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Advances in Green Chemistry: Sustainable Plant Mediated Green Synthesis of Monometallic and Bimetallic Nanoparticles for Antimicrobial, Environmental, and Anticancer Applications-A Review

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Abstract

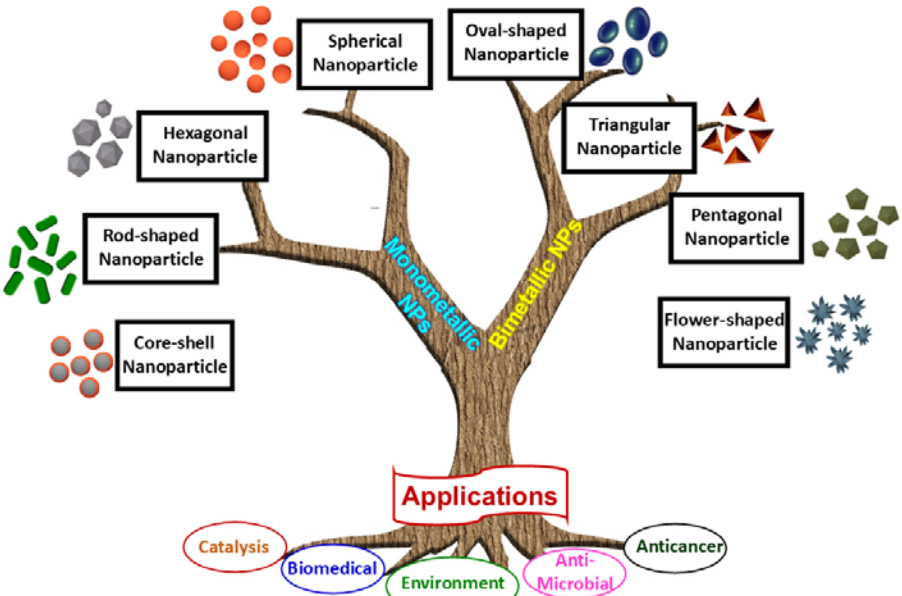
Metallic nanoparticles (NPs) turned up as indispensable tools across world due to their unique properties and functionalities. Metallic NPs can be classified as monometallic (MNPs) or bimetallic (BNPs) based on the number of metal ions they contain. BNPs are more applicable than MNPs due to their enhanced properties caused by size, quantum and surface effects.Developing reliable, eco-friendly and sustainable methods for NPs synthesis is essential for advancing nanotechnology and expanding its applications. Nowadays the widespread applications of metal NPs are hindered by the limitations of traditional physical and chemical synthesis methods, which often involve exorbitant costs, ecological hazard and complex operational procedures.Green synthesis involves using plant extracts containing various plant parts to create NPs.This review explores the current scenario of synthesis, morphology and applications of plant mediated synthesised monometallic and bimetallic nanoparticles within the field of green nanotechnology.Green-synthesized MNPs as well as BNPs have diverse applications in biomedicine, healthcare, environment, agriculture and catalysis.

KEYWORDS: Green synthesis, plant-based synthesis, metallic nanoparticles, bimetallic nanoparticles, applications

INTRODUCTION

Nowadays, science is growing very rapidly, whereas nanoscience has proved to be the greatest and fastest growing multidisciplinary field in recent years for the future developments. Synthesis of novel nanostructures has been an emerging and potential aspect of research around the world. Nanoscience can be defined as the study of manipulating materials at nano scale specifically ranging from 1 to 100 nm (or more precisely, 0.2 to 100 nm) to produce advanced structures, materials and devices [1]. Nanomaterials manifest exclusive characteristics that are distinct from bulk materials because of their nanoscale dimensions and larger ratio of surface-to-volume. With exceptional properties, nanotechnology offers vast opportunities for innovation across fields like biomedicine, health care and drug delivery [2], agriculture and food processing [3], pollution remediation, environmental sustainability [4], catalysis [5]. Nanotechnology, often seen as the universal technology of the 21st century, is poised to address many long-standing challenges. The unique properties of nanoparticles are closely tied to their size, shape, and morphology, allowing for synthesis in varied forms like spheres, rods, prisms, cubes, and hexagons. (scheme 1).Interest in nanoscale materials originates from their unique properties at this scale, which vary with size and shape. By simply modifying methodologies, the ability to control the shape of synthesized nanostructured materials unlocks exciting possibilities for various applications. In other words, how big or small these particles are and the specific configurations they adopt, significantly influence their behaviour. Traditionally, nanoparticles have been synthesized using harsh chemicals and energy consuming processes. That's why a greener approach is procuring momentum nowadays. However, growing concern for environmental impact has driven the evolution of green synthesis methods.

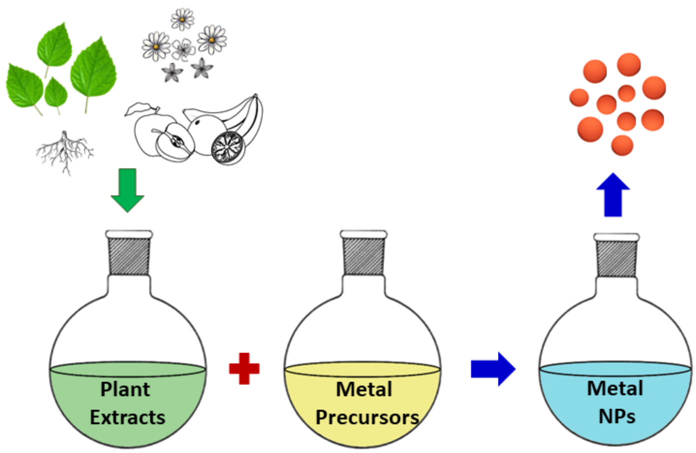
Green synthesis of nanoparticles uses eco-friendly methods to reduce waste and rely on renewable resources. This approach often utilizes biological materials, including (a) plant parts and extracts, (b) microorganisms such as bacteria, yeasts, fungi, or algae, and (c) natural compounds like sugars, proteins, and membranes to aid nanoparticle formation. Among various green synthesis methods, this review focuses on the use of plant extracts for the production of metallic nanoparticles.



Scheme 1: Diverse shapes of metal nanoparticles and their applications in numerous fields

This green synthesis method uses plant extracts from various parts of plants, offering an eco-friendly alternative for nanoparticle production.Recently, it has gained attention for reducing the environmental impact associated with conventional methods, which often involve hazardous chemicals and energy-intensive process.Plant extracts serve dual roles as reducing and stabilizing agents [6], facilitating metal ion transformation into metal nanoparticles(Scheme 2) while preventing aggregation, resulting in stable nanoparticles with controlled size, shape, and surface properties.

Green synthesis produces biocompatible nanoparticles, well-suited for biomedical and environmental applications. This method offers multiple advantages: it's environmentally friendly, cost-effective due to the use of accessible biological resources, scalable for large production, and allows property customization. By adjusting biomaterials and synthesis conditions—like reducing agent concentration, precursor levels, and mixing methods—researchers can fine-tune nanoparticle size, shape, and surface chemistry for targeted uses. Various plant parts, including leaves [7], stems [8], barks [8], roots [9], seeds [9] and fruits have been employed for the synthesis of metal nanoparticles [10].



Scheme 2: Plant extract mediated synthesis of metal nanoparticles from metal precursors

METALLIC NANOPARTICLES

The world of metallic nanoparticles evolves beyond single elements. Metallic nanoparticles come in various flavours, categorized by their composition:

Monometallic: These consist of a single type of metal.

Bimetallic: Two different metals are combined to form the nanoparticle.

While monometallic nanoparticles are valuable, research shows that bimetallic nanoparticles often surpass them in performance, supporting the synergistic effects of multiple metals. This synergy enhances functionality and allows tailored properties, as metal combinations and ratios are carefully chosen for specific applications. This rapidly advancing field holds tremendous promise, particularly in catalysis, electronics, and medicine, with ongoing research likely to unlock further groundbreaking applications and insights.

MONOMETALLIC NANOPARTICLES

Monometallic nanoparticles, composed of a single type of metal atom, serve as foundational elements in the nanoparticle field. Despite their simplicity, they offer significant potential due to their adjustable properties [11].

A. Ag Nanoparticles

Silver nanoparticles (AgNPs) are renowned mainly for their antimicrobial properties and wide range of applications in medicine and environment. A variety of plant parts were used to synthesize AgNPs through green methods (Table 1). For the synthesis of AgNPs, silver Nitrate [$AgNO_3$] solution is commonly used as a precursor. Spherical nanoparticles, with their minimal surface area, exhibit thermodynamic stability. This makes them a common and preferred shape in various applications.Spherical AgNPs synthesized using aqueous extract of different plant source like *Ocimum sanctum* (tulsi) aqueous leaf extract [12], Camellia sinensis (Chinese tea) [27](Figure 1) are very common.Spherical Ag nanoparticles can also be synthesized from alcoholic leaf extracts of Eugenia roxburghii DC (roxburg cherry) [31] and Paulownia Tomentosa (princess tree) [32]. Additionally, leaf biomass powder from Nigella sativa (Kalonji) [33] and latex from Anogeissus latifolia (gum ghatti) [34] serve as effective reducing agents for AgNP synthesis. Mostly spherical AgNPs can be obtained from several fruits like Prunus armeniaca (apricot) [36], flowers like Jasminum nudiflorum (winter jasmine) [38], Tagetes erecta (marigold) [39], Achillea biebersteinii (yellow milfoil) [40], seeds like Pistacia atlantica (Atlantic pistachio) [42]. Besides spherical AgNPs, different shapes like cubic, oval and triangular, hexagonal AgNPs (Figure 2) can also be obtained from different plant source [36, 40, 43, 44].

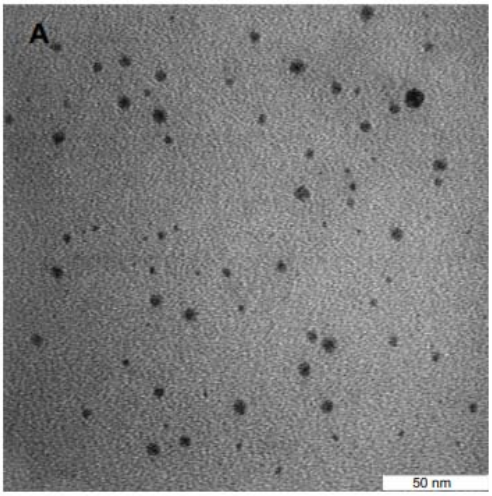


Fig. 1: Monodisperse Ag nanoaprticles (Ref. 27. Copyright 2012, Dovepress)

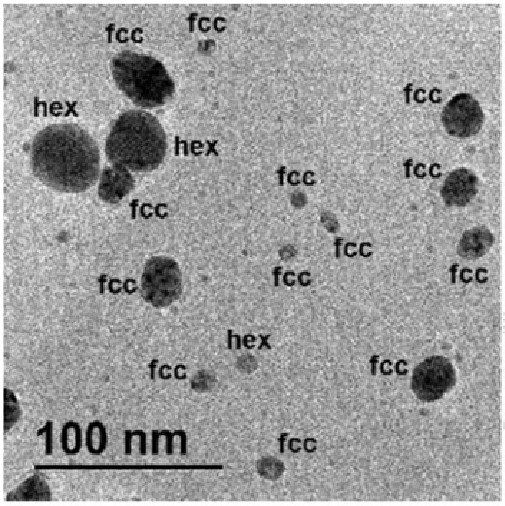


Fig. 2: TEM analysis of hexagonal Ag nanoparticles from Rumex hymenosepalus (Ref. 43. Copyright 2013, Springer)

Table 1: Plant based green synthesis of Ag nanoparticles

Plant Extract	Reducing Agent	Size (nm)	Morphology	Applications	References
Ocimum sanctum (tulsi)	Leaves Extract (aq.)	3-20 (averag e size 9.5)	Spherical	Biomedical Materials	Mallikarjuna *et al.* [12]
Ecliptaprostrata (False Daisy)	Leaves Extract (aq.)	35–60, (averag e size	spherical	larvicidal activity	Rahuman*et al.* [13]

		±45)			
Eclipta	Leaves Extract (aq.)	2-6 (average size ± 3.62)	Spherical	Ecofriendliness and amenability	Jha *et al.* [14]
Panax ginseng (Korean gingseng)	Leaves Extract (aq.)	5-15	Spherical	Antimicrobial agent	Sing *et al.* [15]
Terminalia chebula (haritaki)	Leaves Extract (aq.)	10-30	Spherical	Anti-Bacterial activity	Rao *et al.* [16]
Curcuma longa (turmeric)	Leaves Extract (aq.)	15-40	Spherical	Antimicrobial potency	Maghimaa *et al.* [17]
Acalypha indica (Harita Manjari)	Leaves Extract (aq.)	20-30	Spherical	Inhibitory activity against water borne pathogens	Mohan *et al.* [18]
Artocarpus Heterophylus (Jack Fruit)	Leaves Extract (aq.)	15-25	Spherical	Medicinal and cosmetic purpose	Nande *et al.* [19]
Musa balbisiana (banana) and Ocimumtenuiflorum (black tulsi)	Leaves Extract (aq.)	up to 200	Spherical, triangles, pentagons, hexagons	Antimicrobial potency	Das *et al.* [20]
Enicostemmaaxillare (Indian whitehead)	Leaves Extract (aq.)	15-20	Spherical	Biomedical Materials	Raj *et al.* [21]
Citrullus colocynthis (bitter apple)	Leaves Extract (aq.)	31	Spherical	Antimicrobial, wound healing potency	Satyavani *et al.* [22]
Nelumbo nucifera (lotus)	Leaves Extract (alc.)	25–80, (average size ±45)	Spherical, triangle, truncated triangles, decahedral	larvicidal activity	Santhoshkumar *et al.* [23]
Aloe vera	Leaves Extract (aq.)	15.2 ± 4.2	Spherical	Cancer hyperthermia	Ahmad and Sastry *et al.* [24]
Aloe vera	Leaves Extract (aq.)	± 30	Spherical	therapeutic role in diabetes-related complications.	Ashraf *et al.* [25]
Sapindusmukorossi(Reetha) and Acacia	Leaves Extract (aq.)	20-40 (average size	Spherical	SERS active substrate for rapid	Sur*et al.* [26]

concinna (shikakai)		30)		detection of harmful bacteria	
Camellia sinensis (Chinese tea)	Leaves Extract (aq.)	2-10 (average size ±4.06)	Spherical	Medicinal activity	Radu*et al.* [27]
Honey	Aqueous Extract	Average size ± 4	Spherical	economic viability	Philip*et al.* [28]
Cucumis Prophetarum (wild gourd)	Leaves Extract (aq.)	30-50	Spherical, ellipsoidal	antibacterial activity	Tejavath*et al.* [29]
MurrayaKoenigi (Curry Leaf)	Leaves Extract (aq.)	20-40 (average size ± 30)	Nanobun	Anti-Bacterial activity	Ankamwar*et al.* [30]
Eugenia roxburghii DC (roxburg cherry)	Leaves Extract (alc.)	19-39 (average size ± 24)	Spherical	Anti-Bacterial activity	Acharya *et al.* [31]
Paulownia Tomentosa (princess tree)	Leaves Extract (alc.)	10-45 (average size ± 25)	Spherical	antioxidant activity	Hernandez-Martínez*et al.* [32]
Nigella sativa (Kalonji)	leaf biomass powder	average size ± 15	Spherical, angular	Agricultural	Amooaghaie*et al.* [33]
Anogeissus latifolia (gum ghatti)	0.5% Latex powder 0.1% Latex powder	31.6 ± 21.7 5.7 ± 0.2	Spherical, polydisperse	Anti-Bacterial activity	Beedu*et al.* [34]
T. chebula (haritaki)	Fruit extract	Average size ± 50	Spherical	Anti-Bacterial, antioxidant activity	Sachivkina*et al.* [35]
Prunus armeniaca (apricot)	Fruit extract	Less than 20	Spherical, Triangular	Free radical scavenging activity	Dauthal*et al.* [36]
Abelmoschus esculentus *(lady's finger)*	Flower extract	5.52-31.96 (average size 16.19)	Spherical	Anticancer and antimicrobial activity	Devanesan*et al.* [37]
Jasminum nudiflorum (winter jasmine)	Flower extract	11-78 (average size 25)	Spherical	Antifungal, antioxidant activity	Peng *et al.* [38]
Tagetes erecta (marigold)	Flower Extract	10-90 (average size 46.11)	Spherical, hexagonal	Antimicrobial	Chanda*et al.* [39]

Achillea biebersteinii (yellow milfoil)	Flower Extract	5-35 (average size 12.58)	Spherical, Pentagonal, hexagonal	Anti-Angiogenic activity	Namvar *et al.* [40]
Canna indica (Canna lily), Cosmos bipinnatus (Cosmos), Lantana camara (Lantana)	Flower Extract	28.7-5.5 33.5 to 44.4 21.1 to 30.2	Spherical	Anti-Bacterial, antioxidant activity	Cheng *et al.* [41]
Pistacia atlantica (Atlantic pistachio)	Seed extract	10–50, (average size ±36)	Spherical	Anti-Bacterial activity	Sadeghi *et al.* [42]
Rumex hymenosepalus (wild rhubarb)	Root extract	2-40	Hexagonal	Antioxidant activity	Iñiguez-Palomares *et al.* [43]
Syzygiumcumini (jamun)	Seed and flower Extract	36-77	Oval and cylindrical	Antimicrobial activity	Bernardo *et al.* [44]

B. Au Nanoparticles

Au nanoparticles (AuNPs), known for their biocompatibility have found widespread applications in medical diagnostics and drug delivery. Their ability to bind with biomolecules enables targeted therapies and imaging techniques. Table. 2 summarizes the plant-based synthesis of AuNPs. The concentration of precursor can significantly influence the size of synthesized spherical AuNPs (Figure 3) for Acorus calamus (sweet flag) [45] extract mediated synthesis of AuNPs. Beside this, some spherical AuNPs can be synthesised from leaf extract of Coreopsis lanceolata (tickseed) [46], fruit extracts of Areca catechu nut (Supari) [47], Ananas comosus (pineapple) [48], pomelo (Citrus maxima) [50], Couroupita guianensis (cannonball) [55]. Flower extracts of Gnidia glauca (Fish Poison Bush) [52], Lonicera japonica (Japanese honeysuckle) [53], peel extracts of Annona squamosa (custard apple) [54], and stem extracts of Maytenusroyleanus (prickly spike thorn) [56] can be employed to obtain different shaped AuNPs.

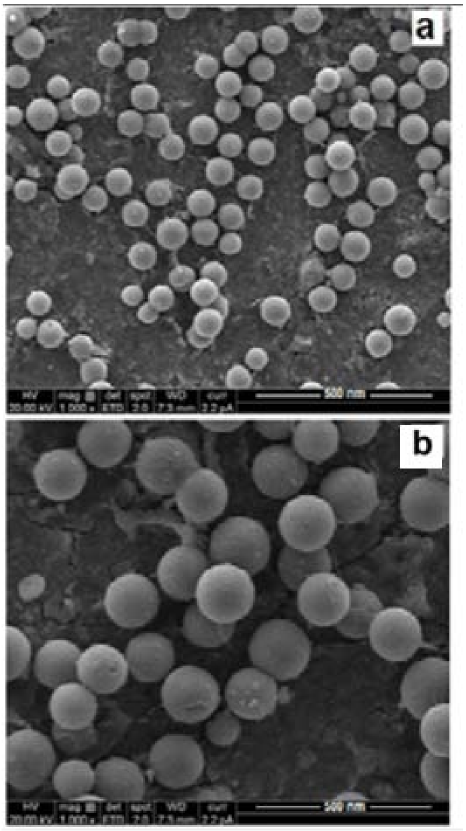


Fig. 3: SEM images of Au nanoparticles obtained from (a) 0.001 M and (b) 0.01 M chloroauric acid (Ref. 45. Copyright 2019, Elsevier)

Table 2: Plant based green synthesis of Au nanoparticles

Plant Extract	Reducing Agent	Size (nm)	Morphology	Applications	References
Acorus calamus (sweet flag)	Rhizome Extract	Average size 10	Spherical	Antibacterial andUV blocking activity	Prabu *et al.* [45]
Coreopsis lanceolata (tickseed)	Leaf Extract	Size range 20-30	Spherical	Agriculture	Thakur *et al.* [46]
Areca catechu nut (Supari)	Fruit Extract	Average size 13.75	Spherical	Catalytic, antioxidant, antibacterial, anticancer activity	Philip*et al.* [47]
Ananas comosus (pineapple)	Fruit Extract	5–20 (average size	Spherical, decahedron, little triangles	Antibacterial activity	Umadevi*et al.* [48]

		±16)			
Benincasa hispida (ash gourd)	Peel Extract (aq.)	Average size 22.18 ± 2	Spherical	In-vitro cytotoxicity against human cervical cancer cell	Khafagy*et al.* [49]
Pomelo (Citrus maxima)	Fruit Extract	Average size 25.77± 10	Spherical, rod	Nanocatalytic activity against organic pollutant	Chi*et al.* [50]
Polianthes tuberosa (tuberose)	Flower Extract	Average size 38.76	Spherical	Antagonistic activity	Rajkuberan*et al.* [51]
Gnidia glauca (Fish Poison Bush)	Flower Extract	Average size 10	Spherical, hexagonal, pentagonal	Nanocatalytic activity against organic pollutant	Chopade*et al.* [52]
Lonicera japonica (Japan ese honeysuckle)	Flower Extract	10–20 Average size 40	Spherical, triangular, few hexagonal.	Anticancer activity on HeLa cells	Kim *et al.* [53]
Annona squamosa (custard apple)	Peels Extract (aq.)	5±2	Spherical	Nanocatalytic activity against organic pollutant	Guttena*et al.* [54]
Couroupita guianensis (Cannonball)	Fruit Extract	Average size 7-48	Spherical, triangular, tetragonal, pentagonal with irregular contours	Antioxidant potency	Sivaramakrishnan *et al.* [55]
Maytenusroyle anus (prickly spike thorn)	Stem extract	Average size 30	Hexagonal	Antileishmanial activity	Ahmad*et al.* [56]
Zingiber officinale (ginger)	Rhizome Extract	5–53 (average size 15.11 ± 8.5)	Spherical	Antimicrobial, Antioxidant, In Vitro Cytotoxic	Guibal*et al.* [57]

C. Cu Nanoparticles

Copper nanoparticles (CuNPs), an affordable metal are valued for their catalytic efficiency and antimicrobial properties, making them essential in environmental and industrial applications. Mainly spherical CuNPs can be formed from leaf extract of Ecliptaprostrata (false daisy) [58], seed extract of Punica granatum (pomegranate), flower extract of Eichhornia crassipes (water hyacinth) [62], rhizome extract of Zingiber officinale (ginger) and Curcuma longa (tumeric) [64] (Table. 3).

Table 3: Plant based green synthesis of Cu nanoparticles

Plant Extract	Reducing Agent	Size (nm)	Morphology	Applications	References
Ecliptaprostrata (false daisy)	Leaves Extract	28-45, average size 36±1.2	Spherical	Antioxidant and cytotoxic	Chunget *al.* [58]
Magnolia Kobus (japanese magnolia)	Leaves Extract	37-110	Spherical	Antibacterial activity	Kim *et al.* [59]
Punica granatum (pomegranate)	Seed Extract	40-80 Average size 43.9	Spherical	Photo-catalytic activity against organic pollutant	Bibi*et al.* [60]
Punica granatum (pomegranate)	Peel Extract	15-20	Spherical	Antimicrobial activity	Kaur *et al.* [61]
Eichhornia crassipes (water hyacinth)	Flower Extract	12–15	Spherical	Detection of hazardous H_2O_2	Roy*et al.* [62]
Ziziphus spina-christi (L.) Willd (Christ's Thorn)	Fruit Extract	5-20 Average size 9	Spherical	Antibacterialpotency	Khani*et al.* [63]
Zingiber officinale (ginger) and Curcuma longa (tumeric)	Rhizome Extract	Average size 20-100	Spherical	Antibacterial potency	Varghese *et al.* [64]
Citrus sinensis (sweet orange)	Fruit Extract	Average size 10.2	Globular	Antibacterial potency	Isildak *et al.* [65]
Alstoniascholaris (Blackboard tree)	Leaves extract	__	Triangular, cylindrical, polygonal	Antimicrobial activity	Labaran*et al.* [66]

D. Co Nanoparticles, Pd Nanoparticles Pt Nanoparticles, Fe Nanoparticles, Ni Nanoparticles, Se Nanoparticles

This section briefly discusses the green synthesis methods for various nanoparticles, including cobalt (CoNPs), palladium (PdNPs), platinum (PtNPs), iron (FeNPs), nickel (NiNPs), and selenium (SeNPs) nanoparticles.

CoNPs are highly regarded for their magnetic properties and catalytic efficiency, particularly in energy storage and biomedical applications. Few references (Table. 4) are available that report on the green synthesis of CoNPs to date. Palladium nanoparticles (PdNPs) exhibit unique properties that make them valuable for various applications exclusively in catalysis. Here, Terminalia chebula (black myrobalan) extract can be used to synthesize unique triangular and pentagonal PdNPs (Figure 4) [74]. Platinum nanoparticles (PtNPs) are prized for their exceptional catalytic activity, making them crucial in fuel cells and various chemical reactions. Iron nanoparticles (FeNPs) are recognized for their magnetic properties, medicinal uses, and effectiveness in environmental remediation. Nickel nanoparticles (NiNPs) are powerhouses packed into a tiny package. Selenium nanoparticle (SeNPs) is a vital micronutrient for the health of humans, animals, and microorganisms. Table. 5, Table 6, Table. 7, Table.8 and Table. 9 respectively document data on the size, morphology, and applications of PdNPs, PtNPs, FeNPs, NiNPs, and SeNPs.

Table 4: Plant based green synthesis of Co nanoparticles (CoNPs)

Plant Extract	Reducing Agent	Size (nm)	Morphology	Applications	References
Trianthemaportulacastrum (Desert horsepurslane)	Leaf Extract	-	Spherical, monodispersed	Antimicrobial, antioxidant activity	Prakash *et al.* [67]
Sechium edule (chayote)	Fruit Extract	13.2–26.4	Prism	Antibacterial activity	Golder*et al.* [68]
Mangifera indica (mango)	Leaf Extract	25–40	Cubic, pentagonal	Ions detection in Industrial Wastewater	Okwunodulu*et al.* [69]

Table 5: Plant based green synthesis of Pd nanoparticles (PdNPs)

Plant Extract	Reducing Agent	Size (nm)	Morphology	Applications	References
Anogeissus latifolia (gum ghatti)	Latex Powder	Average size 4.8 ± 1.6	Spherical	Antibacterial, environmental remediation of organic compounds	Kora *et al.* [70]
Piper longum (Indian long pepper)	Fruit Extract	5-40	Spherical	Environmentally friendly recyclable catalyst	Nasrollahzadeh*et al.* [71]
Catharanthus roseus (Madagascar periwinkle)	Flower Extract	Average size 38 ± 2	Spherical	Photo-catalytic activity against organic pollutant	Ramalingam*et al.* [72]
Origanum vulgare (oregano)	Leaves Extract	2-20, average size ~2.2	Spherical	Catalytic activity	Adil*et al.* [73]
Terminalia chebula (black myrobalan)	Fruit Extract	Below 100	Hexagonal, triangular	Catalytic activity	Mandal*et al.* [74]
Chrysophyllumcainito	Leaves	__	Nanoflower	Catalytic activity	Majumdar *et al.*

(Star apple)	Extract			against organic pollutant	[75]

Table 6: Plant based green synthesis of Pt nanoparticles (PtNPs)

Plant Extract	Reducing Agent	Size (nm)	Morphology	Applications	References
Sechium edule (chayote)	Fruit Extract	28.6	Nanospheres	Antibacterial activity	Golder *et al.* [68]
Bacopa monnieri (Brahmi)	Leaf extract	5-20	Spherical	Antioxidant, neuroscience activity	Nelloreet *al.* [76]
Quercus glauca (ring-cupped oak)	Leaf Extract	5-15	Spherical	Water remediation	Chen*et al.* [77]
Gloriosa superba (fire lily)	Tuber Extract	0.8-3	Spherical	Anticancer activity	Rokade*et al.* [78]
JatropaGlandulifera (glandular jatropha)	Leaf Extract	Below than 100	Spherical, dodecahedron, cubic	Antibacterial activity	Jeyapaul*et al.* [79]
Anacardium occidentale (cashew)	Leaf Extract	__	Irregular rod	Catalytic activity against organic pollutant	Philip*et al.* [80]

Table 7: Plant based green synthesis of Fe nanoparticles (FeNPs)

Plant Extract	Reducing Agent	Size (nm)	Morphology	Applications	References
Terminalia arjuna (Arjun tree)	Bark Extract	20-80	Globular	Catalytic activity against organic pollutant	Manjanna*et al.* [81]
Artocarpus heterophyllus (jackfruit)	Peel Extract	average size ~33	Spherical	Catalytic activity against organic pollutant	Srivastava*et al.* [82]
Arachis hypogaea (red peanut)	Skin Extract	25-77 Average size 43.5	Spherical	Water remediation	Chen *et al.* [83]
Phoenix dactylifera (date palm)		58-79	Spherical	Antibacterial activity	Qadir*et al.* [84]

Table 8: Plant based green synthesis of Ni nanoparticles (NiNPs)

Plant Extract	Reducing Agent	Size (nm)	Morphology	Applications	References
Ocimum sanctum (holy basil)	Leaf Extract	12-36	Spherical, polygonal, cylindrical	Dye and pollutant adsorption	Palanivel *et al.* [85]
Zingiber officinale (Ginger)	Rhizome Extract	74.85±2.5	Spherical	Biomedical and environmental	Abdullah*et al.* [86]

Azadirachta indica (neem) and Psidium guajava (guava)	Leaf Extract	17-77	Spherical	Anticancer activity against HT-29 colon cancer cell	Mariam*et al.* [87]
Peumusboldus (boldo)	Leaves Extract	15-20	Spherical	Antibacterial activity	Taş*et al.* [88]
Citrus paradise (grapefruit)	Peel Extract	50-70	Spherical	Catalytic activity against organic pollutant	Kiran*et al.* [89]

Table 9: Plant based green synthesis of Se nanoparticles (SeNPs)

Plant Extract	Reducing Agent	Size (nm)	Morphology	Applications	References
Allium sativum (garlic)	Bulb Extract	21-50	Spherical	Antimicrobial activity	Jirasripongpun*et al.* [90]
Ceropegia bulbosa (lantern flower)	Tuber Extract	Average size 55.9	Spherical	Antimicrobial, larvicidal activity	Cittrarasu*et al.* [91]
Syzygium nervosum (cleistocalyxoperculatus)	Leaf Extract	50-200	Spherical	Antimicrobial activity	La*et al.* [92]
Trigonella foenum-graecum (fenugreek)	Seed Extract	50-150	Oval	Anticancer activity	Ramamurthy*et al.* [93]
Citrus paradise (grapefruits) and Citrus limon (lemons)	Fruit Extract	__	__	Antibacterial activity	Alvi*et al.* [94]

BIMETALLIC NANOPARTICLES

In recent years, bimetallic nanoparticles featuring alloy or core-shell structures have garnered significant interest. This attention stems from their potential applications across various fields such as catalysis and medical science. Therefore, leveraging our "Nature" (mainly plants) is crucial for the development of nontoxic, environmentally friendly and cost-effective green methods to synthesize bimetallic nanomaterials. Here are a few instances showcasing environmentally friendly methods for producing bimetallic nanoparticles (NPs). Bimetallic Ag-Au and Au-Ag nanoparticles are composed of a combination of silver (Ag) and gold (Au) atoms. Their structure and arrangement can vary, forming either core-shell structures (with one metal at the core and the other forming an outer shell) or alloyed structures where the two metals are uniformly mixed. This combination enhances their optical, catalytic, and biocompatible properties, making Ag-Au nanoparticles valuable in fields like biomedicine, catalysis, and environmental sensing. Table 10 provides an overview of studies documenting various bimetallic nanoparticles like Ag-Pt, Ag-Pd, Au-Pd, Au-Pt, Pt-Co nanoparticles.

Table 10: Plant based green synthesis of bimetallic nanoparticles (BNPs)

Plant Extract	Reducing Agent	Size (nm)	Nanoparticles type & Morphology	Applications	References
Solidago canadensis (Canada goldenrod)	Leaf Extract	Average size ~15	Ag-Au Spherical, triangular, rod	Cytotoxic against rat hepatoma cells and HuTu-80 (human intestinal) cell	Botha*etal.*[95]
Stigmaphyllonovatum (amazonvine)	Root Extract	9.1-20.4 Average size ~15	Ag-Au Triangular	Anticancer potential	Elemike*et al.* [96]
Asparagus racemosus (Shatavari)	Root Extract	10-50	Ag-Au Spherical	Antibacterial and Immunomodulatory Potentials	Amina*etal.*[97]
Artocarpus heterophyllus (jackfruit)	Latex Extract	Average size ~15	Ag@AuSpherical	Antibacterial and antioxidant activity	Sundarrajan*et al.*[98]
Gloriosa superba (flame lily)	Leaf Extract	Average size ±10	Ag/AuSpherical	Antibacterial and antibiofilm activity	Arumuga*et al.*[99]
Punica granatum (pomegranate)	Fruit Extract	1-100	Au-Ag Spherical, pentagonal, rod	Radical scavenging activity	Philip*et al. el* [100]
Pulicaria undulata (desert Golden Daisy)	Plant Extract	10-20	Au-AgSpherical	Catalytic activity against organic pollutant	Tahir*et al.* [101]
Commelinanudiflora (carolina dayflower)	Plant Extract	10-50	Au-AgSpherical, rod, triangular	Antibacterial against oral pathogens	Kuppusamy *et al.*[102]
Vernonia mespilifolia (Blue bitter tea)	Plant Extract	Average size 35.5 ± 0.8	Ag-PtSpherical	Antioxidant, antimicrobial, and cytotoxic activities	Oladipo *et al.*[103]
Crocus sativus (saffron)	Plant Extract	Average size ~36	Ag/PtSpherical	Biological efficacy and catalytic activity	Fakhri *et al.*[104]
Terminalia chebula (Haritaki or Myrobalan)	Fruit Extract	Average size ~20	Ag-PdSpherical	anticancer and antimicrobial activity	Suganthy*et al.*[105]
Citrus limon (lemon)	Leaf Extract	~1.5 - ~18.5d. nm	Au-Pd Spherical	larvicidal activity	Minal*et al.* [106]
Citrus sinensis (orange)	Peel Extract	Average size ±50	Au-Pd Spherical core shell	Antiairpollution activity	Wicaksono*et.al.*[107]
Asarum europaeum (european wild ginger)	Rhizome Extract	5-6	Au-Pt Irregular shape	Catalytic activity against organic pollutant	Dobrucka*et al.*[108]
Dioscorea bulbifera (air potato)	Tuber Extract	20-25	Pt-PdIrregular shape	Anticancer and antioxidant activity	Ghosh*et al.* [109]

Aerva lanata (mountain knotgrass)	Plant Extract	7-12, average size ∼9.5	Ag–Cu Spherical	Cytotoxic and antimicrobial activities	Thirumoorthy*et al.* [110]
Sechium edule (Chayote)	Fruit Extract	13.2–26.4	Pt-Co Spherical core-shell	Antibacterial activity	Golder*et al.* [68]

APPLICATIONS OF PLANT MEDIATED SYNTHESISED MONOMETALLIC AND BIMETALLIC NANOPARTICLES

This part of the review covers a comprehensive analysis of diverse applications for biosynthesized nanoparticles across the biomedical, antimicrobial, antifungal, agriculture and environmental sectors.

A. Larvicidal Activity: Plant extracts mediated synthesised metal nanoparticles have shown assurance in the fight against mosquito-borne diseases. Studies have demonstrated that AgNPs [13,23,44] and SeNPs [91] synthesized from different plant extractexhibited potent larvicidal activity against Culex tritaeniorhynchus, Aedes subpictus, Aedes subpictus, Culex quinquefasciatus, Anopheles stephensiand Aedes albopictus mosquitoes. This eco-friendly approach holds promise for controlling mosquito populations and reducing the global disease burden.

B. Antimicrobial Antibacterial Activity: The rising predominance of multi-drug-resistant microorganisms across various microbial systems emphasizes the urgent need for developing innovative antimicrobial agents. Nowadays metallic nanoparticles have emerged as potent antimicrobial agents, demonstrating potency against bacteria, fungi and viruses. These nanoscale materials offer a promising alternative to traditional antibiotics in combating infectious diseases. AgNPs [15,16,17,18,20,22,29,30,31,35], AuNPs [47,57], CuNPs [59,61,63,64,65,66], CoNPs [67,68],PdNPs [70], PtNPs [68,79], FeNPs [84], NiNPs [88], SeNPs [90,91,92,94], BNPs [68,110]exhibited potent antimicrobial properties against a range of dangerous pathogens, including Escherichia coli, Salmonella enterica, Vibrio parahaemolyticus, Staphylococcus aureus, Bacillus anthracis and Bacillus cereus.

C. Medicinal Activity: Nanoparticles truly have the potential to revolutionize healthcare. Their unique properties, such as small size, large surface area and ability to interact with biological systems, make them ideal candidates for developing innovative medical solutions. Some AgNPs [12, 21], NiNPs [86] nanoparticles have also biomedical properties. Some nanoparticles (AgNPs [12, 19, 27, 37], AuNPs [56]) also have valued medicinal properties. AgNPs from Aloe vera leaves extract have shown promising anti-glycation properties [25]. These nanoparticles effectively reduced the consequences of uncontrolled blood sugar levels, indicating their potential as therapeutic agents for diabetes-related complications. Various studies documented the anticancer potential of biosynthesized AgNPS [24, 37], AuNPs [47, 49, 53, 57], PtNPs [78], NiNPs [87], SeNPs [93], BNPs [96,105,109] nanomaterials against a wide range of life-threatening cancer cell lines. Notably, these nanoparticles outperformed the skin cancer chemotherapy drug, 5-fluorouracil, in inhibiting cancer cell growth.

D. Antioxidant Activity: Antioxidants play a crucial role in protecting our bodies from oxidative damage. By effectively neutralizing harmful free radicals, they help to safeguard our cells and tissues from a range of health issues. AgNPs [32, 35, 38, 41, 43], AuNPs [47, 55, 57], CuNPs [58], CoNPs [67], PtNPs [76], BNPs [98, 103, 109] exhibited potent antioxidant activity effectively scavenging both DPPH and hydroxyl free radicals.

E. Catalytic Activity: The escalating environmental crisis caused by organic dye pollution from industries like textiles, paper, and food demands innovative solutions. Nanoparticles have emerged as promising candidates for remediating this issue. Their catalytic properties enable the degradation of various dyes, toxins, and other contaminants, offering a sustainable approach to environmental cleanup. The catalytic efficiency of AuNPs [47, 50, 52, 54], CuNPs [60], PdNPs [72, 73, 74, 75], PtNPs [80], FeNPs [82, 84], NiNPs [89] and BNPs [101, 104, 108] was demonstrated in degrading model dye pollutants. These nanoparticles have demonstrated significant potential for environmental remediation, including water purification and soil decontamination.

CHALLENGES AND FUTURE PERSPECTIVES

Green synthesis presents an attractive and sustainable alternative to traditional nanoparticle synthesis methods. These approaches are cost-effective, environmentally friendly and scalable, while also prioritizing human health and safety. The extensive exposure of living organisms to the metal nanoparticles requires a thorough understanding of their potential toxicity. Although nanoparticles offer immense potential benefits across various fields, ensuring their safe and responsible use is crucial. Despite progress in understanding nanoparticle behaviour, significant gaps remain in our knowledge of their long-term impacts on human health and the environment. To mitigate potential risks, it is essential to establish stringent guidelines for their production, application and disposal.

Green nanotechnology, with its focus on eco-friendly and sustainable approaches, is addressed for significant growth. Future research will likely explore a wider range of biological sources, including diverse plant extracts, microbes, and biowastes, to further enhance the sustainability of nanoparticle synthesis. As the demand for biocompatible and non-toxic materials rises, green nanotechnology will play a vital role in addressing global challenges, particularly in biomedical applications, environmental remediation, and renewable energy. The integration of green nanotechnology into circular economy principles will contribute to a more sustainable future.

CONCLUSIONS

Nature has perfected the art of creating functional materials on a minuscule scale. We have reported that green route of plant extracts mediated synthesis process (derived from various plant parts like leaves, stems, roots, flowers, barks and seeds) which is capable of producing metallic nanoparticles composed of single metal and bi metals. Green synthesis presents a sustainable and eco-friendly alternative to traditional nanoparticle production methods by offering a promising pathway to create diverse nanomaterials with tailored properties and minimal environmental impact. In addition to these, green synthesis of metal nanoparticles offers several advantages including reduced ecological impact, minimal waste generation and the production of highly stable nanoparticles. This review explores the diverse morphologies of plant-based metal nanoparticles, aiming to inspire innovative applications and foster a deeper understanding in the field of green nanotechnology.

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