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Plant-Mediated green synthesis of copper, gold, and silver nanoparticles: Biomedical applications and future prospects

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This review examines the applicability of using plant-based compounds to achieve ecologically benign and economical synthesis of copper, gold, and silver nanoparticles. Biological methods are preferred in green chemistry over traditional chemical and physical methods because they utilise the natural reduction and capping capabilities of the plant to yield cleaner synthesised products. Applying techniques such as UV-visible spectroscopy, XRD, FTIR, TEM, XPS, and SEM, the paper examines how extract content, pH level, temperature, and reaction time affect nanoparticle properties. The resulting nanoparticles are of low toxicity and high biocompatibility and are thus ideal for a range of biomedical applications such as antibacterial activity, targeted drug delivery, cancer treatment, imaging, and diagnosis. Nanostructures of various types, such as bacterial, fungal, or plant extracts, as well as hybrid nanomaterials, can be synthesised by this consistent method. On the whole, green nanoparticle synthesis is a potential and sustainable alternative to traditional synthesis, and this article contains an extensive review of available data and techniques in producing innovative nanomaterials by this approach.

Keywords*:* Antibacterial, Anticancer, Copper nanoparticle, Gold nanoparticle, Green synthesis, Silver nanoparticle

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Introduction

Nanotechnology is concerned with nanosized materials and structures, which are defined to be between 1 and 100 nm in size. This modern discipline of science is primarily concerned with the creation of nanomaterials and their potential uses in sectors such as optoelectronics, catalysis, sensors, solar energy conversion, magnetic, thermal, and medicine[1]. Nanomaterials have distinct characteristics from bulk materials. The optical, catalytic, and conductive properties of metal nanoparticles are influenced by their size and form[2]. The combination of biological techniques with metal nanoparticles has created a new field of nanomedicine[3]. Nanoparticles have extraordinary properties, including high yield strength, high surface-to-volume ratio, stiffness, flexibility, specific magnetisation, and quantum size, which are not equivalent as bulk substances having same chemical compositions[4]. Nanoparticles are assumed to have been on Earth since its formation, in the form of water, soil, volcanic dust, and minerals. Aside from being naturally created, humans have also begun synthesising nanoparticles[5]. Various physical and chemical approaches are used to synthesise appealing nanoparticles. Biological synthesis is recommended for its safety, cleanliness, cost-effectiveness, and ability to scale up for large-scale nanoparticles production. Nanoparticles are increasingly used in biotechnological applications because of their advanced properties, including biological compatibility, antimicrobial and anti-inflammatory properties, efficient drug administration, biological activity, bioavailability, tumour targeting, and bio-absorption capabilities[6-9]. Here are a few instances of recent studies that went beyond standard and traditional approaches by specifically incorporating into their structure elements to (l) reduce the usage of harmful and reducing inputs of material, (2) increase the efficacy of space, time, and energy, and (3) develop nanoparticles for environmentally friendly substitutes[10]. Nanoparticles can be amorphous or crystalline, having unique atomic arrangements that enable functionalization and serve as carriers for molecules, droplets of liquid, and gases[11].

There are two ways to NP synthesis: (i) top-down and (ii) bottom-up[12]. Top-down methods make use of reduction of size techniques like ions and ball milling, laser ablation, and many more to break down bulk

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material into tiny fragments. Bottom-up approaches use biological and chemical processes to synthesise nanoparticles through self-assembly of atoms[13]. Furthermore, three distinct approaches are used to synthesise NPs: physical, chemical, and biological. Despite all of the techniques used for nanoparticle manufacturing and the adverse effects of both physical and chemical procedures on the surroundings[14]. The green chemistry method can synthesise metal nanoparticles in a secure and cost-effective manner, utilising coffee, tea, micro-organisms, and plant extracts. These synthesis processes do not use harmful solvents, precursors of chemicals, and extra reducing agents[15]. Metallic nanoparticles (MNPs) having desirable physic-chemical properties have been employed in a variety of biomedical applications, including antibacterial agents.

Biosynthetic approaches have been utilised to replace physical and chemical techniques. NPs made from gold, silver, and copper have been claimed to have medical and therapeutic uses, as well as important uses in magnetics, electronics, storage of information, and optical electronics[16]. Plant extract-derived nanoparticles tend to be more stable, and their rate of synthesis is more rapid and simpler than others[17]. Gold nanoparticles are widely used in proximity to human areas due to their cytotoxicity as well as anti-bacterial properties[18]. The process of biosynthesis of nanoparticles of silver offers benefits such as slower kinetics, improved control over the formation of crystals, and high stability[19]. Green-synthesised copper nanoparticles are environmentally friendly and cost-effective. The DPPH experiment demonstrated that the synthesised copper nanoparticles (CuNPs) had good antioxidant activity. As a result of the research, effective antibacterial and antioxidant principles derived from biosynthesised CuNPs can be developed for clinical use in the creation of therapeutic medications for infectious disorders[20]. Green production of nanoparticles has been used with amino acids, phytochemicals, polysaccharides, polyphenols, and vitamins. The extracts of plants have been used extensively to create gold, silver, and copper nanoparticles. These nanoparticles are used in a variety of applications because of their small size, increased surface area, and biological compatibility[21].

This review emphasises plant-mediated syntheses of the three kinds of MNPs (Ag, Au, and Cu), their antibacterial abilities, and other biological applications. Various nanoparticles derived from microorganisms, juice from fruits, polysaccharides, and extracts of plants were discussed. This article highlights the use of green nanoparticle production using plant extracts for antibacterial applications and other biomedical properties. This article examines recent studies on green and easy approaches to synthesising advanced nanomaterials, compared to complex techniques and dangerous substances.

Synthesis of metal nanoparticles using plant extract

Phytosynthesis is the process of producing nanoparticles from extracts of plants. Plants are frequently picked over microorganisms because phytosynthesis is more cost-effective and easily scalable for applications in industry[22]. When plants are used for the synthesis of silver, gold and copper nanoparticles, initially an aqueous solution is made from their leaves, roots, or stems, and a metal salt is added to the prepared aqueous solution. The mixture of metal salt and plant extract is then placed in the dark for a few hours until the plant extract reduces the metal salt, and a change in colour of the prepared mixture is observed. The formed nanoparticles are then separated by centrifuging the nanoparticles and drying the sample in the oven[23]. Nanoparticle reduction is made possible by bioreducing agents that include enzymes, proteins, flavonoids, and terpenoids. Nanoparticle stability preserves characteristics like composition, crystallinity, size, shape, and surface chemistry, which greatly influence microbial activity. Therefore, the final step (stabilisation) is crucial[24].

Green synthesis of silver nanoparticles

Bose and Chatterjee *et al.* Synthesised Silver Nanoparticles Using 0.2 mL of Vasaka (*Justicia adhatoda* L.) leaf extract in 20 mL of 1 mM of AgNO3 and reported that the synthesised nanoparticles size ranges between 5-50 nm, which were spherical in size. Also, they reported that this medicinal leaf extract contains a large number of secondary metabolites and essential oils such as glucoside sitosterol, vasicinine, vasicinol, vasicinone, maiontone deoxyvasicinone, vasicol, kaempferol, etc., which were responsible for the reduction of Ag+ ions[25]. Nakkala *et al.* used *Acorus calamus* rhizome extract to synthesise silver nanoparticles (ACAgNPs). They reported that ACAgNPs were spherical and their average size is 31.86 nm. Biomolecules like beta asarone, calamenol, and alphapinene were also detected, which were responsible for the reduction process. Additionally, the antioxidant and antibacterial properties of AC-AGNPs were strong[26]. Using plant extract from *Boerhaavia diffusa* as a reducing agent, silver nanoparticles were synthesised in a green manner by Kumar *et al.* AgNPs have a face-centred, cubic structure, are spherical in shape, and have an average particle size of 25 nm. They also examined their ability to inhibit the growth of three fish bacterial pathogens, such as *Aeromonas hydrophila*, *Pseudomonas fluorescens*, and *Flavo-bacterium branchiophilum*, etc., as shown in Table 1[27]. Satyanarayana *et al.* synthesised environmentally friendly production of silver nanoparticles (AgNPs) using *Sophora interrupta* and *Asparagus racemosus* leaf extracts. Biogenic AgNPs are 4–15 nm in size, spherical-shaped, thermally stable FCC crystals, according to TEM. AgNPs also demonstrated potent antibacterial activities against *Escherichia coli*, *Klebsiella pneumoniae*, *Bacillus subtilis*, and *Micrococcus luteus*. Moreover, AgNPs also demonstrated notable cytotoxic effects on SKOV3, DU149, and PC3, etc.[28]. Kemala *et al.* developed a more environmentally friendly method of synthesising silver nanoparticles (AgNPs) for use in biomedical applications by employing an aqueous latex extract of *Calotropis gigantea* L. They demonstrated that the produced AgNPs have a spherical shape and range in size from 5 to 30 nm, and 420 nm is the surface plasmonic resonance peak (SPR). They also claimed that synthesised AgNPs could be a promising nanomaterial for therapeutic applications when combined with a nanodrug formulation[29]. Banala *et al.* synthesised silver nanoparticles using *Carica papaya* leaf extract (CPL). The data analysis revealed spherical nanoparticles with a size range of 50–250 nm and showed effective bactericidal activity[30]. Annavaram *et al.* synthesised silver nanoparticles using the fruit extract of *Helicteris isora* L. The outcomes demonstrated that synthesised nanoparticles active against clinically isolated human pathogens such as *E. Coli*, *Pseudomonas aeruginosa*, and *Bacillus subtilis* L.are relatively good bioreductants[31]. Latha M *et al.* synthesised AgNPs using plant leaf extract of *Hemidesmus indicus*, which were spherical in shape with an average particle size of 25.24 nm. Also, they found that silver nanoparticles mediated by *H. indicus* synthesise faster and exhibit greater inhibitory activity (34±0.2 mm) at 40 mg/mL against the isolated bacteria *S. sonnei*[32]. Chandirika *et al.* Biosynthesised Silver Nanoparticles using leaf extract *Abutilon indicum*, whose diameters were found within the range 50-100 nm. They demonstrated the potent antibacterial action of AgNPs against *Streptococcus aurous* and *E. coli*[33]. Gopinath *et al.* synthesised silver nanoparticles using fruit bodies of the plant *Tribulus terrestris,* which were in the 16–28 nm size range. They stated that silver nanoparticles have greater bactericidal efficiency as compared to penicillin[34].

Green synthesis of gold nanoparticles

The production of nanoparticles using metals has attracted researchers' intense attention due to the wide range of applications of nanoparticles in various fields, including cancer therapy, water treatment, food safety, drug delivery, chemistry, fabrics and photo-catalysis, in addition to their cytotoxic, antioxidant, and antibacterial qualities[48]. The production of nanoparticles can be accomplished using a variety of chemical and physical techniques, but all of these approaches have some drawbacks. This one novel and effective method for producing NPs is the green synthesis of nanoparticles utilising plants. Plants are increasingly being used to synthesise nanoparticles because of their widespread availability, low cost, environmental friendliness, and non-toxic nature[49]. Gold (Au) nanoparticles are widely recognised with an immense variety of applications, including targeted delivery of drugs, imaging, diagnosis, and therapies, due to their incredibly small size, large surface area, stability, tunable optical, non-cytotoxicity, physical, and chemical properties[50].

The green synthesis of gold (Au) nanoparticles using plant extracts is becoming more and more popular due to the strong antibacterial properties of nanoparticles and the easy reduction of their salts. Plant extract is beneficial for the synthesis of gold nanoparticles since it reduces environmental impact and can yield huge quantities of nanoparticles compared to microbes. Plant extract has garnered significant attention in recent decades due to its simplicity in reducing metal salts to nanoparticles[51]. Gold nanoparticles (Au NPs) with various sizes, shapes, and morphologies have been synthesised over the past few decades, utilising plant extracts from diverse plant varieties all over the world. Shankar *et al.* Reported the formation of triangular-shaped single-crystalline gold nanotriangles of size 200-500 nm using lemongrass plant (*Cymbopogon flexuosus*) extract with aqueous chloroaurate ions ($AuCl_4$) at room temperature[52]. Chandran *et al.* use chloroauric acid ($HAuCl_4$) and Aloe Vera leaf extract as the

Table 1 — Synthesis of Silver nanoparticles using various parts of plants

S. No.	Plant name	Plant part	Concentration of extract	Shape	Size	SPR Wave length	Functional groups involved	Biomolecules involved	Optimal conditions	Uses	References
1	*Aegle marmelos*	Leaves fruit		Spherical	60 nm	422 nm	aromatic group, polyphenol	Tannic acid, hydrogenases, reductases, quinones, polyphenols	The extracted substance had been placed in a hot water bath at 100°C for ten minutes.	Antimicrobial	35
2	*Acorus calamus*	Rhizome		Spherical	31.83 nm	421 nm	Phenol alcohol, aromatic amine and carbonyl group	Alphapinene, eugenol, methyl eugenol, calamone, azuline, beta asarone, calamenol, sugars, along with flavones	Stored at 4°C in the refrigerator	Chronic diarrhoea, dysentery, complications of the liver, inflammation of the joints, sinusitis, allergic reactions, epilepsy, mental illnesses, tumours in the glands and abdomen, bronchial catarrh, and sporadic fever	26
3	*Asparagus racemosus*	Roots leaves		Spherical	30–50 5–15 nm	413 nm	Alcohols/phenols	Favonoids and phenols, amide-II linkage of the proteins	The supernatant was stored at 4°C	Antibacterial and anticancer	28
4	*Boerhaavia difusa*	Whole plant	10 mL	Spherical	25 nm	410 nm			Silver NP's were allowed to dry in a watch glass	Anti-bacterial, sunscreens and cosmetics	27
5	*Justicia adhathoda*	Leaves	0.2 mL	Spherical	5–50 nm	430 nm			Around 60°C, the combination was stirred about 30 minutes.	Antibacterial agent	25
6	*Abutilon indicum*	Leaves		Crystalline	106 nm	435 nm	Aromatic and aliphatic amines, charged carboxylate group	Proteins	The supernatant has been heated to 50–95 degrees Celsius.	Antioxidant, antibacterial, anti-pyretic, anti- diabetic, for hyperglycemia, conjunctivitis, ulcers, leprosy, skin, and liver conditions	36
7	*Hemidesmus indicus*	Leaves	15 mL	Spherical	25.24nm	430 nm	Hydroxyl groups, carboxylic		Centrifugation for 15 minutes at a speed of 10,000 rpm	Antibacterial efficacy	32
8	*Calotropis gigantea*	Latex	1 mL	Spherical	25.24nm	420 nm	Amines	Proteins, enzymes (enzyme cysteine and aspartic proteinase, lupeol, calotropin, calotoxin, and uscharidin)	The process of the combination was maintained at ambient temperature.	Anti-fertility, anticancer, anti-inflammatory, hepatoprotective, anti myocardial infraction, antidiarrheal, along with antibacterial properties in the nanodrug formulations	37
9	*Tribulus terrestris*	Fruit	100 mL	Spherical	16–28 nm	435 nm	Carboxyl group,aromatic and aliphatic amine		Fruit parts have been washed three times using water and then alongside Milli-Q water.	Antimicrobial	34
10	*Euphorbia hirta*	Leaves	200 mL (1 mM silver nitrate+plant extract)	Spherical	40–50 nm	430 nm			Centrifugation approximately 25 minutes around 18,000 rpm speed	Sedative, anxiety-reducing, pain reliever, antipyretic, anti-inflammatory, anti depressant, antihypertensive, along with	38

(Contd.)

Table 1 — Synthesis of Silver nanoparticles using various parts of plants (Contd.)

S. No.	Plant name	Plant part	Concentration of extract	Shape	Size	SPR Wave length	Functional groups involved	Biomolecules involved	Optimal conditions	Uses	References
11	*Gloriosa superba*	Leaves	5 mL	Triangular	20 nm	425, 538 and 559 nm	Primary amines (N-H) and aliphatic (C-H)	Colchicine, superbine, gloriosol, gloriosine, stigmasterin, and phytosterils,		Develop drugs, antibacterial and antibiofilm activities	39
12	*Piper logum*	Fruits		Spherical	17.6–41 nm					Outstanding cytotoxic activity on HEp-2 cell lines, beneficial as a form of nanomedicine for formulations of chemotherapy drugs	40
13	*Piper nigrum*	Fruits	20 mL	Spherical	32–100 nm	300–800 nm		Vitamins, Piperine,polysaccharides, amino acids, alkaloids, and proteins	Solutions were irradiated with sun light	Antipyretic, anti-inflammatory	41
14	*Plectranthusa mboinicus*	Leaves	20 mL	Spherical	18nm	428 nm	Methyl, methylene and methoxy groups, nitro groups, alkenes, amides, alkyl halides, aliphatic and aromatic groups	Proteins	Aqueous leaf extract is boiled for ten minutes at 60 degrees Celsius in 100 millilitres of Milli-Q water.	Antimicrobial effect	42
15	*Pistacia atlantica*	Seeds	1 mL	Spherical	10–50nm	450–500 nm	Hydroxyl group, carboxylic group	Proteins	Leaves were shade-dried for a week at room temperature	Antibacterial agent	43
16	*Solanum xanthocarpum*	Fruit		Spherical	10nm	406 nm		Caffeic acid, coumarins (aesculetin and aesculin), steroids (carpesterol, diosgenin, campesterol, daucosterol) , triterpenes, quercitrin and apigenin glycosides		Antihyperglycemic, urease inhibitory, anti-oxidant, and congestion, asthma, and chest pain relief	44
17	*Zingiber ofcinale*	Rhizomes		Spherical	10 nm	420 nm			Centrifugation at 15,000 × g for 15 min	Wound dressings, material for catalytic, treatment of infections and cancers of liver and kidneyoptoelectronic, sensing and biotechnological applications	45
18	*Morinda citrifolia*	Roots	3 mL	Spherical	30–55 nm	413 nm	Alcohols, phenolic compounds, methyl, methylene, and methoxy groups.	Flavonoids and terpenoids	Extract was stored in the refrigerator at 4∘C	Cytotoxic effect on HeLa cell lines	46
19	*Musa balbisiana*	Leaf	250 mL	Spherical	50 nm	425 to 475 nm	Ether, methyls, aromatic rings and alkyne bonds.	Flavonoids and terpenoids	Filterate were then refrigerated (4°C)	Antimicrobial property	47

Table 2 — Synthesis of Gold nanoparticles using various different parts of plants

S. No.	Plant name	Plant part	Concentration of extract	Shape	Size	SPR Wave length	Functional groups involved	Biomolecules involved	Optimal conditions	Uses	References
1	*Cymbopogon flexuosus*	Leaves	5 mL	Triangle	200-500 nm	500 nm	C=O , aromatic C-C, N-H	Highly polar, water soluble molecules	Room temperature	STM, centilevers	52
2	*Aloe barbadensis miller*	Leaves	0.1 to 4 mL	Triangle; hexagonal	50-350 nm	560 nm	C=O , aromatic C-C, O-H	Molecules with < 3kDa weight	4 mL extract; Elevated temperature	Optical coatings	53
3	*Crassocephalum rubens*	Leaves	10-50 mL	Spherical	10-20 nm	540 nm	O-H	Alcohols; phenols; flavinoids	50°C	Biomedical uses	54
4	*Salicornia brachiata*	Aerial parts	1 mL	Spherical	22-35 nm	532 nm		Polyphenols, glycosides, flavonoids, carbohydrates, protein	60°C + traces of $NaBH_4$	Medicinal uses	55
5	*Couroupita guianensis*	Flowers	1 to 5 mL	Spherical; triangular; hexagonal	7-48 nm	534 nm	C=C; C-C; O-H; C-O; C-N; C=O	Phytochemicals		Anti-cancer	56
6	*Curcumaekwangsiensis*	Leaves	20 mL	Spherical	8 to 25 nm	539 nm	O-H; C-O; Au-O;	Phenols; flavinoids	25°C + 1.5g NaOH + Stirring	Chemotherapeutics	57
7	*Zataria multiflora*	Leaves	1 to 10 mL	Monodispersed	10 to 42 nm	530 nm	NH2; C=O; -CH3; C-S	Alkaloids; flavinoids	Ph: 7 + room temperature	Chemotherapeutics	61
8	*Punica Granatum*	Fruit	100 mL	Spherical and Triangular	5 to 20 nm	585 nm	O-H; C-H; C=O; C-N; C-OH; C-C; N-H	Proteins	Room temperature + stirring	Anti-cancer	58
9	*Sargassum wightii Greville*	Thallus	1 g seaweed in 500 mL water	Spherical and Plannar	8 to 12 nm	527 nm		May be extracellular polysaccharides	Stirring	Can be used for bioorganic synthesis of Au-NPs	62
10	*Cinnamomum camphora*	Leaves	50 g biomass	Flat; quasi-spherical; sherical; triangular	10 to 40 nm	520 to 1000 nm	–C–O, –C=C, RHC=O; C-O-C	Water soluble biomass (alkaloids; flavones; alkaloids)		Can be used for bioorganic synthesis of Au-NPs	63
11	*Azadirachta indica*	Leaves	1 mL		2 to 100 nm	550 nm		Salanin, Nimbin, Azadirone and Azadirachtins	Room Temperature + Stirring	Non-toxic production of NPs	64
12	*Blueberry (Vaccinium sect. Cyanococcus)*	Fruit	9 mL	Spherical	200 nm	650 to 800 nm		Polyphenols, glycosides, flavonoids, carbohydrates, protein	Room temperature + stirring	Chemotherapeutics	60
13	*Blackberry (Rubus subg. Rubus)*	Fruit	9 mL	Oblong	100 nm	650 to 800 nm		Polyphenols , glycosides	Room temperature + stirring	Chemotherapeutics	60
14	*Pomogranate (Punica granatum)*	Fruit	9 mL	Spherical	5 to 50 nm	650 to 800 nm		Anthocyanins ; polyphenols	Room temperature + stirring	Chemotherapeutics	60
15	*Green tea (synthetic: tea bags)*		9 mL	Spherical	100 nm	650 to 800 nm			Room temperature + stirring	Chemotherapeutics	60
16	*Turmeric powder (synthetic)*		9 mL	Spherical	5 to 60 nm	650 to 800 nm		Phenolic compounds : curcuminoids	Room temperature + stirring	Chemotherapeutics	60
17	*Hibiscus sabdariffa*	Leaf and Stem	30 mL	Spherical	10 to 60 nm	530 to 550 nm	O-H; N-H; R-CH ; C-O	Carboxylic and phenolic compounds	Room temperature + stirring + pH: 2 to 7	Anti-cancer	59

reducing agent for the biological synthesis of gold nanotriangles, and it was found that the amount of *Aloe vera* extract used in the gold ion reduction results in readily accessible size variation, ranging from 50 to 350 nm, as displayed in Table 2[53]. Adewale *et al.* synthesised AuNPs by combining gold (III) chloride trihydrate ($HAuCl_4{\cdot}3H_2O$) with a cold/hot aqueous extract of *Crassocephalum rubens* plant leaves. Synthesised nanoparticles indicated the formation of mostly spherical-shaped AuNPs of size 10-20 with a 540 nm surface plasmon resonance (SPR) band[54]. Ahmed *et al.* presented a quicker and more environmentally friendly method of creating gold (Au) nanoparticles of a size range from 22 to 35 nm by utilising an aqueous extract of the *Salicornia brachiate* (Sb) plant with Chloroauric acid ($HAuCl_4$) and $NaBH_4$ at 600°C[55]. Geetha *et al.* synthesised gold nanoparticles of size 7-48 nm using aqueous flower extract of *Couroupita guianensis* plant for anticancer activity[56].

Chen *et al.* They use an aqueous extract of *Curcumae Kwangsiensis Folium* leaves combined with $HAuCl_4$ at room temperature to achieve gold nanoparticles, which they find to be spherical in shape and size, ranging between 8 and 25 nm. It seems that *Curcumae Kwangsiensis Folium* leaf aqueous extract-mediated green Au nanoparticles may soon be utilised in people as innovative chemotherapy supplements or medications[57]. Chau *et al.* and Mishra *et al.* synthesised spherical-shaped Au NPs of a few nanometers in size using the fruit of *Punica granatum* plant & leaf of *Hibiscus sabdariffa* plant respectively at room temperature for 'anti-cancer' application[58,59]. Antibacterial properties are fundamentally important for safeguarding public health and maintaining hygiene standards.

Nadagouda *et al.* synthesised the Au nanoparticles for chemotherapeutic applications using extracts of blackberry, blueberry, pomegranate, and turmeric with auric chloride ($HAuCl_4$) at room temperature. All the prepared Au NPs have sizes in the range from 20 to 500 nm, depending upon the extracts used. Furthermore, it was observed that *Pomegranate* extract produced more uniform gold nanoparticle shapes and sizes as compared to turmeric, blueberry, blackberry, and tea/coffee extract[60]. In summary, the synthesis of gold nanoparticles using various plant extracts demonstrates their broad potential across multiple disciplines. From anti-cancer and antimicrobial therapies to catalysis and drug delivery systems, these nanoparticles offer versatile and sustainable solutions in biomedical and environmental applications. The diverse properties imparted by plant-mediated synthesis underscore their significance in advancing nanotechnology, paving the way for innovative treatments and technologies that address complex healthcare and environmental challenges. Continued research in this area promises further insights and developments, shaping a promising future for plant-based gold nanoparticles in diverse fields of science and medicine.

Green synthesis of copper nanoparticles

The synthesis of copper nanoparticles (CuNPs) represents a significant advancement in nanotechnology, offering a versatile and eco-friendly approach to producing materials with unique properties and wide-ranging applications. Various studies have been reported by various researchers to biosynthesise Cu NPs, such as Shende *et al.* synthesised copper nanoparticles by *Citrus medica* Linn. *(Idilimbu)* juice. According to reports, the produced CuNPs were found to be effective in substantial inhibition of *E. coli*[65]. Wu *et al.* synthesised copper nanoparticles using *Cissus vitiginea*. The antioxidant and antibacterial activity of the synthesised nano copper against pathogens causing urinary tract infections was assessed and shown to have outstanding antioxidant activity, effectively eradicating them, or dramatically reducing activity against urinary tract infection pathogens[66]. Cheirmadurai *et al.* demonstrated copper nanoparticle biosynthesis on a large scale using *henna* leaf extract as a reductant. They employed the calcined copper nanoparticles' significant electrical conductivity to create conductive nanobiocomposites with collagen waste, as displayed in Table 3. They also showed that the nanobiocomposites light up a light-emitting diode lamp when they are placed between batteries[67]. *Ageratum houstonianum* Mill. leaf extract was used to create green-synthesised copper nanoparticles, which were then studied for their photocatalytic and antibacterial properties. Synthesised (AH-CuNPs) had an average size of about 80 nm and came in cubic, hexagonal, and rectangular shapes. Green Copper Nanoparticle Synthesis employing *Punica granatum* was performed by Padma *et al.* the synthesised nanoparticles were found to be 56-59 nm in size. These environmentally friendly, green, synthesised copper nanoparticles have bactericidal properties against *Staphylococcus aureus*, which causes wounds[68]. Manikandan *et al.* created copper nanoparticles by combining the acidic chitosan solution with the $CuSO_4$ solution[69]. Sbbaiya *et al.* collected *Hibiscus rosasinensis* in order to look into their potential for copper nanoparticle synthesis. The leaf extract containing CuNPs demonstrated strong antioxidant activity in the hydrogen peroxide scavenging assay and Ferric Reducing Antioxidant Power (FRAP) tests. Good antimicrobial activity of synthesised copper nanoparticles is demonstrated against clinically significant pathogens such as *E. coli* and *B. subtilis.* Additionally, they stated that copper nanoparticles produced biologically can be used as an effective medication to treat lung cancer[70]. Mohamed *et al.* synthesised copper and copper oxide nanoparticles using the extract of seedless dates with an average particle size of 78 nm. Their work offers a straightforward, economical, and eco-friendly approach to the synthesis of Cu/Cu_2O nanoparticles from waste seedless dates for the first time[71]. The aqueous extract of the *Millettia*

Table 3 — Synthesis of Copper nanoparticles using various different parts of plants

S. No.	Plant name	Plant part	Concentration(S) of extract	Shape	Size	SPR Wave-length	Functional groups involved	Biomolecules involved	Optimal conditions	Uses	References
1	*Citrus medica*	Fruit juice	20 µg/mL	Nano-wires	33 nm	615 nm	C=O; -C=C-	Carboxylic acid, citric acid	Aluminium container and brought to a boil	Pigeon pea growth and development	65
2	*Citrus medica Linn.*	Fruit juice	60 µg/mL		10-60 nm	613 nm			Gradually heated to boiling (60–100 °C)	Antimicrobial activity	66
3	*Cissus vitiginea*	Leaves	25, 50 and 75 µL	Spherical	10-20 nm	340 nm		Carbohydrates, Flavonoids, Saponnins, Alkaloids, Polyphenol, Anthroquinone, Steroids, Terpenoids, Tannins	Stored at 4 °C	Antimicrobial and antioxidant properties against microorganisms that cause urinary tract infections	67
4	*Punica granatum*	Leaves	50 µL	Spherical	56-59 nm	450 nm			Room temperature	Anti-bacterial effect	68
5	*Gossypium*	Fiber		Spherical	30-35 nm	340 nm			80°C	Anti-microbial	74
6	*Chitosan*			Spherical	20-30 nm	500-600 nm	O-H; N-H; C-H; C-O-C;	Amines, hydoxyl	The colloidal had been centrifuged for 10 minutes at 10,000 rpm for 12 hours.	Antibacterial activity	69
7	*HibicusRosasinensis*	Leaves	200, 500, 1000 µg/mL	Spherical		610 nm	O-H; C-H;C=C; N-H	Alcohol, alkane, alkene, amine	Incubation for 2 days in dark room	Antimicrobial, antioxidant activities	70
8	*Syzygium aromaticum (clove)*	Buds		Spherical	20 nm	580 nm	C-H; C-N; C=O; C=C; C-O	Hydroxyl, alcohols, amines, carboxyl, alkanes, tannins, flavonoids, alkaloids, and carotenoids	30°C of temperature	Antimicrobial properties	75
9	*Punica granatum*	Leaves	100 µg/mL	Spherical	15-20 nm	585 nm	C-H; C-C; C-O-O;	Proteins, enzymes and flavanoid	Room temperature	Antimicrobial activity against opportunistic pathogens	76
10	*Ecliptaprostrata*	Leaves	1,10,100, 250, 500 µg/mL	Spherical, hexagonal and Cubical	28-105 nm	565 nm	O-H; C-H; C-F;	Hydroxy, methylene, aliphatic fluoro	Room temperature	Antioxidant and Cytotoxic activities	77
11	*Ficus carica (figs)*	Fruit	1- 50 µg/mL	Spherical	50-120 nm	412 nm			Room temperature	Antioxidant and Antimicrobial activity	78
12	*Azadirachta indica*	Flower	2-10 mM	Spherical	5 nm	560 nm	N-H; O-H; C=O; C-OH; C-H; C-Cl;	Terpenes, flavonoids, alkaloids, and carotenoids	Room temperature	Anti-bacterial study	79
13	*Passiflora foetida*	Leaves	25, 50, 75, 100 µg/mL	Nano clusters	150-200 nm	350 nm	C=O; O-H; N-H;	Polyphenols, flavonoids, alkaloids, and terpenoids	Centrifugation method at 9000 rpm	Antibacterial activity	80
14	*Moringa oleifera*	Leaves	50, 100, 150, 200, 250 µg/mL		35.8-49.2 nm	620 nm	N-H; C-N;	Amino acids, Proteins, Carbohydrates, Polyphenols, Saponins, Steroids, Alkaloids, tannins, flavonoids, and glycoside		Antioxidant and Antimicrobial activities	81

pinnata flower was used by Thiruvengadam *et al.* to biologically synthesise copper nanoparticles[72]. Punniyakotti *et al.* used *Cardiospermum halicacabum* leaf extract to create copper nanoparticles (Cu NPs). They stated that by adhering to the cell wall and interfering with its growth, Cu NPs regulate the formation of biofilms[73].

Factors affecting the production of different nanoparticles

Effect of pH

The production of nanoparticles is heavily influenced by the reaction pH. Like temperature, pH influences nucleation sites. Higher pH levels increase the total number of nucleation sites, resulting in more metallic nanoparticles being produced. pH significantly influences the morphology and size of nanoparticles. According to Song *et al.*[82], copper metal nanoparticles were stable only in solvents that were nonpolar. This approach uses organic hydrocarbons as a capping agent to preserve copper. Citron's antioxidant as well as acidic properties prevent copper oxidation by inhibiting electro-deposition under low pH levels. According to Gattuso *et al.*, citron juice, which serves the role of capping agent, contains weak acids such as ascorbic acid, saponins, and flavonoids[83]. Armendariz *et al.* investigated the production of Au nanoparticles using *Avena sativa* under varying pH. A lower pH level (pH 2) resulted in fewer NPs, but bigger sizes (25-85 nm). At lower levels of pH, Au NPs may consolidate to produce bigger NPs because of the lack of nucleation centres. Au Nps react with oat biomass at various pH levels. At pH levels of 3 and 4, however, a large number of nanoparticles with an average diameter of 20 nm formed[84]. The size as well as the aspect ratio decreased while the pH level increased.

Effect of temperature

Temperature significantly impacts the dimensions and shape of nanoparticles, as well as the rate of production. Temperature affects the forms (octahedral, triangular, spherical, along rod-like) and sizes of NPs. Increasing temperature leads to faster reactions and the creation of nucleation sites. Temperature affects copper nanoparticles synthesis, with temperatures yielding the best results[85.] While the temperature rises, the kinetics of decline improve because of enhanced Brownian motion[86]. Higher temperatures are being found, they have a substantial effect on the size and shape of copper nanoparticles. High temperatures often result in decreased nanoparticle sizes[87]. A previous study discovered that while the incubation duration grew, so did the amount of copper nanoparticles synthesised, which ultimately reached an endpoint. The influence of temperature was found, with maximal synthesis occurring at elevated temperatures[85]. The stability of gold nanoparticles synthesised using *salix alba* plant extract was tested by heating at 80°C for almost 30 minutes. At this temperature, the stability of the prepared nanoparticles was found to be affected, showing that the temperature serves a very important role in preserving the morphology and characteristics[88]. The dimensions of nanoparticles depend greatly on the reaction temperatures (17-28°C), the silver nanoparticles are small, having the edge lengths of roughly 90 nm for the silver nanoplates, along with diameters approximately 25 nm for sphere-shaped particles. As the temperature rises to 43-55°C, the particle size dramatically increases, with the edge lengths of around 180 nm for nanoplates and diameters up to 48 nm for spheres[89].

Reaction time

The reaction time of green-synthesised nanoparticles has a significant impact on the dimensions, structure, and yield. Longer reaction durations produce bigger nanoparticle sizes. As an instance, in a particular investigation, the increase in the reaction time between 2 and 10 hours for green-synthesised nanoparticles having magnetic properties resulted in larger particle size production[90]. In addition to temperatures and pH levels, reaction time is one of the important factors in regulating the structural characteristics of nanoparticles. Longer reaction durations can lower the pH level of the solution, hence increasing the size of the nanoparticles[91]. In a previous study, the plant extract made from leaves of *Acacia cyanophylla* mixed with silver nitrate, the solution changes colour from green to brown within 10 minutes, and the colour intensifies with time. This change in colour of the solution indicates the conversion of silver ions (Ag^+) to a zero valent silver ion (Ag^0)[92]. Dhotare *et al.* investigated *Ocimum sanctum* leaves extract and discovered that the nanoparticles prepared using the extract show antibacterial properties. There is an enhancement in the antibacterial property of the prepared nanoparticles if the reaction time duration is extended up to 8 hours. This indicates that the reaction time influences the characteristics and efficiency of green-synthesised copper nanoparticles[93].

Characterisations

Metal nanoparticles synthesised using green synthesis are characterised using a variety of analytical methods that assist in establishing their characteristics as well as efficacy. The combined use of these approaches enables the full characterisation of green synthesised nanoparticles of metal, assuring their appropriateness for a wide range of applications, including medical treatment, electronic devices, and environmental sciences. Each approach gives specific details on the size, structure, composition, and stabilisation of the nanoparticles, which is crucial for their efficient use in practical applications.

UV-Vis spectroscopy

UV-Vis spectroscopy, also called UV-Vis, is a popular method for analysis that uses the transmission absorption of UV and visible wavelengths to detect the concentration and composition of a sample. This method is based on the principle in which a molecule absorbs light, due to which electrons get stimulated from their ground state to a higher energy level[94]. The amount of absorbed light is determined by the precise wavelengths as well as concentrations of the absorbing material, as discussed in the Beer-Lambert law. It is an effective instrument for quantitative and qualitative evaluation for a broad range of samples because of its adaptability, ease to use and ability to produce fast results[95].

Awwad *et al.* have created a quick, environmentally responsible, and practical green process that uses *carob* leaf extract at room temperature to create silver nanoparticles from silver nitrate, as illustrated in Fig. 1. The silver nanoparticles activation of surface plasmon vibrations is what causes the colour shifts. A peak centred about 420 nm was formed by the SPR of silver nanoparticles[96]. Using *horse gram* extract, Vidhu *et al.* describe a green chemistry method for creating silver nanoparticles. This process for creating silver nanoparticles is easy, effective, and clean. The samples UV–vis spectra showed clear surface plasmon bands. Particle size, shape, interaction with the medium, local refractive index, and the degree of charge transfer between the particles and the medium all affect where the SPR band appears in UV-vis spectra. For saples, the absorption peak is centred between 410 and 430 nm[97].

Shende *et al.* present a low-cost, nontoxic technique of synthesising copper nanoparticles (CuNPs) utilising citrous juice (*Citrus medica Linn.*). A UV-Vis spectrophotometer was used to evaluate the biogenic copper nanoparticles, revealing a characteristic resonance (SPR) at roughly 631 nm that is unique to CuNPs. The NanoSight-LM20 nanoparticle tracking study revealed that the particles were between 10 and 60 nm in size, with a concentration of 2.18 x 10^8 particles per millilitre[65].

Kumar *et al.* successfully synthesised gold nanoparticles employing *Zingiber officinale* extract as a novel reducing and stabilising agent for gold salts. One crucial method for determining the creation and stability of aqueous metal nanoparticles is UV–vis spectroscopy. When *Z. officinale* extract was added to 1 mM aqueous $HAuCl_4$, gold nanoparticles formed, changing the hue from yellow to wine red. A gold SPR band with a centre at roughly 523 nm was detected[98].

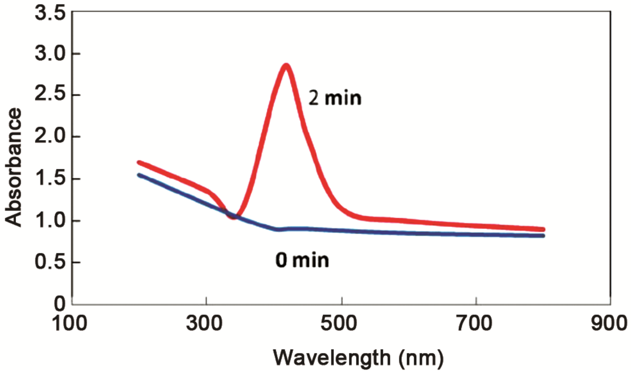

Fig. 1 — UV–vis spectrum. Showing absorption of 10^{-3} M aqueous solution of silver nitrate with carob leaf extract as a function of time Reproduced with reprints)[96].

Transmission electron microscopy

Transmission electron microscopy (TEM) is an effective method for studying the shape and arrangement of nanoparticles. TEM is being used successfully to characterise the size, shape, along crystal structure of different green synthesised nanoparticles, such as silver, gold, and copper. The findings show that TEM is useful for studying the form and characteristics of nanoparticles made utilising environmentally benign, plant-based, and microbiological approaches[99]. Geetha *et al.*'s study reveals that the blossom of the pharmacologically significant tree *Couroupita guianensis* has the ability to biosynthesise gold nanoparticles. The development of gold nanoparticles is confirmed by the TEM images, and as seen in Fig. 2, the freshly created nanoparticles are polydispersed and comprise irregularly shaped spherical, triangular, tetragonal, and pentagonal particles. The diameter of gold nanoparticles ranges from 7 to 48 nm in size dispersion[56].

Cedrus deodara leaf extract was utilised to reduce CuO nanoparticles by Ramzan *et al.*, making the process easy as well as environmentally friendly. TEM data show the production of spherical copper oxide nanoparticles[100]. Kumar *et al.* found that as-synthesised AgNPs had a spherical form after 48

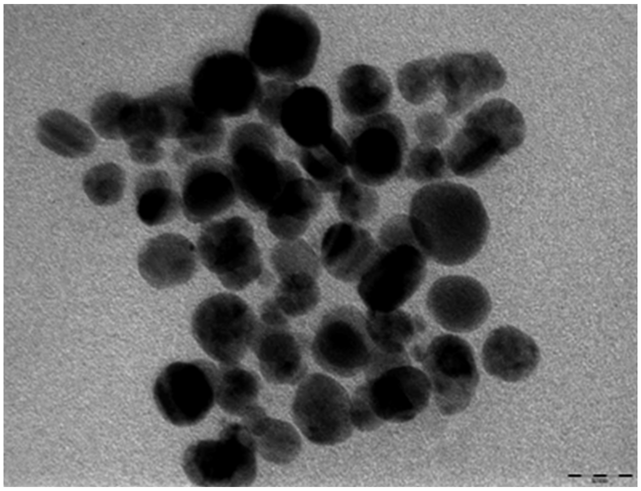

Fig. 2 — TEM Micrograph of *C. guianensis* synthesized gold nanoparticle (*Reproduced with reprints*)[56].

hours, with an average diameter of 12-50 nm at higher magnification levels[101]. Girón-Vázquez *et al.* TEM micrographs revealed that the dimension of silver nanoparticles increased with extract quantity, resulting in a more spherical shape[102].

Fourier transform infrared spectroscopy

Fourier-transform infrared (FTIR) is an effective method for characterising green nanoparticles. It is useful in determining which functional groups are present on a nanoparticle's surface. The ability to identify impurities and unreacted precursors is crucial for quality control. Various studies have utilised FTIR spectroscopy to identify and analyse functional groups, taking advantage of its capability to detect specific vibrational modes corresponding to different chemical bonds. Donga *et al.* synthesised gold nanoparticles from the seeds of the *Mangifera indica* plant. Their FTIR analysis showed a band of absorption at 3549.14 cm^{-1} is indicative of the alcohol group's O–H medium stretching. The alignment of the absorption band at 2885.60 cm^{-1} with the alkane group's C–H medium stretching. The nitro group's stretching in the N–O medium is indicated by the absorption band at 1535.39 cm^{-1} (Ref. 103).

Pradhan *et al.* synthesised copper nanoparticles from a plant using *Aloe vera* plant extract. The produced Cu NPs exhibit several absorption peaks. The alkenyl C=C stretch and the amide C=O stretch peak at 1510 cm^{-1} and 1645 cm^{-1}, respectively. The peak at 1750 cm^{-1} is caused by the carbonyl functional group C=O being present. At 3325 cm^{-1}, the absorption peaks at the phenolic group OH[104]. The functional groups linked with phytochemicals of *Seriphidium oliverianum* were discussed by Aroob *et al.*, including glycoalkaloid, tropane alkaloid, and atropine, which are attributed to hydroxyl, aromatic, phenolic, and amino groups, confirming the plant extract's action as a reducing agent in CuO NP production[105].

Kokila *et al.* synthesised silver nanoparticles from *Cavendish banana* peel extract. FTIR spectrum indicates the O–H stretching vibrations of phenols and carboxylic acids, which are responsible for the broad and intense absorption peak at approximately 3394 cm^{-1}. The O–H functional group, which is situated at about 2355 cm^{-1}, may have been involved in the shift from 3,394 to 3,388 cm^{-1}. The peak at 1641 cm^{-1} may be attributed to either the C = N bending in the carboxyl or the C = O stretching in the amide unit[106] as shown in Fig. 3.

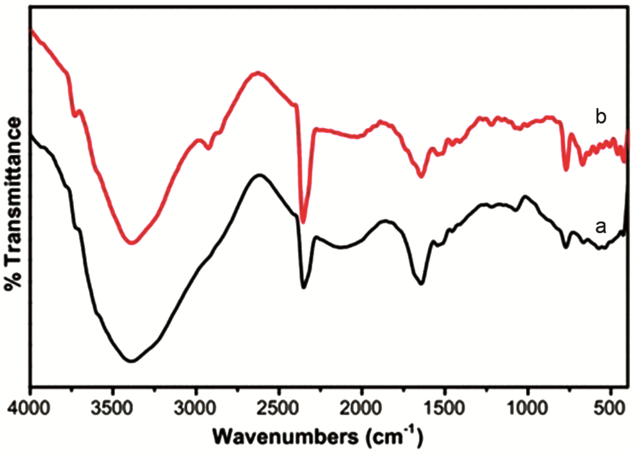

Fig. 3 — FT-IR spectra for a CBPE, b Bio-reduced by CBPE silver nanoparticles (Reproduced with reprints)[106].

X-Ray diffraction analysis

Green synthesis, or the synthesis of nanoparticles using plant-mediated processes, depends heavily on X-ray diffraction (XRD). It is essential for characterising the crystalline structure of the synthesised nanoparticles. By analysing the diffraction patterns, one can identify the crystalline phases and the average crystallite size of the nanoparticles synthesized[107]. Various studies have utilised X-ray diffraction (XRD) to determine crystallite size, leveraging its ability to analyse the broadening of diffraction peaks to estimate the dimensions of crystalline regions.

Muralikrishna *et al.* synthesised gold nanoparticles using (*Aloe vera*) Aqueous Extract. Bragg reflections matching the (111), (200), and (220) sets of lattice planes are observed, which may be indexed based on the gold's fcc structure, and these reflections are indicative of a typical XRD pattern of the metal Au[108]. Ali *et al.* synthesised gold nanoparticles using the plant extract of *cucurbita maxima*. The planes 111, 200, 220, 311, 222, 331, and 420 for the ethanolic extract correspond to the XRD peaks at 111, 200, 311, 222, and 400°, which are indexed to the face-centred cubic structures of silver nanoparticles. Also, the evaluated particle size was found to be 65 nm[109]. Geetha *et al.*'s study reveals that the blossom of the pharmacologically significant tree *Couroupita guianensis* has the ability to biosynthesise gold nanoparticles, as displayed in Fig. 4. XRD was used to undertake a structural examination of the gold nanoparticles that were made from the sample. The gold nanoparticles were given a face-centred cubic shape based on the angular positions of the Bragg peaks[56]. Suresh *et al.* synthesised copper nanoparticles from

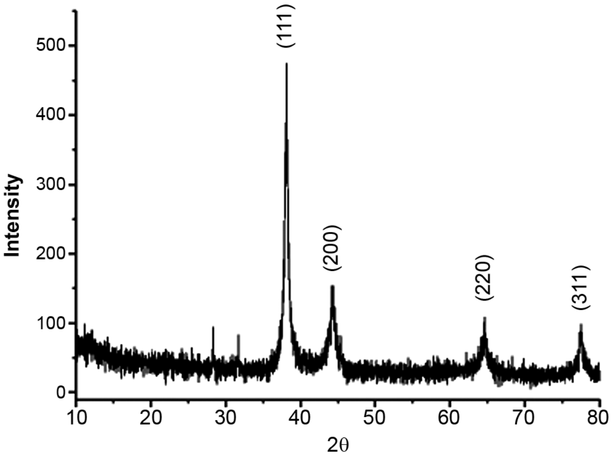

Fig. 4 — XRD pattern of green synthesised stabilized gold nanoparticles (*Reproduced with reprints*)[56].

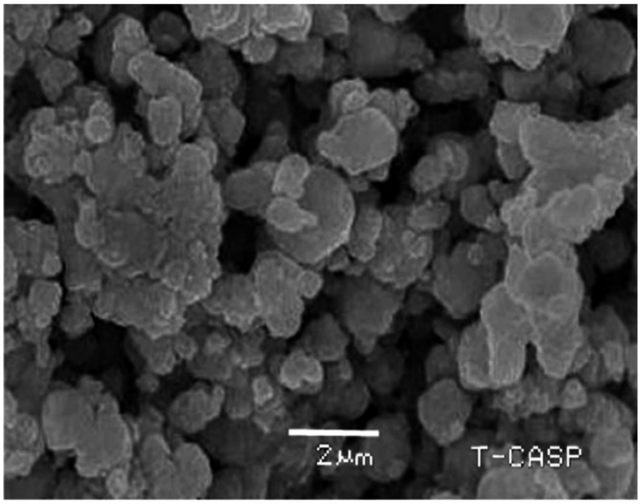

Fig. 5 — SEM micrograph of CuNPs (*Reproduced with reprints)*[114].

herbal tea (*Tea Decoction*). Around 2θ = 43°, 50°, and 74°, three primary characteristic diffraction peaks for Cu were observed. These correspond to the crystallographic planes of (111), (200), and (220) face-centred cubic (FCC) Cu crystals. Using these profiles, the lattice parameter "a" was computed, and the average value of the lattice parameter was found to be consistent with the reported value of 3.61[110].

Scanning Electron Microscope (SEM)

Scanning Electron Microscopy (SEM) is a powerful technique used for the characterisation of nanomaterials; by directing a focused electron beam onto a sample surface, SEM generates high-resolution images that reveal their morphology, size, and distribution. SEM offers exceptional clarity in observing the shape, size, composition, and crystallography of nanoparticles, which is essential for understanding their properties and applications. SEM is equipped with an energy-dispersive X-ray spectroscopy (EDS) system; SEM also determines the elemental composition of different types of nanoparticles, offering insights into their chemical make-up[111]. Parida *et al.* synthesised the gold nanoparticles using "onion (*Allium cepa*)" extract and prepared the films of the prepared sample on the carbon-coated copper grid and performed the SEM analysis using a Hitachi S-4500 SEM machine and observed that the size of the Au nanoparticles is ~100 nm, with spherical and cubic shape[112]. Mubarak Ali *et al.* synthesised the silver and gold nanoparticles using leaves of *M. piperita* and characterised them using SEM analysis. From SEM images, the morphology of the silver and gold nanoparticles was observed and found to be approximately spherical with average diameters of 90 nm and 150 nm, respectively[113]. In order to create copper nanoparticles (CuNPs), Tahir *et al.* used leaf extract from *Grewia asiatica* L., which was discovered to be a highly potent antibacterial and larvicidal substance, as illustrated in Fig. 5. Scanning electron microscopy was used to study the plant CuNPs, revealing their surface shape. As seen in Fig. 5 CuNPs were discovered within a 2 µm range[114.]

Bankar *et al.* used a new, non-toxic, environmentally benign biological substance called banana peel extract (BPE) to create bio-inspired silver nanoparticles. Silver nitrate was reduced using boiled, crushed, acetone-precipitated, and air-dried peel powder. After brief incubation times, investigations using a scanning electron microscope (SEM) showed that silver nanosized crystallites predominated. Some micro-aggregates were also seen when the reaction mixtures were cultured for 15 days[115]. Geethalakshmi *et al.* synthesised gold and silver nanoparticles using *Trianthema decandra* plant extract. The SEM micrograph for the gold nanoparticles shows a variety of shaped structures, including spherical, cubic, triangular, and hexagonal structures with sizes ranging from 33.7 nm to 99.3 nm. They speculate that the fact that the nanoparticles are forming at different periods may be the reason for the variation in particle sizes between 36 and 94 nm[116].

X-Ray photoelectron spectroscopy

X-Ray Photoelectron Spectroscopy (XPS) is a powerful analytical technique used to study and analyse the surface chemistry of nanomaterials. XPS is widely used in various types of nanomaterials to determine the elemental composition of surfaces, including thin films, coatings, and bulk materials. XPS works on the principle of the photoelectric effect, where X-rays are often used to irradiate a nanomaterial, causing electrons to eject from the material's surface. By measuring the kinetic energy of these ejected electrons, the binding energy of the electrons within the nanomaterial can be determined. Binding energy allows for the quantification and identification of elemental composition at the surface of the material.

Vinay *et al.* synthesised silver (Ag) nanoparticles using *Rauvolfa tetraphylla* (L.) seed extract to reduce $AgNO_3$. In the XPS studies of the synthesised nanoparticles, information about the oxidation state of C1s and the Ag 3D state for silver (Ag) NPs was obtained. They also conclude that the traces of seed extract are responsible for the C (1s) signals in the XPS survey[117].

Tausif Ahmad *et al.* synthesised gold (Au) nanoparticles of spherical shape using *Elaeis guineensis* (oil palm) leaf extract by reducing $HAuCl_4$. In the XPS studies, sharp peaks of gold, nitrogen, and carbon were observed. Two peaks of Au corresponding to $4f_{7/2}$ and $4f_{5/2}$ were also observed at 84.08 eV and 87.78 eV, respectively[118]. According to Rodríguez-León *et al.*'s work, AuNPs were created using bark extract from Mimosa tenuiflora (Mt) at varying concentrations of metallic precursors. The samples clearly indicate the presence of oxygen (O 1s), carbon (C 1s), and gold (Au 4f) in the XPS survey scan analysis for $AuMt_1$ and $AuMt_2$, with peaks centred about 532, 284, and 85 eV, respectively, as illustrated in Fig. 6[119].

Applications

The green synthesis of metal nanoparticles provides an economically viable and environmentally friendly replacement to existing techniques, with many potential uses in environmental, medical research, and industrial fields. Their particular features allow them to effectively address important issues, including pollution and medical concerns, while simultaneously encouraging sustainable practices in a variety of sectors. Green synthesised metal nanoparticles have a wide range of applications, including environmental cleanup, medicine, and industry[120].

Anticancer

The green production of metal nanoparticles with extracts from plants is a potential method for cancer treatment, along with diagnostics. According to the Ahmed *et al.* study, room-temperature water extract of *Jurinea dolomiaea* leaves and roots was used to create silver nanoparticles (AgNPs). AgNPs' anticancer potential was investigated using the MTT assay against

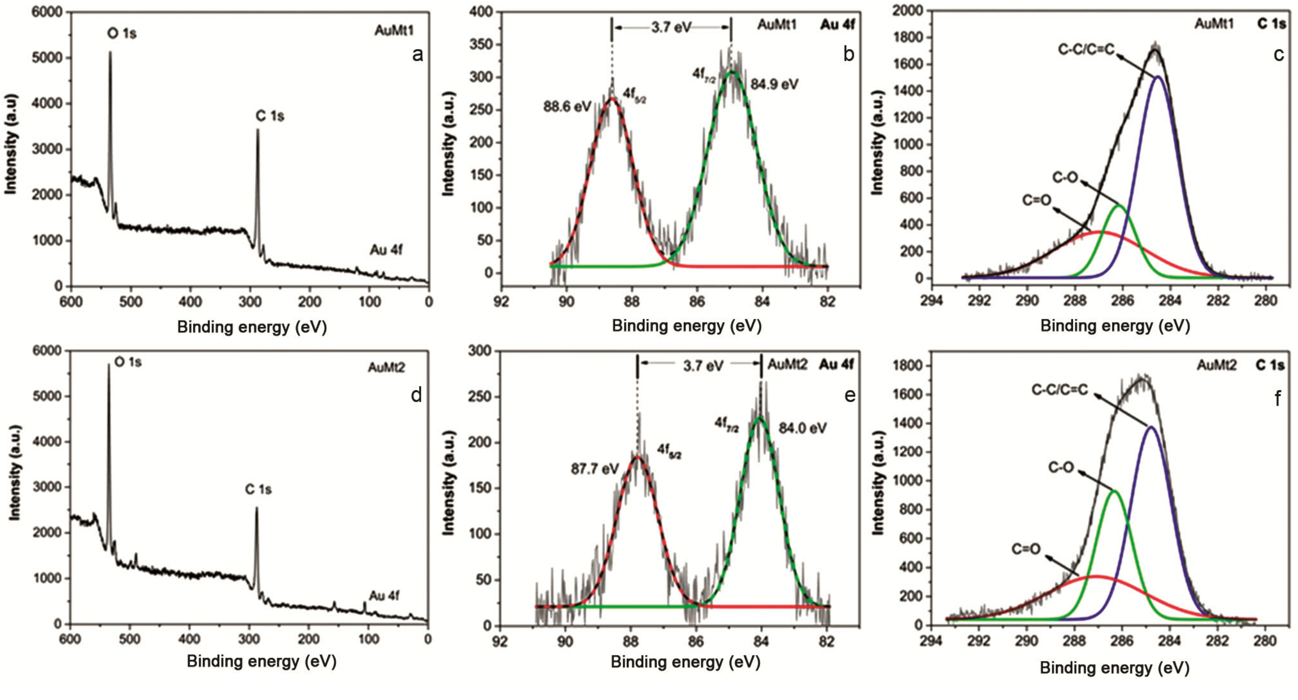

Fig. 6 — XPS spectra of AuMt1 and AuMt2. a,d) Survey spectra, b,e) Au4f high resolution, and c,f) C1s high resolution. (*Reproduced with reprints*)[119].

the mouse embryonic fibroblast (NIH-3 T3) cell line, the cervical cancer cell line (HeLa), and the breast cancer cell line (MCF-7)[121]. Chandrasekaran *et al.* demonstrated that *Carica papaya* fruit latex served as an effective direct bioreductant for the production of functionalised silver nanoparticles. *Carica papaya* silver nanoparticles (CPAgNPs) effectively inhibited the human breast carcinoma cell line (MCF 7) growth in a dose-dependent way, with a substantial IC_{50} value seen[122].

Palaniyandi *et al.* used the green technique to create AuNPs laced with extracts of the red algae *Halymenia pseudofloresii* (Hp-AuNPs). Lung cancer cells were used to test the anticancer screening. Hp-AuNPs efficiently inhibit the development of lung cancer cell colonies in the clonogenic assay at a concentration of 30 µg/mL, while the reactive oxygen species (ROS) generation assay verified that Hp-AuNPs cause apoptosis in lung cancer cells. As a result, the special biologically produced Hp-AuNPs can act as an anticancer agent and may also be employed for other biomedical applications[123].

Dadhwal *et al.* discovered that *H. rhamnoides* has the ability to produce copper nanoparticles with improved therapeutic characteristics. Flavonoids, enzymes, and proteins enhanced the bioreduction, capping, and stabilisation of the synthesised nanoparticles of copper. The investigation reveals that Copper nanoparticles have the potential to serve as an anticancer medication. This study is significant for successfully suppressing the dependence on the concentration of copper nanoparticles in HeLa cancer cells[124]. Yaqub *et al.* found that green nanoparticles, particularly ginger-mediated Copper nanoparticles, have higher anti-cancer effects towards HeLa as well as HepG2 cell lines. As a result, the chemically and environmentally friendly biosynthesised copper nanoparticles can be further functionalised for increased efficacy in biomedical applications, taking advantage of current antibiotics as well as anticancer medications, resulting in the development of affordable therapies for infections along with cancer-associated diseases in future years[125].

Antidiabetic

Because of their antioxidant and antidiabetic effects, green-synthesised metal nanoparticles have attracted attention for prospective uses in diabetes treatment. The use of green synthesised metal nanoparticles, particularly silver nanoparticles, provides a potential strategy in diabetes control. Their dual function as antioxidants as well as enzyme inhibitors demonstrates their promise as a natural therapy alternative for diabetes patients to reduce blood sugar levels[126].

Synthesis of silver nanoparticles with *Justica wynaandensis*. Within 30 minutes of applying the silver nitrate solution to it. Silver nanoparticles synthesised with an IC50 value of 493.87 mg/mL showed strong anti-diabetic and anti-inflammatory properties when treated with BSA. This investigation highlights the significant influence of silver nanoparticles from *Justica wynaadensis* on medicines. In a work by Rehman *et al.*, *Azadirachta indica*-conjugated nanoparticles of silver were synthesised from seed extract. The biosynthesised silver nanoparticles have been shown to exhibit good anti-diabetic properties, which have been attributed to the presence of natural chemicals covering the nanoparticles, which are naturally anti-diabetic. The concluded nanomaterial demonstrated synergistic anti-diabetic capabilities[127].

Leemarose *et al.*'s green production of gold nanoparticles using *Anacardium occidentale* extract from roots is a successful, sustainable way to employ phytoconstituents to their full potential. The gold nanoparticle's antioxidant capability was investigated and found to have an estimated effectiveness of 74%. *In vitro* α-glucosidase inhibitory test indicates a possible antidiabetic efficacy of 79% for gold nanoparticles[128]. Kumar *et al.* synthesised gold nanoparticles from an antidiabetic plant material, resulting in nanoparticles of gold with an average dimension ranging from 15 to 25 nm. These nanoparticles were stable throughout a pH range from 3.4 to 10.2 and might potentially be employed for antidiabetic therapy. Selecting plants having medicinal properties can open up new opportunities for using herbal medicine in nanoscience for both drug delivery and biological applications[129].

The copper nanoparticles synthesised by Ali *et al.*, made from *Mucuna pruriens* seed extract, have significant antioxidant as well as antidiabetic action. Copper nanoparticles have strong antioxidant and anti-diabetic properties. Copper nanoparticles' ability to scavenge free radicals makes them suitable for medical and therapeutic purposes, including managing diabetes of type 2[130].

Antibacterial

The term "antibacterial property" describes the ability of a substance to either stop or eradicate bacterial growth. This characteristic is essential for maintaining the safety and sterility of diverse environments, treating and preventing bacterial infections, and maintaining product quality .

In a study by Kumar *et al.*, copper nanoparticles were created using extracts from *Nigella sativa* seeds at different concentrations (5%, 6%, 8%, and 10%), and their antibacterial and antiobesity properties were assessed. With inhibition zones of 25 mm and 24 mm, respectively, the produced nanoparticles demonstrated strong antibacterial activity against *E. coli* and *Pseudomonas aeruginosa*[131].

AgNPs were created by Chand *et al.* using a green synthesis method using *neem* extract (NE) alone and mixed plant extracts of neem, onion, and tomato (NOT) as a combined reducing and stabilising agent at different pHs. They demonstrated that synthesised AgNPs exhibited antibacterial properties against *Staphylococcus aureus*[132]. Tamileswari *et al.* synthesised AgNPs using the vegetable extract of *Raphanus sativus* (radish). The findings demonstrated that *Raphanus sativus*-derived silver nanoparticles exhibited efficacious antibacterial activity in comparison to ampicillin. Among these, *Bacillus subtilis* exhibited the largest zone of inhibition, measuring 14 mm[133].

Abdel-Raouf *et al.* demonstrate the preparation of gold nanoparticles (Au) utilising powdered or extracted *Galaxaura elongata*. With *G. elongata* extract in an aqueous medium under typical air conditions, it has been discovered that stable Au nanoparticles can develop quickly. The antibacterial properties of the nanoparticles were also assessed, and AuNPs made from ethanolic extract demonstrated superior antibacterial effects against *E. coli*, *Klebsiella pneumoniae*, and MRSA, respectively, with maximum inhibition zones of 17–16 mm, followed by *Staphylococcus aureus* and *Pseudomonas aeruginosa* (13 mm). Additionally, it was discovered that the nanoparticles made from *G. elongata* powder were quite effective against *K. pneumoniae* (13.5 and 13 mm) and *E. coli*, respectively[134].

Anti-inflammatory

The tendency of nanoparticles to reduce or prevent inflammation at the cellular or molecular level is referred to as their anti-inflammatory properties. Because of these characteristics, nanoparticles are especially helpful in the treatment of inflammatory illnesses and other medical applications[135]. *Tinospora cordifolia* extract was used by Prakash *et al.* as a reducing agent during the chemical reduction process used to create CuNPs because of its high phenolic and flavonoid content. Synthesised NPs were evaluated for anti-inflammatory qualities. *T. cordifolia* leaf extract was found to mediate Cu NPs, as healed extraction was 56.35% and diclofenac 89.31%, respectively[136].

Bag *et al.* synthesised gold NPs using the fruit extract of *Bursera serrata*. Green synthesis and characterisation of gold nanoparticles are achieved. *B. serrata* was found to contain a significant amount of quercetin, which has anti-inflammatory properties[137]. In order to determine the impact of antibacterial, antioxidant, and anti-inflammatory capabilities in both *vivo* and *in vitro*, Sunayana *et al.* used a synthetic gold nanoparticle (VnAuNPs) and an extract of Vitex negundo, a traditional anti-inflammatory folk medicine in India. Significant anti-inflammatory properties (COX-2, lipoxygenase, as well as xanthine oxidase inhibitory activity) were demonstrated by VnAuNPs in both *in vitro* (HeLa cell model) and *in vivo* (paw oedema along with acetic acid-induced writhing test) studies of carrageenan-induced paw oedema in Swiss albino mice. According to the findings, the produced VnAuNPs may be useful in the treatment of inflammatory conditions[138].

Aqueous leaf extracts of *Azadirachta indica* and *Aloe barbadensis* in their combined form, known as *A. indica* and *A. barbadensis* bio-AgNPs, were utilised in the green synthesis method by Dhanalakshmi *et al.* to produce silver nanoparticles, which inhibited albumin denaturation[139]. Kedi *et al.* silver nanoparticles using *Selaginella myosurus* aqueous extract. Synthesised silver nanoparticles have demonstrated their anti-inflammatory properties through their activities, and as such, they may be a viable source for anti-inflammatory drugs[140].

Antifungal

Antifungals are drugs that either prevent or stop the growth of fungi or spores that cause infection. The interest of the public has been attracted globally due to the increasing drug resistance of pathogenic fungi. The limited availability of fungicides, the extreme toxicity of certain fungicides, and drug resistance are some of the drawbacks of antifungal medications[141]. Therefore, it is important to develop novel antifungal drugs that are easy to induce antifungal properties. Green synthesised nanomaterials have been considered as potential antifungal drugs due to their good antifungal activity, nontoxicity, abundant availability and low cost. Green synthesis of gold, silver, and zinc nanoparticles using natural resources like plant extracts offers a sustainable and eco-friendly approach for antifungal applications. These nanoparticles have noteworthy antifungal impacts due to their ability to rupture fungal cell membranes, generate reactive oxygen species (ROS), and interfere with metabolic processes[142].

Ege Ediz *et al.* synthesised the silver nanoparticles using the extract of *phaseolus vulgaris* L. and investigated their antifungal activities towards the different pathogenic fungi, i.e., *Sclerotinia sclerotiorum, Alternaria alternate, Fusarium oxysporum, Fusarium acuminatum, Fusarium tricinctum, Fusarium graminearum, Fusarium incarnatum*, *Rhizoctonia solani,* and *Colletotrichum sp.*, using the technique of well diffusion agar and concluded that the obtained AgNPs show higher levels of antifungal activity even in low concentrations of the synthesised AgNPs, especially in the case of *Fusarium tricinctu*[143].

Using an extract from Celastrus paniculatus leaves, Mali *et al.* sought to investigate the environmentally friendly green production of copper nanoparticles (CuNPs). Using the poison food technique, the produced CuNPs revealed strong antifungal activity against *F. oxysporum*. This substance was shown to be an effective antifungal agent against fungi that cause damage to plants. *Fusarium oxysporum's* maximal mycelial inhibition was 76.29±1.52[144].

Folorunso Femi Adekunle *et al.* focused on the evaluation of the antifungal potency of gold nanoparticles synthesised using the extract of *Garcinia kola* leaves. Synthesised gold nanoparticles were employed for the antifungal screening of various fungi, *Candida albican*, *Fusarium oxysperium, Aspergillus flaws*, and *Penicillium camemeri*. They observed that the antifungal activity of the green-synthesised AuNPs increases with an increase in concentration. Also, their findings indicated that ‘Aspergillus flaws’ established the most resistance to the synthesised AuNPs' inhibitory activity, whereas *Fusarium oxysperium* exhibited the greatest susceptibility to its activity among the test fungi[145].

Future perspective

A future prospect for plant-mediated green synthesis of copper, gold, and silver nanoparticles in biomedical fields is based on gaining a better understanding and engineering of the synthesis methods to achieve a fine level of control over nanoparticle size, shape, and surface properties[146]. This will enable researchers to tailor these nanoparticles' properties for therapeutic, imaging, and targeted drug delivery applications. To create plant extracts that yield nanoparticles with maximum biocompatibility and activity, the role of phytochemicals in the reduction and stabilisation processes must be understood using advanced spectroscopic and molecular methods. For promoting clinical translation, toxicological and pharmacokinetic studies continue to be necessary, especially for the understanding of long-term safety, degradability, and systemic interactions in the living organism. It is possible that efficiency of synthesis, stability, and newer functionalities could be enhanced by extending the research scope to include newer and less explored plant species, particularly those with unique or copious secondary metabolites. New applications for the creation of advanced nanostructures with a variety of functions will be made possible by further marrying green synthesis methods with state-of-the-art technology, including AI for rapid optimisation and microfluidics for scaling production. Embracing these research paths would make the approach even more environmentally friendly and speed up its impact on the biomedical sector, from regenerative medicine to cancer therapies and antimicrobial coatings.

Conclusion

Using plants for green synthesis is a sustainable and promising route for producing nanoparticles of copper, gold and silver with significant therapeutic promise. Bioactive phytochemical classes such as polyphenols, flavonoids, terpenoids, amino acids and carbohydrates, serve as natural reducing and stabilising agents, allowing the use of environmentally friendly processes for nanoparticle fabrication. Nanoparticles that are green synthesized from plant extracts have been widely applied in biomedicine. Silver nanoparticles have shown significant anticancer activity through inducing apoptosis and generating reactive oxygen species while maintaining biocompatibility. Gold nanoparticles are excellent antibacterial agents, with activity against methicillin-resistant *Staphylococcus aureus*. Copper nanoparticles have demonstrated significant anti-inflammatory, anti-obesity and antidiabetic effects, and also possess high photocatalytic efficiency for possible future use in environmental remediation. Although advancements have been made to green system and establishing biomedical functions of nanoparticles, several obstacles remain before they may be clinically translated. It will be necessary to standardise syntheses and gain control over particle size distribution, conduct comprehensive long-term toxicity studies, and develop scalable products. Standardising quality control measures and conducting systematic clinical trials would be required for safety and efficacy. Future efforts to integrate computation modelling with the latest advances in characterisation for particle design should commence. Providing personalised medicine will depend on developing individual drug delivery mechanisms or combination drug delivery system or approaches. Furthermore, continued efforts of preclinical research should confirm feasibility and effectiveness of methods described for improvement of global health. Upon considering, utilising plants for cost-effective, environmentally friendly green synthesis is an eco-affable, cost effective viable avenue for nanomedicine. There are ample opportunities for future nanomedicine in making significant strides toward improving global health.

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Conflict of interest

No potential conflict of interest was reported by the author(s).

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