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REVIEW PAPER

Synthesis of Inorganic Nanoparticles Using Traditionally Used Indian Medicinal Plants

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Abstract

Considering the exclusive environmental conditions and geological characteristics, Indian flora is extensive and rich in medicinal plants. From primeval times, plant parts and their metabolites have been widely explored for various practices including medicinal as well as culinary. The phytochemicals present in these plants are potential reducing agents for the bio-fabrication of these nanoparticles. The non-toxic nature and combination of the plant phytochemicals with precursor ions act as key aspects for synthesized nanoparticles. The present review highlights the potential applications of Inorganic nanoparticles synthesized from 148 traditionally used medicinal plants present in the Indian geographical region. In addition, parameters that influence the green synthesis of Inorganic nanoparticles such as the extraction methods, solvents used for extraction, the concentration of precursor and plant phytochemicals, pH, temperature, reaction time, and characterization techniques of the nanoparticles are discussed. Thus, the review provides information on the research that has been done in the area of green synthesis using Indian medicinal plants.

Keywords Green synthesis · Nanoparticles · Indian medicinal plants · Phytochemicals · Reducing agents

Introduction

India is known to have rich biodiversity, with more than 8000 species of medicinal plants. The Himalayas and Tropical forests of the Western Ghats are the hotspots of traditional medicinal plants. About 1800 species of medicinal plants are extensively available for their use in traditional healing practices such as Ayurveda, Siddha, Tibetan, and Unani [1]. Extensive information about the properties and uses of these plants has been well documented in ancient Indian monumental works like Charaka Samhita and Susruta Samhita. The climatic conditions and geographical location significantly support the maintenance of these medicinal plants and thus help in the sustenance of the same in traditional medications. Fruit, roots, leaves, bark, and sometimes whole plants are used in the preparation of traditional medicines [2, 3]. Studies have revealed the abundance of vast varieties of phytochemicals like phenolic acids, flavonoids, etc. in these medicinal plant species which is the major factor that makes use of these medicinal plants in different medicinal practices [4].

Recent researches try to explore the practicability of the utilization of phytochemicals in the field of nanotechnology as a result of advancements in the field of medicinal research. Nano in Greek means "dwarf", but nano is infinitely smaller than a dwarf. The nanoworld deals with tiny objects which are nanometric (10^{-9} m) in size at least in one dimension. Nanoparticles (NPs) have a maximum size of 100 nm. These particles exist in the nanometer range. The nanometer dimension gives them their unique properties. The newly synthesized NPs can have variations in their size, shape, and even in their distribution [5]. The science of nanomaterials deals with their generation and the properties exhibited by them because of their small size. The subject of nanoscience has gained great importance because of its promising applications in various areas such as the chemical and textile industry, material industry, medical diagnostics, drug delivery, and electronics [6].

Diverse methods for the fabrication of NPs are getting popularized. Nanofabrication by chemical and physical

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synthesis methods utilizes unsafe chemicals and requires high energy utilization, which affects the environmental conditions. The bio-fabrication techniques of NPs synthesis include the practice of using biological agents including carbohydrate sources, plant extracts, and microorganisms as reducing and capping agents [7]. Those methods which utilize plants for NP synthesis have supremacy over other synthesis methods as they are uncomplicated, one-step, worthwhile, ecological, and reproducible. Often results are in more safe and steady materials. Microorganisms are also utilized to synthesize NPs, but at the same time, the rate of NP synthesis is slow in comparison with green synthesis, due to long incubation periods [8]. The plant-mediated green synthesis is obtaining more attention, as these processes are flexible, in-expensive and non-toxic than other methods. The phytochemicals present in the plant extracts act as both reducing and capping agents in the NPs synthesis [9]. The authors compile and summarize the current knowledge about the use of phytochemicals from Indian medicinal plants in the synthesis of NPs, optimization parameters, characterization methods, and its applications.

Nanoparticle Synthesis

General Mechanism of NP Synthesis

Top-down and bottom-up approaches are two types of NPs synthesis. The top-down approach uses macroscopic particles as the starting blocks of the synthesis procedure. In these methods, bigger-sized particles are reduced to small-sized NPs through a series of reactions like grinding of bulk materials to smaller-sized particles and further to nano-sized particles. Physical and Chemical vapor deposition, Ion implantation, Electron beam, and X-ray lithography utilize the top-down approach [10]. In bottom-up methods, NPs are synthesized from molecules at the atomic level and these units are clustered to get stable nanostructures. Sol–gel, Colloidal precipitation, Hydrothermal, Organometallic chemical, and electro-deposition utilize the bottom-up approaches [11].

NP synthesis methods are classified into physical, chemical, and biological. Physical methods require high energy and are suitable for small-scale purposes only. Chemical synthesis methods involve the usage of chemicals that may produce toxic byproducts damaging the environment. Biological methods explore the use of plant materials and microorganisms for synthesis [10]. Biological methods of synthesis are more advantageous over other methods as they are economical, nontoxic, low energy consumption, less consuming, and easily scalable as the raw materials are easily available in the environment. These methods are highly suitable for biological applications and in vivo applications such as drug delivery and can be used as bioactive agents in biological reactions [12]. Biological methods that utilize plant parts are collectively called green synthesis methods. Green synthesis utilizes phytochemicals, like flavonoids, phenolic acids, terpenoids, proteins, organic acids, and alkaloids as reducing and capping agents [13].

Green Synthesis of NPs from Indian Medicinal Plants

The huge number of phytochemicals present in medicinal plants make them potential agents for the green synthesis of NPs. Studies report the extensive utilization of various Indian medicinal plants as reducing agents in the reduction of various kinds of metallic, metal oxide, bimetallic as well doped NPs. Commonly available medicinal plants such as *Azadirachta indica*, *Aloe vera*, and *Phyllanthus emblica* are comprehensively practiced in the biosynthesis of NPs [14, 15, 16]. Studies have reported the reducing potential of *Acalypha indica plant* extract during the synthesis of Silver, Copper oxide, and Tin oxide NPs. FTIR studies of the plant extracts support the influence of phytochemicals on the bioreduction process as well as the properties of the synthesized NPs [17, 18, 19, 20]. Ag NPs have been reported using the plant extracts of *Aloe Vera*, *Andrographis paniculata*, *and Annona muricata* [14, 21, 22, 23]. All these plants are potential medicinal plants known for their potential pharmaceutical properties. Various reports have proven the potential of different medicinal plants as reducing and capping agents in the synthesis of different NPs. (Table 1).

Types of Nanoparticles

Based on the chemical composition, NPs are mainly categorized as organic, inorganic, and carbon-based NPs. Organic NPs include liposomes, micelles, ferritin, dendrimers, etc., and these are widely used in biological systems mainly for drug delivery purposes as they are efficient in targeted drug delivery. Most plant-based NPs are inorganic. This category includes metal NPs, metal oxide NPs, bimetallic NPs, and doped NPs. Carbon-based NPs include different nanomaterials of various shapes and sizes. Fullerenes, graphene, carbon nanotubes, carbon nanofibers, and carbon black are examples of carbon-based NPs (Table 1) [24].

Metal NPs

Silver (Ag), Gold (Au), Zinc (Zn), Copper (Cu), Cobalt (Co), Aluminium (Al), Iron (Fe), Cadmium (Cd), Lead (Pb), Selenium (Se) are generally used as precursors for metal NPs synthesis. During the green synthesis of metallic NPs, the crude extract phytochemicals act as reducing

Table 1 Green synthesis of nanoparticles using traditionally used Indian Medicinal Plants

Plant	Type of nanoparticle	Part used	Characterization methods	Size and shape (nm)	SPR peak(nm)	Reference
Abroma augusta Linn	Au	Bark	UV, FTIR, SPRS, TEM, XRD	23.4; spherical	549.5	[66]
Acalypha indica	Ag	Leaves	UV, SEM, XRD, EDS, HR-TEM	20–30; spherical	420	[18]
Acalypha indica	CuO	Leaves	FTIR, UV, XRD, SEM, EDAX, XPS, TEM	2–100; crystalline	294	[17]
Acalypha Indica	SnO_2	Leaves	XRD, FTIR, UV, ZP, SEM-EDAX, AFM, TGA,	5–38; crystalline	200–290	[19]
Achillea wilhelmsii	Au	Leaves	UV, FTIR, XRD, TEM, DLS	2.7–38.7; spherical	540	[46]
Achyranthes aspera	Au	Leaves	UV, SEM, TEM, SAED	50–80; spherical	540	[84]
Actinodaphne madraspatana	Ag	Bedd leaves	UV, TEM, XRD, FTIR, ZP	20–60; spherical	434	[141]
Aegle marmelos	ZnO	Fruit pulp	UV, FTIR, XRD, SEM, EDX, TEM, ZP, PL	20; crystalline	372	[37]
Aegle marmelos	Ag	Fruit pulp	UV, HR-TEM, FTIR, XRD, FE-SEM	10–75; FCC cubic crystalline	445	[62]
Afzelia quanzensis	Ag	Bark	UV, SEM, XRD, FTIR	10–80; spherical	427	[142]
Ailanthus excelsa	Ag	Leaves	UV, FTIR, SEM	22–30; spherical	446	[143]
Allium cepa	Au	Bulbs	UV, XRD, SEM, TEM	100; spherical, cubic	540	[108]
Allium sativum	Ag	Garlic clove	UV, XRD, FESEM, FETEM, EDX, DLS	4–22; spherical	408	[53]
Aloe Vera	Ag	Leaves	UV, SEM	10–60; spherical	405	[14]
Aloe Vera	ZnO	Peel extract	UV, FTIR, XRD, SEM, TEM	50–220; hexagonal	240	[94]
Aloe Vera	Ag/Cu	Leaf gel	FTIR, XRD, SEM, EDX	60–70	N/A	[144]
Aloe vera	ZnO	Leaf gel	UV, FTIR, XRD, SEM, EDX	9–18; crystalline	344–360	[51]
Aloe vera	TiO_2	Leaves	XRD, FT-RS, FTIR, SEM, TGA/DTA,	15–30; spherical	N/A	[145]
Alpinia officinarum	Ag	Rhizome	UV, FTIR, XRD, TEM, SAED	100; FCC crystalline	445	[124]
Alysicarpus monilifer	Ag	Leaves	UV, TEM, XRD, FTIR, EDX	15; spherical	422	[146]
Amaranthus spinosus	ZnO	Leaves	UV, FTIR, XRD, SEM, EDX	21.1; crystalline	678	[147]
Ammonum subulatum	Au	Fruit	UV, XRD, FTIR, TEM	15–20; spherical	536	[148]
Andrographis paniculata	Carbon Dots	Leaves	UV, XRD, FTIR, TEM, EDS, TGA, ZP	8–11;	265	[149]
Andrographis paniculata	Cu	Leaves	UV, FTIR, XRD, TEM, DLS	8–20; spherical	535	[87]
Andrographis paniculata	Ag	Leaves	UV, FTIR, SEM, DLS	70–95;	420—455	[23]
Angelica archangelica	Au	Root	UV, FTIR, TEM, AFM	4–8; spherical, ovals, heart or polyhedral	520–540	[65]

Table 1 (continued)

Plant	Type of nanoparticle	Part used	Characterization methods	Size and shape (nm)	SPR peak(nm)	Reference
Annona muricata	Ag	Root bark	UV, TEM, PCM, FTIR, ZP	22; spherical	420	[49]
Annona muricata	Ag	Leaves	UV, XRD, FTIR, FE-SEM, HR-TEM, EDX	45; crystalline spherical	420	[22]
Anogeissus latifolia	Ag	Gum	UV, TEM, XRD, FTIR, SAED, RS	5.7; spherical	412	[150]
Artemisia vulgaris	Ag	Leaves	UV, FTIR, TEM	20–50; globular	427	[43]
Artocarpus heterophyllus	Ag	Seeds	UV, TEM, SAED, EDX, FTIR,	10.78; irregular	420	[151]
Asparagus racemosus	Cu	Root	UV, FTIR, XRD, SEM, TEM	50–100; rod shaped	275	[67]
Astragalus gummifer	Ag	Gum	UV, FTIR, TEM, XRD	18; FCC crystalline	418–428	[127]
Atropa acuminata	Ag	Leaves	UV, XRD, TEM, ZP, FTIR,	Spherical	428	[60]
Avicennia alba	Ag	Leaves	UV, DLS, SEM, TEM, XRD, AFM	18.3; spherical, cuboidal	448	[45]
Azadirachta indica	Ag	Leaves	UV, XRD, FTIR, TEM, EDS, TGA, ZP	5–35; spherical	450	[152]
Azadirachta indica	Au	Leaves	UV, XRD, FTIR, TEM, EDS, TGA, ZP	Planar, hexagonal	550	[152]
Azadirachta indica	Ag/Au	Leaves	UV, XRD, FTIR, TEM, EDS, TGA, ZP	50–100;	557	[152]
Azadirachta indica	Ag	Leaves	UV, FTIR, SEM, XRD	400; spherical	400	[56]
Azadirachta indica	Ag	Leaves	UV, XRD, FTIR, SEM, EDX, TEM	29; spherical	437	[111]
Azadirachta indica	Ba	Leaves	XRD, FTIR, EDX, TGA, FEG-SEM,	80; crystalline	N/A	[153]
Azadirachta indica	Ag	Leaves	UV, SEM, TEM, FTIR	9–56; crystalline	433	[154]
Azadirachta indica	Ag	Leaves	SEM, TEM, FTIR, UV	9–13;	433	[16]
Azadirachta indica	Ag	Leaves	UV, SEM, FTIR, XRD	41–60; crystalline	442	[93]
Azadirachta indica	Ag	Leaves	DLS, UV	420–450; spherical	400	[113]
Azadirachta Indica	Cu	Leaves	UV, FTIR, FE-SEM, TEM, XRD, ZP	48; crystalline, cubical	560	[16]
Azadirachta indica,	Ag	Leaves	UV, DLS, SEM, TEM, EDS, FTIR	200; Spherical, triangular and cuboidal	425–475	[107]
Azadirachta indicia	ZnO	Leaves	ZP, XRD, SEM, FTIR	19.57 ± 1.56; non-spherical	N/A	[155]
Azolla microphylla	Au	Whole plant	UV, FTIR, FESEM, EDX, XRD, HRTEM, TG–DTA	17–40; crystalline	540	[156]
Bauhinia tomentosa	FeO	N/A	UV, FTIR	70; crystalline	550	[157]
Blumea balsamifera	Cu	Leaves	FTIR, SEM, EDS,	150–350; spherical	N/A	[158
Boerhaavia diffusa	Ag	Whole plant	UV, SEM-EDAX, XRD, TEM	25; spherical	418	[159]

Table 1 (continued)

Plant	Type of nanoparticle	Part used	Characterization methods	Size and shape (nm)	SPR peak(nm)	Reference
Brassica oleracea var. botrytis	Ag	Leaves	UV, FTIR, XRD, SEM, TEM, SAED, XPS, BET	35.08; FCC	422	[160]
Buchanania lanzan	Ag	Gum	UV, FTIR, SEM, TEM, AFM, ZP	14.74–19.86; spherical	415–440	[105]
Callistemon viminalis	HgO	Flower	FTIR, UV, XRD, TEM	2–4; cubic crystalline	243	[48]
Calotropis gigantea	ZnO	Leaves	UV, DLS, XRD, FTIR, SEM, EDX, AFM	10; crystalline	350	[134]
Camellia sinensis	FeO	Leaves	SEM, EDS, XRD, BET, UV, FTIR	10–100; spherical	230 -240	[69]
Cannabis sativa	Au	Leaves	UV, SEM, DLS, ZP	10–35; spherical	538	[161]
Carica papaya,	SnO_2	Leaves	XRD, FTIR, DLS, SEM-EDAX, AFM, TGA, UV	5–38; crystalline	200–290	[19]
Cassia alata,	Ag	Leaf metabolites	UV, SEM, XRD	17–30; spherical	400	[59]
Cassia auriculata	Au	Leaves	XRD, TEM, SEM—EDAX, FTIR, UV	15–25; spherical	536	[162]
Cassia fistula	ZnO	Leaves	UV, FTIR, XRD, SEM, DLS,	3–68; spherical	320	[68]
Cassia fistula	ZnO	Leaves	UV, XRD, TEM	5–15; crystalline	370	[109]
Cassia javanica	Ag	Leaves	UV, TEM, FTIR	100; spherical	435	[163]
Centella asiatica	Au	Leaves	UV, TEM, XRD, SAED, FTIR,	2–22; spherical	534	[164]
Centella asiatica	Ag	Leaves	UV, FTIR, SEM, TEM, XRD,	13; FCC crystalline	430	[165]
Ceropegia thwaitesii	Ag	Leaves	UV, SEM, DLS, XRD, FTIR, XPS, AFM, TEM	100; spherical	430	[104]
Cinnamomum camphora	Ag	Callus	UV, TEM, SEM–EDX, DLS, FTIR, XRD	5.47–9.48; crystalline	420	[166]
Cinnamomum tamala	Ag	Leaves	UV, FTIR, XRD, TEM	10–12; spherical	460–470	[167]
Cissus quadrangularis	Ag	Stem	UV, FTIR, XRD, SEM	37–44; spherical, rod, triangle	410–460	[168]
Citrus aurantifolia	CuO	Leaves	XRD, UV, SEM, FTIR	22; crystalline	240–300	[130]
Citrus limon	$CoFe_1.9Sm_{0\cdot1O4}$	Fruit	XRD, FEG-SEM, VSM,	10—22; crystalline	N/A	[58
Clausena dentata	Se	Leaves	UV, FTIR, EDAX, SEM,	46.32–78.88;	420	[169]
Cleome viscosa L	Ag	Fruits	UV, FTIR, XRD, FESEM-EDAX, TEM	5–30; spherical	410–430	[41
Coleus aromaticus	Ag	Leaves	UV, XRD, SEM, EDS, FTIR	44; spherical	460	[170]
Commelina benghalensis	Ag	Leaves	UV, FTIR, SEM, XRD	32–48; crystalline	423–452	[171]
Coriandrum sativum	Ag	Seeds	UV, TEM, XRD, PDS, DLS, AFM, SEM	13.09; spherical	421	[117]
Crataegus monogyna	Ag	Fruit	UV, DLS, SEM, FTIR	60;	390–423	[172]

Table 1 (continued)

Plant	Type of nanoparticle	Part used	Characterization methods	Size and shape (nm)	SPR peak(nm)	Reference
Crataegus monogyna	Cu	Fruit	UV, DLS, SEM, FTIR	100; spherical	600	[172]
Cupressus macrocarpa	Ag	Leaves	UV, TEM, XRD, FTIR	13.5–25.8; spherical	429	[173
Curculigo orchioides	Ag	Rhizome	UV, TEM, XRD, FTIR	5–28; spherical	430	[174]
Cycas circinalis,	Ag	Leaves	UV, FTIR, SEM, XRD	32–48; crystalline	423- 452	[171]
Cycas revoluta	Ag	Leaves	XRD, TEM, UV	2–6; FCC	449	[153]
Cynodon dactylon	Si	Leaves	UV, FTIR, DLS, ZP, XRD, SEM, TEM,	7–80; spherical	350	[40]
Cynodon dactylon	Ag	Leaves	UV, SEM	10–60; spherical	420	[14]
Dalbergia spinosa	Ag	Leaves	UV, TEM, FTIR	18 ± 4; spherical	439	[175]
Desmostachya bipinnata	Ag	Leaves	UV, XRD, FTIR, SEM, EDAX	53; sphere shaped	433	[176]
Dillenia indica	Se	Leaves	UV, FTIR, XRD, SEM, DLS	248; oval	383	[177]
Diospyros paniculata	Ag	Root	UV, XRD, TEM, FEG-SEM	19; crystalline	428	[36]
Eclipta prostrata	FeO	N/A	UV, FTIR, SEM, EDX, XRD, TEM	18–78; spherical	370	[70
Elaeocarpus floribundus	ZnS	Leaves	XRD, TEM, UV, FTIR, EDAX, PL	3–8; spherical	N/A	[178]
Emblica officinalis	Ag	Fruit	FESEM, TEM, XRD, EDX, DLS, UV, FTIR	40–70; crystalline	468	[57]
Emblica officinalis	Au	Fruit	FESEM, TEM, XRD, EDX, DLS, UV, FTIR	40–70; crystalline	430	[57]
Emblica officinalis	Ag/Au	Fruit	FESEM, TEM, XRD, EDX, DLS, UV, FTIR	40–70; crystalline	416	[57]
Emblica officinalis	Ag	Fruit	UV, UV—VIS NIR, FTIR, TEM	10–20;	400	[179]
Emblica officinalis	Au	Fruit	UV, UV—VIS NIR, FTIR, TEM	15–25; spherical	530	[179]
Emblica Officinalis	Ag	Fruit	UV, FTIR, XRD, AFM, SEM/EDS	15; crystalline, spherical	432–436	[35]
Enicostemma axillare	Ag	Leaves	XRD, TEM, SEM–EDS, UV, ZP	15–20; spherical	417	[180]
Eucalyptus globulus	FeO	Leaves	SEM, EDS, XRD, BET, UV, FTIR	10–100; spherical	230–240	[69]
Eulophia herbacea	Ag	Leaves	UV, ZP, SEM, EDS, XRD, DLS	11.70; FCC crystalline	447	[128]
Euphorbia hirta	Ag	Leaf metabolites	UV, SEM, XRD	17–30; spherical	400	[59]
Ficus amplissima,	Ag	Leaves	UV, FTIR, SEM, XRD	32–48; crystalline	423–452	[171]
Fraxinus excelsior	Ag	Leaves	FTIR, UV, SEM, TEM, EDX	25–40; spherical	425	[92]
Garcinia gummigutta	ZnO	Leaves	UV, XRD, FTIR, SEM	10–20; hexagonal	372	[52]
Gmelina arborea	Ag	Fruit	UV, TEM, SAED, EDX	8–32; spherical, crystalline	418 ± 3.0	[54]

Table 1 (continued)

Plant	Type of nanoparticle	Part used	Characterization methods	Size and shape (nm)	SPR peak(nm)	Reference
Hamamelis virginiana	Au	Bark	UV, FTIR, TEM, AFM	4–8; spherical, ovals, heart or polyhedral	220–230	[65]
Heliotropium indicum	Ag	Leaves	UV, FTIR, XRD, SEM, TEM	18–45; spherical, triangle, truncated triangles, and decahedral	420	[132]
Heritiera fomes	Ag	Leaves	UV, TEM, EDX, XRD, FTIR	15–40; spherical, cuboidal	403, 340, 434, and 426	[181]
Hibiscus sabdariffa	ZnO	Leaves	UV, FTIR, XRD, SEM, EDX	9–18; crystalline	344–360	[51]
Hypericum perforatum	Au	Flower	UV, FTIR, TEM, AFM	4–8; spherical, ovals, heart or polyhedral	520–540	[65]
Hyssops officinalis	ZnO	N/A	TEM, FESEM, XRD, FTIR	10–100; pseudo-spherical	N/A	[182]
Indigofera aspalathoides	Ag	Leaves	UV, FTIR, SEM, EDAX, XRD	20–50; square	420	[95]
Indoneesiella echioides	Ag	Leaves	UV, FTIR, XRD, TEM	29; spherical	420	[112]
Iresine herbstii	Ag	Leaves	SEM, EDX, XRD, FTIR	44 to 64; Cubic	438	[74]
Ixora coccinea	Ag	Leaves	UV, FTIR, XRD, FESEM,	13–57; spherical	430	[183]
Jatropha curcas	Cu	Leaves	UV, FTIR, XRD, SEM, TEM	10–12; crystalline	266, 337	[184]
Jatropha curcas	Pb	Latex	XRD, TEM, EDAX, FTIR, DLS	10–12.5;	218	[185]
Jatropha gossypifolia	Ag	Latex	UV, FTIR, SEM, TEM, EDS, XRD, ZP	5–40; crystalline	430	[186]
Justicia adhatoda	Ag	Leaves	UV, TEM	5–50; well-shaped	5–50	[187]
Justicia procumbense	ZnO	leaf, stem, root	UV, FTIR, SEM, XRD	10; spherical	370	[44]
Lantana camara	Au	Fruit	UV, TEM, SAED, DLS, XRD	150–300; triangle	540	[83]
Leptadenia reticulata	Ag	Leaves	UV, TEM, XRD	50–70; spherical, crystalline	450	[73]
Leucas aspera	Ag	Leaves	UV, FTIR, XRD, HR-TEM	20 to 40; spherical	428	[129]
Lippia nodiflora	Ag	Leaves	UV, FTIR, SEM, XRD	32–48; crystalline	423–452	[171]
Mammea suriga	Ag	Root bark	UV, SEM, EDX, XRD, FTIR	50–95; spherical	420- 490	[188]
Mammea suriga	Au	Root bark	UV, SEM, EDX, XRD, FTIR	> 100; spherical	500–570	[188]
Melia azadarach	ZnO	Leaves	UV, FTIR, XRD, SEM, DLS,	3 -68; spherical	324	[68]
Memecylon edule	Ag	Leaves	UV, SEM, TEM, EDAX, FTIR,	50–90; square,	475	[189]
Memecylon edule	Au	Leaves	UV, SEM, TEM, EDAX, FTIR,	10–45; triangular, circular, hexagonal	400–480	[189]
Mentha arvensis	Ag	Leaves	UV, SEM, EDS, TEM, TG-DA, XRD, FTIR	10; spherical	424	[15]
Mentha arvensis	TiO_2	Leaves	XRD, UV, FTIR, SEM	20–70; spherical	400	[32]

Table 1 (continued)

Plant	Type of nanoparticle	Part used	Characterization methods	Size and shape (nm)	SPR peak(nm)	Reference
Mentha arvensis	CuO	Leaves	UV, XRD, FE-SEM	22–25; crystalline	346	[47]
Mimosa pudica	ZnO	Leaves	UV, FTIR, SEM, XRD	14.7; spherical, granular	300	[86]
Moringa Oleifera	SnO_2	Leaves	XRD, FTIR, DLS, SEM, EDAX, TGA, UV	5–38; crystalline	200–290	[19]
Murraya koenigii	Ag	Leaves	UV, FTIR, XRD	5–100; spherical	420	[125]
Murraya Koenigii,	SnO_2	Leaves	XRD, FTIR, DLS, SEM, EDAX, TGA, UV	5–38; crystalline	200–290	[19]
Murraya koneigii	Ag	Leaves	UV, XRD, FTIR, SEM, TEM	35–80; crystalline	411	[114]
Musa balbisiana	Ag	Leaves	UV, DLS, SEM, TEM, EDS, FTIR	200; Spherical, triangular, cuboidal	425–475	[107]
Nepeta leucophylla	Ag	Root	UV, FTIR, XRD, TEM, FESEM	20; spherical	410	[190]
Nigella arvensis	Au	Leaves	UV, XRD, FTIR, TEM	3–37; crystalline	546	[121]
Nyctanthes arbor-tristis	Ag	Leaves	SEM, TEM, EDX, XRD, SAED, AFM	10–50; polycrystalline	460	[96]
Nyctanthes arbor-tristis	Au	Flower	UV, FTIR, TEM, XRD, NMR	19.8; spherical	N/A	[191]
Nyctanthes arbor-tristis	Ag	Seeds	UV, FTIR, XRD, SEM	50–80; crystalline	420	[192]
Ocimum gratissimum	Ag	Leaves	UV, FTIR, SEM–EDX, XRD	15.31–17.64; crystalline	420	[193
Ocimum sanctum	Ag	Leaves	UV, FTIR, SEM–EDX, XRD	15.31–17.64; crystalline	420	[193
Ocimum tenuiflorum	Ag	Leaves	UV, DLS, SEM, TEM, EDS, FTIR	200; Spherical, triangular, cuboidal	425–475	[107]
Orange peel extract	Pt	Fruit peel	XRD, EDX, TEM, CV	1.6–4.0; spherical	N/A	[194]
Paederia foetida	Ag	Leaves	UV, DLS, AFM, TEM, XRD	4–15; FCC cubic crystalline	429	[195]
Parthenium hysterophorous	ZnO	Leaves	UV, FTIR, SEM, ZP	16–108.5; spherical	327, 330	[196]
Peganum harmala	Ag	Seeds	UV, FTIR, XRD, SEM, EDS, TEM	12.73–35.61; spherical	447	[197]
Phyllanthus amarus	Ag	Whole plant	UV, TEM, XRD, EDX, DLS, ZP, FTIR	15.7, 24 ± 8, 29.78; spherical	420–430	[61]
Phyllanthus emblica	Ag	Leaves	UV, FTIR, FE-SEM, EDX, TEM, XRD	15 to 30; quasi round, spherical triangle, decahedral	418	[123]
Phyllanthus niruri	Ag	Leaves	UV, FTIR, SEM, DLS	70 -120	420–455	[23]
Piper nigrum	Ag	N/A	UV, FTIR, TEM	5–50; crystalline, spherical	440	[39]
Piper nigrum	Ag	Leaves	UV, FTIR, XPS, TEM, DLS, ZP	20–50; spherical	420	[198]
Plukenetia volubilis	CuO	Leaves	UV, TEM, DLS, FTIR, XRD,	6–10; semi-crystalline	255	[50]
Plumbago indica	Ag	Root	UV, XRD, TEM	50 to 70; spherical	420	[199]

Table 1 (continued)

Plant	Type of nanoparticle	Part used	Characterization methods	Size and shape (nm)	SPR peak(nm)	Reference
Pongamia pinnata	Ag	Seeds	UV, TEM, DLS, ZP, FTIR, FESEM, FS	16.4; spherical	439	[200]
Portulaca oleracea	Ag	Leaves	UV, SEM	10–60; spherical	415	[14]
Psidium guajava	TiO	Leaves	XRD, FTIR, FESEM, EDX	32.58; spherical	N/A	[55]
Psidium guajava	Se	Leaves	UV, FTIR, TEM, SEM	8–20; spherical	381	[201]
Pterocarpus marsupium	Au	Wood	UV, FTIR, XRD, DLS, SEM, AFM, TEM	72–85; spherical	538	[202]
Punica granatum	FeO	Leaves	SEM, EDS, XRD, BET, UV, FTIR	10–100; spherical	23–240	[69]
Punica granatum	Pt	Crust	UV, TEM, HRTEM, XRD, FESEM, FTIR	20.12; spherical	N/A	[203]
Quercus virginiana	FeO	Leaves	SEM, EDS, XRD, BET, UV, FTIR	10–100; spherical	230–240	[69]
Rauvolfia tetraphylla	Ag	Leaves	XRD, FTIR, UV, SEM, TEM	40; spherical	463	[126]
Rosmarinus officinalis	Ag	Leaves	UV, FTIR, XRD, SEM, TEM	10–33; crystalline	450	[115]
Salmalia malabarica	Ag	Gum	UV, FTIR, XRD, TEM	8.04; FCC crystalline	418–428	[99]
Seripheidium quettense	Ag	Aerial parts	UV, FTIR, XRD, SEM	49.96–54.36; crystalline	428	[64]
Sida acuta	Ag	Leaves	UV, FTIR, SEM, TEM, EDX	18–35; spherical, triangle, truncated triangles, decahedral	420	[131]
Solanum torvum	ZnO	Leaves	UV, TEM, FTIR, XRD, DLS, ZP	15–45; spherical	359	[49]
Solanum trilobatum	Pd	Leaves	UV, FTIR, SEM	60–100; poly-disperse	270	[204]
Solanum trilobatum	MgO	Leaves	UV, FTIR, XRD, EDX, SEM, DLS	30–42; spherical	362	[205]
Sonneratia apetela	Ag	Leaves	DLS, SEM, TEM, SEM, EDX, AFM	18.3; spherical, cuboidal	419–448	[45]
Sonneratia caseolaris,	Ag	Leaves	DLS, SEM, TEM, SEM, EDX, AFM	18.3; spherical, cuboidal	419–448	[45]
Sphagneticola trilobata	ZnO	Root	FTIR, SEM, XRD, EDX	65–80; crystalline, irregular	N/A	[30]
Strychnos potatorum	Ag	Leaves	UV, SEM, XRD	28; cubic, hexagonal	430	[206]
Saccharum officinarum	Cu_2O	Bagasse	UV, FTIR, XRD, TEM, SEM	38.02; spherical	256	[207]
Syzygium cumini	Ag	Leaves	AFM, SEM, FTIR	29–92; spherical	N/A	[42]
Syzygium cumini	Ag	Seeds	UV, SEM, ZS, XRD, FTIR	40 -100; crystalline	416	[38]
Syzygium Cumini	ZnO	Leaves	UV, XRD, SEM, FTIR	16.40; hexagonal, spherical	320–350	[130]
Tectona grandis	Ag	Seeds	UV, FTIR, SEM/EDS, FESEM, TEM	10–30;	440	[208]
Terminalia arjuna	Au	Fruit	UV, FTIR, XRD, AFM, EDX, TEM, DLS, ZP	20–50; spherical	523	[110]

Table 1 (continued)

Plant	Type of nanoparticle	Part used	Characterization methods	Size and shape (nm)	SPR peak(nm)	Reference
Terminalia arjuna	Ag	Leaves	UV, DLS, TEM, FTIR	8–16; spherical, irregular	440	[133]
Terminalia belerica	Ag	Fruit	FESEM, TEM, XRD, EDX, DLS, UV, FTIR	40–70; crystalline	468	[57]
Terminalia belerica	Au	Fruit	FESEM, TEM, XRD, EDX, DLS, UV, FTIR	40–70; crystalline	430	[57]
Terminalia belerica	Ag/Au	Fruit	FESEM, TEM, XRD, EDX, DLS, UV, FTIR	40–70; crystalline	416	[57]
Terminalia chebula	Ag	Fruit	FESEM, TEM, XRD, EDX, DLS, UV, FTIR	40–70; crystalline	468	[57]
Terminalia chebula	Au	Fruit	FESEM, TEM, XRD, EDX, DLS, UV, FTIR	40–70; crystalline	430	[57]
Terminalia chebula	Ag/Au	Fruit	FESEM, TEM, XRD, EDX, DLS, UV, FTIR	40–70; crystalline	416	[57]
Thespesia populnea	Ag	Leaf metabolites	UV, SEM, XRD	17–30; spherical	400	[59]
Tinospora cordifolia	Ag	Stem	ZP, ZS,	0.4;	N/A	[209
Tinospora cordifolia	Ag	Leaves	UV, FTIR, SEM, DLS	50–70;	420–455	[23]
Trigonella foenum -graecum	Ag –ZnO	Leaves	FTIR, UV, DRS, SEM–EDX, TEM, XRD, ZP, DLS	75; spherical	450, 369	[210]
Urtica dioica L	Au	Leaves	UV, TEM, XRD, DLS, FTIR, ZP	1–195; crystalline	550	[97]
Ventilago maderas-patana	Ag	Leaves	UV, FTIR, XRD, AFM, SEM, TEM	1–6; spherical	411	[106]
Vetiveria zizanioides	Au	Root	UV, SEM, DLS, ZP	10–35; spherical	538	[161]
Vigna unguiculata L	Ag	Stem	UV, SEM, EDX, FTIR, XRD	25; FCC cubic crystalline	455	[211]
Viola canescens	ZnO	Callus	UV, FTIR, SEM, XRD	< 9; crystalline	N/A	[212]
Vitex negundo	Au	Leaves	UV, FTIR, XRD, EDX, SEM, TEM	20–70; spherical	540	[213]
Vitex negundo	Ag	Leaves	TEM, XRD, UV	10–30; face cantered cubic	422, 447	[214]
Vitis vinifera (Grape vinegar)	Ag	Fruit vinegar	FTIR, SEM, XRD, EDX	6–40; spherical	424	[213]
Withania somnifera	Se	Leaves	FTIR, UV, XRD, FE-SEM, EDX, TEM	45–90; spherical	310	[25]
Wrightia tinctoria	Ag	Leaf metabolites	UV, SEM, XRD	17–30; spherical	400	[59]
Zingiber officinale	CeO_2	Rhizome	TEM, XRD, UV, DLS, FTIR	5; quasi- spherical	290	[116]

UV UV—visible spectroscopy, *FTIR* Fourier transform infrared spectroscopy, *XRD* X-ray diffraction, *SEM* Scanning electron microscopy, *TEM* Transmission electron microscopy, *DLS* Dynamic light scattering, *ZP* Zeta potential, *HR-TEM* High resolution transmission electron microscopy, *FESEM* Field emission scanning electron microscopy, *AFM* Atomic force microscopy, *EDS* Energy dispersive spectrometry, *EDX* Energy dispersive spectrophotometer, *XPS* X-ray photoelectron spectroscopy, *TGA* Thermogravimetric analysis, *DTA* Differential thermal analysis, *EDAX* Energy dispersive X-ray analysis, *SAED* Selected area electron diffraction, *SPRS* Surface plasmon resonance spectroscopy, *ZS* Zeta sizer, *VSM* Vibrating sample magnetometer, *PL* Photoluminescence, *CV* Cyclic voltammetry, *FS* Fluorescence spectroscopy, *RS* Raman Spectroscopy, *UV- VIS NIR* UV- Visible near -infrared, *NMR* Nuclear magnetic resonance, *XPS* X-ray photoelectron spectroscopy, *BET* Brunauer-Emmet-Teller, *FEG SEM* Field emission gun scanning electron microscopy, *N/A* Not available

agents in the bio-reduction of metal ions. The successful synthesis of Ag NPs was reported using leaf extracts of *Ocimum gratissimum* and *Ocimum sanctum* [20]. Spherical-shaped Se NPs were synthesized using *Withania somnifera* plant leaves extract. The synthesized NPs were reported to have potential biological applications such as antimicrobial and photocatalytic activities [25]. Numerous studies have reported the green synthesis of metal NPs to possess potential biological activities.

Metal Oxide NPs

Metals react with atmospheric oxygen to produce metal oxides and show more reactivity than metals. Metal oxide NPs are generally modifications of metal NPs. These oxides of NPs possess good biological and catalytic activities that can be potentially used in environmental applications [17]. Cerium oxide (CeO_2), Aluminium oxide (Al_2O_3), Iron oxide (Fe_2O_3), Silicon oxide (SiO_2), Zinc oxide (ZnO), Copper oxide (CuO), and Titanium oxide (TiO_2) are generally synthesized metal oxide NPs.

Bimetallic NPs

Combinations of different metals are also used in the synthesis of NPs. Different metal solutions are mixed using a bio-reducing agent like plant extracts for the formation of bimetallic NPs. Plant extracts of ginger rhizomes have shown efficient bio-reducing activity in the synthesis of three bimetallic Cu–Ag, Cu–Ni, and Ni–Ag NPs [26]. Combinations of metals like Au–Cu, Ni–Cu, Ag–Ni, and ZnO–Ag have generally been used for NP preparations. The combinations of these metals show synergistic effects in combined nanostructure form.

Doped NPs

The improved efficiency of doped semiconductor NPs has been widely studied by recent research developments. Combinations of organic nanostructures such as polymeric NPs, Carbon-based NPs as well as inorganic NPs are intensively applied for formulating doped NPs. Carbon-doped ZnO NPs have reported the construction of wurtzite crystal-structured NPs with improved magnetic properties [27]. Nitrogen-doped TiO_2 NPs with increased photocatalytic activity were synthesized by the thermal deposition method [28]. Metal doped, as well as organic material-doped NPs, have been extensively studied for their increased biological, thermal, catalytic, magnetic, and other optical properties [28, 29, 30].

Optimization of Green Synthesis

The bio-construction of metallic NPs takes place by reducing metal ions by the phytochemicals existing in plant extracts. This bio-reduction process can be considered the initial step of the NP synthesis process. After the initialization of the green synthesis, phytochemicals also act as crucial agents in stabilizing and regulating the morphological characteristics of the synthesizing NPs [31

Extraction Methods and the Solvents Used

The extraction methods for crude extract preparation are crucial for the quality of plant phytochemicals extracted. Commonly used method for extraction involves boiling, Soxhlet extraction, reflux extraction, and maceration among others. Boiling is a simple method that is used in the extraction of crude extracts using plant materials. However, the chances of phytochemical loss during this extraction are high. Maceration is a conventional extraction method that uses smaller-sized plant material followed by the application of pressurized conditions with subsequent filtration of the plant extract. Soxhlet extraction is a widely used extraction technique in the extraction of bioactive compounds from plant materials. [33]. Advanced extraction techniques such as Ultrasound-assisted extraction, Pulsed-electric field extraction, Enzyme-assisted extraction, Microwave-assisted extraction, Pressurized liquid extraction, and Supercritical fluid extraction can also be used for the extraction of bioactive phytochemicals [33, 34].

The solvents play an important role in the optimization of green synthesis. As the number of phytochemicals is a leading factor in the green synthesis efficiency the maximum number of phytochemicals acquired during the extraction will increase the optimization. Methanol, ethanol, and water are good solvents that can be used for the extraction of the maximum number of bioactive molecules. Other solvents such as chloroform, dichloro-methanol, ether, and acetone are also used for the extraction procedure [33]. *Emblica officinalis* fruit extract was obtained through the boiling method and subsequent filtration process. The study has reported the formation and efficient production of Ag NPs using the resulting aqueous fruit extract [35]. In another study, methanolic extract of *Diospyros paniculata* root was obtained through the soxhlet extraction technique for the bioreduction of Ag ions to Ag NPs [36]. Table 1 mentions the different extraction methods and solvents used for extraction from different plants.

Precursor Concentration

Various precursors are utilized for NPs synthesis. Ag NO_3 is the extensively used precursor for the synthesis of Ag NPs.

In the green synthesis of Ag NPs, the frequently reported metal ion concentration was 1 mM. Also, other concentrations such as 1, 2, 3, 4, 5, 8, 10, and 50 mM are used by researchers [18, 37, 38, 39, 40, 41, 42, 43, 44]. It is observed that higher metal ions concentrations help in the reduction of reaction time. Researchers have used 1, 5, and 10 mM Ag NO_3 solutions for the bio-synthesis of Ag NPs using mangrove plant extracts. Among these concentrations of $AgNO_3$ solutions, higher concentrations have produced Ag NPs in lesser time [45]. Studies have proved that changing concentrations of Ag ions during the green synthesis of Ag NPs significantly influence the morphological characteristics of the resulting NPs. Similarly, Chloroauric acid (HAuCl4) is used as the precursor for the green synthesis of Au NPs [46]. ($Cu(NO_3)_2$), for CuO NPs, $Zn(NO_3)_2$ $6H_2O$ for ZnO NPs, $SnCl_2.2H_2O$ for SnO_2 NPs, $Hg(CH_3COO)_2$ for HgO NPs, $TiO(OH)_2$ for TiO_2 NPs, $Pb(CH_3COO)_2$ for Pb NPs were efficiently utilized in the green synthesis studies [19, 47, 48, 49, 50, 51, 52].

The high concentrations of metal ions effectively produce more NPs within less time. It is vital in the case of green synthesis, which utilizes plant extract with less amount of phytochemicals. The deficiency of the phytochemicals/effective reducing agents can be satisfied by using high metal ion concentrations, thereby helping in the subsequent reduction of reaction time [18, 38, 41

The Concentration of Plant Phytochemicals

Plant extract phytochemicals such polyphenols, alkaloids, tannins, flavonoids, terpenoids, ketones, aldehydes, amides, and carboxylic acids serve as reducing and capping agents for the bio-reduction of NPs in the biological synthesis [17, 41, 53–55]. These biomolecules donate electrons for the reduction of precursor molecules. Studies have proved the efficiency of plant-mediated reducing agents, including terpenoids and flavonoids, in the bio-reduction of Ag salt to Ag NPs [56]. FTIR studies on *Annona muricata* plant-mediated Ag NP synthesis have reported the utilization of plant phytochemicals such as alkaloids, polyphenols, carbohydrates, glycosides, and flavonoids in the bioreduction of NPs. These biomolecules influence the antimicrobial and antioxidant properties of the established NPs [21]. Studies have used varying concentrations of crude extracts to analyze the significance of phytochemical concentrations on the bioreduction process [17, 40, 57, 58]. The quantitative and qualitative analysis of phytochemicals carried out in different nanofabrication studies has proved the importance of the presence and concentration of these biomolecules in the bioreduction of NPs [25, 35, 59–62](Table 2).

The Effect of pH

pH is crucial for NPs synthesis as it affects the morphological characteristics of the synthesized NPs. The pH of the reaction mixture influences the redox reaction and thereby the binding among the metal ions and the plant phytochemicals that act as capping agents by altering the charge on metabolites during the nanofabrication process. Consequently, the stability of the NPs is also influenced by the pH of the reaction medium [32]. Few researchers have demonstrated the impact of pH on the NP's green synthesis. The study has proposed two reaction pathways to demonstrate the formation of Ag NPs based on pH changes that develop by the addition of NaOH during green synthesis. Silver nitrate, glucose, sodium hydroxide (NaOH), and starch, respectively were used as precursors, reducing agents, accelerators, and stabilizers for the reduction synthesis of Ag NPs. pH was reduced to a minimum value and then increased with the consequent addition of NaOH. pH performs an influential part in the nano-synthesis mechanism by influencing the rate of the reduction process, consequently affecting the topology of the synthesizing NPs [32, 63

In a similar study, *Seriphidium quettense* mediated green synthesis of biogenic nanoparticles, the optimization of the synthesis was done by optimizing the plant extract pH. They used crude extract at various pH of 4, 5, 6, 7, 8, and 9 and proved the importance of pH in the bioreduction of NPs. It was observed that the increased pH has increased the rate of NPs formation and alkaline pH synthesized stable NPs. At the same time, acidic pH has produced aggregates of NPs. Studies have proved that the basic pH supports the synthesis of smaller-sized NPs than acidic pH [64].

The Effect of Temperature

The temperature at which the bioreduction of the NPs takes place is a crucial factor in the green synthesis of nanomaterials. Most researchers synthesize NPs at room temperature (RT). At the same time, it has been also reported that higher temperatures can reduce the reaction time and ease the green synthesis process. It is evident from the studies that temperature is an influential factor that can affect the size, shape, yield, and stability of green synthesized NPs. The NPs synthesis at RT is considered a simple and natural method of green synthesis. The stability of the plant phytochemicals is a crucial as well as advantageous factor in the green synthesis of Inorganic NPs at RT. But it may cause an increase in the reaction time. Green synthesis of Ag NPs using *Artemisia vulgaris* was established at room temperature with stirring conditions for 18 h. The resulting Ag NPs have reported λ_{max} at 427 nm, and the TEM analysis showed a globular structure having a size of 20–50 nm [43]. In a concurrent study, Ag NPs synthesis using *Gmelina arborea*

Table 2 Phytochemical constituents of plants used in green synthesis of nanoparticles

Plant	Phytochemicals	Biological activity	Reference
Ag NPs			
Aegle marmelos	Carotenoids, phenolics, alkaloids, pectins, tannins, coumarins, flavonoids, terpenoids,	Antibacterial	[62]
Andrographis paniculata	Polyols, flavonoids, polyphenols, terpenoids	Antiviral	[23]
Annona muricata	Steroids, alkaloids, antioxidants, polyphenols, carbohydrates, glycosides, flavonoids	Antimicrobial	[21]
Atropa acuminata	Phenolics, flavonoids, tannins	Antioxidant, anti-inflammatory, anticancer, larvicidal	[60]
Azadirachta indica	Steroids, tannins, saponins, alkaloids	Larvicidal	[91]
Cassia alata	Alkaloids, flavonoids, saponins, tannins	Antibacterial	[59]
Cinnamomum tamala	Flavonoids, terpenoids, poly phenols, anthocyanins	Antibacterial	[165]
Cleome viscosa L	Secondary metabolites	Antibacterial, anticancer activity	[41]
Emblica Officinalis	Alkaloids, phenolic compounds, amino acids, carbohydrates, tannins	Antibacterial	[35]
Eulophia herbacea	Carbohydrates, flavonoids, saponins, tannins-phenol, proteins	Antibacterial	[126]
Euphorbia hirta	Alkaloids, flavonoids, saponins, tannins	Antibacterial	[59]
Fraxinus excelsior	Flavonoids, alkaloids, glycosides, terpenoids, phenolic compounds, amino acid residues, peptides of protein	Antioxidant	[90]
Indigofera aspalathoides	Amino acids, Carbohydrates, Terpenoids, Tannins, Alkaloids, Steroids, Flavonoids, Saponins, Glycosides, Lipids	Wound healing	[93]
Leptadenia reticulata	Phenols, terpenoids, polysaccharides, flavones	Antibacterial, antioxidant, cytotoxic	[73]
Nyctanthes arbor-tristis	Flavonoids—rutin, hesperidin, quercitrin and kaempferol-3-o'glucoside	Antioxidant, antimicrobial	[94]
Phyllanthus amarus	Terpenoids, flavones, ketones, aldehydes, amides, carboxylic acids, organic acids, quinones	Antibacterial	[61]
Phyllanthus niruri	Polyols, flavonoids, polyphenols, terpenoids	Antiviral	[23]
Psidium guajava	Alcohols (free OH), alkenes, carboxylic acids, nitro compounds, alkynes	Antibacterial, antioxidant	[55]
Rauvolfia tetraphylla	Alkaloids, Flavonoids, Phenols, Tannins, Cardiac glycosides, Saponins, Amino acids, Terpenoids	Anticancer, antioxidant, antimitotic	[124]
Thespesia populnea	Alkaloids, flavonoids, saponins, tannins	antibacterial	[59]
Tinospora cordifolia	Saponins, terpenoids, flavonoids, hydrolysable tannin, glycosides, cardiac glycosides	Cytotoxic	[207]
Tinospora cordifolia	Polyols, flavonoids, polyphenols, terpenoids	Antiviral	[23]
Wrightia tinctoria	Alkaloids, flavonoids, saponins, tannins	Antibacterial	[59]
AuNPs			
Abroma augusta L	Polyphenols, flavonoids, and steroids	Catalytic reduction	[66]
Achillea wilhelmsii	Alkaloids, phenolic compounds, flavonoids and proteins, primary and secondary amines or amides	Antioxidant	[46]
Ammonum subulatum	Cineole, β-Pinene, α-Terpineol	N/A	[146]
Angelica archangelica	Flavonoids, polyphenolic carboxylic acids, tannins, coumarins	N/A	[65]
Hamamelis virginiana	Flavonoids, polyphenolic carboxylic acids, tannins, coumarins	N/A	[65]
Hypericum perforatum	Flavonoids, polyphenolic carboxylic acids, tannins, coumarins	N/A	[65]
Nigella arvensis	Flavonoids, alkaloids, phenolic compounds and proteins	Antibacterial, antioxidant, cytotoxicity, catalytic activities	[119]
Nyctanthes arbortristis	Alkanes, aromatic amines, aliphatic amines	N/A	[189]

Table 2 (continued)

Plant	Phytochemicals	Biological activity	Reference
Pterocarpus marsupium	Carbohydrates, flavonoids, and polyphenols	Antioxidant, cytotoxicity	[200]
Terminalia arjuna	Tannin, terpenoid, saponins, flavonoids, glycosides and polyphenolic compounds	Seed germination enhancing	[108]
Urtica dioica L	Flavanol glycosides, protein, vitamins, and phenolic compounds	N/A	[95]
Vitex negundo	Phenols, ketones and quinones, carboxylic acids, aldehyde, or esters	Antioxidant, antibacterial activity	[211]
ZnO NPs			
Aloe Vera	Hydroxyl group, an aromatic group, amine group, saturated primary alcohol, carbonate group, alcohols	Antimicrobial activity	[92]
Aloe vera,	Alkaloids, Carbohydrates, Flavonoids, Fixed oils and fats, Glycosides, Gums and mucilage, Phenolic compounds, Phytosterols, Proteins, amino acids, Saponins, Tannins, Terpenoids	Antibacterial, antioxidant, nti-proliferative	[51]
Amaranthus spinosus	Proteins, Carbohydrates, Phenols, Tannins, Flavonoids, Saponins, Glycosides, Steroids, Terpenoids, Alkaloids	Antimicrobial activity	[145]
Calotropis gigantea	Eicosatrienoic acid methyl ester, hexatriacontane, trimethyl undecatriene, trifluoroacetic acid), volatile essential oil (phytol), flavonoids (varinging, quercitrin, hesperitin, and kaempferol), acalyphamide, 2-methylanthraquinone, tri-o-methyl ellagic acid, sitosterol, glucoside, stigmasterol, quinine, tannins, resins, essential oils	Seedling growth enhancement	[132]
Cassia fistula	Aldehydes, proteins, amine, alcohol, carboxylic acid, ether, ester	Antibacterial	[68]
Hibiscus sabdariffa	Alkaloids, Carbohydrates, Flavonoids, Fixed oils and fats, Glycosides, Gums and mucilages, Phenolic compounds, Phytosterols, Proteins, amino acids, Saponins, Tannins, Terpenoids	Antibacterial, antioxidant, anti-proliferative	[51]
Justicia procumbense	Flavonoid, Phenol, Anthocyanin, Tannin, Carbohydrate, Alkaloid	Antimicrobial activity	[44]
Melia azadarach	Aldehydes, proteins, amine, alcohol, carboxylic acid, ether, ester	Antibacterial	[68]
Parthenium hysterophorous	Alcohols, phenols, alkenes, alkanes, carbonyls, aromatics, alkyl halides and alkynes	Enzymatic and microbial activity	[194]
Solanum torvum	Phenols, polyphenols, primary amines,	Sub chronic toxicity on rats	[49]
Sphagneticola trilobata	Tannins, polyphenols, and flavonoids	Toxic metal removal, seed germination, root, plant growth	[30]
Viola canescens	Phenols, alkaloids, flavonoids, phosphine	Antibacterial	[210]
Cu NPs			
Asparagus racemosus	Phenolic compounds, carbohydrates, saponins, proteins, carboxylate (COO) groups, amine groups,	Antibacterial	[67]
Plukenetia volubilis	Polyphenols, alkaloids and sugar	Catalytic reduction	[50]
Fe NPs			
Bauhinia tomentosa	Alcohol and phenol group,	Antioxidant, antimicrobial	[155]
Camellia sinensis	Alcohols and polyphenols, alcohols and polyphenols, minor organic compounds	Adsorption of Arsenic	[69]
Eclipta prostrata	Flavonoids, alkaloids, steroids, tannins, coumestans and saponins	Photodegradation	[70]
Eucalyptus globulus	Alcohols and polyphenols, alcohols and polyphenols, minor organic compounds	Adsorption of Arsenic	[69]

Table 2 (continued)

Plant	Phytochemicals	Biological activity	Reference
Punica granatum	Alcohols and polyphenols, alcohols and polyphenols, minor organic compounds	Adsorption of Arsenic	[69]
Quercus virginiana	Alcohols and polyphenols, alcohols and polyphenols, minor organic compounds	Adsorption of Arsenic	[69]

N/A Not available

extracts was done at 60 °C with a continuous stirring at 1000 rpm. The study reported the change from colorless to yellowish-brown within 5 min implying the development of Ag NPs [54].

During the green synthesis of gold nanoparticles (Au NPs), chloroauric acid (HAuCl4) was reduced by plant extracts of *Angelica archangelica, Hypericum perforatum, and Hamamelis virginiana* was done at RT, and a pH of 8. The study has produced Au NPs of 4–8 nm and appeared in various structures such as spherical, and polyhedral and also reported the formation of aggregates of Au NPs [65]. *Abroma augusta* (*L.*) bark extract mediated biological synthesis of Au NPs at RT took several hours for the formation of Au NPs [66]. In another study, nettle (*Urtica dioica L.*) leaves mediated bio construction of Au NPs was done at 65^0 C within 15 min [67]. In the case of zinc nanoparticles (Zn NPs), in *Cassia fistula* and *Melia azadarach* mediated bio fabrication of Zn NPs from 0.01 M, Zinc acetate dihydrate was done at 70^0 C reporting the formation of small-sized NPs at high temperatures [68]. Fe NPs were synthesized at RT using 0.1 M $FeCl_3$ solutions in a proportion of 2: 1 with plant extract and the synthesized Fe NPs showed potential degradation of arsenic in wastewater [69]. Unlike this, the *Eclipta prostrata* mediated synthesis of Fe NPs using 5 g of precursor ion and 50 ml plant extract at 70 °C, took 45 h to complete the reaction [70

Effect of Reaction Time

Reaction time is another influential aspect in the formation of NPs. It influences their shapes, sizes, and stabilities. Considering the plant-mediated synthesis of NPs, the clearest advantages are the mild processes involved and the less time the process takes. As soon as the precursor solutions are mixed with plant extracts, usually, a color change takes place, indicating the formation of NPs. The size of the synthesized NPs increases with reaction time. Though the time needed for reaction varies depending on other factors of synthesis like reaction temperature, the concentration of plant extracts, pH, and type of plant extracts, usually the reaction requires shorter periods. At the same time, it is to be noted that some researchers reported that the entire transformation of Ag^+ and the formation of stable Ag NPs required several days [71

Separation and Purification of Green Synthesized NPs

NP characterizations and applications require separation and purification processes. The centrifugation method is an extensively used practice to remove unreacted elements and by-products from the reaction mixture. Mainly green synthesized NPs are purified by the centrifugation method. In this method, the synthesized NPs are centrifuged at a high rpm (10,000 rpm) for a fixed time to remove the unreacted enzymes and proteins, and the resulting pellet was washed with deionized water [18, 76].

Methods such as oven drying and calcinating in a muffle furnace are also used for the purification of green synthesized NPs. Purification techniques such as precipitation methods, electrophoretic deposition methods, and chromatographic methods can also be used in the post-synthesis processing of the NPs. As these methods require additional solvents for the purification process, the use of green nontoxic solvents in the bioreduction of NPs will be more economical and can be practiced for environmental applications [77]

Characterization of the Synthesized Nanoparticles

Particle and pore sizes, shapes, surface area, fractal dimensions, and crystallinity describes the NPs. There are varieties of microscopic, spectroscopic, optical, thermodynamic, and, x-ray diffraction analysis methods for NPs characterization. UV–visible Spectrophotometry (UV–vis), Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), Transmission Electron Microscopy (TEM), Auger Electron Spectroscopy (AES), Zeta Potential, Dynamic Light Scattering (DLS), Fourier Transform Infrared Spectroscopy (FTIR), Energy Dispersive Spectroscopy (EDS), Atomic Force Microscopy (AFM), Scanning Tunneling Microscopy (STM), etc. are the commonly used methods [32].

UV–Visible Spectrophotometry (UV–vis)

One of the essential tools that are used to identify, characterize and analyze nanomaterials is UV–vis spectroscopy. Light waves of 300–800 nm can be used to demonstrate distinct metal NPs in the size range of 2–100 nm [78]. Shape, size, and interaction of the particles with the medium influence the Surface Plasmon Resonance (SPR) bands in UV–vis spectrophotometry.

It allows rapid recognition and demonstration of metal NPs. The counteraction between the light and mobile surface electrons of Ag NPs produces stable absorbance bands called, SPR in 400–500 nm wavelength. Many research studies have shown that, through the phenomenon called the 'Excitation of the LSPR,' AgNPs shows an SPR peak in 380–450 nm [18]. It is also to be noted that AuNPs of 5–50 nm produces a sharp SPR peak at 520–530 nm, but AuNPs less than 5 nm do not give any LSPR absorption peaks in this region. The wavelength of LSPR is based on the shape, size, and chemical composition of NPs [79]. One of the universal approaches to tracking the production and stability of metal NPs in an aqueous solution is UV–Vis absorption spectroscopy. Particle shape, size, and particle–particle interaction (agglomeration) with the medium are some of the factors that influence the absorption spectrum of metal NPs.

The majority of the SPR peaks of the synthesized AgNPs are within the desired wavelength range of 400–500 nm. Some green synthesis studies have recorded SPR peaks below 400 nm during the characterization process [80

The particle size and shape influence the specific vibration modes of the electrons. Hence size, the frequency, as well as width of the SPR peaks, confides in the size and shape of the NPs synthesized. The surrounding medium and dielectric constant of the precursor also play an influential role [32]. Similarly, the concentration of the precursor ions can also influence the SPR peak. In a green synthesis study, the UV visible spectrum was analyzed during the bioreduction process using 1 mM metal ion solution, the synthesized NPs have shown SPR peak at 440 nm, and at the same time 2 mM solution has given a peak at 445 nm; also 3 mM, 4 mM, and 5 mM have shown peaks at 448 nm, 463 nm, and 476 nm respectively. During the study, the resulting spectrum has shown a redshift with a gradual increase in the molar concentration of metal ion solution. The increment occurs in the mean size of the Ag NPs as the concentration of the metal ion solution increases [39, 71

The researchers have proved that the biosynthesized metallic NPs have greater electromagnetic absorption in the visible spectrum as a result of their SPR. Similarly, Au NPs have shown SPR peaks between 520 nm – 550 nm with the most repeated peak at 540 nm [46, 65, 83, 84]. ZnO NPs have reported SPR peaks in a range of 300–372 nm [44, 86]. Cu NPs and Fe NPs have reported SPR peaks between 255 nm-535 nm and 230 nm-370 nm respectively [69, 87].

Fourier Transform Infrared Spectroscopy (FTIR)

FTIR, a crucial approach in the characterization of NPs is used to analyze the IR spectrum of a compound's absorption/emission, and collectively assemble huge spectral information [88]. The outcome of the FTIR spectroscopy analysis enables us to determine the functional groups of the crude extracts along with the synthesized NPs using those extracts.

FTIR allows the study of absorptive and emissive properties of the materials. It utilizes IR radiations to study the chemical bonds between atoms. During the FTIR analysis, both plant extracts and the synthesized NPs undergo the assay, and the IR spectra produced by both samples are compared to verify the formation of NPs. The differences between the peaks formed in both spectra and the specific peaks formed due to the existence of NPs validate the formulation of NPs during the analysis [89, 90].

Research has reported that plant phytochemicals act as capping agents at the time of NP synthesis and cause the reduction of the precursor ions during the reaction. FTIR studies have demonstrated phytochemicals like flavonoids, alkaloids, tannins, terpenes, and quinones are the principal agents of bioreduction [44, 59, 92, 93]. Amino acids, Saponins, Alkaloids, flavonoids, Terpenoids, Glycosides, Cardiac glycosides, Carbohydrates, Steroids, Lipids, Proteins, Carbohydrates, Glycosides, and Phenols also help in the green synthesis of NPs [21, 94].

FTIR analysis done using the *Indigofera aspalathoides* mediated biosynthesis of Ag NPs has proved the importance of phytochemicals like Carbohydrates, Alkaloids, Amino acids, Terpenoids, Saponins, Tannins, Lipids, Steroids, Flavonoids, Glycosides on the bioreduction of silver during the reaction [95]. The presence of Flavonoids such as rutin, hesperidin, quercitrin, and kaempferol-3-glucoside has been investigated during the *Nycanthes arbor-tristis* mediated green synthesis of Ag NPs [96]. A green synthesis study has examined the role of plant phytochemicals in NP synthesis through FTIR analysis. They proved the presence of phenolic compounds in crude plant extracts which participate in the bioreduction of metal ions to metal NPs [97]. In a similar study, green synthesis of ZnO NPs, Phenols, Anthocyanin, Flavonoids, Tannin, Carbohydrate, and Alkaloids were analyzed using the FTIR technique and they have proved the role of these phytochemicals in the bio fabrication of the NPs as well as their biological applications [44]. Specific phytochemicals used by researchers to synthesize the NPs showed metabolites like alkaloids, tannin, flavonoids, and saponin from, *Euphorbia hirta*, *Wrightia tinctoria Cassia*

alata, and *Thespesia populnea* showed the production of Ag NPs having rod and spherical shapes with 17 and 30 nm size employing good antimicrobial activity against *Pseudomonas aeruginosa,* and *Bacillus subtilis* [59]. The practice of using pure phytochemicals for the green synthesis of NPs may probably regulate the drawbacks of the use of crude extracts such as varying morphologies of synthesizing NPs and can improve the application of the synthesized NPs.

X-ray Diffraction Analysis (XRD)

XRD is a powerful tool for the characterization of NPs as it is employed for the investigation of the crystalline structure and phase identification of the NPs. It is considered one of the crucial nondestructive methods for the characterization of nanomaterials [98]. XRD analysis delivers crucial pieces of information about the synthesized NPs, such as their structure, phase, and preferred crystal orientations. The Average crystallite size (D_{hkl}) is estimated using Scherrer's formula: mean crystallite size = $(0.9 \times \lambda)/(\beta \cos \theta)$, where θ is the diffraction angle of the highest intensity peak, β is the full width at half maximum (FWHM) of the highest-intensity peak, k is the Scherrer constant (0.9), and **λ** is the wavelength of the incident X-rays [79].

XRD was utilized to determine the crystal structure of eco-friendly green synthesized stable Ag NPs using *Salmalia malabarica*. The study analyzed the crystal angles and the FCC lattice of the synthesized NPs and found them to have an average crystallite size of 8.04 nm which was confirmed using TEM analysis [99]. The majority of the reviewed studies have utilized XRD analysis as one of the crucial characterization methods in their studies. In another study, based on the green synthesis of FeO nanocatalyst, XRD analysis was carried out to substantiate the formulation of nano-catalyst and investigate its structural characteristics. XRD spectrum of iron oxide nano-catalyst reported predominant peaks at angles of 18.97°, 30.09°, 35.42°, 37.02°, 43.05°, 53.09°, 57.07°, and 64.98° confirming the presence of FeO NPs [70

Microscopic Analysis

AFM, SEM, and TEM are the major microscopic analytic techniques used for the characterization of NPs. SEM and TEM investigate the physiological prospects of the NPs, including the size distribution and morphology at the nanometer to micrometer scale [100]. Compared to SEM, TEM gives 1000-fold higher resolution images. AFM measures the individual particle size and other physical properties of the NPs [101].

In both SEM and TEM, an electron source and electromagnetic lenses are employed to produce and focus electrons on the specimen which triggers the emission of high-energy backscattered electrons and low-energy secondary electrons from the analyzed sample surface. These emitted electrons visualize the surface morphology of the NPs. However, unlike TEM, SEM analysis is more economical as it doesn't need any elaborate specimen preparation techniques. At the same time, it can accommodate large and bulky specimens for analysis [102]. It is visible from the table that the majority of the reviewed research has used SEM analysis to investigate the topology of the formulated NPs. During TEM analysis, the electron beam is passed through the ultra-thin section of samples. It visualizes the internal structure of the sample to get a two-dimensional image of the particles analyzed. It needs a complicated sample preparation to create an ultra-thin section of the sample. Even though TEM is costlier than SEM, as it gives the detailed 2D structure of the NPs, most researchers prefer TEM for the characterization of the synthesized NPs.

AFM gives both qualitative and quantitative information such as morphology, size, roughness, and surface texture. It also provides statistical information, such as size, volume distributions, and surface area. It can portray a broad range of particle sizes in the same scan (1–8 μm). It provides visualization in 3D images with high resolution. In addition to this, it can identify nanomaterials in multiple mediums, including controlled environments, ambient air, and even liquid dispersions [103]. In the current study, many researchers have used AFM to characterize the synthesized NPs [96, 104, 105, 106]. In a recent study, optical microscopy was utilized to confirm the development of NPs by observing the concentric rings of the Ag NPs [57].

Pure NPs such as metal NPs usually show small size ranges of less than 100 nm and NPs in a combined form such as bimetallic, metal oxides show a relatively bigger size. *Avicennia alba* leaf-mediated Ag NPs have reported the formulation of spherical and cuboidal shapes with 18.3 nm size [45]. At the same time, larger-sized Ag NPs have also been reported in the *Azadirachta indica* leaf-mediated Ag NPs shown at 200 nm with spherical, triangular, and cuboidal shapes [107]. Similarly green synthesized Au NPs having 4–8 nm with spherical, ovals, heart, or polyhedral shapes as well as NPs with 100 nm size ranges have also been reported [65, 108]. Interestingly small sized plant-mediated ZnO NPs also reported. ZnO NPs synthesized from *Cassia fistula* have been reported to have 3–68 nm and 5–15 nm sizes in two different studies [68, 109]. The larger sizes of the NPs may be due to the agglomeration of the synthesized NPs.

Applications of the Green Synthesized NPs

Green synthesized NPs are nontoxic, their biological activities can be efficiently utilized in living environments. Furthermore, the properties of the plant used for green synthesis are also considered an influential factor in the biological activities of the synthesized NPs. NPs synthesized from Indian medicinal plants have shown significant biological properties.

Antimicrobial Activity

The antimicrobial activity of silver is known from time immemorial. Generally, silver is used in its nitrate form to promote antimicrobial effects. Whereas, silver in the form of NPs results in a considerable increase in the surface area and provides increased scope for interactions with microbial cells [72]. The antimicrobial activity of Ag NPs is used in various industries like the health sector, food industry, textile industry, and environmental applications.

The size of the NPs acts as a vital part of their increased antimicrobial effect. NPs are reported to influence the cell permeability of microbial cells, thereby causing cell death. Furthermore, these NPs adhere to the bacterial cell membrane by developing bonds between the thiol groups of enzymes and cause the inactivation of enzymes in the cell membrane that is responsible for the trans-membrane energy generation and ion transport. Additionally, these NPs entering the bacterial cell form interactions with the amino acids and enzymes through the -SH groups, generating ROS, leading to the disturbance in the cell function and thereby resulting in cell death [32]. Bacterial studies have suggested the presence of phosphorus, and sulfur, which build the delicate bases of the DNA. NPs can bind to these weak bases and damage their DNA which would finally result in cell death. This way of cell lysis could be the leading cause of its antibacterial property [31

The green synthesized NPs are proven to have great antimicrobial potential against various Gram-positive, and Gram-negative bacteria as well as some fungal strains. Ag NPs synthesized from Triphala (*Emblica officinalis*, *Terminalia belerica,* and *T. chebula)* have shown significant antimicrobial activity on *Escherichia coli, Pseudomonas aeruginosa, Staphylococcus aureus*, and *Bacillus subtilis* [18]. Some studies have proved the combined action of NPs synthesized from various plant extracts against diverse groups of microbes [14, 107].

Green synthesized Au NPs from *Terminalia arjuna* fruit have been reported to have inhibitory effects on *S. aureus B. subtilis, P. vulgaris*, and *K. pneumoniae* [110]. In a comparable study, Zn NPs synthesized using *Justicia procumbense* have shown broad-spectrum antimicrobial activity against *Pseudomonas aeruginosa*, *Escherichia coli*, *Aspergillus niger*, *Staphylococcus aureus*, *A. fumigatous,* and *A. flavus* [44]. Biosynthesized CuO NPs from the mint leaf have shown synergistic antibacterial activity against *Bacillus subtilis* and *Escherichia coli* strains that have shown 35–38 nm inhibition zones in the analysis. The study has concluded the potentiality of CuO NPs to fight against microbes [47].

A detailed mechanism of antifungal activities of the NPs has not been studied extensively. Few researchers have reported antifungal activity against various fungal strains by green synthesized NPs [36, 111, 112]. NPs synthesized using *Azadirachta indica* have shown good antimicrobial activity against different bacterial and fungal strains [56, 107, 111, 113]. Various spices, including *Piper nigrum*, *Zingiber officinale*, *Coriandrum sativum*, *Murraya koneigii*, and *Rosmarinus officinalis*, have also been utilized for green synthesis of NPs as well as in antimicrobial applications [39, 114, 115, 116, 117]. It is evident from the reports that the green synthesized NPs have been less explored against Gram-positive bacteria in comparison with gram-negative strains (Table 3). It may be attributed to the thick peptidoglycan layer in the cell membrane of gram-positive microbes, which interferes with the easy entry of NPs into the bacterial cell. Studies need to be done to overcome this limiting factor in the journey of nontoxic green synthesized NPs in the medical field.

Antioxidant Activity

Antioxidants inhibit the oxidative processes of the cell by scavenging or chelating free catalytic metals and thereby acting as electron donors. These antioxidants can be classified as natural and synthetic, which are further divided into primary and secondary antioxidants. Phytochemical studies done on various plants have proved that plants are the source of natural antioxidants like carotenoid, ascorbic acid, and tocopherol. Studies done on synthetic antioxidants have revealed their negative health effects, so it is advised to use naturally occurring antioxidants as substitutes [118]. Modern scientific research is now focusing more on natural antioxidants that originated from plants. These safe antioxidant agents can prevent the human body from many degenerative and chronic diseases [119].

Among metal NPs like Au, Ag, Ce, Pt, Pd, and Zn, Ag NPs are popular for their potential anti-oxidative activities [120]. Ag NPs synthesized using aqueous extract of ginger, garlic, and cayenne pepper reduced 2,2'-azinobis (3-ethylbenzothiazoline-6-sulphonic acid), and 2,2-diphenyl-1-picrylhydrazyl radicals [81]. Numerous research has been done to explore the antioxidant activity of green synthesized NPs from various medicinal plants.

For example, NPs synthesized from *Atropa acuminata* have shown potential antioxidant properties [60]. Green synthesized Au NPs from *Nigella arvensis* leaf extract have been reported to have good antioxidant activity. During the study plant extract and the synthesized Au NPs recorded potential antioxidant activity in terms of DPPH scavenging activity and were found to be 32% and 12%, respectively [121]. The antioxidant properties of the green synthesized NPs may be associated with the phytochemicals that aid in the reduction of NPs as well as their nano-characteristics (Table 2).

Anticancer Activity

Despite extensive research on cancer biology, cancer persists as an aggressive killer worldwide. The scientific world needs novel anticancer agents to withstand this condition. In traditional medicine, elements obtained from plants have been used to cure diseases. Nowadays, treatment options derived from plants and natural products have received increasing consideration as novel cancer therapeutic agents [122]. Green synthesized NPs are one of the crucial milestones in the evolution of novel, effective cancer treatment.

Numerous studies have proved the anticancer capability of green-synthesized NPs. Ag NPs synthesized using *Cleome viscosa* were examined for their anticancer activity against human A549 and PA1 cell lines. The study has reported significant anticancer activities on lung and ovarian cancer cell lines with IC50 values at 28 and 30 mg/mL [41]. *Atropa acuminata*-mediated green synthesized Ag NPs have shown potential anticancer activity [60]. In a recent study, the anticancer effect of green synthesized NPs using *Phyllanthus emblica* leaf extract was investigated against diethyl nitrosamine-induced hepatocellular carcinoma (HCC) in Wistar rats. And the results of the study have proved the chemoprotective property of the bioengineered Ag NPs against HCC. The green synthesized NPs knocked down the production of free radicals and restore all the biochemical parameters in the DEN-induced group. The study has also reported that the Ag NPs modulated the pro-inflammatory cytokines and inflammatory mediators in a dose-dependent manner in Hepatic cancer [121]. Green synthesized Ag NPs from *Alpinia officinarum* were reported to have the potential to be used as an effective nephroprotective against cisplatin-induced nephrotoxicity via the down-regulating apoptotic pathway [122]. Recently researchers have also concentrated on the use of nanocomposites as anticancer agents. Green synthesized CuO NPs decorated with graphene oxide were reported to have 70% cytotoxic activity against HCT-116 Human colon cancer cell lines at 100 µg/ml. The study also reported that the GO-CuO nanocomposites have appreciable activity toward cancer cell lines in comparison to NPs as such. Numerous studies have proved the anticancer potential of green synthesized NPs [64, 73, 121, 123, 124] (Table 4).

Other Applications of the Green Synthesized NPs

The green synthesized NPs are widely studied for applications such as photocatalytic and larvicidal activities. These eco-friendly NPs can effectively be used in environmental remediation, including the degradation of toxic chemicals. Ag NPs synthesized from *Astragalus gummifer* (gum tragacanth) are used for the degradation of Congo red and methylene blue [127]. The catalytic potential of the *Salmalia malabarica*/gum-capped Ag NPs to trigger the reduction of 4-nitrophenol (4-NP) in the presence of $NaBH_4$ was reported [99]. Several studies have proved the potential of the green synthesized NPs to be used as potential catalytic agents in the degradation of toxic chemicals, including synthetic dyes used in industries [128, 129]. Metal oxide NPs such as ZnO NPs, SnO_2 NPs, CuO NPs, FeO NPs and TiO2 NPs have good photocatalytic potentials due to their band gap properties [17, 19, 30, 69, 79, 130] (Table 4).

Green synthesized NPs are also reported to have larvicidal activities against many vector mosquitoes. Green synthesized Ag NPs from *Sida acuta* plant extract have shown significant activity against *Culex quinquefasciatus*, *Anopheles stephensi*, and *Aedes aegypti* mosquitoes larvae [131]. In a concurrent study, the efficient inhibitory potential of Ag NPs produced from *Heliotropium indicum* leaf extract against adult mosquitoes of *Anopheles stephensi*, *Aedes aegypti*, *Culex quinquefasciatus*, and *Aedes aegypti* was determined [132]. Bio-synthesized NPs from *Ventilago maderaspatana* have been reported to have intensive toxicity on Filariasis, Malaria, and Zika Virus Mosquito Vectors [106]. Also, NPs synthesized using *Terminalia arjuna*, *Leptadenia reticulata*, *Azadirachta indica*, and *Annona muricata* leaf extracts are proved to have the potentials to be used as potential mosquito vector control agents [22, 73, 93, 133] (Table 4).

Various reports have proved the potentiality of green synthesized Ag, ZnO, and Au NPs for enhancing seed germination activity in the agricultural field. Green synthesized NPs using *Calotropis gigantea, Terminalia arjuna,* and *Syzygium cumini* are proven to have seed germination enhancement properties [130, 134].

Toxicity of the Green Synthesized NPs

Compared to the NPs synthesized through physical and chemical methods, green synthesized NPs are less toxic as there are no toxic chemicals taking part in the synthesis process. Low concentrations of NPs are nontoxic or less toxic compared to high concentrations of NPs. Green synthesized

Table 3 Antimicrobial activity of green synthesized nanoparticles

Plant	Test microorganism	Method	Reference
Ag NPs			
Aegle marmelos	*B. linens, S. epidermidis*	-	[62]
Afzelia quanzensis	*E. coli, S. aureus*	Disc diffusion method	[142]
Ailanthus excelsa	*S. aureus, P. aeruginosa, E. coli, K. pneumonia*	Agar well diffusion method	[143]
Aloe vera	*B. subtilis, B. cereus, S. aureus, E. faecalis, S. typhi, Shigella sp., E. coli, P. aeruginosa, A. baumannii*	Disc diffusion method	[14]
Alysicarpus monilifera	MRSA, CoNS	Disc diffusion assay	[146]
Annona muricata	*B. subtilis, S. aureus, K. Pneumonia, E. Coli, P. aeruginosa*	Well diffusion method	[21]
Anogeissus latifolia	*S. aureus E. coli, P. aeruginosa*	Agar diffusion method	[150]
Artemisia vulgaris	*K. pneumonia, P. aeruginosa, E. coli, B. cereus, S. aureus,*	Disc diffusion method	[43]
Artocarpus heterophyllus	*B. cereus, B. subtilis, S. aureus, P. aeruginosa*	Agar well diffusion method	[151]
Avicennia alba	*E. coli, A. tumefaciens, S. mutans, S. aureus, Tricophyton rubrum, A. flavus*	Disc diffusion method	[45]
Azadirachta indica	*E. coli, Bacillus sp.*	Disc diffusion method	[107]
Azadirachta indica	*E. coli*	N/A	[56]
Azadirachta indica	*Penicillium sp., Fusarium sp., and Aspergillus sp., R. solanacearum*	N/A	[111]
Azadirachta indica	*E. coli*	Agar Well Diffusion Assay	[113]
Boerhaavia diffusa	*A. hydrophila, P. fluorescens, F. branchiophilum*	Agar well diffusion method	[159]
Buchanania lanzan	*E. coli, A. avium, S. intermedius, P. macerans, S. rubidaea, E. mallatovora, E. faecalis, S. haemolyticus, P. mirabilis, S. epidermidis, S. chromogenes, E. agglomerans, S. capitis sp., Urealyticus*	Agar well diffusion method	[105]
Cassia alata	*P. aeruginosa, B. subtilis*	Agar Well Diffusion Assay	[59]
Centella asiatica	*S. aureus*	Agar well-diffusion method	[165]
Cinnamomum tamala	*E. coli, K. pneumonia, S. aureus*	Disc diffusion method	[167]
Cissus quadrangularis	*K. planticola, B. subtilis*	Disc diffusion method	[168]
Cleome viscosa	*B. subtilis, S. aureus, E. coli, K. pneumoniae*	Well diffusion method	[41
Coleus aromaticus	*B. subtilis, K. planticola*	Disc diffusion method	[170]
Coriandrum sativum	*B. subtilis*	Agar well diffusion method	[117]
Cupressus macrocarpa	*S. mutans, S. aureus*	Kirby-Bauer method	[173
Cynodon dactylon	*B. subtilis, B. cereus, S. aureus, E. faecalis, S. typhi, Shigella sp., E. coli, P. aeruginosa, A. baumannii*	Disc diffusion method	[14]
Dalbergia spinosa	*B. subtilis, P. aeruginosa, S. aureus, E. coli*	Disc diffusion method	[175]
Desmostachya bipinnata	*E. coli, S. aureus, S. mutans, C. albicans*	Well-plate method	[176]
Diospyros paniculata	*B. subtilis, B. pumilis, S. pyogenes, S. aureus, E. coli, K. pneumoniae, P. vulgaris, P. aeruginosa, A. niger, A. flavus, P. notatum, S. cerevisiae, C. albicans*	Agar well diffusion method	[36]
Emblica Officinalis	*S. aureus, B. subtilis, E. coli, K. pneumonia*	Agar disc diffusion method	[35]
Eulophia herbacea	*E. coli, S. aureus, P. aeruginosa, B. subtilis*	Agar well diffusion method	[128]
Euphorbia hirta	*P. aeruginosa, B. subtilis*	Agar Well Diffusion Assay	[59]
Hawthorn berries	*A. niger, E. coli, S. cerevisiae*	N/A	[172]
Heritiera fomes	*B. subtilis, K. pneumoniae, S. typhi*	Disc diffusion method	[181]
Indoneesiella echioides	*R. rhodochrous, A. hydrophila, S. aureus, P. aeruginosa, C. albicans*	Well diffusion method	[112]
Iresine herbstii	*S. aureus, E. faecalis, E. coli, K. pneumoniae, P. aeruginosa*	Agar well-diffusion method	[74]
Justicia adhatoda	*P. aeruginosa*	Disc diffusion method	[187]
Leucas aspera	*E. coli, B. subtilis*	Well diffusion assay	[129]
Mammea suriga	*B. subtilis, S. aureus, E. coli, P. aeruginosa*	Disc diffusion method	[188]
Mentha	*Staphylococcus and E. coli*	Disc diffusion method	[15]
Murraya koneigii	*E. coli, E. faecalis, P. aeruginosa, C. albicans*	Agar well diffusion method	[114]
Musa balbisiana	*E. coli, Bacillus sp.*	Disc diffusion method	[107]
Nycanthes arbor-tristis	*S. aureus, P. mirabilis, S. typhi, A. baumannii, E. coli, S. typhimurium*	Agar disc diffusion method	[96]
Ocimum gratissimum	*B. subtilis, E. coli*	Well diffusion method	[193

Table 3 (continued)

Plant	Test microorganism	Method	Reference
Ocimum sanctum	*B. subtilis, E. coli*	Well diffusion method	[193
Ocimum tenuiflorum	*E. coli, Bacillus sp.*	Disc diffusion method	[107]
Paederia foetida	*B. subtilis, B. cereus, E. coli, P. aeruginosa*	Agar well-diffusion method	[195]
Peganum harmala	*E. coli, S. aureus*	Disc diffusion method	[197]
Phyllanthus amarus	*P. aeruginosa*	Agar well diffusion method	[61]
Piper nigrum	*E. coli, S. aureus*	Disc diffusion method	[39]
Plumbago indica	*B. subtilis, Streptococcus spp., S. aureus, E. coli, P. vulgaricus, P. aeruginosa, K. pneumonia, C. albicans, C. tropicalis, C. neoformans*	Disc–well diffusion assay	[199]
Pongamia pinnata	*E. coli*	Agar well diffusion method	[200]
Portulaca oleracea	*B. subtilis, B. cereus, S. aureus, E. faecalis, S. typhi, Shigella sp., E. coli, P. aeruginosa, A. baumannii*	Disc diffusion method	[14]
Psidium guajava	*A. hydrophila, P. mirabilis, E. coli, S. aureus, P. aeruginosa*	Disc diffusion method	[55]
Rosmarinus officinalis	*S. aureus, B. subtilis, E. coli, P. aeruginosa*	Disc diffusion method	[115]
Salmalia malabarica	*E. coli, S. aureus*	Disc diffusion method	[99]
Seripheidium quettense	*E. coli, K. pneumonia, B. subtilis, A. niger*	Well diffusion method	[64]
Sonneratia apetela	*E. coli, A. tumefaciens, S. mutans, S. aureus, T. rubrum, A. flavus*	Disc diffusion method	[45]
Sonneratia caseolaris	*E. coli, A. tumefaciens, S. mutans, S. aureus, T. rubrum, A. flavus*	Disc diffusion method	[45]
Strychnos potatorum	*S. aureus, K. pneumoniae*	Well diffusion method	[206]
Tectona grandis	*B. cereus, S. aureus, E. coli*	Well diffusion method	[208]
Terminalia arjuna	*E. coli, S. aureus*	Disc diffusion method	[133]
Thespesia populnea	*P. aeruginosa, B. subtilis*	Agar Well Diffusion Assay	[59]
Trigonella foenum–graecum	*S. aureus, E. coli, C. albicans*	Disc diffusion method	[210]
Wrightia tinctoria	*P. aeruginosa, B. subtilis*	Agar Well Diffusion Assay	[59]
Au NPs			
Achillea wilhelmsii	*B. subtilis and S. epidermidis, E. coli, S. enterica*	Well diffusion assay	[46]
Cannabis sativa	*Penicillium sp., Mucor sp., Fusarium sp., Aspergillus sp., A. flavus, A. fumigatus*	Disc diffusion agar method	[161]
Nigella arvensis	*E. coli, P. aeruginosa, S. marcescens, S. aureus, B. subtilis, S. epidermidis*	Well diffusion assay	[121]
Terminalia arjuna	*B. subtilis, S. aureus, K. pneumoniae, P. vulgaris*	Disc diffusion method	[110]
Vetiveria zizanioides	*Penicillium sp., Mucor sp., Fusarium sp., Aspergillus sp., A. flavus, A. fumigatus*	Disc diffusion agar method	[161]
Vitex negundo	*E. coli, B. subtilis, P. aeruginosa, S. aureus, S. typhimurium, S. pyogenes*	Well-diffusion method	[213]
ZnO NPs			
Aegle marmelos	*E. coli, P. aeruginosa, S. aureus,*	Disc diffusion method	[37]
Aloe Vera	*S. epidermidis, K. pneumoniae, E. coli, A. niger, A. oryzae*	Agar well diffusion method	[94]
Aloe vera	*E. coli, K. pneumoniae, P. aeruginosa, S. aureus*	Disc diffusion method	[51]
Amaranthus spinosus	*P. aeruginosa, S. typhi, S. dysenteriae*	Agar well diffusion method	[147]
Cassia fistula	*E. coli, S. aureus*	Disc diffusion method	[68]
Hibiscus sabdariffa	*E. coli, K. pneumoniae, P. aeruginosa, S. aureus*	Disc diffusion method	[51]
Justicia procumbense	*E. coli, S. aureus, P. aeruginosa, A. niger, A. fumigatous, A. flavus*	Disc diffusion method	[44]
Melia azadarach	*E. coli, S. aureus*	Disc diffusion method	[68]
Viola canescens	*S. pneumoniae, S. aureus, K. pneumoniae, E. coli*	Agar well diffusion method	[212]
CuO NPs			
Andrographis paniculata	*P. aeruginosa, E. coli, S aureus, K. pneumoniae*	N/A	[87]
Asparagus racemosus	*E. coli, B. subtilus, K. pneumonia, A. hydrophila, P. fuorescens, Y. ruckeri, F. branchiophilum, E. tarda*	Well diffusion method	[67]
Menthe	*E. coli, B. subtilis*	Agar well diffusion method	[47]
Fe NPs			
Bauhinia tomentosa	*E. coli, S. aureus, S. typhi*	Well diffusion method	[157]

N/A Not available

Table 4 Other applications of green synthesized nanoparticles

Plant	Type of NPs	Application	Size and shape (nm)	Reference
Acalypha indica	CuO	Anticancer, catalytic applications	2–100; crystalline	[17]
Acalypha Indica	SnO_2	Catalytic Degradation of Rhodamine B	5–38; crystalline	[19]
Annona muricata	Ag	Larvicidal potential against dengue, malaria and filariasis vector	45; crystalline spherical	[22]
Astragalus gummifer	Ag	Catalytic reduction activities with methylene blue and Congo red dyes	18; FCC crystalline	[125]
Atropa acuminata	Ag	Potential antioxidant, anti-inflammatory, anticancer and larvicidal activities	428; spherical	[60]
Azadirachta indica	Ag	Mosquito control	41–60; crystalline	[91]
Brassica oleracea var. botrytis	Ag	Photo catalytic degradation of methylene blue dye	35.08; FCC	[158]
Calotropis gigantea	ZnO	Seedling enhancement	10; crystalline	[132]
Camellia sinensis,	Fe	Removal of arsenic from water	10–100; spherical	[69]
Carica papaya,	SnO_2	Catalytic Degradation of Rhodamine B	5–38; crystalline	[19]
Citrus aurantifolia	CuO	Photo-catalyst for dye removal and antibacterial agent for contaminated water	22; crystalline	[128]
Eucalyptus globulus	Fe	Removal of arsenic from water	10–100; spherical	[69]
Eulophia herbacea	Ag	Reduction of methylene blue and Congo red	11.70; FCC crystalline	[126]
Garcinia gummi-gutta	ZnO	Biodiesel production	10–20; hexagonal	[52]
Gmelina arborea	Ag	Catalytic reduction of Methylene Blue	8–32; spherical, crystalline	[54]
Heliotropium indicum	Ag	For the control of the *A. stephensi*, *A. aegypti,* and *C. quinquefasciatus*	18–45; spherical, triangle, truncated triangles, decahedral	[130]
Jatropha gossypifolia	Ag	Degradation of methylene blue	5–40; crystalline	[184]
Lemon juice	Cobalt ferrite	Magnetic properties	10–22; crystalline	[58]
Leucas aspera	Ag	Degradation of Optilan Red and Lanasyn Blue dyes	20–40; spherical	[127]
Moringa Oleifera	SnO_2	Catalytic Degradation of Rhodamine B	5–38; crystalline	[19]
Murraya Koenigii	SnO_2	Catalytic Degradation of Rhodamine B	5–38; crystalline	[19]
Phyllanthus emblica	Ag	Chemo protective potential in the prevention and intervention of hepatocellular carcinoma	15–30; quasi round, spherical	[121]
Plumbago indica	Ag	Antitumor Activity	50–70; spherical	[197]
Punica granatum,	Fe	Removal of arsenic from water	10–100; spherical	[69]
Quercus virginiana	Fe	Removal of arsenic from water	10–100; spherical	[69]
Sida acuta	Ag	Larvicidal activity against *C. quinquefasciatus, A. stephensi*, and *A. aegypti*	18–35; spherical, triangle, truncated triangles, decahedral	[129]
Syzygium Cumini	ZnO	Seed germination and wastewater purification	16.4; hexagonal, spherical	[128]
Terminalia arjuna	Au	Enhanced seed germination activity	20–50; spherical	[108]
Ventilago maderaspatana	Ag	Larvicidal activity against *A. stephensi, A. aegypti,* and *C. quinquefasciatus*	1–6; spherical	[104]
Vigna unguiculata L	Ag	Adsorbent for malachite green (MG) in a Batch system	25; FCC cubic crystalline	[209]

NPs can be used as an alternative to physical and chemical synthesized NPs. Toxicity analysis of the synthesized NPs is an important aspect of its biological applications. Even though green synthesized NPs are less toxic due to the reagents used, the toxicity of the NPs in the environment should also be studied. The exposure of NPs to the environment can happen at the stage of synthesis, storage, application, or improper disposal of the NPs after their use. And the NPs that are there in the environment can be accumulated in the human body through inhalation, ingestion, or through absorption. As inhalation is the main route of NP exposure to the human body, the effects on the respiratory system as well as skin problems are prominent in humans [135].

Long-term exposure of NPs to the human body can cause various adverse effects on the different parts of the body such as Alzheimer's and Parkinson's disease on exposure to the brain, respiratory issues such as Asthma, Bronchitis, Lung cancer, gastrointestinal disorders such as Colon cancer,

Crohn's disease, skin problems such as Dermatitis and autoimmune diseases [135, 136]. NPs also show toxic effects on Plants and other living organisms in the environment. The exposure of NPs to the aquatic ecosystem can affect the survival of the aquatic flora and fauna at different levels [137]. The phytotoxic and cytotoxic studies done during the green synthesis studies have revealed the level of toxicity of the synthesized NPs.Several studies have reported the potential of certain green synthesized NPs for enhancement of seed germination. It is also reported that the same NPs have toxic effects at higher concentrations [107]. NPs also show adverse effects on certain disease vectors such as mosquitoes that can be effectively utilized in pest control applications [138]. Metal oxide NPs and doped NPs show higher toxic effects as compared to the NPs in their pure form. Studies have reported the harmful effects of AlO_2 and TiO_2 NPs in the human body system as well on other living organisms [139, 140].

Conclusion

The current review is an attempt to explore the available data on green synthesized NPs using Indian medicinal plants. This review examines the influencing parameters of green synthesis, and common characterization techniques of green nanotechnology as well as their potential biological applications. Various research has been performed to explore the opportunities of traditional medicinal plants for the green synthesis of NPs as a substitute for many toxic chemicals. Despite such huge research to explore the advanced biological properties of the green synthesized NPs, the demand for practical usage of these results in huge amounts is persisting. The plant phytochemicals that are utilized in the green synthesis of NPs are an important reason for their biological properties. The biomolecules that act as reducing and capping agents in the plant extracts are an essential part of the green synthesis mechanism. It is noted that the green synthesized NPs are varying in size and shape. Therefore, the use of specific phytochemicals may improve the results. Moreover, to meet the high demand for NPs for various applications in different fields of science, medicine, industries as well as in agriculture, research needs to focus on the unexplored traditional plants and also scale up the process to an industrial or large scale.

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