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.

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
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 physiochemical 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 1. Various methods for making nanoparticles.](image1)

![Figure 2. Mechanistic approach for green synthesis of Gold nanoparticles (Au NPs).](image2)
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 monosperman, 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.

**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)          | Opuntia ficus-indica           | Barbary fig                  | Leaves    | Diverse                     | TEM, UV                      | 10–20     |
| Rajan et al. (33)           | Arecaceae catechu              | Palm                         | Nuts      | Spherical                   | UV–VIS, TEM, XRD, and FTIR   | 13.7      |
| Ganesan and Prabu (36)      | Acorus calamus                 | Sweet flag                   | Rhizome   | Spherical                   | SPR, UV–VIS, XRD and FTIR    | <100      |
| Chandran et al. (37)        | Aloe vera                      | Indian Aces                  | Leaves    | Spherical                   | UV–VIS, NIR, TEM             | 15.2      |
| Sheny et al. (13)           | Anacardium occidentale         | Cashew tree                  | Leaves    | Spherical                   | UV–VIS, FTIR, XRD, HTEM      | 6–17      |
| Sheny et al. (38)           | Anacardium occidentale         | Cashew tree                  | Oils      | Hexagonal                   | UV–VIS, TEM and FTIR         | 36        |
| Bindhu and Umadevi (39)     | Ananas comosus                 | Pineapples                   | Fruit     | Tetrahedral                 | UV–VIS, TEM and XRD          | 16        |
| Venkatachalam et al. (40)   | Cassia auriculata              | Matura tea                   | Flower    | Spherical                   | UV–VIS, XRD, GC–MS, FTIR, TEM and SEM with EDAX | 12–41 |
| Mukundan et al. (41)        | Bauhinia tomentosa             | Yellow bauhinia              | Leaves    | Spherical                   | SPR, EDAX, FESEM, and HRTem  | 31.32     |
| Shankar et al. (42)         | Azadirachta indica             | Neem                         | Leaves    | Planar                      | UV–VIS, TEM and XRD          | 10–30     |
| Babu et al. (43)            | Bacopa monnieri                | Waterhyssop                  | Leaves    | Spherical                   | TGA, UV–VIS, TEM and XRD     | 3–45      |
| Geetha et al. (44)          | Couroupita guianensis          | Cannonball tree              | Fruit     | Diverse                     | UV–VIS, FTIR, XRD, SEM and TEM | 7–48     |
| Vilchis-Nestor et al. (45)  | Camellia sinensis              | Green tea                    | Leaves    | Irregular                   | UV–VIS–NIR, TEM              | 40        |
| Kumar et al. (46)           | Cassia auriculata              | Matura tea                   | Leaves    | Triangular and spherical    | XRD, FTIR, UV–VIS and TEM    | 18.48–56.18 |
| Dwivedi and Gopal (47)      | Chenopodium album              | Goosefoot                    | Leaves    | Spherical                   | EDX, FTIR, TEM and XRD       | 55–80     |
| Huang and et al. (48)       | Cinnamomum camphora            | Camphor tree                 | Leaves    | Triangular and spherical    | SPR, EDX, FTIR and XRD       | 3–5       |
| Narangini and Sivakumar (48)| Coleus forskohlii              | Indian Coleus                | Root      | Triangular                  | UV–VIS, XRD, FTIR and TEM    | 25–40     |
| Sreekanth et al. (49)       | Dioscorea batatas              | Chinese yam                  | Leaves    | Irregular                   | XRD, FTIR, UV–VIS and TEM    | 18.48–56.18 |
| Dorost and Jamshidi (50)    | Diospyros ferrea               | Black ebony or sea ebony     | Pod       | Diverse                     | TEM, SEAD, SEM-EDAX, XRD, DLS and FTIR | 11     |
| Pattanayak and Nayak (51)   | Dracocophalum kotschi          | Cardamom                     | Leaves    | Spherical                   | SPR, XRD and UV–VIS          |           |
| Ankamwar et al. (52)        | Emblica officinalis            | Amla                         | Leaves    | Spherical                   | UV–VIS–NIR and TEM           | 16.8      |
| Guo et al. (53)             | Eucommia ulmoides              | Hardy rubber tree            | Leaves    | Spherical                   | ZP, EDX, ZP, DLS and XRD     | 16.4      |
| Raghunandan et al. (54)     | Psidium guajava                | Guava                        | Leaves    | Spherical                   | EDAX, UV–VIS, XRD and FESEM, AFM and TEM | 27       |
| Tamuly et al. (55)          | Gymnocladus asamnicus          | Pod                           | Diverse   | UV–VIS, XRD and HRTEm       | 4–22                         |
| Philip (56)                 | Hibiscus rosa-sinensis         | Shoeblack plant              | Leaves    | Spherical                   | XRD, TEM, UV–VIS and FTIR    | 13        |
| Bindhu et al. (57)          | Hibiscus cannabinus            | Renaf                         | Leaves    | Spherical                   | XRD, TEM and FTIR, EDX and SPR | 13       |
| Kumar et al. (27)           | Zingiber officinale            | Ginger                       | Leaves    | Spherical                   | DLS, TEM and FTIR            | 5–15      |
| Basavegowda et al. (58)     | Hovenia dulcis                 | Japanese Raisin              | Leaves    | Hexagonal                   | TEM, XRD, EDX and FTIR       | 20        |
| Lokina et al. (59)          | Punica granatum                | Pomegranate                  | Fruit     | Spherical                   | TEM, XRD, TGA and FTIR       | 5–17      |
| Aromal et al. (60)          | Macrotyma uniflorum            | Horse gram                   | Leaves    | Spherical                   | TEM, XRD and FTIR            | 14–17     |
| Song et al. (61)            | Magnolia kobus                 | Mango                        | Leaves    | Diverse                     | ICP, SEM, EDX, XPS and FTIR  | 3–500     |
| Yang et al. (62)            | Diospyros kaki                 | Persimmon, kaki              | Leaves    | Diverse                     | ICP, SEM, EDX, XPS and FTIR  | 3–500     |
| Sumon et al. (63)           | Magnolia kobus                 | Mango                        | Leaves    | Spherical                   | UV–VIS, TEM, XRD and FTIR    | 6.03–18   |
| Philip et al. (64)          | Morinda citrifolia             | Indian mulberry, beach mulberry | Roots | Spherical                   | UV–VIS, XRD, FTIR, FESEM, EDX and TEM | 12.17–38.26 |
| Muthukumar et al. (65)      | Murraya koenigii               | Curry tree                   | Leaves    | Diverse                     | UV–VIS, TEM, XRD and FTIR    | ~20,      |
| Muthukumar et al. (65)      | Carica papaya                  | Papaw                        | Leaves    | Spherical                   | HRTEm, XRD, SEM and FTIR     | 2–20      |
| Tahir et al. (66)           | Nerium oleander                | Oleander                     | Leaves    | Spherical                   | TEM, XRD and FTIR            | 3.5–9     |
| Philip and Unni (67)        | Ocimum sanctum                 | Tuli, basil                  | Seed      | Hexagonal                   | UV–VIS, TEM, XRD and FTIR    | 30        |
| Khalil et al. (68)          | Olea europea                   | Olive                        | Leaves    | Triangle                    | UV–VIS, TEM, XRD and FTIR    | 50–100    |
| Parida et al. (69)          | Allium cepa                    | Onion                        | Leaves    | Cubic                       | UV–VIS, TEM, XRD, EDX        | ~100      |
| Zayed and Eisa (70)         | Phoenix dactylifera            | Date                         | Leaves    | Spherical                   | UV–VIS, TEM and FTIR         | 32–45     |
| Islam et al. (71)           | Pistacia integerrima           | Chakarangi                   | Galls     | Spherical                   | UV–VIS, SEM and FTIR         | 20–200    |
| Mata et al. (72)            | Plumeria alba                  | White frangipani, Champa     | Flower    | Spherical                   | UV–VIS, TEM, XRD and FTIR    | 28 ± 5.6–15.6 ± 3.4 |
| Paul et al. (73)            | Pogostemon bengalensis         | Pangala                      | Leaves    | Cubic                       | UV–VIS, TEM, XRD and FTIR    | 13.07     |

(Continued)
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 1. Continued.

| References | Plant species | Common name | Part used | Shape | Characterization | Size (nm) |
|------------|---------------|-------------|-----------|-------|------------------|-----------|
| Byranvand and Kharat (74) | Pomegranate | Pomegranate Juice | Spherical | TEM, SAED, XRD, EDX and UV–VIS | 5–15 |
| Dubey et al. (75) | Rosa rugosa | Rosa rugosa Leaves | Triangular and hexagonal | UV–VIS, TEM, XRD, FTIR | 11 |
| Ahmed et al. (76) | Salix alba | White willow Leaves | Spherical | XRD, TEM, FT and FESEM | 22–35 |
| Islam et al. (83) | Salix alba | White willow | UV–VIS, AFM, SEM, and XRD and FTIR | 50–80 |
| Dhas et al. (77) | Sargassum myriocystum | Leaves | Triangular and spherical | UV–VIS, FTIR, TEM, SEM–EDAX, and XRD | 15 |
| Gopinath et al. (78) | Sargassum muticum | Japanese wire weed, Vegetable hummingbird | Spherical | UV–VIS, TEM, XRD and ZP | 5.42 ± 1.18 |
| Vijayakumar et al. (79) | Sesbania grandiflora | Vegetable | Triangular | FESEM, TEM, UV–VIS, TEM, XRD, EDX and FTIR | 7–34 |
| Oza et al. (80) | Prasiliola crispa | Whole plant | Spherical | UV–VIS, TEM, XRD FTIR and DLS | 9.8 |
| Muthuvel et al. (81) | Solanum nigrum | Black nightshade | Spherical | UV–VIS, TEM, XRD FTIR, ZP and DLS | 50 |
| Khademi-Azandehi and Moghadam (82) | Stachys lavandulifolia | Betony Aerial parts | Spherical and triangular | UV–VIS, TEM, FTIR and DLS | 56.3 |
| Sadeghi et al. (83) | Stevia rebaudiana | Sweet Leaf Leaves | Spherical | UV–VIS, TEM, SEM, FTIR and XRD | 5–20 |
| Rajathi et al. (84) | Stoechosperum marginatum | Whole plant | Hexagonal and triangular | TEM, SEM, FTIR and XRD | 18.7–93.7 |
| Dubey et al. (85) | Tanacetum vulgare | Tansy Fruit | Triangular, hexagonal and spherical | TEM, XRD, EDX and FTIR | 10–40 |
| Ramakrishna et al. (86) | Turbinaria conoides | Agar-agar lesong Whole plant | Diverse | UV–VIS, DLS, TEM, DLS, ZP and FTIR | 12–57 |
| Ramakrishna et al. (86) | Stylidium teneurum | Whole plant | Anisotropic | UV–VIS, DLS, TEM, DLS, ZP and FTIR | 5–45 |
| Sadeghi (87) | Zizyphus mauritiana | Indian jujube | Spherical | UV–VIS, TEM, XRD and FTIR | 20–40 |
| Devi et al. (88) | Vitis negundo | Sambhalu, Nirgundi Leaves | Spherical | UV, FESEM, particle size analysis, ZP, SAED and HRTEM | 98.65–71.86 |
| Geethalakshmi and Sarada (89) | Triandema decandra | Black Pigweed | Leaves | UV, FTIR, SEM and EDX | 37.7–79.9 |
| Bindhu and Umadevi (90) | Solanum lycopersicum | Tomato | Spherical | UV–VIS, TEM, EDS, XRD and FTIR | 14 |
| Sujitha and Kannan (91) | Citrus limon | Lemon | Spherical | UV–VIS, TEM and XRD | 32.2 |
| Citrus reticulata | | Mandarin orange | Spherical | UV–VIS, TEM and XRD | 43.4 |
| Citrus sinensis | | Sweet orange | Spherical | UV–VIS, TEM and XRD | 56.7 |
| Mirabilis jalapa | Marvel of Peru Flowers | Spherical | UV–VIS, TEM, XRD, EDAX and AFM | 60–70 |
| Godipurge et al. (93) | Rivea hypocrateriformis | Night Glory Aerial parts | Spherical | UV–VIS, XRD, FTIR, FESEM/ TEM, TGA and EDAX | 10–50 |
| Baharara et al. (94) | Zataria multiflora | Avishan-E-Shirazi Biota | Diverse | FTIR, TEM, DLS and ZP | 10–42 |
| Noruzi et al. (95) | Thuja orientalis | Leaves | Spherical | UV–VIS, TEM and XRD | 20 |
| Gopinath et al. (96) | Gloriosa superba | Flame lily, Climbing lily, Creeping lily Leaves | Spherical | UV–VIS, TEM, XRD AFM and TEM | 5–10 |
| Wang et al. (97) | Dendropanax morihera | Leaves | Spherical | UV–VIS, TEM-EDX, DLS and XRD | 25 |
| Khan et al. (98) | Dimocarpus longan | Longan | Fruit | XRD | 25 |
| Vijayakumar et al. (30) | Musa paradisiaca | Banana Peel | Diversity | UV–VIS, SEM, DLS, FTIR and XRD | 300 |
| Oza et al. (99) | Chlorella pyrenoidusa | Whole plant | Spherical | UV–VIS, HRTEM and XRD | 25–30 |
| Poojary et al. (100) | Mammea suriga | Indian rose chestnut, Ceylon ironwood | Root | Square | UV–VIS, TEM, EDX, XRD and FTIR | 50–22 |
### Table 2. Antimicrobial activities of gold nanoparticles synthesized using plant extracts.

| Plants species          | Microbes tested                                    | Method used          | Ref          |
|-------------------------|----------------------------------------------------|----------------------|--------------|
| Areca catechu           | Klebsiella pneumoniae, Escherichia coli, Staphylococcus aureus, Pseudomonas aeruginosa, Enterobacter | Agar well diffusion  | Rajan et al. (35) |
| Acorus calamus          | Escherichia coli, Staphylococcus aureus            | Ganesan and Prabu (36) |
| Ananas comosus          | Staphylococcus aureus, Pseudomonas aeruginosa      | Bindhu and Umadevi (39) |
| Coleus forskohlii       | Pseudomonas aeruginosa, Escherichia coli and Staphylococcus aureus and Pseudomonas aeruginosa | Naraginti and Sivakumar (48) |
| Diospyros ferrrea        | Bacillus cereus, Klebsiella pneumoniae, Candida albicans and Microsporum gyipseum | Armash (127) |
| Dracocephalum kotschyi   | Escherichia coli, Ps. aeruginosa, and Proteus vulgaris | Dorosti and Jamshidi (50) |
| Galalaxa elongate        | Escherichia coli, Klebsiella pneumoniae and MRSA, Staphylococcus aureus and Pseudomonas aeruginosa | Abdel-Rauf et al. (128) |
| Hibiscus cannabinus      | Pseudomonas aeruginosa and Staphylococcus aureus   | Bindhu et al. (57) |
| Hoveni dulcis           | Escherichia coli and Staphylococcus aureus         | Basavegowda et al. (58) |
| Punica granatum         | Staphylococcus aureus, Salmonella typhi, Vibrio cholerae Candida albicans and Aspergillus flavus | Lokina et al. (59) |
| Mentha piperita          | Staphylococcus aureus and Escherichia coli         | Muller Hinton Agar plate | MubarakAli et al. (28) |
| Maytenus royleanus       | Leshmenia                                           | Ahmad et al. (29)    |
| Trichoderma sp           | Pseudomonas syringae, Escherichia coli, and Shigella sonnei | Broth and plate assay | Mishra et al. (129) |
| Carica papaya            | Escherichia coli, Bacillus subtilis, Staphylococcus aureus, and Proteus vulgaris | Disc diffusion      | Muthukumar et al. (65) |
| Catharanthus roseus      | Staphylococcus aureus, Bacillus subtilis, Escherichia coli and Proteus vulgaris | Well diffusion method | Bhu et al. (130) |
| Nepenthes khasiana       | Escherichia coli, Bacillus, Candida albicans and Aspergillus niger | Islam et al. (71) |
| Pistacia integerrima     | Klebsiella pneumonia, Bacillus subtilis and Staphylococcus aureus, Alternaria solani, Aspergillus niger and Aspergillus flavus | Mota et al. (72) |
| Plumeria alba            | Escherichia coli                                   | Geethalakshmi and Sarada (89) |
| Trianthera decandra L    | Staphylococcus aureus, Enterococcus faecalis, Streptococcus faecalis, Escherichia coli, P. vulgaris, Pseudomonas aeruginosa, Bacillus subtilis, Yersinia enterolcolica, Klebsiella pneumoniae and Candida albicans | Well diffusion method | Muthuvel et al. (87) |
| Solanum nigrum           | Staphylococcus saprophyticus, Bacillus subtilis, Escherichia coli and Pseudomonas aeruginosa | Muthuvel et al. (87) |
| Salicornia brachiata     | Salmonella typhi, Escherichia coli, Pseudomonas aeruginosa and Staphylococcus aureus | Disc diffusion method | Ahmed et al. (76) |
| Dioscorea batatas        | Staphylococcus epidermidis, Staphylococcus aureus, and Escherichia coli | Broth dilution method | Sreekhanth et al. (49) |
| Euphorbia hirta          | Escherichia coli, Pseudomonas aeruginosa and Klebsiella pneumoniae | Luria medium         | Annamalai et al. (23) |
| Zizyphus mauritana       | Staphylococcus aureus                              | Sadeghi (87)         |
| Caesalpinia pulcherrima  | Aspergillus flavus, Escherichia coli, Aspergillus niger, and Streptobacillus | Nagaraj et al. (131) |
| Helianthus annuus        | Aspergillus flavus, Aspergillus niger, Escherichia coli and Streptobacillus | Liny et al. (122) |
| Carthamus tinctorius L   | Aspergillus niger, Aspergillus flavus, Escherichia coli and Streptobacillus | Nagaraj et al. (133) |
| Salix alba               | Klebsiella pneumonia, Bacillus subtilis Staphylococcus aureus | Well diffusion method | Islam et al. (33) |
| Solanum lycopersicums    | Staphylococcus aureus and Pseudomonas aeruginosa, | Bindhu and Umadevi (90) |
| Rivea hypocrateriformis  | Staphylococcus aureus, Klebsiella pneumonia, Bacillus subtilis, Candida albicans, Escherichia coli, Pseudomonas aeruginosa, Trichophyton rubrum and Chrysosporum indicum | Godipurge et al. (93) |
| Gloriosa superba         | Staphylococcus aureus, Streptococcus pneumoniae, Klebsiella pneumoniae and Escherichia coli | Disc diffusion      | Gopinath et al. (96) |
| Dimocarpus longan        | Staphylococcus aureus and Bacillus subtilis, | Khan et al. (98) |
| Mammee suringa           | Staphylococcus aureus, B. subtilis, Escherichia coli and Pseudomonas aeruginosa | 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 radicles, 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 (O2•- and ‘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, imagining, 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 bioactive 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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**Disclosure statement**

No potential conflict of interest was reported by the authors.

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