazi	Leaves	Diverse	FTIR, TEM, DLS and ZP	10–42
Noruzi et al. (95)	<i>Thuja orientalis</i>	Biota	Leaves	Spherical	UV-VIS, TEM and XRD	
Gopinath et al. (96)	<i>Gloriosa superba</i>	Flame lily, Climbing lily, Creeping lily	Leaves	Triangular and spherical	FTIR, XRD and EDX AFM and TEM	20
Wang et al. (97)	<i>Dendropanax moribifera</i>		Leaves	Polygonal	UV-VIS, TEM-EDX, DLS and XRD	5–10
Khan et al. (98)	<i>Dimocarpus longan</i>	Longan	Fruit		XRD	25
Vijayakumar et al. (30)	<i>Musa paradisiaca</i>	Banana	Peel	Diverse	UV-VIS, SEM, DLS, FTIR and XRD	300
Oza et al. (99)	<i>Chlorella pyrenoidosa</i>		Whole plant	Spherical	UV-VIS, HRTEM and XRD	25–30
Poojary et al. (100)	<i>Mammea suriga</i>	Indian rose chestnut, Ceylon ironwood	Root	Square	UV-VIS, SEM, EDX, XRD and FTIR	50–22

Abbreviations: SPR, surface plasmon resonance; SAED, selected area (electron) diffraction; FESEM, field emission scanning electron microscope; NIR, near-infrared region; ZP, zeta potential; AFM, atomic-force microscopy; XPS, X-ray photoelectron spectroscopy; TGA, thermogravimetric analysis; FFT, fast fourier transform.

under electromagnetic radiations, thermal degradation of malignant cells occurs (102,103). Their ability of scattering light in the visible light region suggests that these NPs can be used as an alternative contrast mediator in microscopy. Under dark field light scattering, Au NPs can be used to detect metabolites, tumors, endocytosis and receptors in cells (104). Some Au NP-based

diagnostic kits are under clinical trials (105). Green synthesized Au NPs have also been used in the development of biosensors, quantification of blood glucose, disease markers, toxic metals and insecticides (104,106,107). Au NPs also have the potential to degrade and detoxify toxic pollutants (108,109). Some other applications have been shown in Figure 4.

Table 2. Antimicrobial activities of gold nanoparticles synthesized using plant extracts.

Plants species	Microbes tested	Method used	Ref
<i>Areca catechu</i>	<i>Klebsiella pneumoniae</i> , <i>Escherichia coli</i> , <i>Staphylococcus aureus</i> , <i>Pseudomonas aeruginosa</i> , <i>Enterobacter</i>	Agar well diffusion	Rajan et al. (35)
<i>Acorus calamus</i>	<i>Escherichia coli</i> , <i>Staphylococcus aureus</i>		Ganesan and Prabu (36)
<i>Ananas comosus</i>	<i>Staphylococcus aureus</i> , <i>Pseudomonas aeruginosa</i>		Bindhu and Umadevi (39)
<i>Coleus forskohlii</i>	<i>Pseudomonas aeruginosa</i> , <i>Escherichia coli</i> and <i>Staphylococcus aureus</i>		Naraginti and Sivakumar (48)
<i>Diospyros ferrea</i>	<i>Bacillus cereus</i> , <i>Klebsiella pneumoniae</i> , <i>Candida albicans</i> and <i>Microsporum gypseum</i>	Disc diffusion	Armash (127)
<i>Dracocephalum kotschy</i>	<i>Escherichia coli</i> , <i>Ps.aeruginosa</i> , and <i>Proteus vulgaris</i>	Cup-plate agar method	Dorosti and Jamshidi (50)
<i>Galaxaura elongate</i>	<i>Escherichia coli</i> , <i>Klebsiella pneumoniae</i> and MRSA, <i>Staphylococcus aureus</i> and <i>Pseudomonas aeruginosa</i>	Agar well diffusion	Abdel-Raouf et al. (128)
<i>Hibiscus cannabinus</i>	<i>Pseudomonas aeruginosa</i> and <i>Staphylococcus aureus</i>	Disc diffusion	Bindhu et al. (57)
<i>Hoveniadiculcis</i>	<i>Escherichia coli</i> and <i>Staphylococcus aureus</i>	Disc diffusion	Basavegowda et al. (58)
<i>Punica granatum</i>	<i>Staphylococcus aureus</i> , <i>Salmonella typhi</i> , <i>Vibrio cholerae</i> <i>Candida</i> <i>albicans</i> and <i>Aspergillus flavus</i>		Lokina et al. (59)
<i>Mentha piperita</i>	<i>Staphylococcus aureus</i> and <i>Escherichia coli</i>	Muller Hinton Agar plate	MubarakAli et al. (28)
<i>Maytenus royleanus</i>	<i>Leshmenia</i>		Ahmad et al. (29)
<i>Trichoderma sp</i>	<i>Pseudomonas syringae</i> , <i>Escherichia coli</i> , and <i>Shigella sonnei</i>	Broth and plate assay	Mishra et al. (129)
<i>Carica papaya</i>	<i>Escherichia coli</i> , <i>Bacillus subtilis</i> , <i>Staphylococcus aureus</i> , and <i>Proteus</i> <i>vulgaris</i>	Disc diffusion	Muthukumar et al. (65)
<i>Catharanthus roseus</i>	<i>Staphylococcus aureus</i> , <i>Bacillus subtilis</i> , <i>Escherichia coli</i> and <i>Proteus</i> <i>vulgaris</i>		
<i>Nepenthes khasiana</i>	<i>Escherichia coli</i> , <i>Bacillus</i> , <i>Candida albicans</i> and <i>Aspergillus niger</i>	Well diffusion method	Bhau et al. (130)
<i>Pistacia integerrima</i>	<i>Klebsiella pneumoniae</i> , <i>Bacillus subtilis</i> and <i>Staphylococcus aureus</i> , <i>Alternaria solani</i> , <i>Aspergillus niger</i> and <i>Aspergillus flavus</i>	well diffusion	Islam et al. (71)
<i>Plumeria alba</i>	<i>Escherichia coli</i>	Disc diffusion method	Mata et al. (72)
<i>Trianthema decandra L</i>	<i>Staphylococcus aureus</i> , <i>Enterococcus faecalis</i> , <i>Streptococcus faecalis</i> , <i>Escherichia coli</i> , <i>P. vulgaris</i> , <i>Pseudomonas aeruginosa</i> , <i>Bacillus subtilis</i> , <i>Yersinia enterocolitica</i> , <i>Klebsiella pneumoniae</i> and <i>Candida albicans</i>	Disc diffusion	Geethalakshmi and Sarada (89)
<i>Solanum nigrum</i>	<i>Staphylococcus saprophyticus</i> , <i>Bacillus subtilis</i> , <i>Escherichia coli</i> and <i>Pseudomonas aeruginosa</i>		Muthuvel et al. (81)
<i>Salicornia brachiata</i>	<i>Salmonella typhi</i> , <i>Escherichia coli</i> , <i>Pseudomonas aeruginosa</i> and <i>Staphylococcus aureus</i>	Disc diffusion method	Ahmed et al. (76)
<i>Dioscorea batatas</i>	<i>Staphylococcus epidermidis</i> , <i>Staphylococcus aureus</i> , and <i>Escherichia coli</i>		Sreekanth et al. (49)
<i>Euphorbia hirta</i>	<i>Escherichia coli</i> , <i>Pseudomonas aeruginosa</i> and <i>Klebsiella pneumoniae</i>	Broth dilution method	Annamalai et al. (23)
<i>Zizyphus mauritiana</i>	<i>Staphylococcus aureus</i>	Luria medium	Sadeghi (87)
<i>Caesalpinia pulcherrima</i>	<i>Aspergillus flavus</i> , <i>Escherichia coli</i> , <i>Aspergillus niger</i> , and <i>Streptobacillus</i>		Nagaraj et al. (131)
<i>Helianthus annuus</i>	<i>Aspergillus flavus</i> , <i>Aspergillus niger</i> , <i>Escherichia coli</i> and <i>Streptobacillus</i>		Liny et al. (132)
<i>Carthamus tinctoriusL</i>	<i>Aspergillus niger</i> , <i>Aspergillus flavus</i> , <i>Escherichia coli</i> and <i>Streptobacillus</i>		Nagaraj et al. (133)
<i>Salix alba</i>	<i>Klebsiella pneumoniae</i> , <i>Bacillus subtilis</i> <i>Staphylococcus aureus</i>	Well diffusion method	Islam et al. (33)
<i>Solanum lycopersicum</i>	<i>Staphylococcus aureus</i> and <i>Pseudomonas aeruginosa</i> ,		Bindhu and Umadevi (90)
<i>Rivea hypocrateriformis</i>	<i>Staphylococcus aureus</i> , <i>Klebsiella pneumoniae</i> , <i>Bacillus subtilis</i> , <i>Candida</i> <i>albicans</i> , <i>Escherichia coli</i> , <i>Pseudomonas aeruginosa</i> , <i>Trichophyton</i> <i>rubrum</i> and <i>Chrysosporium indicum</i>		Godipurge et al. (93)
<i>Gloriosa superba</i>	<i>Staphylococcus aureus</i> , <i>Streptococcus pneumoniae</i> , <i>Klebsiella</i> <i>pneumoniae</i> and <i>Escherichia coli</i>	Disc diffusion	Gopinath et al. (96)
<i>Dimocarpus longan</i>	<i>Staphylococcus aureus</i> and <i>Bacillus subtilis</i> .		Khan et al. (98)
<i>Mammea suriga</i>	<i>Staphylococcus aureus</i> , <i>B. subtilis</i> , <i>Escherichia coli</i> and <i>Pseudomonas</i> <i>aeruginosa</i>		Poojary et al. (100)

Antimicrobial activity of gold nanoparticles

Gold has been used for several centuries in the treatment of various disorders. Robert Koch first explored the biocidal potential of gold (110). Apart from their other applications, the antimicrobial activity of Au NPs has been mostly exploited (89). Nanoparticles mostly impede the electrostatic flux across membranes, resulting in distorted membranes (111,112). Moreover, nanoparticles also enhance the expression of genes helping in redox processes and thus leading to fungal and bacterial death (113). This antimicrobial potential is attributed to the distinctive surface chemistry, smaller size, polyvalent and photothermic nature (114–116). But the exact mechanism is poorly understood (117). Au NPs primarily react with sulfur or

phosphorus-holding bases, which are the most preferred spots for Au NPs attack. When NPs attach to thiol functional groups of enzymes (nicotinamide adenine dinucleotide (NADH) dehydrogenases), they interrupt the respiratory chains by generation of high amount of free radicals, leading to cell death (118). Another proposed hypothesis for cellular death is that these NPs decrease the ATPase activities; GNP may also inhibit the binding of tRNA to ribosomal subunit (118). While killing *Leishmania*, an elevated number of electrons are produced by Au NPs which yield ROS (O_2^{-2} and $\cdot OH$). These radicals destroy DNA and other cellular components of the pathogen (29). Another possible mechanism is that these Au NPs hamper the transmembrane H^+ efflux (119). The smaller size could also be attributed to antimicrobial potential, almost

250 times lesser than that of bacterial cell, which makes them easier to adhere with the cell wall and impede the cellular process leading to cellular death (89). Herdt et al. stated that gold surface can degrade DNA after interaction with their surface (120).

Antimicrobial potential of the NPs are affected by the size and surface chemistry (121). Increase in size will decrease their activity and vice versa (122). Which is also supported by study of Ahmad et al (119), according to their study 7 nm Au NPs restrict the trans membrane H^+ efflux of the *Candida species* more than the 15 nm Au NPs. Moreover, despite the size the antimicrobial activity was also different in case of cell wall composition. Au NPs showed highest activity against gram-negative bacteria than gram-positive bacteria. The cell wall of the gram-positive bacteria contains a thick layer of peptidoglycan, consisting of linear polysaccharide chains cross-linked by short peptides, thus forming a more rigid structure leading to difficult penetration of the Au NPs compared to the gram-negative bacteria where the cell wall possesses thinner layer of peptidoglycan (81,123). Other than the size of NPs and cell wall structure of bacteria, surface modification (coating or capping agents) concentration and purification methods also affect the antibacterial activity (124). Au NPs coated with cotton material exhibited better antibacterial activity (36). The efficacy of the antibacterial activity of Au NPs can also be increased by coating with antibiotics (125). The coating of aminoglycoside antibiotics with Au NPs has an antibacterial effect on a range of gram-positive and gram-negative bacteria (4). The synthesized Au NPs have shown enhanced antibacterial activity (35). It is very interesting that all these green synthesized Au NPs show efficient antibacterial activity against certain bacterial strains, especially compared to chemically synthesized Au NPs which showed nearly no antimicrobial activity against similar strains (126). The antibacterial activity may be due to the synergistic effect of the combination of Au NPs and extracts (124). Au NPs are synthesized using diverse plant extracts have been used for investigating their antimicrobial activities against different microbes (Table 2).

Conclusion and future prospects

Gold nanoparticles have multiple applications in various fields of science such as electronics, disease diagnostics and treatment, imaging, probes, catalytic, remediation and cellular transportation. Au NPs are being synthesized through different physicochemical methods. But, biogenic reduction of the gold salt to synthesize Au NPs is an inexpensive, eco-friendly and safe process. No toxic chemicals or contaminants are produced in this

process. Moreover, Au NPs of controlled size and morphology are also synthesized in huge amounts. Their stability and reduction potential are attributed to bio-active molecules present in these biological resources. Among these bio reductants, plant extracts are more beneficial than other biological resources. Therefore, in this prospect, using plant sources for Au NPs synthesis can open new horizons in future. But, a detailed study is needed to explore the exact mechanism and metabolites involved in the reduction process. Once explored, it will revolutionize the synthesis of Au NPs on both laboratory and commercial scale.

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