J. Water Environ. Nanotechnol., 7(4): 389-406 Autumn 2022

REVIEW PAPER

Antimicrobial and Environmental Applications of Inorganic Nanoparticles Synthesised from Plants

Sahithya K*, Mouli T, Devika PR, Harshitha CK

Department of Microbiology, Indian Academy Degree College-Autonomous, Bengaluru-560043, Karnataka, India

Received: 2022-07-31 Accepted: 2022-09-09 Published: 2022-10-01

ABSTRACT

Nanoscale materials are widely used in many fields including medicine, engineering, and the environment that focuses on the synthesis of nano dimensional particles is a timely topic. Nanomaterials synthesized by chemical approaches have intended effects on the environment and human health. In response to these challenges, plant-mediated synthesis of inorganic nanoparticles has been a highly innovative research area over the last decade. Aqueous and solvent extracts have been employed as efficient resources in synthesis-controlled nanostructures and the fabrication of various nanomaterials. The present article unveils the possible role of plant biomolecules including amino acids, aldehydes, terpenoids, ketones, tannins, and phenolics in the reduction and stabilization of various metal and metal oxide nanoparticles. The green synthesized nanoparticles evolved as efficient alternative agents in solving the serious threats faced in the field of biomedical, energy conversion, environment, automobiles, electronics, and optical. Moreover, catalytic, and antimicrobial applications of green nanoparticles are also critically discussed.

Keywords: *Antimicrobial applications, Biogenic nanoparticles, Environmental pollutants, Plant extracts, Remediation.*

How to cite this article
Sahithya K, Mouli T, Devika PR, Harshitha CK. Antimicrobial and Environmental Applications of Inorganic Nanoparticles Synthesised from Plants . J. Water Environ. Nanotechnol., 2022; 7(4): 389-406.
DOI: 10.22090/jwent.2022.04.006

INTRODUCTION

Advances in material chemistry in the last few decades have played a prominent role in the development of nanoscience and nanotechnology which deals with the modification and utilization of particles of the order of one billionth of a meter (1 x 10^{-9} m) called nanomaterials. Nanoscience is a microscopic and molecular approach to the regulation of matter on larger scales, where the physiochemical properties of nanoparticles vary significantly from their larger counterparts. Unique characteristic features of nanomaterials have paved the way for new scientific inventions in the field of nanoscience and nanotechnology [1,2]. Nanomaterials have been categorized as organic (e.g., carbon-based nanomaterials) and inorganic (e.g., metal and metal oxide nanoparticles). Based on their overall dimension, nanomaterials are classified as zero-dimensional (e.g., quantum dots), one-dimensional (e.g., nanotubes), two-dimensional (e.g., nanosheets), and three-dimensional (e.g., nanoflowers). Further depending on their physicochemical features, they are subdivided into polymeric-based nanomaterials (e.g., nanobiocomposites), carbon-based nanomaterials (e.g., carbon nanotubes), lipid-based nanomaterials (e.g., liposomes), semiconductor-based nanomaterials (e.g., CdTe), layered nanomaterials (e.g., perovskites and LDH)

* Corresponding Author Email: *sahikandimalla@gmail.com*

and ceramic based nanomaterials (e.g., nano-oxides of Si, Al, Ti, and Zr) [3,4]. Among all the inorganic nanomaterials, transition metal and metal oxide-based nanoparticles such as Cu, Fe, Co, Mn, Zn, Cr, Ni, Ag, Ti, and Au are of the most important scientific concern due to their outstanding and diverse applications in various sectors such as chemical, photonics, electronic, food science, energy harvesting, environmental, biomedical, pharmaceutical, agricultural and industrial [5-7].

An increased thrust in the scientific realm influenced the researchers to develop two major approaches *viz.*: top-down and bottom for the synthesis of nanomaterials with desired properties (Fig. 1). In a top-down approach, the active bulk material is reduced to nano-sized nanomaterial under the influence of chemicals, radiation or mechanical shearing. Different techniques utilize the top-down principle to produce nanomaterials which include lithography, mechanical milling, sputtering, etching, pulse laser ablation, pulse wire discharge, evaporation condensation reaction, and ion implantation. However, top-down approaches suffer from limitations which include high cost, use of toxic chemicals, ineffective in producing nanomaterials with desired properties, and difficulties to control the size of nanoparticles. The bottom-up approach involves the pile-up of the atoms, ions, and molecules to form complex structures of nano dimension. A few techniques of the bottom-up approach are the chemical vapor deposition process, laser pyrolysis, sol-gel method, plasma arcing, wet synthesis, self-assembly process, electrochemical, sonochemical, metal organic decomposition, hydrothermal, solvothermal, and spinning [8].

Anthropogenic activities including combustion of fossil fuels, oil spills, agriculture, deforestation, mining, and various industrial sectors such as food, textile, paper, and pharmaceutical have

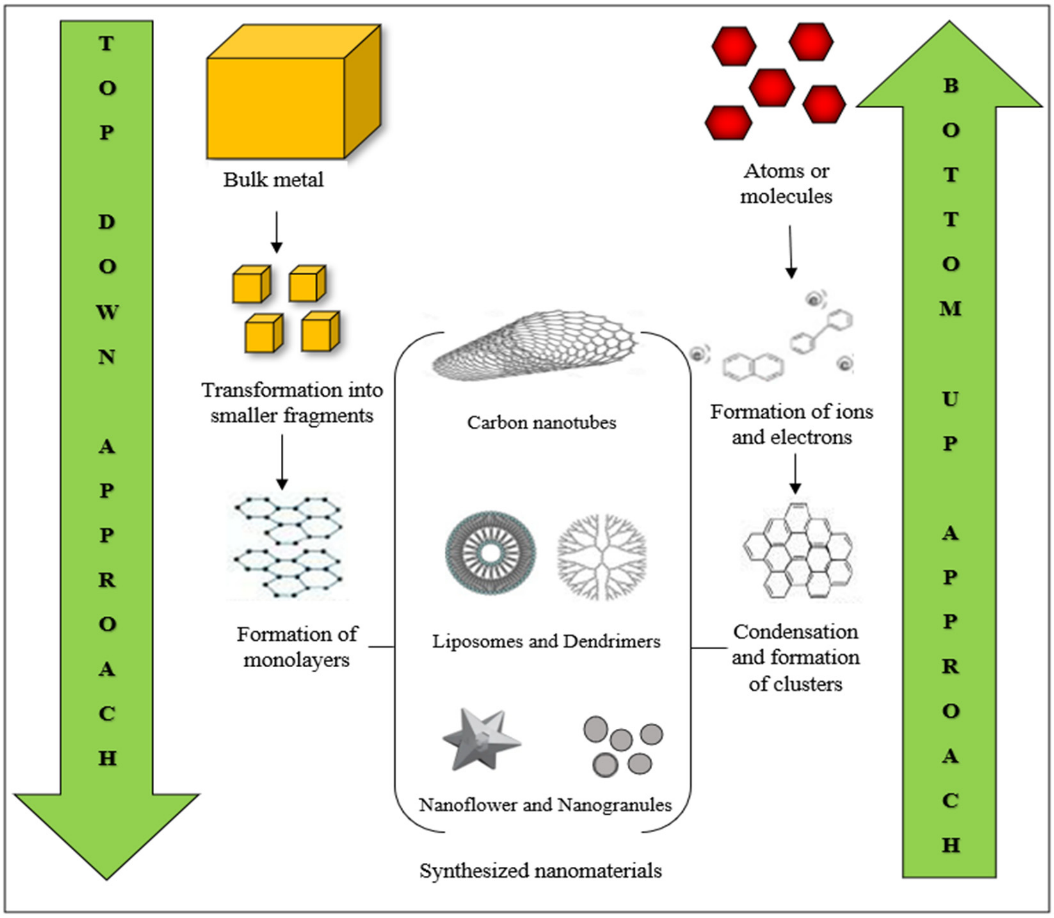

Fig. 1. Schematic representation of major approaches involved in the nanomaterial synthesis

Table 1. Limitations of conventional nanoparticle synthesis methods

Method	Drawbacks	References
Hydrothermal	Slow kinetics of crystallization; rigorous pressure; High-cost; Long reaction period	[16]
Irradiation	Aggregation of particles	
Laser ablation	High-cost; Lager number of colloids required; High energy consumption; Time-consuming	
Mechanical activation	High energy consumption; High calcination temperature; contamination of iron	
Micro-emulsion	Complex process; Low yield; High influence of surfactant traces on purity of final product; Low thermal stability	
Sonochemical	High-cost; Contamination by precursors	
Co-precipitation	Hazardous by-products; high calcination temperature	

been significant contributors to environmental contamination. Several research studies indicated the impact of high environmental contamination on living organisms and their positive relationship with increasing health problems [9]. Myriad nanoparticles have found applications in environmental remediation as sensors, adsorbents, and photocatalysts for the elimination of toxic chemicals and pollutants. Recent advances in novel polymer fabricated nanomaterials employed for the treatment of industrial effluents and wastewater contaminated with radionuclides, metal ions, and chemical solutes were highlighted by several researchers [10,11].

In addition to the environmental applications, a plethora of engineered nanomaterials proved to be strategically effective antimicrobial agents complementary to traditional antibiotics, antifungal, and antiviral agents. Antimicrobial nanomaterials include diversified groups of inorganic metal and their oxides as they possess a range of intrinsic and chemical composition properties that influence innate antimicrobial mechanisms such as the disruption of the plasma membrane, diffusion into the cytoplasm, and the degradation of nucleic acids and enzymes. [12-14].

Herein, we provide a comprehensive view of scientific investigations made in the synthesis of inorganic nanoparticles using plants as a model for biological sources of nanoparticle synthesis and their diversified application in the field of environmental remediation and the biomedical industry.

CONVENTIONAL METHODS OF NANOPARTICLE SYNTHESIS

The efficiency of nanoparticles is greatly influenced by the shape, size, and surface topology which is further reliant on the method of synthesis. For several decades, conventional techniques falling under the category of physical or chemical methods such as hydrothermal, sol-gel, combustion, reactive grinding, mechanical activation, microemulsion, co-precipitation, microwave irradiation, laser ablation, sputtering, sonochemical reduction, polyol method, and thermal deposition have been utilized to synthesize the nanomaterials of specific dimension to control the properties of nanomaterials [15,16].

However, these methods are known to suffer from significant drawbacks as presented in Table 1. The effort to synthesize the nanomaterials of desired properties and dimensions involving sustainable approaches opened unique and new opportunities in this emerging field of research [17].

NANOTECHNOLOGY AND GREEN CHEMISTRY

Researchers have developed multiple routes for the synthesis of nature-friendly nanoparticles utilizing natural sources to provide the advantages of clean, nontoxic, and environmentally adequate synthesis methods. The green and biological synthesis of nanoparticles is an attractive practice that enables synthesis in an aqueous environment with minimum cost and low energy investment which could easily be scaled up to a higher level. Numerous studies have already showcased the greater efficiency of plants [18-20], edible and nonedible mushrooms [21,22], and microorganisms [23-25] for the synthesis of inorganic nanoparticles as shown in Fig. 2. The application of green chemistry principles in the synthesis of nanoparticles have paved the way for sustainable development in the field of nanotechnology.

ROLE OF PLANTS IN THE SYNTHESIS OF METAL AND METAL OXIDE NANOPARTICLES

The insight that plants could bioaccumulate and reduce metal ions has opened multiple options for considering their use as an alternate

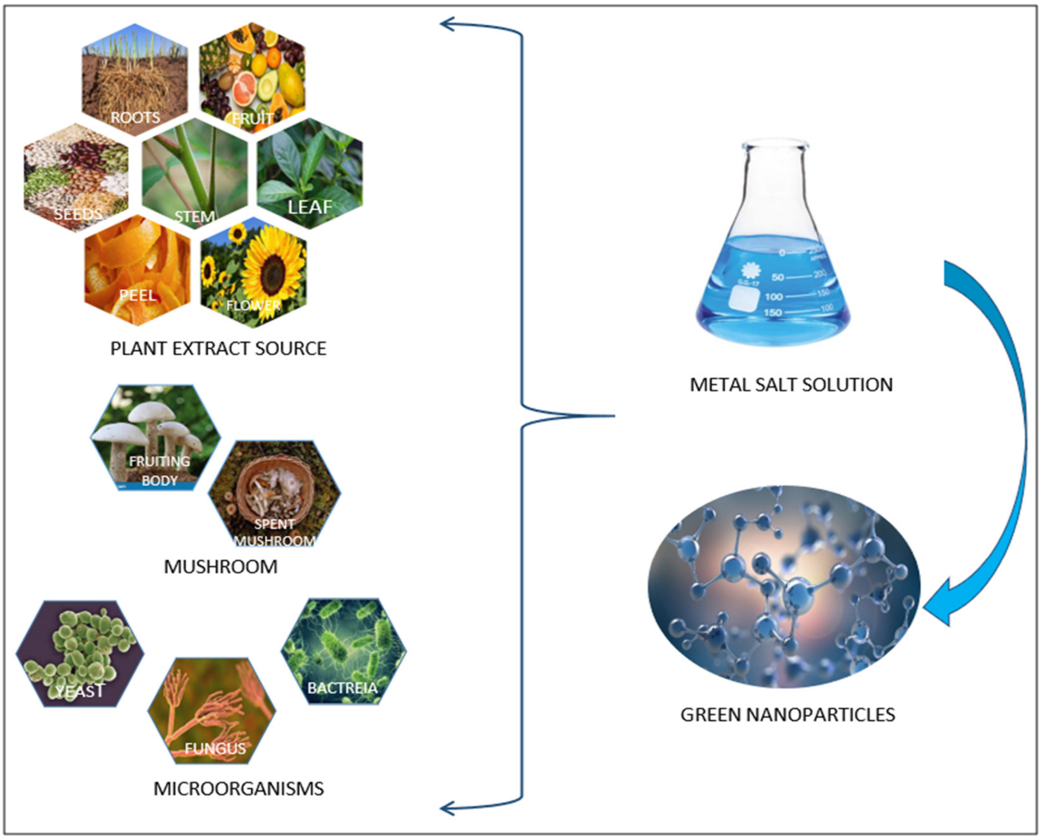

Fig. 2. Few examples of biomaterials used in the synthesis of green inorganic nanoparticles

way of synthesizing nanoparticles. The plant-mediated synthesis of nanomaterials provides multiple advantages over the microbial synthesis approach in low cost, reliability, simplicity, non-pathogenicity, short reaction time, and control over the reaction. Several plants including *Aloe barbadensis, Acalypha indica, Apiin, Avena sativa, Azadirachta indica, Camellia sinensis, Brassica juncea, Cinnamomum, Carica papaya, Coriandrum sativum, Emblica officinalis, Eucalyptus, Garcinia, Jatropha, Medicago sativa, Ludwigia adscendens, Mentha piperita, Nelumbo nucifera, Ocimum sanctum, Pelargonium roseum, Psidium guajava, Sedum alfredii, Tanacetum vulgare,* and *Terminalia catappa* have been reportedly employed for the synthesis of inorganic nanoparticles [26,27]. The process of nanoparticle synthesis is initiated by the addition of metal ions solution to an aqueous extract of various parts of the plants such as roots, stems, bark, leaves, flowers, and fruits at different reaction conditions [28,29]. The phytochemicals (*viz.,* aldehydes, alkaloids, flavonoids, ketones, organic acids, phenolic acids, and terpenoids) and bioactive compounds (complex terpenes, enzymes, vitamins, and minerals) in the plant extracts have greater potential to reduce metal ions into their corresponding metal and metal oxide nanoparticles. In addition, polysaccharides, proteins, enzymes, and amides in plant extracts play a dual role by acting as both reducing and stabilization agents [30,31]. Some examples of potential plants investigated for the synthesis of inorganic nanoparticles are shown in Fig. 3.

Flavonoids, a large group of polyphenolic compounds comprising anthocyanins, chalcones, flavones, flavanols, flavanones, and isoflavonoids are known for their chelation and bioreduction properties. The release of reactive hydrogen or oxygen atoms from the tautomeric transformation of flavonoids from enol-form to keto-form is believed to be involved in the bioreduction of metal ions. For example, *Ocimum sanctum* leaf extracts naturally contain high amounts of quercetin (flavonoid) containing OH^- and keto groups.

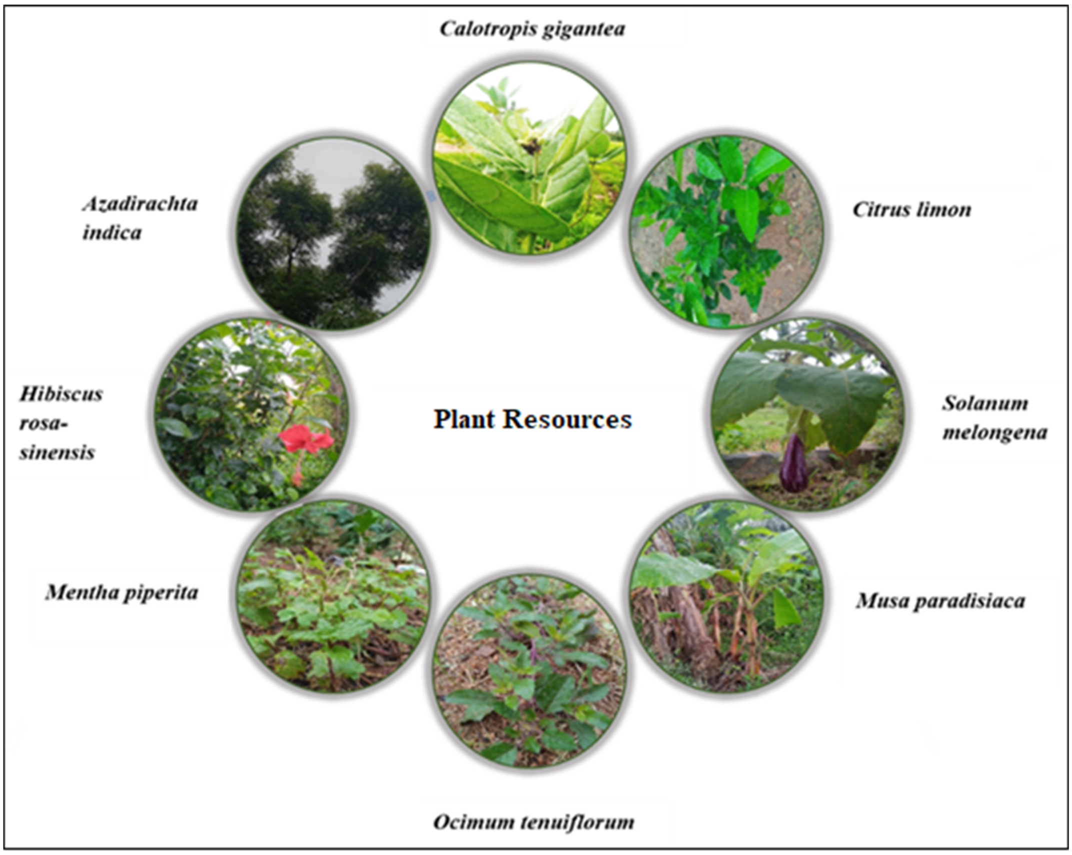

Fig. 3. Common plants used in the synthesis of inorganic nanoparticles

During the synthesis of Ag nanoparticles, quercetin reacts with $AgNO_3$ as an acid using OH^- groups attached to the carbon atoms of an aromatic ring that participates in the reduction of Ag ions to Ag nanoparticles and prevents agglomeration in the reaction medium [32]. In addition, quercetin can chelate carbonyl and hydroxyl groups at the C3 and C5 site and catechol groups at C3 and C4 positions which are further involved in the chelation of several metal ions *viz.,* Al^{3+}, Cr^{3+}, Co^{2+}, Cu^{2+}, Fe^{2+}, Fe^{3+}, Pb^{2+} and Zn^{2+} [31].

Phenolic acids are plant-derived essential biomolecules containing phenolic rings and functional groups of esters, glycosides, or carboxylic acids. Their benzene ring plays a significant role in the reduction and metal chelation. Various studies demonstrated the reducing ability of caffeic acid, chlorogenic acid, cinnamic acid, coumaric acid, ellagic acid, gallic acid, ferulic acid, and protocatechuic acid [33,34]. Propyl gallate, an ester derivative of gallic acid, has been applied as a reducing and stabilization agent for the synthesis of Ag nanoparticles by Ping and Nian, [35]. The hydrogen bonds of propyl gallate-coated Ag nanoparticles deliver a chain structure that results in a plasmon resonance peak in the IR wavelength region which allows the determination of major antioxidants.

Terpenoids are volatile organic components constituting 90 % of essential oils produced by plants as secondary metabolites. Isoprenoids, a basic unit of terpenoids, act as the building blocks of other metabolites including plant chlorophyll, carotenoids, hormones, sterols, and turpentine. Mono and sesquiterpenoids are identified to play a significant role in the synthesis of nanoparticles [36]. Leaf extracts of *Leucas martinicensis* have produced spherical and crystalline Ag nanoparticles with the action of terpenoids [37]. In addition, the ability of *A. indica* in the synthesis of ZnO nanoparticles was attributed to the strong reduction or oxidation reaction carried out by terpenoids present in the leaf extracts [38].

Monosaccharides such as glucose and fructosecontaining keto groups are capable of undergoing a series of tautomeric transformations involving the development of nanoparticles. The reducing ability of polysaccharides is greatly dependent on the ability of monomeric sugars to adopt an open chain form within an oligomer to provide access for metal ions to an aldehyde or keto group [39]. Various amino acids serve as excellent capping and stabilization agents in the development of inorganic nanoparticles. Several researchers reported the inherent ability of amino acids in directing and assembling superstructures [40,41]. Courrol and Matos [42], conducted the experiments using 21 amino acids for the synthesis of silver nanoparticles where authors observed that five amino acids *viz.,* tryptophan, tyrosine, methionine, cysteine, and histidine were proficient in the reduction and stabilization of nanoparticles. In another study, photo-reduced gold nanoparticles were synthesized using arginine, aspartic acid, valine, threonine, and tryptophan. A relationship between polarizability and the oxidation potential of an amino acid was reported during the nanoparticle formation upon irradiation.

APPLICATIONS OF BIOGENIC METAL AND METAL OXIDE NANOPARTICLES

In recent years, nanomaterials have found applications in almost all disciplines due to their improved properties at the nanoscale. Some of the major applications of nanotechnology are fundamental fields, mainly environmental remediation, agriculture, electronics, and medicine. With the scientific community on a constant lookout for highly biocompatible and sustainable ways of environmental pollution mitigation, the toxic effects of xenobiotics have put nanoscience and nanotechnology as the front runners [43-45]. The applications of biogenic nanoparticles in the elimination of environmental pollutants and their antimicrobial abilities have been briefly reviewed.

ENVIRONMENTAL APPLICATIONS

Several noble and transition-based nanoparticles synthesized using plants are utilized for water purification due to their high reactivity and photocatalytic characteristics owing to the narrow band gap. They are also known for their extraordinary absorption capability exhibiting advantages such as fast kinetics and high regeneration ability. Numerous metal and metal oxide nanoparticles have been investigated for the remediation of several contaminants, but most studies have been dedicated to the removal of heavy metals and chlorinated pollutants from an aqueous environment [46]. Several nanomaterials have been frequently utilized for environmental remediation since they are flexible toward both *in-situ* and *ex-situ* applications. Table 2 provides an overview of inorganic nanoparticles synthesized from plant extracts and their reported environmental applications.

TITANIUM DIOXIDE NANOPARTICLES

Titanium dioxide has been documented for water treatment and air purification due to its characterized photocatalytic, semiconducting, low cost, nontoxicity, and energy-converting properties [47-50]. TiO_2 nanoparticles are easily activated by photons producing highly reactive oxidants like OH^-, thus frequently employed for the elimination of organic contaminants from various media. Goutam et al., [51], described the synthesis of TiO_2 nanoparticles by using leaf extracts of *Jatropha curcas* and their application for the degradation of tannery wastewater in self-designed fabricated parabolic trough reactors. At the end of photocatalytic treatment, 76.4 % removal of Cr and 82.6 % removal of COD from wastewater were reported. Crystalline anatase TiO_2 nanoparticles synthesized from extracts of *Diospyros ebenum* at 600 °C were evaluated for the mineralization of crystal violet under UV light irradiation [52]. The results suggested the improved photocatalytic activity of nanoparticles due to the fine crystallite size and higher surface area available for catalysis.

SILVER NANOPARTICLES

Another frequently utilized nanoparticle for the elimination of environmental pollutants is silver and its oxides. Silver nanoparticles are well known to exhibit unique size and shape which provides them with diverse optical and electrical properties [53-56]. Chand et al. [57] developed a novel route to synthesize silver nanoparticles using three plants *viz*., onion, tomato, and acacia catechu. The obtained spherical nanoparticles showed complete degradation of MO, MR, and CR within 20 min and 15 min respectively. In another study, Ag nanoparticles synthesized from *Ficus hispida Linn* reduced 4-NP into 4-Aminophenol in 15 min of exposure [58]. Mehata et al. [59], applied Ag nanoparticles synthesized using a medicinal plant, *Kalanchoe pinnata* which is also known as *Bryophyllum pinnatum* for the photocatalysis of RhB

Table 2. Environmental applications of inorganic nanoparticles synthesized using plants.

Types of NPs	Morphology (Size in nm)	Source	Phytochemicals involved	Pollutant name	Removal	Mechanism	References
TiO_2	Spherical; 20.3	*Malva parviflora*	-	MO dye	100 %	Photocatalytic degradation	[104]
	Spherical; 10 to 120	*Jatropha curcas*	Phenols	Tannery wastewater	82.2 %	Photocatalytic degradation	[51]
	Spherical; 25 to 50	*Prunus × yedoensis*	Phenols	Phosphate	10 mg/l	Photocatalytic degradation	[48]
	Spherical; 10 to 12	*Diospyros ebenum*	Aldehydes, alcohols and carboxylic acids	CV dye	100 %	Photocatalytic degradation	[52]
	Spherical; 60 to 100	*Ageratina alttissima*	Alcohol and phenol	MB dye Alizarin red CV dye MO dye	86.7 % 76.3 % 77.5 % 69.0 %	Photocatalytic degradation	[49]
	Spherical; 124	*Azadirachta indica*	-	MR dye	~ 66 %	Photocatalytic degradation	[50]
Ag	Spherical; 38	*Kalanchoe pinnata*	-	RhB dye	87.0 %	Photocatalytic degradation	[59]
	Spherical, hexagonal, cubic; 20-100	*Eucalyptus*	Flavonoids, aromatic amine and alcohol	Azo dyes	90.0 %	Adsorption	[54]
	Spherical; 14 to 25	Mixture of *Onion, tomato, Acacia catechu* extract	Terpenoids, flavones and polysaccharides	MO dye MR dye CR dye	95.0 % 97.0 % 98.5 %	Photocatalytic degradation	[57]
	Spherical and cuboidal;	*Cissus quadrangularis*	Flavonoids, terpenoids and alkaloids	MB dye	100 %	Photocatalytic degradation	[60]
	Spherical; 20	*Ficus hispida Linn. f.*	Sterols, tri-terpenic acid and flavonoids	4-NP	~ 97.0 %	Photocatalytic reduction	[58]
	Spherical; 20 to 30	*Leucas martinicensis*	Alcohols or aliphatic amines	MB dye	~ 99.0 %	Adsorption	[37]
Pt	Spherical; 1 to 3	*Atriplex halimus*	Terpenoids, flavonoids and alkaloids	MB dye	91.1 %	Photocatalytic degradation	[62]
Au	Spherical; 4 to 13	*Avicennia marina*	Alcohols and phenols	4-NP	100 %	Adsorption	[64]
	Spherical; 20	Green tea leaves	-	MB dye	100 %	Adsorption	[63]
Fe	Spherical; 15 to 45	Black tea leaves and vineyard pruning residues	-	SDZ	69 %	Adsorption	[68]
	Spherical; 5	15 species of plants	Aliphatic amine and phenols	Cr ions	698.6 mg/g	Adsorption	[67]
CuO	Spherical; 150	*Mentha piperita L.* leaves and *Citrus × sinensis* peels	Phenols and alcohols	Pb(II) Ni(II) Cd(II)	88.8 mg/g 54.9 mg/g 15.6 mg/g	Adsorption	[77]
	Spherical; 2 to 6	*Psidium guajava*	Alkaloids, flavonoids and terpenoid	Industrial dyes	83 %	Photocatalytic degradation	[78]
	Spherical; 120	*Madhuca longifolia*	-	Wastewater treatment	77 %	Photocatalytic degradation	[79]
ZnO	Spherical; 17.8	*Psidium guajava*	Flavonoids	CR dye MB dye	120.3 mg/g 90.3 mg/g	Adsorption	[84]
	agglomerated sponge-like 10 to 15	*Ulva lactuca*	Amino acids	MB dye	90 %	Photocatalytic degradation	[70]
	Spherical; 40	*Peganum harmala*	Polyphenolic compounds and proteins	Cr ions	74.6 mg/g	Adsorption	[82]
	Spherical; 11.6	*Eucalyptus globulus*	Polyphenols and tertiary alcohol	MB & MO dyes	98.3 %	Photocatalytic degradation	[71]
	Spherical; 8	*Camellia Sinensis*	Polyphenols	MB dye	84.3 %	Photocatalytic degradation	[20]
	Spherical; 15 to 25	*Artocarpus heterophyllus*	Terpenoids and flavonoids	RB dye	80 %	Photocatalytic degradation	[83]
	Spherical; 100	*Buchanania lanzan*	Flavonoids	MG dye	~ 97.0 %	Photocatalytic degradation	[75]

Continued Table 2. Environmental applications of inorganic nanoparticles synthesized using plants.

Types of NPs	Morphology (Size in nm)	Source	Phytochemicals involved	Pollutant name	Removal	Mechanism	References
	Polyhedron; 20 to 120	*Corymbia citriodora*	Citronellal, linalool, catechin, gallic acid, coumaric acid and protocatechuic acid	MB dye	83.4 %	Adsorption	[76]
	Spherical; 9.6 to 25.5	*Azadirachta indica*	Terpenoids and reducing sugars	MB dye	82.1 %	Photocatalytic degradation	[38]
	Spherical; 15 to 46	*Vitex trifolia*	Alcohols, aromatic and aliphatic amines	MB dye	92.1 %	Photocatalytic degradation	[72]
	Spherical; 52 to 253	*Coriandrum sativum*	-	Anthracene	96.0 %	Photocatalytic degradation	[74]
	Hexagonal; 52 to 76	*Beta vulgaris*	Flavonoids and betalains	MG and MB dyes	95.0 % 80.0 %	Photocatalytic degradation	[80]
	Hexagonal; 9 to 38	*Azadirachta indica*	Flavonoids, limonoids, isoazadirolide and azadirachtin	MB dye	92.0 %	Photocatalytic degradation	[93]
	Spherical; 20 to 30	*Garcinia xanthochymus*	Flavonoids, garciniax-anthone and xanthochymol	MB dye	94.0 %	Photocatalytic degradation	[81]
	Spherical; 12 to 72	*Citrus paradisi*	Flavonoids, limonoids and carotenoids	MB dye	56 %	Photocatalytic degradation	[29]
	Spherical; 5 to 15	*Cassia fistula*	Polyphenols and flavonoids	MB dye	98.7 %	Photocatalytic degradation	[75]
Cr_5O_{12}	Spherical; 56.9	*Azadirachta indica*	Alkaloids, flavonoids and azadirachtin	MO dye	59.0 to 95.0 %	Photocatalytic degradation	[106]
Ni	Spherical;	*Citrullus colocyn*	Alkaloids, flavonoids, and carotenoids	RY-160 dye	91.4 %	Photocatalytic degradation	[44]
Mo	Spherical; 25 to 35	*Centella asiatica*	Isoprenoids and phenylpropanoid derivatives	DG dye Navy Blue dye	81.3 % 82.4 %	Photocatalytic degradation	[43]

under dark conditions. Ag nanoparticles including bimetallic nanoparticles have found applications as sensors in the sensing and detection of pollutants. For instance, green Ag-doped Ce nanoparticles synthesized from *Cissus quadrangularis* were highly efficient in the detection of Cd^{2+} ions even in presence of other heavy metals such as Co^{2+}, Pb^{2+}, Hg^{+}, Ni^{2+}, As^{3+}, Mn^{2+}, Zn^{2+} and Fe^{3+} [60].

PLATINUM AND GOLD NANOPARTICLES

In addition to silver, other noble metals such as Pt-based nanoparticles and Au-based nanoparticles were successfully synthesized by many researchers using various plant extracts [61]. Eltaweil et al. [62], proposed a promising route of the green synthesis of Pt nanoparticles with the size 1 to 3 nm using leaf extract of *Atriplex halimus* and further investigation suggested the high catalytic activity for the complete degradation of MB in 5 min at 100 ppm of dye concentration. To investigate the efficacy of reducing agents in the degradation of organic compounds, Gupta et al. [63] explored the use of Sn(II) to enhance the degradation of MB by Au nanocatalysts synthesized from green tea leaves. It has been demonstrated that $SnCl_2$ acts as a reducing agent facilitating the electron transfer and Au nanoparticles as a catalyst in the reaction. Furthermore, encapsulation of nanoparticles using natural polymers is important to overcome concerns regarding aggregation and recoverability. Nabikhan et al. [64], fabricated Au nanoparticles synthesized from an aqueous extract of *Avicennia marina* using sodium alginate and used as a heterogenous catalyst against 4-NP which was proved to be a potent, eco-friendly nano biocomposites catalyst for the remediation. A fever report in the literature suggested the unexplored efficiency of these nanoparticles for environmental applications.

IRON-BASED NANOPARTICLES

Iron-based nanosorbents are particularly attractive due to their inherent magnetic property that favors their easy separation from the reaction medium [65,66]. Iron and its oxide-based nanoparticles synthesized from plant extracts are studied for the elimination of several contaminants such as antibiotics, heavy metals, and textile dyes. Xiao et al. [67], reported the synthesis of iron nanoparticles with increased stability using 15 different plant extracts *viz*., *N. indicum, A. moluccana (L.) Willd, C. camphora (L.) Presl., P. orientalis (L.) Franco, G. robusta, B. variegata L., Black tea, Oolong tea, A carambola L., D. regia, E. citriodora, L. speciosa Pers., S. aromaticum, S. jambos (L.) Alston* and *D. longan Lour*. The major phytochemicals responsible for the reduction and stabilization of Fe nanoparticles were also determined. Nanoparticles synthesized by *S. jambos (L.) Alston* extract exhibited significant adsorption capacity with 698.6 mg Cr (VI) per g of iron. Similarly, for the synthesis of zero-valent iron nanoparticles, Conde-Cid and his co-workers [68] employed two natural aqueous extracts, black tea leaves, and vineyard pruning residues. It was concluded that the prepared nanoparticles were able to eliminate 58 % of sulfadiazine via an adsorption mechanism whereas 69 % through a catalytic degradation mechanism.

COPPER BASED NANOPARTICLES

Other prevalent transition metal nanoparticles are Cu and their respective oxide-based nanoparticles which are generally used against environmental remediation [**69-76**]. Green synthesized CuO nanoparticles prepared using extracts of mint leaves and orange peels were utilized for the removal of heavy metals. Maximum uptake capacity followed the order of Pb(II) > Ni(II) > Cd(II) which was recorded at an adsorbent dosage of 0.33 g/L and pH 6.0 within 60 min of contact time [77]. Cu nanoparticles synthesized using *Psidium guajava extract* were reported as an excellent heterogeneous catalyst exhibiting the maximum degradation (93 % and 81 %) of industrial dyes NB and RY-160 respectively [78]. In another article, *Madhuca longifolica*-based CuO nanoparticles demonstrated 77 % of photocatalytic degradation of MB dye after 150 min of visible light irradiation suggesting the durability of the green nanoparticles [79].

ZINC OXIDE-BASED NANOPARTICLES

ZnO nanoparticles possess unique physiochemical properties, due to dimensional characteristics and surface morphology. These are known to exhibit good adsorptive and catalytic behavior, making them suitable materials in the field of environmental remediation [80,81]. Fazlzadeh et al [82] demonstrated the synthesis of ZnO nanoparticles using powdered *Peganum harmala* seed extract (ZnO) and the synthesized nanoparticles were coated with powdered activated carbon of *Peganum harmala* seed (PPAC) for enhancing adsorption capacity. ZnO/PAC showed the highest adsorption efficiency (68.4 mg/g) for the Cr(VI) followed by PPAC and bare ZnO. The study revealed the significance of surface modification of nanoparticles for enhanced removal of heavy metals. MB, a widely used thiazine dye was removed from aqueous samples with ZnO nanoparticles synthesized using an aqueous extract of *Ulva lactuca*. The degradation of dye was carried out using natural sunlight. Under optimum conditions, the process showed 90.4 % degradation of dye. The photo-nanocatalyst proved to be effective for the oxidation and degradation of MB which proceeded at high reaction rates [70]. Vidya et al. [83], reported the synthesis of ZnO nanoparticles utilizing leaf extracts of *Artocarpus heterophyllus* with an average size of 15 to 25 nm. The green synthesized ZnO nanoparticles showed outstanding photocatalytic degradation efficiency (> 80 % within 1 h) against Rose Bengal dye, the main water-pollutant released by the textile industries.

BIMETALLIC NANOPARTICLES

Several investigations have demonstrated the utilization of bimetallic nanoparticles as a means of overcoming some of the drawbacks associated with monometallic nanoparticles. Mixed metallic oxide nanomaterials synthesis from the green route has also been investigated by several researchers for their efficiency in environmental remediation. For instance, Sahoo et al. [84], reported the preparation of ZnO-$ZnFe_2O_4$ mixed nanocomposites using leaf extracts of *Psidium guajava* and evaluated wastewater remediation. Results suggested significant adsorption of CR and MB from wastewater with the maximum adsorption capacity of 120.3 mg/g and 90.3 mg/g respectively. The study also revealed the prominent role played by the mixed nanocomposite in improving plant immunity in addition to the growth and development of the plant. In another study, Cu-Ag and Cu-Ni bimetallic nanoparticles prepared using ginger rhizome powder were utilized as nano-catalysts for the reduction of 2-NP, 4-NP, MO, CR, and RhB. In addition to their outstanding ability to degrade, the nano-catalysts also showed excellent stability and reusability [85], Ismail, et al., 2018.

ANTIMICROBIAL APPLICATIONS OF NANOPARTICLES

As a result of rapid evolution through genetic mutations, several microorganisms have established resistance against various antimicrobial agents. Thus, many researchers have devoted themselves to developing new potential therapeutic agents to fight against resistant pathogenesis which is one of the major challenges in recent years. Biogenic inorganic nanoparticles have shown remarkable antimicrobial action against multi-drug resistant microorganisms via multiple mechanisms targeting cell membranes, proteins, and genetic material (Table 3). Similarly, noble metals reduced to nano dimension are also being coated on wound dressing as a preventable measure of microbial infection in wounds [86-88]. There are several examples where metallic and metal oxide nanoparticles synthesized from plants have been explored for antimicrobial activity against many microbial pathogens. Table 4 summarizes the various inorganic nanoparticles investigated for their antimicrobial activity.

ANTIBACTERIAL EFFECT OF NANOPARTICLES

Metal and metal oxide nanoparticles often exhibit high antibacterial properties against bacterial pathogens. Through vast analysis of literature, it has been observed that nanoparticles can be bacteriostatic or/and bactericidal depending on their dimension, concentration, and capping method against both gram-positive and gram-negative [89,90]. In the case of gram-positive bacterial strains, the cell wall composition shows a thick layer of peptidoglycan with a strongly negative surface charge that enables the electrostatic interaction between nanoparticles and cells. This facilitates the penetration of nanoparticles allowing the entry of negatively charged superoxide radical anions and peroxide ions to ensure cell destruction at relatively low concentrations [91,92]. Unlike, gram-positive bacteria, gram-negative strains contain a thin peptidoglycan polymer covered by an outer polysaccharide membrane with structural lipopolysaccharides. This enables the generation of reactive oxygen species and oxidative stress resulting in bacterial cell destruction and inhibition [93-95]. Sundrarajan et al. [97] stated that ZnO nanoparticles are involved in oxidative stress via the generation of reactive oxygen species and damage the structural protein of bacterial strains. Nanoparticles may also interfere with genetic material and destroys the respiration chain and thus inhibit cell respiration [98].

Ag nanoparticles synthesized using aqueous extracts of *Cissus quadrangularis* exhibited antibacterial activity against *Escherichia coli, Bacillus subtilis, Streptococcus pneumoniae,* and *Staphylococcus aureus* at 60 g/ml. [60]. Similarly, Ag nanoparticles synthesized from *Leucas martinicensis* leaf extract inhibit *S. aureus, B. subtills, S. typhi,* and *E. coli* with a zone of clearance of about 11.4 mm, 13.0 mm, 9.4 mm, and 11.5 mm respectively. Several researchers attributed the

Table 3. Mechanism of antimicrobial action of inorganic nanoparticles.

Nanoparticles	Possible Mechanism of action	References
Ag	Cell wall disruption; Cell membrane disintegration; Massive free radical production; Cytotoxicity, DNA fragmentation; Vital enzyme inhibition, loss of cellular fluids; Disruption in electron transport; Inhibits cellular respiration and cellular growth; Affects the permeability	[17,98, 100, 102]
ZnO	Generation of free reactive oxygen species; Loss of membrane integrity; Inhibits cell growth	[69,97,105]
Au	Damage the cell wall	[89,90]
TiO_2	Generation of free reactive oxygen species	[91]
Cu	Damage the cell membrane, cytoplasm components, and intracellular enzymes	[92]
Cr	Cell cytotoxicity	[106]
Fe	Ruptures the cell membrane	[65,66]
Pt	Membrane damage; Increase the level of free reactive oxygen species; Injury of DNA; Induces apoptosis or necrosis	[61,86]

Table. 4 Antimicrobial activity of inorganic nanoparticles synthesized using plants.

Type of NPs	Morphology (Size in nm)	Source	Phytochemicals Involved	Application	Antimicrobial activity method	References
Ag	Spherical; 38	*Kalanchoe pinnata*	-	*Escherichia coli*	Disk diffusion method	[59]
	Spherical; 14-17	*Acanthospermum australe*	Amines	298 fungal and bacterial microorganisms	Broth microdilution method	[107]
	Spherical; 5-30	*Conocarpus lancifolius*	Flavanones and carboxylic acids	*Staphylococcus aureus, Streptococcus pneumoniae, Rhizopus stolonifer* and *Aspergillus flavus*	Agar well diffusion method	[100]
	Spherical; 18	*Citrus limetta*	Alcoholic groups	*Candida albicans, C. glabrata, C. parapsilosis, C. tropicalis, Escherichia coli, Streptococcus mutans, Micrococcus luteus, Staphylococcus epidermidis* and *S. aureus*	Agar well diffusion method	[99]
	Spherical and quasi-spherical; 1.2-62	*Lysiloma acapulcensis*	Alkyl halides, proteins and phenols	*Candida albicans, Escherichia coli, Staphylococcus aureus* and *Pseudomonas aeruginosa*	Agar well diffusion method	[101]
	Spherical; 45-110	*Brillantaisia patula* and *Crossopteryx febrifuga*	Alcohols, phenols, carboxylic acids and aldehydes	*Escherichia coli, Pseudomonas aeruginosa* and *Staphylococcus aureus*	Broth microdilution method	[55]
	Spherical and cuboidal Varied sizes	*Cissus quadrangularis*	Flavonoids, triterpenoids, carbonyl and carboxylic acids	*Escherichia coli, Bacillus subtilis, Streptococcus pneumoniae* and *Staphylococcus*	Agar well diffusion method	[60]
	Spherical Hexagonal, triangular, rod; Variable sizes	*Myristica fragrans*	Phenols	*Pseudomonas aeruginosa, Escherichia coli, Staphylococcus aureus* and *Bacillus subtilis*	Disk diffusion method	[56]
	Spherical; 20-93	*Phyllanthus emblica*	Carboxylic acids, ketones, and aldehydes	*Acidovorax oryzae*	Agar well diffusion method	[14]
	Spherical; 25-100	*Centaurea pumilio*	Alcohols and flavonoids	*Staphylococcus aureus, Streptococcus pyogenes, Pseudomonas aeruginosa, Escherichia coli* and *Candida albicans*	Agar well diffusion method	[30]
	Spherical; 20	*Ficus hispida*	Triterpenoic acid and flavonoids	*Escherichia coli* and *Bacillus subtilis*	Agar well diffusion method	[58]
	Spherical; 14-17	*Ocimum sanctum*	Amines, amides and quercetin	*Escherichia coli*	Agar well diffusion method	[32]
	Spherical; 34	*Acalypha indica*	Flavonoids, terpenoids and proteins	*Aspergillus fumigatus, A. niger* and *A. flavus*	Disk diffusion method	[108]
	Spherical; 8	*Typha angustifolia*	Alcohols, carbonyl groups, alkaloids and flavonoids	*Escherichia coli* and *Klebsiella pneumoniae*	Disk diffusion method	[94]
	Spherical; 20, 28	*Clitoria ternatea* and *Solanum nigrum*	Amines	*Pseudomonas aeruginosa, Staphylococcus aureus, Escherichia coli* and *Streptococcus viridans*	Disk diffusion method	[95]
	Spherical; 20-30	*Leucas martinicensis*	Alcohols and alkaloids	*Bacillus subtilis, Escherichia coli* and *Salmonella typhi*	Disk diffusion method	[37]
	Spherical; 40-50	*Coleus aromaticus*	Aromatic amine, phenolic groups and secondary alcohols	*Bacillus subtilis* and *Klebsiella planticola*	Disk diffusion method	[102]
	Spherical; 90	*Mentha piperita*	Amines	*Escherichia coli* and *Staphylococcus aureus*	Agar well diffusion method	[96]
ZnO	Spherical; 3-68	*Cassia fistula* and *Melia azadarach*	Proteins, alcohols and flavonoids	*Escherichia coli* and *Staphylococcus aureus*	Agar well diffusion method	[12]
	Spherical; varied	*Ulva lactuca*	Alcohols, phenols and aromatic compounds	*Proteus vulgaris, Bacillus licheniformis, Escherichia coli* and *Bacillus pumilis*	Agar well diffusion method	[70]
	Spherical; 70	*Passiflora caerulea*	Terpenoids, flavonoids and alkaloids	*Escherichia coli, Streptococcus* sp., *Klebsiella* sp. and *Enterococcus spp.*	Disk diffusion method	[105]
	Spherical; 9.6-25.5	*Azadirachta indica*	Proteins, alcohol and phenolic groups	*Staphylococcus aureus, Escherichia coli* and *Streptococcus pyogenes*	Shake flask method	[38]
	Spherical; 15-46	*Vitex trifolia*	Alcohols, terpenoids, flavonoids, amines, aromatic and aliphatic amines	*Staphylococcus aureus, Bacillus subtilis, Escherichia coli, Pseudomonas aeruginosa, Candida albicans, Proteus mirabilis* and *Candida tropicalis*	Disk diffusion method	[72]
	Spherical; 9-38	*Azadirachta indica*	Terpenoids	*Klebsiella aerogenes* and *Staphylococcus aureus*	Agar well diffusion method	[93]

Continued Table. 4 Antimicrobial activity of inorganic nanoparticles synthesized using plants.

Type of NPs	Morphology (Size in nm)	Source	Phytochemicals Involved	Application	Antimicrobial activity method	References
	Spherical; 6-11	*Buchanania lanzan*	-	*Klebsiella aerogenes, Escherichia coli, Pseudomonas desmolyticum* and *Staphylococcus aureus*	Agar well diffusion method	[34]
	Spherical; 5-15	*Cassia fistula*	-	*Klebsiella aerogenes, Escherichia coli, Pseudomonas desmolyticum* and *Staphylococcus aureus*	Agar well diffusion method	[75]
	Spherical; 100	*Pongamia pinnata*	Alcohol and carboxylic acids or their esters	*Staphylococcus aureus* and *Escherichia coli*	Agar diffusion method	[97]
Cr_5O_{12}	Spherical; 57	*Azadirachta indica*	Proteins, terpenoids and flavonoids	*Candida albicans, S. aureus* and *Enterobacter* sp.	Agar well diffusion method	[106]
TiO_2	Spherical; 20-30	*Malva parviflora*	-	*Salmonella typhimurium, Streptococcus pyogenes* and *Candida albicans*	Disk diffusion method	[104]
	Spherical; 25-50	*Prunus × yedoensis*	-	*Staphylococcus aureus* and *Escherichia coli*	Agar well diffusion method	[48]
	Spherical; 10-12	*Diospyros ebenum*	aldehydes, alcohols and carboxylic acids	*Escherichia coli*	Agar well diffusion method	[52]
Au	Spherical; 50	*Solanum nigrum*	Flavonoids, alkaloids and tannins	*Escherichia coli, Pseudomonas aeruginosa, S. saprophyticus* and *Bacillus subtilis*	Disk diffusion method	[90]
	Spherical; 150	*Mentha piperita*	Amino acids	*Escherichia coli*	Agar well diffusion method	[96]
Pt	Spherical; 1-3;	*Atriplex halimus*	Glycosides, terpenoids, flavonoids and alkaloids	*Escherichia coli* and *Klebsiella pneumonia*	Agar well diffusion method	[62]
CuO	Spherical; 120	*Madhuca longifolia*	-	*Escherichia coli, Staphylococcus aureus* and *Bacillus subtilis*	Agar well diffusion method	[79]

antibacterial properties of silver to the existence of Ag° core [99]. However, Ag nanoparticles accumulate at the microbial membranes forming aggregates and causing perforation leading to death [100-102]. Eltaweil et al. [62] reported the antibacterial activity of Pt nanoparticles synthesized using an aqueous extract of *Atriplex halimus* leaves against *K. pneumonia* with a zone of inhibition of about 17 mm. Mohammed et al. [103], investigated the efficiency of biologically synthesized zinc nanoparticles against *Salmonella typhimurium ATCC 14028, B. subtilis ATCC 6633,* and *Micrococcus luteus ATCC 9341* and compared them with chemically synthesized zinc nanoparticles.

Nanoparticles of metallic compounds and metallic oxides have also shown potent antibacterial efficacy. Visible light-driven S-doped TiO_2 nanoparticles exhibited antibacterial activity by interfering with the cell integrity of *S. typhimurimin* with a MIC value of 25 mg/ml [104]. ZnO nanoparticles synthesized from *U. lactuca* are effective against a set of gram-positive and gram-negative bacterial strains and significantly showed the reduction of *B. licheniformis, B. pumilis, E. coli,* and *P. vulgaris* by 90 %, 89 %, 90 %, and 91 % respectively under visible light exposure [105]. Research on CuO and Cr_5O_{12} nanoparticles also revealed their antibacterial activity against *E. coli, S. aureus, B. subtilis,* and *Enterobacter* [79, 106].

ANTIFUNGAL EFFECT OF NANOPARTICLES

Fungi display the versatility of adaptation to any medium and are capable of colonizing different substrates or media in precarious environmental conditions. This characteristic of fungal species has been significantly contributing to the ever-increasing infection morbidity and mortality rate. Fungistatic and fungicidal activities of several metals and metal-derived nanoparticles have been studied to control outbreaks caused by pathogenic fungi. Spherical Ag nanoparticles synthesized from the medicinal plant *Acanthospermum austral* of size 14 nm are proven to have the potent antimycotic property tested against *Microsporum canis, M. gypseum, Epidermophyton floccosum, Trichophyton rubrum, T. mentagrophytes, T. tonsurans, Malassezia furfur, M. sympodialis, M. globose, M. restricta, Candida albicans, C. krusei, C. tropicalis, C. parapsilosis* and *C. glabrata* with a MIC value ranging from 2.0 μg/ml to 32.0 μg/ml [107]. Similarly, Ag nanoparticles derived from another medicinal plant *Acalypha indica* have exhibited antifungal activity against 3 *Aspergillus* species with an IC_{50} value of 5 mg/ml [108]. The fungicidal property of nanoparticles is associated with their ability to attach the sulfur-containing proteins of the cell membrane causing irreversible damage to the cytoplasmic membrane. In addition, metallic nanoparticles often produce reactive oxygen species and hydroxyl radicals, disrupting the mitochondria and leading to the death of fungal cells.

Metallic oxides of various nanoparticles synthesized from plant extracts are also possessed antifungal properties against several members of the *Saccharomycetaceae* and *Trichocomaceae* families. Previous studies on antifungal activities of ZnO nanoparticles revealed that the nanoparticles disrupt the cell wall and alter the membrane permeability of *C. Albicans* and *C. tropicalis* through the generation of hydrogen peroxide and superoxide radicals at an MFC ranging from 6.25 µg/ml to 50 µg/ml [72]. Helmy et al. [104] claimed that TiO_2 nanoparticles produced from *Malva parviflora* extract at a concentration of 100 µm/ml inhibit the growth of *C. Albicans*. Oxidative stress on yeast cells by reactive oxygen species formation led to physical and chemical damage to the intracellular components and genetic materials.

CONCLUSION AND FUTURE INSIGHTS

Improvement of eco-friendly and reliable processes for the synthesis of inorganic nanoparticles is a significant step in the field of applied nanotechnology and nanoscience. Green nanotechnology presents a simple and nontoxic protocol of nanoparticle synthesis and it is of enormous interest due to economic prospects and feasibility. Several regulatory bodies are starting to devote additional attention to nanomaterials to differentiate the nanoparticles produced by green chemistry and classical chemistry. However, this flourishing technology needs to be optimized to identify the exact phytochemicals accountable for the synthesis of nanoparticles; there should be a thorough evaluation of the toxic effects of long-term exposure to the biogenic nanoparticles on flora and fauna. Another challenge is achieving high reproducibility, the levels of phytochemicals in the plants are easily influenced by environmental factors such as soil pH, water stress, and change in climate and location. Hence, it is certain that the properties of plant extracts may vary from batch to batch, which will influence the physiochemical properties of synthesized nanoparticles. In addition, efforts should be geared by researchers toward the cost-benefit analysis for commercial purposes as there is no data available to date. Future research and development of prospective green nanoparticle synthesis should be directed toward extending laboratory-based work to an industrial scale by considering traditional/present issues, especially health and environmental effects. Accordingly, ample possibilities remain for the exploration of new applications of biogenic nanoparticles.

COMPETING INTERESTS

The authors have no conflict of interest to declare.

ACKNOWLEDGEMENT

The authors gratefully acknowledge Indian Academy Degree College-Autonomous for their support.

ABBREVIATIONS

CdTe: Cadmium telluride; LDH: Layered double hydroxides; Si: Silica; Al – Alumina; Ti: Titania; Zr: Zirconia; Cu: Copper; Fe: Iron; Co: Cobalt; Mn: Manganese; Zn: Zinc; Cr: Chromium; Ni: Nickel; Ag: Silver; Au: Gold; OH^-: Hydroxyl ions; $AgNO_3$: Silver nitrate; C: Carbon; $Al^{3+:}$ Aluminium ions; Cr^{3+}: Chromium ions; Co^{2+}: Cobalt ions; Cu^{2+}: Copper ions; Fe^{2+}: Ferrous ions; Fe^{3+}: Ferric ions; Pb^{2+}: Lead ions; Zn^{2+}: Zinc ions; IR: Infrared rays; ZnO: Zinc oxide; TiO_2: Titanium oxide; $SnCl_2$: Stannous chloride; COD: Chemical Oxygen Demand; MO: Methyl Orange; MR: Methyl Red; CR: Congo Red; 4-NP: 4-Nitrophenol; RhB: Rhodamine B; Ce: Cerium; Cd^{2+}: Cadmium ions; Hg^+: Mercury ions; Ni^{2+}: Nickel ions; As^{3+}: Arsenic ions; Mn^{2+}: Manganese ions; Pt: Platinum; MB: Methylene Blue; ICP-OES: Inductively coupled plasma-optical emission spectrometry; NB: Nile Blue; RY-160: Reactive Yellow 160; 2-NP: 2-Nitrophenol; CeO_2: Cerium (IV) oxide; Cr_5O_{12}: Chromium oxide; CV: Crystal Violet; SDZ: Sulfadiazine; RB: Rose Bengal; MG: Malachite Green; DG: Direct Green; NR: Neutral Red.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

1. Ying S, Guan Z, Ofoegbu PC, Clubb P, Rico C, He F, Hong J (2022) Green synthesis of nanoparticles: Current developments and limitations. Environ. Technol. Innov. 26:102336. https://doi.org/10.1016/j.eti.2022.102336
2. Chung IM, Rajakumar G, Thiruvengadam M (2018) Effect of silver nanoparticles on phenolic compounds production and biological activities in hairy root cultures of *Cucumis anguria*. Biologia Futura 69:97-109. https://doi.org/10.1556/018.68.2018.1.8
3. Saleem H, Zaidi SJ (2020) Developments in the application of nanomaterials for water treatment and their impact on the environment. Nanomaterials 10(9), 1764. https://doi.org/10.3390/nano10091764
4. Sahithya K, Das N (2017) Enhanced removal of dichlorvos from aqueous solution using zinc-silver bimetallic nanoparticles embedded in montmorillonite-biopolymer nanobiocomposites: Equilibrium, kinetics and thermodynamic studies. Res. J. Pharm. Technol. 10:1105-1114. https://doi.org/10.5958/0974-360X.2017.00200.1
5. Khan I, Saeed K, Khan I (2019) Nanoparticles: Properties, applications and toxicities. Arab. J. Chem. 12:908-931. https://doi.org/10.1016/j.arabjc.2017.05.011
6. Ameta SK, Rai AK, Hiran D, Ameta R, Ameta SC (2020) Use of Nanomaterials in Food Science. In: Ghorbanpour M, Bhargava P, Varma A, Choudhary D. (eds) Biogenic nano-particles and their use in agro-ecosystems. Springer, Singapore, pp. 457-488. https://doi.org/10.1007/978-981-15-2985-6_24
7. Mabrouk M, Das DB, Salem ZA, Beherei HH (2021) Nanomaterials for biomedical applications: Production, characteristics, recent trends and difficulties. Molecules 26:1-27. https://doi.org/10.3390/molecules26041077
8. Nair GM, Sajini T, Mathew B (2022) Advanced green approaches for metal and metal oxide nanoparticles synthesis and their environmental applications. Talanta Open 5:100080. https://doi.org/10.1016/j.talo.2021.100080
9. Manisalidis I, Stavropoulou E, Stavropoulos A, Bezirtzoglou E (2020) Environmental and Health Impacts of Air Pollution: A Review. Front. Public Health. 8:1-13. https://doi.org/10.3389/fpubh.2020.00014
10. Das PK, Mohanty C, Purohit GK, Mishra S, Palo S (2022) Nanoparticle assisted environmental remediation: Applications, toxicological implications, and recommendations for a sustainable environment. Environ. Nanotechnol. Monit. Manag. 18:100679. https://doi.org/10.1016/J.ENMM.2022.100679
11. Kundu S, Karak N (2022) Polymeric photocatalytic membrane: An emerging solution for environmental remediation. Chem. Eng. J. 438:135575. https://doi.org/10.1016/j.cej.2022.135575
12. Naseer M, Aslam U, Khalid B, Chen B (2020) Green route to synthesize Zinc Oxide Nanoparticles using leaf extracts of *Cassia fistula* and *Melia azadarach* and their antibacterial potential. Sci. Rep. 10:9055. https://doi.org/10.1038/s41598-020-65949-3
13. Ogunsona EO, Muthuraj R, Ojogbo E, Valero O, Mekonnen TH (2020) Engineered nanomaterials for antimicrobial applications: A review. Appl. Mater. Today. 18:100473. https://doi.org/10.1016/j.apmt.2019.100473
14. Masum M, Siddiqa MM, Ali KA, Zhang Y, Abdallah Y, Ibrahim E, Qiu W, Yan C, Li B (2019) Biogenic synthesis of silver nanoparticles using *Phyllanthus emblica* fruit extract and its inhibitory action against the pathogen *Acidovorax oryzae* strain RS-2 of rice bacterial brown stripe. Front. Microbiol. 10:820. https://doi.org/10.3389/fmicb.2019.00820
15. Cele T (2020) Preparation of Nanoparticles. Eng. Nanomater - Heal Saf. https://doi.org/10.5772/INTECHOPEN.90771
16. Bloch K, Pardesi K, Satriano C, Ghosh S (2021) Bacteriogenic Platinum Nanoparticles for Application in Nanomedicine. Front. Chem. 9:624344. https://doi.org/10.3389/fchem.2021.624344
17. Hano C, Abbasi BH (2022) Plant-based green synthesis of nanoparticles: Production, characterization, and applications. Biomolecules 12:1-9. https://doi.org/10.3390/biom12010031
18. Aboyewa JA, Sibuyi NRS, Meyer M, Oguntibeju OO (2021) Green synthesis of metallic nanoparticles using some selected medicinal plants from southern Africa and their biological applications. Plants 10:1929. https://doi.org/10.3390/plants10091929
19. Silva LP, Reis IG, Bonatto CC (2015) Green Synthesis of Metal Nanoparticles by Plants: Current Trends and Challenges. In: Basiuk, V., Basiuk, E. (eds) Green Processes for Nanotechnology. Springer, Cham. https://doi.org/10.1007/978-3-319-15461-9_9
20. Nava OJ, Luque PA, Gomez-Gutierrez CM, Nestor ARV, Beltran AC, Gonzalez MLM, Olivas A (2017) Influence of *Camellia sinensis* extract on Zinc Oxide nanoparticle green synthesis. J. Mol. Struct. 1134:121-125. https://doi.org/10.1016/j.molstruc.2016.12.069
21. Faisal S, Khan MA, Jan H (2021) Edible mushroom (*Flammulina velutipes*) as biosource for silver nanoparticles: from synthesis to diverse biomedical and environmental applications. Nanotechnol. 32:065101. https://doi.org/10.1088/1361-6528/ABC2EB
22. Bhardwaj K, Sharma A, Tejwan N, Bhardwaj S, Bhardwaj P, Nepovimova E, Shami A, Kalia A, Kumar A, Kamel A. Abd-Elsalam, Kuca K (2020) *Pleurotus* macrofungi-assisted nanoparticle synthesis and its potential applications: A review. J. Fungi 6:1-21. https://doi.org/10.3390/jof6040351
23. Jadoun S, Chauhan NPS, Zarrintaj P, Barani M, Varma RS, Chinnam S, Rahdar A (2022) Synthesis of nanoparticles using microorganisms and their applications: A review. Env. Chem. Lett. 20:3153-3197. https://doi.org/10.1007/s10311-022-01444-7
24. Bahrulolum H, Nooraei S, Javanshir N, Tarrahimofrad H, Mirbagheri VS, Easton AJ, Ahmadian G (2021) Green synthesis of metal nanoparticles using microorganisms and their application in the agrifood sector. J. Nanobiotechnology 19:1-26. https://doi.org/10.1186/s12951-021-00834-3
25. Zhang X, Yan S, Tyagi RD, Surampalli RY (2011) Synthesis of nanoparticles by microoranisms and their application in enhancing microbiological reaction rates. Chemosphere. 82(4): 489-494. https://doi.org/10.1016/j.chemosphere.2010.10.023
26. Jadoun S, Arif R, Jangid NK, Meena RK (2021) Green synthesis of nanoparticles using plant extracts: a review. Environ. Chem. Lett. 19(1):355-374. https://doi.org/10.1007/s10311-020-01074-x
27. Iravani S (2011) Green synthesis of metal nanoparticles using plants. Green Chem. 13:2638. https://doi.org/10.1039/C1GC15386B
28. Singh J, Dutta T, Kim KH, Rawat M, Samddar P, Kumar P (2018) "Green" synthesis of metals and their oxide nanoparticles: Applications for environmental remediation. J. Nanobiotechnology 16:1-24. https://doi.org/10.1186/s12951-018-0408-4
29. Kumar B, Smita K, Cumbal L, Debut A (2014) Green approach for fabrication and applications of zinc oxide

nanoparticles. Bioinorg Chem Appl 2014:523869. https://doi.org/10.1155/2014/523869
30. Mostafa E, Fayed M, Radwan RA, Bakr RO (2019) *Centaurea pumilio* L. extract and nanoparticles: A candidate for healthy skin. Colloids Surf. B 182:110350. https://doi.org/10.1016/j.colsurfb.2019.110350
31. Makarov VV, Love AJ, Sinitsyna OV, Makarova SS, Yaminsky IV, Taliansky ME, Kalinina NO (2014) "Green" nanotechnologies: Synthesis of metal nanoparticles using plants. Acta Naturae 6:35-44. https://doi.org/10.32607/20758251-2014-6-1-35-44
32. Jain S, Mehata MS (2017) Medicinal Plant Leaf Extract and Pure Flavonoid Mediated Green Synthesis of Silver Nanoparticles and their Enhanced Antibacterial Property. Sci. Rep. 7:1-13. https://doi.org/10.1038/s41598-017-15724-8
33. Amini SM, Akbari A (2019) Metal nanoparticles synthesis through natural phenolic acids. IET Nanobiotechnology 13:771-777. https://doi.org/10.1049/iet-nbt.2018.5386
34. Suresh D, Nethravathi PC, Udayabhanu, Kumar MAP, Naika HR, Nagabhushana H, Sharma SC (2015) *Chironji* mediated facile green synthesis of ZnO nanoparticles and their photoluminescence, photodegradative, antimicrobial and antioxidant activities. Mater. Sci. Semicond. Process 40:759-765. https://doi.org/10.1016/j.mssp.2015.06.088
35. Ping W, Yong-Nian N (2013) Silver nanoparticles preparation using antioxidant propyl gallate and its analytical application. Chem. J. Chin. Univ. Chin 34 (4) 837-840. http://dx.doi.org/10.7503/cjcu20120696
36. Mashwani ZR, Khan MA, Khan T, Nadhman A (2016) Applications of plant terpenoids in the synthesis of colloidal silver nanoparticles. Adv. Colloid Interface Sci. 234:132-141. https://doi.org/10.1016/J.CIS.2016.04.008
37. Ashokkumar S, Ravi S, Kathiravan V, Velmurugan S (2014) Rapid biological synthesis of silver nanoparticles using *Leucas martinicensis* leaf extract for catalytic and antibacterial activity. Environ. Sci. Pollut. Res. 21:11439-11446. https://doi.org/10.1007/s11356-014-3012-7
38. Bhuyan T, Mishra K, Khanuja M, Prasad R, Varma A (2015) Biosynthesis of zinc oxide nanoparticles from *Azadirachta indica* for antibacterial and photocatalytic applications. Mater Sci Semicond Process 32:55-61. https://doi.org/10.1016/j.mssp.2014.12.053
39. Meshram SM, Bonde SR, Gupta IR, Gade AK, Rai MK (2013) Green synthesis of silver nanoparticles using white sugar. IET Nanobiotechnology 7:28-32. https://doi.org/10.1049/iet-nbt.2012.0002
40. Aygun A, Ozdemir S, Gulcan M, Cellat K, Sen F (2020) Synthesis and characterization of Reishi mushroom-mediated green synthesis of silver nanoparticles for the biochemical applications. J. Pharm. Biomed. Anal. 178:112970. https://doi.org/10.1016/j.jpba.2019.112970
41. Kulandaisamy AJ, Rayappan JBB (2018) Significance of Nanoparticles and the Role of Amino Acids in Structuring Them-A Review. J. Nanosci. Nanotechnol. 18:5222-5233. https://doi.org/10.1166/jnn.2018.15388
42. Courrol LC, Matos RA de (2016) Synthesis of Gold Nanoparticles Using Amino Acids by Light Irradiation. Catal Appl Nano-Gold Catal. https://doi.org/10.5772/63729
43. Mamatha KM, Srinivasa murthy V, Ravikumar CR, Murthy HCA, Kumar VGD, Kumar AN, Jahagirdar AA (2022) Facile green synthesis of Molybdenum oxide nanoparticles using *Centella Asiatica* plant: Its photocatalytic and electrochemical lead sensor applications. Sensors International 3:100153. https://doi.org/10.1016/j.sintl.2021.100153
44. Kiran S, Rafique MA, Iqbal S, Nosheen S, Naz S, Rasheed A (2020) Synthesis of nickel nanoparticles using *Citrullus colocynthis* stem extract for remediation of Reactive Yellow 160 dye. Environ. Sci. Pollut. Res. 27:32998–33007. https://doi.org/10.10/s11356-020-09510-9
45. Guerra FD, Attia MF, Whitehead DC, Alexis F (2018) Nanotechnology for environmental remediation: Materials and applications. Molecules 23:1-23. https://doi.org/10.3390/molecules23071760
46. Mazumder JA, Perwez M, Noori R, Sardar M (2019) Development of sustainable and reusable silver nanoparticle-coated glass for the treatment of contaminated water. Environ. Sci. Pollut. Res. 26:23070-23081. https://doi.org/10.1007/s11356-019-05647-4
47. Mohamed EF, Awad G (2020) Photodegradation of gaseous toluene and disinfection of airborne microorganisms from polluted air using immobilized TiO_2 nanoparticle photocatalyst–based filter. Environ. Sci. Pollut. Res. 27:24507-24517. https://doi.org/10.1007/s11356-020-08779-0
48. Manikandan V, Velmurugan P, Jayanthi P, Park JH, Woo-Suk Chang WS, Park YJ, Cho M, Oh BT (2018) Biogenic synthesis from *Prunus × yedoensis* leaf extract, characterization, and photocatalytic and antibacterial activity of TiO_2 nanoparticles. Res. Chem. Intermed. 44:2489-2502. https://doi.org/10.1007/S11164-017-3242-7
49. Ganesan S, Babu IG, Mahendran D, Arulselvi PI, Elangovan N, Geetha N, Venkatachalam P (2016) Green engineering of titanium dioxide nanoparticles using *Ageratina altissima* (L.) King & H.E. Robines. medicinal plant aqueous leaf extracts for enhanced photocatalytic activity. Ann. phytomedicine 5:69–75. https://doi.org/10.21276/ap.2016.5.2.8
50. Sankar R, Rizwana K, Shivashangari KS, Ravikumar V (2015) Ultra-rapid photocatalytic activity of *Azadirachta indica* engineered colloidal titanium dioxide nanoparticles. Chemosphere 5:731-736. https://doi.org/10.1007/s13204-014-0369-3
51. Goutam SP, Saxena G, Singh V, Yadav AK, Bharagava RN, Thapa KB (2017) Green synthesis of TiO2 nanoparticles using leaf extract of *Jatropha curcas L.* for photocatalytic degradation of tannery wastewater. Chem. Eng. J. 336:386-396. https://doi.org/10.1016/J.CEJ.2017.12.029
52. Senthilkumar S, Ashok M, Kashinath L, Sanjeeviraja C, Rajendran A (2017) Phytosynthesis and Characterization of TiO_2 Nanoparticles using *Diospyros ebenum* Leaf Extract and their Antibacterial and Photocatalytic Degradation of Crystal Violet. Smart Science 6:1-9. https://doi.org/10.1080/23080477.2017.1410012
53. Chinnappa K, Ananthai PK, Srinivasan PP , Glorybai CD (2022) Green synthesis of rGO-AgNP composite using *Curcubita maxima* extract for enhanced photocatalytic degradation of the organophosphate pesticide chlorpyrifos. Environ. Sci. Pollut. Res. https://doi.org/10.1007/s11356-022-19917-1
54. Sarkar M, Denrah S, Das M, Das M (2021) Statistical optimization of bio-mediated silver nanoparticles synthesis for use in catalytic degradation of some azo dyes. Chemical Physics Impact 3:100053. https://doi.org/10.1016/j.chphi.2021.100053
55. Kambale EK, Nkanga CI, Mutonkole BPI, Bapolisi AM, Tassa DO, Liesse JMI, Memvanga PB (2020) Green synthesis of antimicrobial silver nanoparticles using aqueous leaf extracts from three Congolese plant species (*Brillantaisia patula*, *Crossopteryx febrifuga* and *Senna siamea*). Heliyon 6: e04493. https://doi.org/10.1016/j.heliyon.2020.e04493
56. Sasidharan D, Namitha TR, Johnson SP, Jose V, Mathew P

(2020) Synthesis of silver and copper oxide nanoparticles using *Myristica fragrans* fruit extract: Antimicrobial and catalytic applications. Sustain. Chem. Pharm. 16:100255. https://doi.org/10.1016/j.scp.2020.100255

57. Chand K, Cao D, Fouad DE, Shah AH, Dayo AQ, Zhu K, Lakhan MN, Mehdi G, Dong S (2020) Green synthesis, characterization and photocatalytic application of silver nanoparticles synthesized by various plant extracts. Arab. J. Chem. 13:8248-8261. https://doi.org/10.1016/j.arabjc.2020.01.009
58. Ramesh A V, Rama D, Battu G, Basavaiah K (2018) A Facile plant mediated synthesis of silver nanoparticles using an aqueous leaf extract of *Ficus hispida Linn.F.* for catalytic, antioxidant and antibacterial applications. S Afr J Chem Eng 26:25-34. https://doi.org/10.1016/j.sajce.2018.07.001
59. Mehata MS, Aryan, Ruby, (2021) Green synthesis of silver nanoparticles using *Kalanchoe pinnata* leaves (life plant) and their antibacterial and photocatalytic activities. Chem. Phys. Lett. 778:138760. https://doi.org/10.1016/j.cplett.2021.138760
60. Pragathiswaran C, Violetmary J, Faritha A, Selvarani K, Nawas PMA (2021) Photocatalytic degradation, sensing of Cd^{2+} using silver nanoparticles synthesised from plant extract of *Cissus quadrangularis* and their microbial activity. Materials Today: Proceedings 45:3348-3356. https://doi.org/10.1016/j.matpr.2020.12.656
61. Jan H, Gul R, Andleeb A, Ullah S, Shah M, Khanum M, Ullah I, Hano C, Abbasi BH (2021) A detailed review on biosynthesis of platinum nanoparticles (PtNPs), their potential antimicrobial and biomedical applications. J. Saudi Chem. Soc. 25:101297. https://doi.org/10.1016/j.jscs.2021.101297
62. Eltaweil AS, Fawzy M, Hosny M, El-Monaem EMA, Tamer TM, Omer AM (2022) Green synthesis of platinum nanoparticles using *Atriplex halimus* leaves for potential antimicrobial, antioxidant, and catalytic applications. Arab. J. Chem. 15:103517. https://doi.org/10.1016/j.arabjc.2021.103517
63. Gupta N, Singh HP, Sharma RK (2010) Single-pot synthesis: Plant mediated gold nanoparticles catalyzed reduction of methylene blue in presence of stannous chloride. Colloids Surf. A Physicochem. Eng. Asp. 367:102-107. https://doi.org/10.1016/j.colsurfa.2010.06.022
64. Nabikhan A, Rathinam S, Kandasamy K (2018) Biogenic gold nanoparticles for reduction of 4-nitrophenol to 4-aminophenol: An eco-friendly bioremediation. IET Nanobiotechnology 12:479-483. https://doi.org/10.1049/iet-nbt.2017.0210
65. Vitta Y, Figueroa M, Calderon M, Ciangherotti C (2020) Synthesis of iron nanoparticles from aqueous extract of *Eucalyptus robusta* and evaluation of antioxidant and antimicrobial activity. Material Science for Energy Technologies 3:97-103. https://doi.org/10.1016/j.mset.2019.10.014
66. Subbulakshmi KS, Kadirvelu K (2017) Green synthesis of Iron oxide nanoparticles using *Lagenaria siceraria* and evaluation of its antimicrobial activity. Defence Life Sci Journal 2:422. https://doi.org/10.14429/dlsj.2.12277
67. Xiao Z, Yuan M, Yang B, Liu Z, Huang J, Sun D (2016) Plant-mediated synthesis of highly active iron nanoparticles for Cr (VI) removal: Investigation of the leading biomolecules. Chemosphere 150:357-364. https://doi.org/10.1016/j.chemosphere.2016.02.056
68. Conde-Cid M, Paiga P, Moreira MM, Albergaria JT, Rodriguez EA, Estevez MA, Matos CD (2021) Sulfadiazine removal using green zero-valent iron nanoparticles: A low-cost and eco-friendly alternative technology for water remediation. Environ. Res. 198:110451. https://doi.org/10.1016/j.envres.2020.110451
69. Prasad AR, Williams L, Garvasis J, Shamsheera KO, Basheer SM, Kuruvilla M, Joseph A (2021) Applications of phytogenic ZnO nanoparticles: A review on recent advancements. J. Mol. Liq. 331:115805. https://doi.org/10.1016/j.molliq.2021.115805
70. Ishwarya R, Vaseeharan B, Kalyani S, Balan Banumathi, Govindarajan M, Alharbi NS, Kadaikunnan S, Al-anbr MN, Khaled JM, Benelli G (2018) Facile green synthesis of zinc oxide nanoparticles using *Ulva lactuca* seaweed extract and evaluation of their photocatalytic, antibiofilm and insecticidal activity. J. Photochem. Photobiol. B, Biol. 178:249-258. https://doi.org/10.1016/j.jphotobiol.2017.11.006
71. Siripireddy B, Mandal BK (2017) Facile green synthesis of zinc oxide nanoparticles by *Eucalyptus globulus* and their photocatalytic and antioxidant activity. Adv Powder Technol 28:785-797. https://doi.org/10.1016/j.apt.2016.11.026
72. Elumalai K, Velmurugan S, Ravi S, Kathiravan V, Raj GA (2015) Bio-approach: Plant mediated synthesis of ZnO nanoparticles and their catalytic reduction of methylene blue and antimicrobial activity. Adv Powder Technol 26:1639-1651. https://doi.org/10.1016/j.apt.2015.09.008
73. Fu L, Fu Z (2015) *Plectranthus amboinicus* leaf extract-assisted biosynthesis of ZnO nanoparticles and their photocatalytic activity. Ceram. Int. 41:2492-2496. https://doi.org/10.1016/j.ceramint.2014.10.069
74. Hassan SSM, Azab WIME, Ali HR, Mansour MSM (2015) Green synthesis and characterization of ZnO nanoparticles for photocatalytic degradation of anthracene. Adv. Nat. Sci, Nanosci. Nanotechnol. 6:045012. https://doi.org/10.1088/2043-6262/6/4/045012
75. Suresh D, Nethravathi PC, Udayabhanu, Rajanaika H, Nagabhushana H, Sharma SC (2015) Green synthesis of multifunctional zinc oxide (ZnO) nanoparticles using *Cassia fistula* plant extract and their photodegradative, antioxidant and antibacterial activities. Mater Sci Semicond Process 31:446-454. https://doi.org/10.1016/j.mssp.2014.12.023
76. Zheng Y, Fu L, Han F, Wang A, Cai W, Yu J, Yang J, Peng F (2015) Green biosynthesis and characterization of zinc oxide nanoparticles using *Corymbia citriodora* leaf extract and their photocatalytic activity. Green Chem Lett Rev 8:59-63. https://doi.org/10.1080/17518253.2015.1075069
77. Mahmoud A D, Al-Qahtani K, Alflaij SO, Salma F. Al-Qahtani SF, Alsamhan FA (2021) Green copper oxide nanoparticles for lead, nickel, and cadmium removal from contaminated water. Scientific Reports. 11, 12547. https://doi.org/10.1038/s41598-021-91093-7
78. Singh J, Kumar V, Kim KH, Rawat M (2019) Biogenic synthesis of copper oxide nanoparticles using plant extract and its prodigious potential for photocatalytic degradation of dyes. Environ. Res. 177:108569. https://doi.org/10.1016/j.envres.2019.108569
79. Das P, Ghosh S, Ghosh R, Dam S, Baskey M (2018) *Madhuca longifolia* plant mediated green synthesis of cupric oxide nanoparticles: A promising environmentally sustainable material for waste water treatment and efficient antibacterial agent. J. Photochem. Photobiol. B, Biol. 189:66-73. https://doi.org/10.1016/j.jphotobiol.2018.09.023
80. Kumar MAP, Suresh D, Nagabhushana H, Sharma SC (2015) *Beta vulgaris* aided green synthesis of ZnO nanoparticles and their luminescence, photocatalytic and antioxidant properties. Eur. Phys. J. Plus 130:109. https://doi.org/10.1140/epjp/i2015-15109-2
81. Nethravathi PC, Shruthi GS, Suresh D, Udayabhanu, Naga-

bhushana H, Sharma SC (2015) *Garcinia xanthochymus* mediated green synthesis of ZnO nanoparticles: Photoluminescence, photocatalytic and antioxidant activity studies. Ceram. Int. 41:8680-8687. https://doi.org/10.1016/j.ceramint.2015.03.084

82. Fazlzadeh M, Khosravi R, Zarei A (2017) Green synthesis of zinc oxide nanoparticles using *Peganum harmala* seed extract, and loaded on *Peganum harmala* seed powdered activated carbon as new adsorbent for removal of Cr(VI) from aqueous solution. Ecol. Eng. 103:180-190. https://doi.org/10.1016/j.ecoleng.2017.02.052
83. Vidya C, Prabha MNC, Raj Mala (2016) Green mediated synthesis of zinc oxide nanoparticles for the photocatalytic degradation of Rose Bengal dye. Environ. Nanotechnol. Monit. Manag. 6:134-138. https://doi.org/10.1016/J.ENMM.2016.09.004
84. Sahoo SK, Panigrahi GK, Sahoo A, Pradhan AK, Dalbehera A (2021) Bio-hydrothermal synthesis of ZnO–$ZnFe_2O_4$ nanoparticles using *Psidium guajava* leaf extract: Role in wastewater remediation and plant immunity. J. Clean. Prod. 318:128522. https://doi.org/10.1016/j.jclepro.2021.128522
85. Ismail M, Khan MI, Khan SB, Khan MA, Akhtar K, Asiri AM (2018) Green synthesis of plants supported Cu-Ag and Cu-Ni bimetallic nanoparticles in the reduction of nitrophenols and organic dyes for water treatment. J. Mol. Liq. 260:78-91. https://doi.org/10.1016/j.molliq.2018.03.058
86. Ruiz AL, Garcia CB, Gallon SN, Webster TJ (2020) Novel silver-platinum nanoparticles for anticancer and antimicrobial applications. Int. J. Nanomedicine 15:169-179. https://doi.org/10.2147/IJN.S176737
87. Burdusel AC, Gherasim O, Grumezescu AM, Mogoanta L, Ficai A, Andronescu E (2018) Biomedical applications of silver nanoparticles: An Up-to-Date Overview. Nanomater 8:681. https://doi.org/10.3390/NANO8090681
88. Correa JM, Mori M, Sanches HL, Cruz AD, Poiate E, Poiate IAVP (2015) Silver nanoparticles in dental biomaterials. Int J Biomater 2015:485275. https://doi.org/10.1155/2015/485275
89. Castillo-Henriquez L, Alfaro-Aguilar K, Ugalde-alvarez J, Vega-Fernandez L, Oca-Vasquez GM, Vega-Baudrit JR (2020) Green synthesis of gold and silver nanoparticles from plant extracts and their possible applications as antimicrobial agents in the agricultural area. Nanomaterials 10:1-24. https://doi.org/10.3390/nano10091763
90. Muthuvel A, Adavallan K, Balamurugan K, Krishnakumar N (2014) Biosynthesis of gold nanoparticles using *Solanum nigrum* leaf extract and screening their free radical scavenging and antibacterial properties. Biomed. Prev. Nutr. 4:325–332. https://doi.org/10.1016/j.bionut.2014.03.004
91. Naikoo GA, Mustaqeem M, Hassan IU, Awan T, Arshad F, Salim H, Qurashi A (2021) Bioinspired and green synthesis of nanoparticles from plant extracts with antiviral and antimicrobial properties: A critical review. J. Saudi Chem. Soc. 25:101304. https://doi.org/10.1016/j.jscs.2021.101304
92. Rajeshkumar S, Menon S, Venkat Kumar S, Tambuwala MM, Bakshi HA, Mehta M, Satija S, Gupta G, Chellappan DK, Lakshmi T, Dua K (2019) Antibacterial and antioxidant potential of biosynthesized copper nanoparticles mediated through *Cissus arnotiana* plant extract. J. Photochem. Photobiol. B, Biol. 197:111531. https://doi.org/10.1016/j.jphotobiol.2019.111531
93. Madan HR, Sharma SC, Udayabhanu, Suresh D, Vidya YS, Nagabhushana H, Rajanaik H, Anantharaju KS, Prashantha SC, Maiya PS (2016) Facile green fabrication of nanostructure ZnO plates, bullets, flower, prismatic tip, closed pine cone: Their antibacterial, antioxidant, photoluminescent and photocatalytic properties. Spectrochim. Acta. A Mol. Biomol. Spectrosc. 152:404-416. https://doi.org/10.1016/j.saa.2015.07.067
94. Gurunathan S (2015) Biologically synthesized silver nanoparticles enhance antibiotic activity against Gram-negative bacteria. J. Ind. Eng. Chem. 29:217-226. https://doi.org/10.1016/j.jiec.2015.04.005
95. Krithiga N, Rajalakshmi A, Jayachitra A (2015) Green synthesis of silver nanoparticles using leaf extracts of *Clitoria ternatea* and *Solanum nigrum* and study of its antibacterial effect against common nosocomial pathogens. J. Nanosci. 2015:928204 https://doi.org/10.1155/2015/928204
96. Mubarak AD, Thajuddin N, Jeganathan K, Gunasekaran M (2011) Plant extract mediated synthesis of silver and gold nanoparticles and its antibacterial activity against clinically isolated pathogens. Colloids Surf. B 85:360–365. https://doi.org/10.1016/j.colsurfb.2011.03.009
97. Sundrarajan M, Ambika S, Bharathi K (2015) Plant-extract mediated synthesis of ZnO nanoparticles using *Pongamia pinnata* and their activity against pathogenic bacteria. Adv. Powder. Technol. 26:1294-1299. https://doi.org/10.1016/j.apt.2015.07.001
98. Aritonang HF, Koleangan H, Wuntu AD (2019) Synthesis of silver nanoparticles using aqueous extract of medicinal plants' (*Impatiens balsamina* and *Lantana camara*) fresh leaves and analysis of antimicrobial activity. Int. J. Microbiol. 2019:8642303. https://doi.org/10.1155/2019/8642303
99. Dutta T, Ghosh NN, Das M, Adhikary R, Mandal V, Chattopadhyay AP (2020) Green synthesis of antibacterial and antifungal silver nanoparticles using *Citrus limetta* peel extract: Experimental and theoretical studies. J. Environ. Chem. Eng. 8:104019. https://doi.org/10.1016/j.molstruc.2021.131361
100. Oves M, Rauf, MA, Aslam M, Qari HA, Sonbol H, Ahmad I, Zaman GS, Saeed M (2022) Green synthesis of silver nanoparticles by *Conocarpus Lancifolius* plant extract and their antimicrobial and anticancer activities. Saudi. J. Biol. Sci. 29:460-471. https://doi.org/10.1016/j.sjbs.2021.09.007
101. Garibo D, Borbon-Nunez HA, de Leon J, Mendoza EG, Estrada I, Toledano-Magana Y, Tiznado H, Ovalle-Marroquin M, Soto-Ramos AG, Blanco A, Rodriguez JA, Romo O A, Chavez-Almazan, LA, Susarrey-Arce A (2020) Green synthesis of silver nanoparticles using *Lysiloma acapulcensis* exhibit high-antimicrobial activity. Sci. Rep. 10:12805. https://doi.org/10.1038/s41598-020-69606-7
102. Vanaja M, Annadurai G (2013) *Coleus aromaticus* leaf extract mediated synthesis of silver nanoparticles and its bactericidal activity. Appl. Nanosci. 3:217-223. https://doi.org/10.1007/s13204-012-0121-9
103. Mohammed AW (2020) Comparison of chemical and biological properties of metal nanoparticles (Au, Ag), with metal oxide nanoparticles (ZnO-NPs) and their applications. Adv. J. Chem. A, 3(2), 192–210. https://doi.org/10.33945/SAMI/AJCA.2020.2.8
104. Helmy ET, Abouellef EM, Soliman UA, Pan JH (2021) Novel green synthesis of S-doped TiO_2 nanoparticles using *Malva parviflora* plant extract and their photocatalytic, antimicrobial and antioxidant activities under sunlight illumination. Chemosphere 271:129524. https://doi.org/10.1016/j.chemosphere.2020.129524
105. Santhoshkumar J, Kumar SV, Rajeshkumar S (2017) Synthesis of zinc oxide nanoparticles using plant leaf extract against urinary tract infection pathogen. Resource-Efficient Technologies 3:459-465. https://doi.org/10.1016/j.

reffit.2017.05.001

106. Rajendaran K, Muthuramalangam R, Ayyadurai S (2019) *Azadirachta indica* as a bio-material: Rapid synthesis of Cr_5O_{12} shell nanoparticles to study its photocatalytic and antimicrobial properties. J. King. Saud. Univ. Sci. 31:1235-1244. https://doi.org/10.1016/j.jksus.2018.11.005

107. Mussin J, Robles-Botero V, Casanas-Pimentel R, Rojas F, Angiolella L, Martin-Martinez S, Giusiano G (2021) Antimicrobial and cytotoxic activity of green synthesis silver nanoparticles targeting skin and soft tissue infectious agents. Sci. Rep. 11:1-12. https://doi.org/10.1038/s41598-021-94012-y

108. Menon S, Agarwal H, Kumar SR, Kumar SV (2017) Green synthesis of silver nanoparticles using medicinal plant *Acalypha indica* leaf extracts and its application as an antioxidant and antimicrobial agent against foodborne pathogens. Int. J. Appl. Pharm. *9*:42-50. https://doi.org/10.22159/ijap.2017v9i5.19464