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Green Synthesis of Metallic Nanoparticles and Their Prospective Biotechnological Applications: an Overview

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Abstract

The green synthesis of nanoparticles (NPs) using living cells is a promising and novelty tool in bionanotechnology. Chemical and physical methods are used to synthesize NPs; however, biological methods are preferred due to its eco-friendly, clean, safe, cost-effective, easy, and effective sources for high productivity and purity. High pressure or temperature is not required for the green synthesis of NPs, and the use of toxic and hazardous substances and the addition of external reducing, stabilizing, or capping agents are avoided. Intra- or extracellular biosynthesis of NPs can be achieved by numerous biological entities including bacteria, fungi, yeast, algae, actinomycetes, and plant extracts. Recently, numerous methods are used to increase the productivity of nanoparticles with variable size, shape, and stability. The different mechanical, optical, magnetic, and chemical properties of NPs have been related to their shape, size, surface charge, and surface area. Detection and characterization of biosynthesized NPs are conducted using different techniques such as UV–vis spectroscopy, FT-IR, TEM, SEM, AFM, DLS, XRD, zeta potential analyses, etc. NPs synthesized by the green approach can be incorporated into different biotechnological fields as antimicrobial, antitumor, and antioxidant agents; as a control for phytopathogens; and as bioremediative factors, and they are also used in the food and textile industries, in smart agriculture, and in wastewater treatment. This review will address biological entities that can be used for the green synthesis of NPs and their prospects for biotechnological applications.

Keywords Nanotechnology · Green synthesis · Nanoparticles · Biotechnological application · Antimicrobial

Introduction

The term nanotechnology incorporates the production of novel materials at the nanoscale range between 1 and 100 nm. Nanoparticles (NPs) with attractive shapes are synthesized by numerous physical and chemical methods. Nowadays, biological syntheses are preferred because they are safe, clean, cheap and easily scaled up for the well-built scale synthesis of NPs. NPs have great applications in different fields as magnetic devices, photocatalysts, microelectronic devices, anti-corrosive coatings, biomedicals, and electrocatalysts and also in powder metallurgy. The biotechnological applications of NPs have increased day by day due to its cutting-edge character, biocompatibility, anti-inflammatory and antimicrobial activity, effective drug delivery, bioactivity, bioavailability, tumor targeting, and bio-absorption [1–11]. On the other hand, NPs can be used in industrial and electronic fields as catalysts and as conductors in transistors and in cancer detection apparatus [12, 13]. Recently, magnetic NPs have been used in multidisciplinary fields such as in cancer treatment, drug delivery, tumor detection, resonance imaging, and separation processes [14]. Biological activities of magnetic NPs could be attributed to their smaller size, magnetic properties, high biocompatibility, and easy surface modifications [15].

Green synthesis of NPs using different biological entities can overcome many of the destructive effects of physical and chemical techniques. These include the biosynthesis of NPs at mild pH, pressure, and temperature and do not require toxic or hazardous substances as well as avoid the addition of external reducing, capping, and stabilizing agents [16]. Recently, various published reports enumerate different forms of metal, metal oxide, and dioxide NPs including core/shell (CS) NPs [17]; polymer-coated NPs [18]; Ag-NPs [19]; Cu-NPs [20]; CuO-NPs [4]; ZnO-NPs [8]; Au-NPs [21]; Pt-, Pd-, Si-, and Ni-NPs [22–25]; FeO-NPs [26]; TiO_2-NPs [27]; and ZrO_2-NPs [28]. Each one of these NPs has its specific characters and applications. NPs have different classifications according to their properties as shown in Fig. 1.

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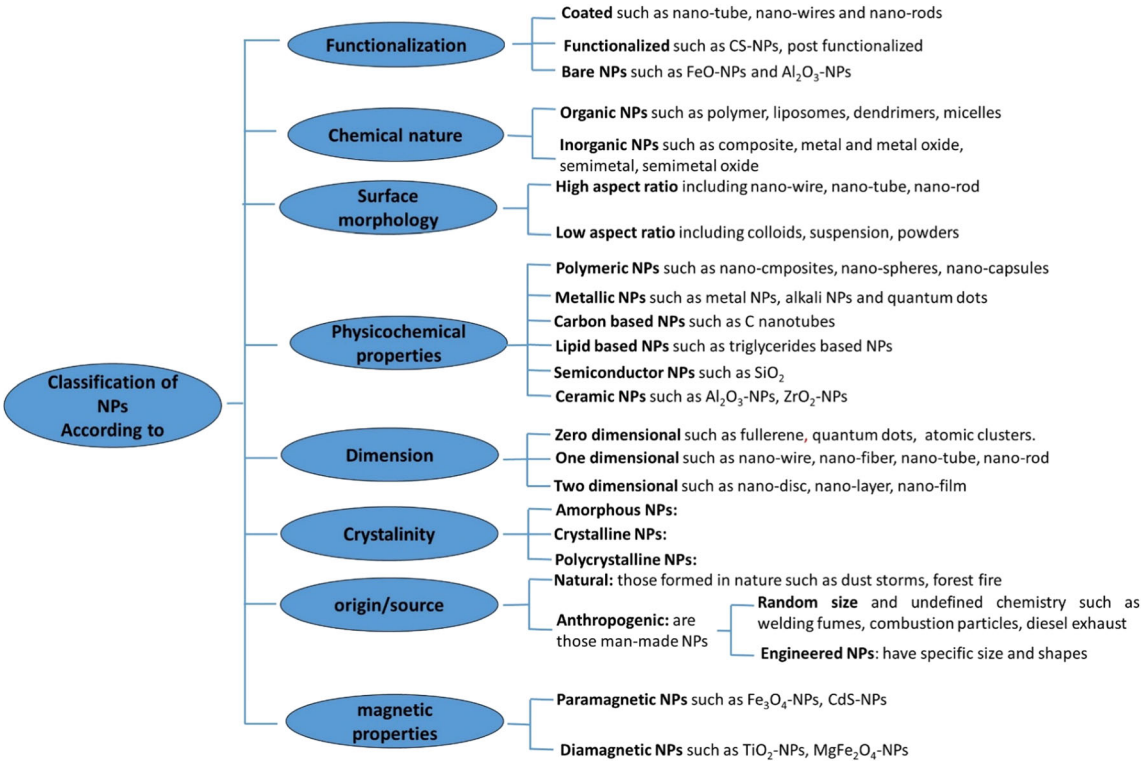

Fig. 1 Classification of NPs according to different approaches [29]

Methods for NPs Synthesis

Two approaches of nanoparticle synthesis are known as top-down and bottom-up methods. In the top-down method, the rupture of bulk materials to fine particles is conducted by various techniques such as evaporation–condensation, laser ablation, or other physical methods as seen in Fig. 2. In contrast, in the bottom-up method, the atoms are assembled to nuclei and then grown to NPs. Biological and chemical methods which are used for NPs synthesis are considered bottom-up approach.

An array of chemical, physical, and biological techniques have been utilized to synthesize nanomaterials with specific shapes and sizes [30].

Physical and Chemical Techniques for NPs Synthesis

A number of researchers have developed different chemical and physical methods to accomplish the synthesis of NPs such as geometries which can be utilized in varied applications. Photolithography, ball milling, ion beam lithography, microcontact printing, dip pen lithography, evaporation–condensation, electrochemical synthesis, and nanoimprint lithography are reflected as novel techniques for realizing such sole geometries in NPs [31]. The geometries can be also accomplished by physical methods [32]. On the other hand, the chemical procedures start with reducing the metal ions to metal atoms which is followed by controlled bulk of atoms [33]. Generally, chemical and physical methods have been expanded for the synthesis of numerous types of NPs owing to their specificity and creation of monodisperse NPs [34]. Various methods, such as metal ion reduction by any type of reducing agents as hydrazine hydrate, sodium citrate, and sodium borohydride [35]; solvothermal synthesis [36]; sol–gel technique and microwave-assisted synthesis [37]; laser ablation and microemulsion [38]; and ion sputtering, gamma-ray irradiation, electrochemical reduction, and autoclaving, have been used for the synthesis of metal NPs [39]. The greatest commonly used techniques for NPs synthesis are related to one or more disadvantages such as high operation cost, toxicity, and energy inefficiency, thus raising many environmental concerns.

These methods often need numerous treating steps, controlled pressure, pH, temperature, much expensive equipment, and toxic chemicals. In addition, these techniques also generate several by-products which are toxic to ecosystems. A variety of different chemical methods, so-called bottom-up construction techniques of NPs, are thus now settled in polar as well as in nonpolar solvents. Therefore, today, metallic NPs can be synthesized in numerous shapes, sizes, solvents, and material compositions [40]. The various physical and chemical techniques which are used for NP synthesis are costly, and they produce highly toxic and dangerous chemicals which cause different biological hazards. Therefore, the requirement of generating an eco-friendly method using biological and green synthesis approaches is urgently recommended [41].

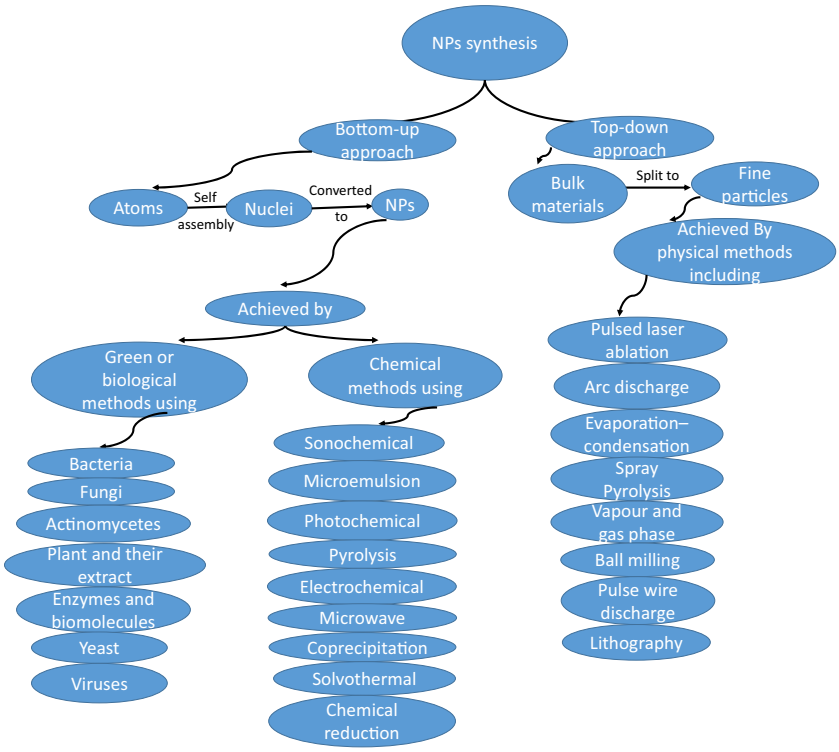

Fig. 2 Flowchart describes NPs synthesis using different approaches

Green Synthesis of NPs

Green or the biological synthesis of NPs avoids many of the harmful features by allowing the synthesis of NPs at mild pressure, temperature, and pH and at a significantly lower cost [42]. The green synthesis of NPs by biomass filtrate obtained from various biological systems such as yeast, bacteria, actinomycetes, fungi, algae, and plant extract has been reported.

Various microorganisms, especially bacteria and fungi, have been investigated to produce different metal NPs of silver, gold, zinc, titanium, copper, alginate, and magnesium [43]. Several reports have appeared that metal NPs, such as silver, gold, silver–gold alloy, tellurium, platinum, copper, zinc, selenium, palladium, silica, zirconium, quantum dots, titanium, and magnetite, can be biosynthesized by actinomycetes, bacteria, fungi, and viruses [5, 8, 20, 44, 45]. Recently, different organisms including unicellular and multicellular are used for the green synthesis of NPs as represented in Fig. 3.

The green synthesis of NPs reflects a bottom-up approach where NPs are formed due to the oxidation/reduction process of metallic ions by secreted biomolecules such as enzymes, proteins, sugars, carbohydrates, etc. [46]. However, a complete understanding of microbial NP synthesis mechanism is yet to be completely developed because each kind of microorganisms interrelates with metallic ions using several routes. The biochemical processing and the interaction activities of a specific microorganism as well as the effect of environmental conditions such as temperature and pH eventually affect the size, shape, and morphology of the synthesized NPs [47]. Therefore, the main challenges that can hinder the green synthesis processes can be briefly summarized in the following points: optimization processes that are required for the green synthesis of NPs with specific sizes and shapes are reflected in their biological activities. Also, determining the role of each compound in the biofabrication process requires complete chemical analysis for biological biomass filtrate. Scale-up NP production needs more studies for commercial uses. The mechanism of NP fabrication requires more explanations. On the other hand, the synthesis of nanomaterial by green approaches needs co-operation between basic science, chemical engineering, and industrial media to produce novel commercial materials.

Nanoparticles are formed either by intracellular or extracellular depending on the type of microorganisms [5]. For the biological synthesis of NPs, living cell extracts have been exploited by researchers. The main biological routes used for the synthesis of NPs are briefly discussed in the following sections.

Bacterial-Mediated NPs Synthesis

Bacteria are preferred to synthesize NPs due to its required slight conditions, easy purification, and high yield. Therefore, bacteria have become the widely studied microorganism, with the title of "the factory of nanomaterials." In recent years, *Bacillus thuringiensis* was used to synthesize Ag-NPs with size ranging from 43.52 to 142.97 nm [48]. Also, bacterial species belonging to *Bacillus licheniformis*, *Klebsiella*

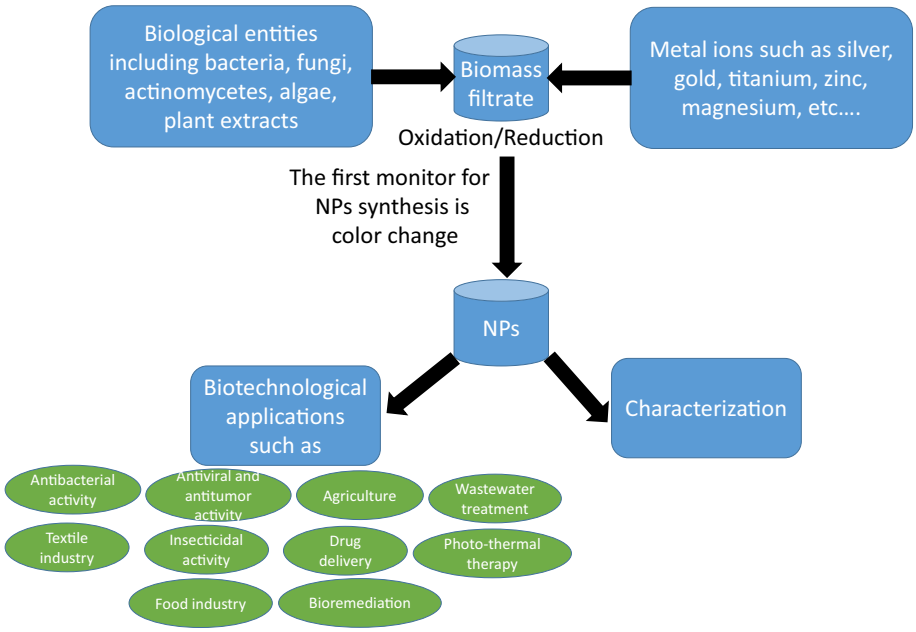

Fig. 3 Flowchart represents the green synthesis of nanoparticles and their prospective biotechnological applications

pneumonia, and *Morganella psychrotolerans* were used for Ag-NPs synthesis [49]. On the other hand, titanium dioxide nanoparticle was synthesized by *Bacillus subtilis* and *Lactobacillus* sp. [50]. Gold nanoparticles were synthesized by *Pseudomonas aeruginosa*, *Rhodopseudomonas capsulata*, *Escherichia coli* DH5α, *Bacillus subtilis*, and *Bacillus licheniformis* [51], while *Escherichia coli*, *Clostridium thermoaceticum*, and *Rhodopseudomonas palustris* were used previously for the synthesis of cadmium nanoparticles [52]. Bacteria can be used as biocatalyst for inorganic material synthesis; they can act as bioscaffold for mineralization or take an active part in nanoparticle synthesis [53]. Bacteria can synthesize nanomaterials in broth media during an incubation period either as extracellular or intracellular. This phenomenon makes the biosynthesis of NPs using bacteria a reasonable, flexible, and suitable technique for large-scale production. Data represented in Table 1 summarize the sizes and different applications of NPs synthesized by different bacterial species.

Synthesis of NPs by Actinomycetes

Actinomycetes are good sources for the biosynthesis of NPs with appreciable surface and size characteristics due to a wide range of secreted secondary metabolites. Actinobacteria have the ability to produce metallic NPs either through intra- or extracellular methodologies. Extracellular production has gotten additional commercial advantages in contrast to the intracellular one since polydispersity plays an important role [91]. The literature reports widely on the intra- or extracellular synthesis of metallic nanomaterials by actinomycetes [4, 20, 92]. Gold NPs are successfully synthesized by *Rhodococcus* sp., *Thermoactinomycete* sp., *Streptomyces viridogens*, *S. hygroscopicus*, *Nocardia farcinica*, and *Thermomonospora* [93]. On the other hand, silver, copper, zinc, and manganese nanoparticles [4, 20, 94, 95] were successfully synthesized by using *Streptomyces* spp. A representative list of the size and applications of NPs synthesized by actinomycetes is shown in Table 2.

Synthesis of NPs by Fungi and Yeast

Fungi have been extensively used for NPs biosynthesis due to the high efficiencies of fungal metabolites to fabricate different NPs [5, 8, 116]. Fungi are considered a good current addition to the catalog of microorganisms that are used for NPs fabrications. The widespread use of different fungal species can be attributed to their ability to secrete well-built amounts of proteins or enzymes and they are easier to trade in the laboratory [117]. The use of fungi in synthesizing metallic NPs has received great interest due to having certain advantages that overcome other organisms. The ease of scaling up and downstream handling, the economic feasibility, and the presence of mycelia presenting an increased surface region are valuable advantages that should be taken into consideration [42]. Also, fungi have been given more attention as they are involved in the study on biological synthesis of metallic nanomaterials due to their tolerance and metal bioaccumulation capability [118]. The broadness of fungi scale-up has resulted in a split favor of utilizing them in the synthesis of NPs (e.g., utilizing a thin solid substrate fermentation system). Since fungi are very effectual secretors of extracellular enzymes or proteins, therefore achieving vast construction of enzymes is viable [119]. The economic facility and livability of using biomass is another advantage for the application of the green approach facilitated by fungal cells or metabolites to synthesize metallic nanomaterials (Fig. 4). Moreover, several

Table 1 A representative list of size and applications of different NPs synthesized by bacterial species

NPs	Synthesized by	Size	Applications	Reference
Ag	*Pseudomonas* sp.	20–70 nm	Antibacterial activity	[49]
	Bacillus thuringiensis	43.5–142.9 nm	Larvicidal activity against *Culex quinquefasciatus* and *Aedes aegypti*	[48]
	Bacillus licheniformis	40 nm	–	[54]
	Ochrobactrum anhtropi	38–85 nm	Antibacterial activity	[55]
	Bacillus spp.	77–92 nm	Antimicrobial activity, antiviral activity	[56]
	Pantoea ananatis	8.06–91.31 nm	Antibacterial against multidrug resistant	[57]
	Bacillus brevis NCIM 2533	41–68 nm	Antibacterial activity	[58]
	Bacillus mojavensis BTCB15	105 nm	Antibacterial activity against multidrug resistant	[53]
	Actinobacter	13 nm	Antibacterial activity	[59]
	Sinomonas mesophila	4–50 nm	Antimicrobial activity	[60]
	Bacillus endophyticus	5 nm	Antimicrobial activity	[61]
	Bacillus brevis	41–68 nm	Antibacterial activity	[58]
	Bacillus licheniformis Dahb1	18–63 nm	Antibiofilm activity	[62]
	Bacillus methylotrophicus DC3	10–30	Antimicrobial activity	[63]
Au–Ag	*Stenotrophomonas* GSG2	Gold (10–50); silver (40–60)	–	[64]
Cu	*Kocuria flava*	5–30 nm	–	[65]
	Shewanella loihica	10–16 nm	Antibacterial activity	[66]
	Shewanella oneidensis MR-1	20–40 nm	Biocatalysts	[67]
Pt	*Shewanella loihica*	1–10 nm	Decolorization of dyes	[68]
	Shewanella oneidensis MR-1	2.83–61.03 nm	Biocatalysts for reduction of 4-nitrophenol	[69]
Pd	*Shewanella loihica*	1–12 nm	Degradation of dyes	[68]
	Shewanella oneidensis MR-1	10–100 nm	Electrocatalysts	[70]
Pd–Pt	*Shewanella loihica*	2–7 nm	Degradation of dyes	[68]
TeO_3–SeO_3	*Ochrobactrum* sp.	–	Reduce of toxic substances	[71]
Au	*Pseudomonas aeruginosa*	15–30 nm	–	[72]
	Rhodopseudomonas capsulata	10–20 nm	–	[73]
	Escherichia coli DH5α	25 nm	Direct electrochemistry of hemoglobin	[74]
	Bacillus subtilis	20–25 nm	Degradation of dyes	[51]
	Shewanella loihica	2–15 nm	Degradation of dyes	[68]
	Micrococcus yunnanensis	53 nm	Antibacterial and anticancer activity	[75]
	Mycobacterium sp.	5–55 nm	Anticancer activity	[76]
	Halomonas salina	30–100 nm	–	[77]
	Shewanella oneidensis MR-1	3–15 nm	Biocatalysts for reduction of nitroaromatic compounds	[78]
CdS	*E. coli*	2–5 nm	–	[52]
	Pseudomonas aeruginosa	20–40	Removal of heavy metal as cadmium	[79]
TiO_2	*Bacillus mycoides*	40–60 nm	Used in solar cells	[80]
	Bacillus amyloliquefaciens	15.2–87.6 nm	Photocatalytic for dye removal	[50]
	Aeromonas hydrophila	28–54 nm	Antibacterial activity	[81]
	Lactobacillus sp.	8–35 nm	–	[82]
Te	*Shewanella baltica*	8–75 nm	Photocatalytic activity	[83]
Co_3O_4	*Bacillus subtilis*	2–5 nm	–	[84]
Se	*Lysinibacillus* sp. ZYM-1	100–200 nm	Photocatalytic activity	[85]
	Bacillus subtilis	50–400 nm	H_2O_2 sensoristic device	[86]
ZnO	*Bacillus megaterium* NCIM2326	45–95 nm	Antimicrobial activity	[87]
ZnO	*Halomonas elongata* IBRC-M 10214	18.11 nm	Antimicrobial activity	[88]
	Sphingobacterium thalpophilum	40 nm	Antimicrobial activity	[89]
	Staphylococcus aureus	10–50 nm	Antimicrobial activity	[90]

Table 2 A representative list of size and applications of different NPs synthesized by actinomycetes species

NPs	Synthesized by	Size	Applications	Reference
Ag	*Streptomyces* spp.	11–63 nm	Antimicrobial, antioxidant, larvicidal activities	[19]
	Nocardiopsis sp. MBRC-1	45 nm	Antimicrobial activity, in vitro cytotoxicity against HeLa cell line	[96]
	Streptacidiphilus durhamensis	8–48 nm	Antimicrobial activity	[97]
	Streptomyces rochei MHM13	22–85	Antimicrobial activity and enhancement of antibiotic action	[98]
	Streptomyces sp.	15–25 nm	–	[94]
	Saccaropolyspora hirsuta	10–30 nm	Antimicrobial activity	[99]
	Streptomyces parvulus	100 nm	Antimicrobial activity	[100]
	Streptomyces seoulensis	121 nm	Antimicrobial activity	[100]
	Streptomyces owasiensis	160 nm	Antimicrobial activity	[100]
	Nocardiopsis flavascens	5–50 nm	Cytotoxicity	[101]
	Streptomyces fradiae	100–200 nm	Antioxidant activity	[102]
	Streptomyces griseoplanus	19–20 nm	Antifungal against plant pathogen	[103]
	Rhodococcus sp.	5–50 nm	Antimicrobial activity	[104]
	Streptomyces sp. Al-Dhabi-87	20–50 nm	Antimicrobial activity, antibacterial activity against multidrug-resistant bacteria	[105]
Ag–Au	*Streptomyces* sp.	8.4 nm (Ag); 10 nm (Au)	Antibacterial activity	[93]
	Gordonia amicalis HS-11	5–25 nm	Antioxidant activity	[102]
CuO	*Streptomyces* sp.	78–80 nm	Antimicrobial, antioxidant, cytotoxicity, biocontrol of phytopathogen, and larvicidal activities	[4]
Cu	*Streptomyces capillispiralis* Ca-1	3.6–59 nm	Antimicrobial, biocontrol of phytopathogen, and larvicidal activities	[20]
Au	*Streptomycetes viridogens* HM10	18–20 nm	Antibacterial activity	[106]
	Streptomyces sp.	90 nm	Antifungal activity	[107]
	Nocardiopsis sp. MBRC-48	11.57 nm	Antimicrobial and cytotoxicity activities	[108]
	Streptomyces griseoruber	5–50 nm	Dye degradation	[109]
	Rhodococcus sp.	5–15 nm	–	[110]
	Streptomyces hygroscopicus	10–20 nm	–	[111]
	Streptomyces sp.	5–50 nm	Antimalarial activity	[112]
Se	*Streptomyces minutiscleroticus* M10A62	10–250 nm	Antibiofilm, antiviral; antioxidant activity, antiproliferative activity	[113]
	Streptomyces bikiniensis Ess_amA-1	17 nm	Anticancer activity	[114]
ZnO	*Streptomyces* sp.	20–50	Antimicrobial activity	[115]

species of fungi grow rapidly and formed huge amount of mass cells and maintaining them in a specific laboratory is actual easy [8]. Fungi can form metal NPs in different structures as meso- and nanostructures via reducing enzyme extra- or intracellularly and the process of biomimetic mineralization [120].

The synthesis of NPs using fungi and their biotechnological applications, especially in medicine, are considered under the term of myco-nanotechnology. This scientific term is the boundary between "mycology" and "nanotechnology" and has significant potential, due to the extensive range and variety of the fungi [5, 32, 45]. Different species of fungi can be used to produce gold and silver nanoparticles such as *Phanerochaete chrysosporium*, *Pleurotus sajorcaju*, *Coriolus versicolor*, and *Schizophyllum commune* [121, 122]. Other species including *Aspergillus niger*, *Aspergillus terreus*, *Fusarium keratoplasticum*, *Fusarium oxysporum*, and *Alternaria alternata* have been reported to biosynthesize zinc oxide and iron oxide nanoparticles [5, 123]. *Fusarium* spp., *Fusarium keratoplasticum*, *Helminthosporium tetramera*, and *Schizophyllum radiatum* were used for the biosynthesis of Ag-NPs [124–127]. Interestingly, *Penicillium aurantiogriseum*, *P. waksmanii*, *P. citrinum*, *Fusarium oxysporum*, and *Aspergillus sydowii* were used for Au biosynthesis [128–130], while *Aspergillus* sp. was used for the biosynthesis of iron nanoparticles [131]. *Fusarium oxysporum* can be used to produce zinc sulfide (ZnS), lead sulfide (PbS), cadmium sulfide (CdS), and molybdenum sulfide (MoS) nanomaterials, when the appropriate salt is added to the growth medium [132].

A few studies reported the successful biosynthesis of Ag-NPs by yeasts, counting the yeast strain MKY3, *Candida albicans*, *Saccharomyces boulardii*, and *Candida utilis*

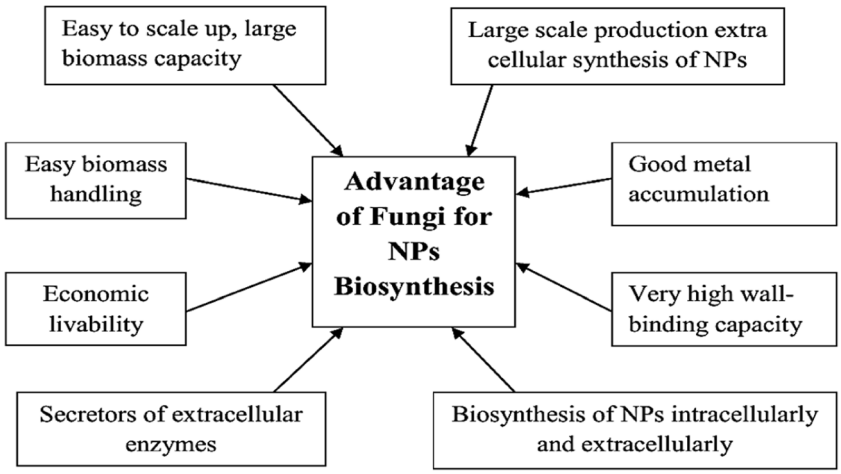

Fig. 4 Advantages of fungi as biofactories for NPs production [120]

[133]. Extremophilic yeasts that have been isolated from acid source drainage are used as biocatalyst for gold and silver NPs synthesis [134]. The yeast strain *Magnusiomyces ingens* LHF1 has been explored for intracellular production of stable selenium nanoparticles [135]. Data in Table 3 summarize the sizes and applications of different NPs synthesized by fungi and yeasts.

Algal-Mediated NPs Synthesis

Algae are sea microorganisms that have been reported not only to uptake heavy metals from the environment, but also to synthesize metallic NPs. For example, the dried algal cells of *Chlorella vulgaris* were expanded to produce Au-NPs by reduced tetrachloroaurate ions to form Au-NPs [172]. Studies are ongoing on the bioreduction and biosorption of Au (III) ions by *Fucus vesiculosus* which is defined as a brown alga [173]. Bioreduction with *Fucus vesiculosus* might be expanded as a replacement eco-friendly treatment for claiming Au from leachates of microelectronic scraps and dilute hydrometallurgical mixes. Diatoms can be used as a resource for fabrication of siliceous materials [174]. The phytoplanktonic alga, *Phaeodactulum tricornatum*, possesses phytochelatin-covered CdS nanocrystals fabricated in response to Cd [175]. Rapid formation of Au-NPs through extracellular biosynthesis has been created viable in a marine alga of *Sargassum wightii* Greville [176]. Konishi et al. [177] reported that *Shewanella algaehas* have the ability to reduce aqueous $PtCl_6$ to elemental Pt at neutral pH under room temperature within 60 min using lactate as the electron donor. Biogenic Pt-NPs of 5 nm are observed in the periplasm, which is a preferable position for simple and quick recovery [177]. Brayner and co-authors described the synthesis of platinum, gold, palladium, and silver NPs using cyanobacteria [178]. Other alga like *Turbinaria conoides* was used for gold nanoparticle biosynthesis [179]. On the other hand, four marine macroalgae, viz., *Pterocladia capillacae*, *Jania rubins*, *Ulva faciata*, and *Colpmenia sinusa*, were used for the biosynthesis of Ag-NPs [179–181]. As seen in Table 4, there are some representative examples for NPs synthesized by different algae with their size and applications.

Synthesis of NPs by Viruses

The usage of viruses in the biosynthesis of nanoparticles is a novel method that has been capable to produce inorganic nanomaterials such as cadmium sulfide (CdS), silicon dioxide (SiO_2), iron oxide (Fe_2O_3), and zinc sulfide (ZnS). Semiconductor nanomaterials such as ZnS and CdS are of interest to the green chemistry and electronics industry approaches for their synthesis has been widely investigated. The use of whole viruses to synthesize quantum dots has been inspected over the previous decade [226]. The bacteriophage has an exact detection moiety for ZnS surfaces. In 2003, Chuanbin Mao's group found a new synthesis route to a semiconductor nanoscale heterostructure using M13 bacteriophage [229]. Also, Yoon Sung Nam and his group arrived at the biosynthesis of a high-performance, flexible nanogenerator using anisotropic $BaTiO_3$ nanocrystals on an M13 viral template by the genetically programmed nature assembly of metal ion precursors [230]. An attractive characteristic of viruses is their complicated surface protecting the capsid protein structure that forms an extremely sensitive surface with the cooperation of metal ions [47]. In a similar study, low concentrations of TMVs (tobacco mosaic virus) were inserted to Au or Ag solutions before the addition plant cell extracts of *Hordeum vulgare* or *Nicotiana benthamiana*. The presence of the virus not only decreased the size of the biosynthesized NPs, but also radically increased their numbers in contrast to the solutions without the virus [225]. Illustrative examples for NPs synthesized by different viruses are listed in Table 4.

Synthesis of NPs by Plant Extracts

Biosynthesis of metallic nanoparticles using plant extracts is firstly reported by Gardea-Torresdey et al. [231], who reported

Table 3 A representative list of size and applications of different NPs synthesized by fungal and yeast species

NPs	Synthesized by	Size	Applications	Reference
Fungi				
Ag	*Rhizopus stolonifer*	2.86 nm	–	[136]
	Candida glabrata	2–15 nm	Antibacterial activity	[137]
	Trametes trogii	5–65 nm	–	[138]
	Trichoderma longibrachiatum	10 nm	Antimicrobial against phytopathogen	[122]
	Fusarium oxysporum	21.3–37 nm	Antibacterial activity	[139]
	Aspergillus terreus	16–57 nm	Antibacterial activity	[140]
	Ganoderma sessiliforme	45 nm	Antibacterial, antioxidant, and anticancer activities	[141]
	Rhodotorula glutinis	15.45 nm	Antifungal, cytotoxicity, and dye degradation	[142]
	Aspergillus sp.	5–30 nm	Antibacterial and cytotoxicity activities	[45]
	Fusarium keratoplasticum A1-3	6 to 36 nm	Increasing antibacterial activity of cotton fabrics	[124]
	Arthroderma fulvum	15.5 nm	Antifungal activity	[143]
	Penicillium aculeatum Su1	4–55 nm	Antimicrobial activity, drug delivery	[144]
	Fusarium oxysporum 405	10–50 nm	Colloidal stability	[145]
	Fusarium oxysporum	5–13 nm	Antibacterial and antitumor activities	[146]
	Metarhizium anisopliae	28–38 nm	Larvicidal activity	[147]
	Trichoderma harzianum	20–30 nm	Antifungal activity	[148]
	Fusarium oxysporum	34–44 nm	Antibacterial activity	[149]
	Candida albicans ATCC 10231	10–20 nm	–	[150]
Ag/AgCl	*Macrophomina phaseolina*	5–30 nm	Antibacterial activity	[117]
Au	*Cladosporium cladosporioides*	60 nm	Antibacterial and antioxidant activities	[151]
	Trichoderma harzianum	32–44 nm	Dye degradation; antibacterial activity	[152]
	Pleurotus ostreatus	10–30 nm	Antimicrobial, anticancer activities	[121]
	Aspergillus sp.	2.5–6.7 nm	Reduction of nitrophenol compounds	[153]
	Rhizopus oryzae	16–43 nm	Hemocompatible activity	[154]
Pt	*Penicillium chrysogenum*	5–40 nm	Cytotoxicity	[155]
ZnO	*Aspergillus niger*	53–69 nm	Dye degradation; antibacterial activity	[156]
	Candida albicans	25 nm	Synthesis of steroidal pyrazolines	[157]
	Fusarium keratoplasticum A1-3	10 to 42 nm	Antibacterial, cytotoxicity activities, and loaded on textile	[5]
	Aspergillus niger G3-1	8–38 nm	Antibacterial, cytotoxicity activities and medical textile	[5]
	Aspergillus terreus	10–45 nm	Antibacterial, cytotoxicity, medical textile and UV protection	[8]
	Pichia kudriavzevii	10–61 nm	Antibacterial and antioxidant activities	[158]
Te	*Aspergillus welwitschiae*	60 nm	Antibacterial activity against MRSA	[159]
ZnS; ZnS-Gd	*Aspergillus flavus*	12–24 nm (ZnS); 10–18 nm (ZnS-Gd)	Detection of heavy metals in water	[160]
Fe_2O_3	*Alternaria alternata*	75–650 nm	–	[123]
Al_2O_3	*Colletotrichum* sp.	30–50	Antimicrobial activity	[161]
CoO	*Aspergillus nidulans*	20.3 nm	–	[162]
Yeast				
Ag	*Rhodotorula* sp. ATL72	8–21 nm	Antimicrobial activity	[133]
	Saccharomyces cerevisiae	2–7 nm	–	[34]
	Saccharomyces cerevisiae	2–20 nm	–	[163]
	Cryptococcus laurentii	35–400 nm	Antifungal against plant pathogen	[164]
	Rhodotorula glutinis	15–220 nm	Antifungal against plant pathogen	[164]
	Rhodotorula mucilaginosa	11	Bioremediation	[165]
	Rhodotorula glutinis	15.5 nm	Antifungal activity; reduction of nitrophenol compound; and dye degradation	[166]
Au–Ag alloy	Commercial yeast	–	Electrochemical sensor	[167]
Ag and Au	*Phaffia rhodozyma*	5–9 nm (Ag); 4–7 nm (Au)	Antifungal activity	[134]

Table 3 (continued)

NPs	Synthesized by	Size	Applications	Reference
Au	*Saccharomyces cerevisiae*	–	Enhancement of surface plasmon applications	[168]
	Magnusiomyces ingens LHF1	20–28 nm	Reduction of nitrophenol compounds	[169]
Pd	*Saccharomyces cerevisiae*	32 nm	Dye degradations	[170]
ZnO	*Pichia kudriavzevii*	10–61 nm	Antimicrobial and antioxidant activities	[158]
Se	*Magnusiomyces ingens* LHF1	70–90 nm	Antibacterial activity	[135]
CdTe	*Saccharomyces cerevisiae*	2.0–3.6 nm	Applications in bio-imaging and biolabeling	[171]

the synthesis of Ag-NPs using *Alfalfa sprouts*. The major important and special feature of nanoparticles is that they exhibit larger surface region to volume ratio [232]. Plant extracts such as soya, *Aloe barbadensis* Miller, and *Tridax procumbens* leaf cell extract have been used for the synthesis of Cu and CuO-NPs [233, 234]. Recently, plant-mediated biosynthesis of ZnO-NPs has been accomplished in *Parthenium hysterophorus*, *Sapindus rarak*, *Passiflora foetida*, *Acalypha indica*, *Ficus benghalensis*, and *Zingiber officinale* [235]. Several reports were made on the biosynthesis of nanoparticles (Au, Ag, ZnO, Fe, etc.) using aqueous extracts of numerous plant parts. An aqueous leaf cell extract of *Couroupita guianensis* and *Turnera ulmifolia* for the biosynthesis of Ag-NPs [236, 237], *Allium cepa* cell extract for Au-NPs [238], *Eucalyptus* leaf extract for the construction of Fe-NPs and composites [239], and plant extracts of *Punica granatum* for the biosynthesis of ZnO-NPs [240] were used.

The green synthesis of NPs using plant extracts has more advantages than using microorganisms because it is a single-step method, is nonpathogenic and economic, produces a huge amount of metabolites, is cost-effective, and is an eco-friendly approach [241]. Plant-mediated biosynthesis of NPs with their size and applications is summarized in Table 5.

Factors Affecting NPs Synthesis

Adjusting the sizes and shapes of metal nanomaterials appears either to be compelled by their environmental development or shifted by functional molecules [5]. Improving the reaction conditions for the synthesis of nanoparticles, including temperature, pH, incubation period, aeration, salt concentration, redox conditions, mixing ratio, and irradiation, has been investigated [289, 290]. The size and shape of NPs depend on chemical and physical factors. The optimum metal ion concentration, temperature, and pH of the reaction mixture play key roles in nanoparticle synthesis. The rate of intracellular nanoparticle creation and then the size of the NPs could, to an amount, be influenced by scheming parameters such as temperature, pH, substrate concentration, and exposure period to substrate [291].

NPs Characterization

Physicochemical characterization of generated NPs is an important stage that should be carefully considered before nanoparticle application. Studying the size, shape, surface area, homogeneity, stability, and other features will provide valuable information of nanoscale systems and insight into the synthesis control of nanoparticles for commercial applications. Some common techniques of characterization such as the color change test; UV–visible spectrometry; Fourier transformation infrared spectroscopy (FT-IR); electron microscopy including transmission, high-resolution, scanning, and field-emission scanning (TEM, HR-TEM, SEM, and FE-SEM); energy-dispersive spectroscopy (EDX-map); dynamic light scattering (DLS); powder X-ray diffraction (XRD); vibrating sample magnetometer (VAM); thermogravimetric analysis (TGA); and other instruments are shown with their functions in Table 6 [5, 292–298].

Biotechnological Applications of NPs

The advantages of nanotechnology are growing quickly in several fields [255, 281]. Nanoparticles are applicable to many emerging technologies such as in sunscreens and cosmetics, water filtrations, ink, glare filters, stain-resistant clothing, agriculture and pharmaceutical, finished fabrics, and dressings for injuries or burns [8, 185]. The major biotechnological applications of NPs will be addressed below.

Antimicrobial Activities and Cytotoxicity Agents

The major challenges for medicinal practitioners are summarized in the appearance of new drug-resistant microbes. Therefore, the development of novel drugs is necessary to cope with various diseases. The applications of NPs in medicine have different advantages such as in early detection systems, diagnosis using NP-based imaging, and treatment of different diseases caused by drug-resistant microbes [171, 275]. The development of nanotechnology and methods used for the synthesis of nanocomposites/NPs has likewise revolutionized the field of biomedicine because of their

Table 4 A representative list of size and applications of different NPs synthesized by algae and viruses

NPs	Synthesized by	Size	Applications	References
Algae				
Ag	Red algae *Portieria hornemannii*	60–70 nm	Antibacterial activity against fish pathogens	[182]
	Marine macroalgae *Padina* sp.	~25–60 nm	Antibacterial and antioxidant activities	[183]
	Microchaete NCCU-342	60–80 nm	Dye decolorization ability	[184]
	Macroalgae (*Ulva lactuca* L.)	31 ± 8 nm	Cancer therapy	[185]
	Brown alga *Padina pavonia*	49.58–86.37 nm	One-pot method for synthesis	[186]
	Gelidium amansii	27–54 nm	Antimicrobial property	[187]
	Caulerpa serrulata	10 ± 2 nm	Catalytic and antibacterial activities	[188]
	Acanthophora specifera	33–81 nm	Antimicrobial activity	[189]
	Gracilaria birdiae	20.3 nm	Antibacterial activity	[190]
	Sargassum muticum	43–79 nm	Control tool against mosquito vectors and bacterial pathogens	[191]
	Anabaena flos-aquae	5–25 nm	Anticancer and cytotoxic activity against T47D cell lines	[192]
	Polysiphonia algae	5–25 nm	Anticancer activity against MCF-7 cell line	[193]
Au	Marine algae *Gelidiella acerosa*	5.8–117.6 nm	Biological potential	[194]
	Macroalgae (*Ulva lactuca* L)	7.9 nm	Cancer therapies	[185]
	Marine algae extract	8–20 nm	One-pot method for synthesis	[195]
	Brown algae *Cystoseira baccata*	8.4 nm	Cancer therapies	[196]
	Pithophora oedogonia	32.06 nm	Determination of carbendazim molecules in soil	[197]
	Sargassum tenerrimum	5–45 nm	Evaluation of their catalytic activity	[198]
	Spirulina platensis	20–30 nm	Antibacterial efficacy	[199]
Pd	*Chlorella vulgaris*	70 nm	Catalytic activity	[200]
	Chlorella vulgaris	5–20 nm	Easy and fast bioprocess	[201]
	Sargassum bovinum	5–10 nm	Electrocatalytic activities	[202]
	Sargassum ilicifolium	60–80 nm	–	[203]
ZnO	Microalgae *Chlorella* extract	20 ± 2.2 nm	Photocatalytic activity	[204]
	Sargassum muticum	30–57 nm	Supplemental drug in cancer treatments	[205]
	Chlamydomonas reinhardtii	55–80 nm	Photocatalytic activity	[206]
	Agathosma betulina	15.8 nm	One-pot method for synthesis	[207]
	Sargassum muticum	30–57 nm	One-pot method for synthesis	[208]
CuO	Brown alga *Cystoseira trinodis*	6–7.8 nm	Photocatalytic and antibacterial activities	[209]
	Green alga *Botryococcus braunii*	10–70 nm	Antimicrobial activity	[210]
	Brown algae *Sargassum polycystum*	–	Antimicrobial and anticancer activities	[211]
	Bifurcaria bifurcata	5–45 nm	Antimicrobial activity	[212]
Fe_3O_4	Brown seaweed extract	11.2–33.7 nm	Antimicrobial potency	[213]
	Brown seaweed	10–19.5 nm	Bioremediation	[214]
	Sargassum muticum	18 ± 4 nm	High functional bioactivity	[215]
$CuFe_2O_4$@Ag	*Chlorella vulgaris*	20 nm	Antibacterial activity, antibiofilm activity, inhibit efflux pump genes in *Staphylococcus*	[216]
Fe_3O_4@Ag	*Spirulina platensis*	30–68 nm	Effect on the expression of norA and norB genes in *Staphylococcus aureus*	[217]
Fe_3O_4/Ag	*Spirulina platensis*	30–50 nm	Anticancer activity	[218]
Viruses				
Au nanowires	Tobacco mosaic virus	50 nm in diameter and 150–400 nm in length	Properties of nanowires	[219]
Nanoconjugates	Hepatitis E virus	27–34 nm	Cancer therapy	[220]

Table 4 (continued)

NPs	Synthesized by	Size	Applications	References
Au	Bacteriophage	20–50 nm 50–150 nm 150–500 nm	Biosensor electrode	[221]
Au-DNs	M13 virus		Biosensor platform	[222]
Nanocarriers	Potato virus X	12 nm	Doxorubicin delivery in cancer therapy	[223]
TiO_2	M13 virus	20–40 nm	Photo-electrochemical properties	[224]
Metal nanoparticles	Cowpea mosaic virus and Tobacco mosaic virus	≤ 100 nm	Nanotechnology industry.	[225]
Nanoassemblies	Cucumber mosaic virus	~ 29 nm	Anticancer activity, and drug delivery	[226]
Pd	Tobacco mosaic virus (TMV)	2.9–3.7 nm	Multiwalled carbon nanotubes Catalyst and recyclable	[227]
Ni, Co, Fe, Pd, Co–Pd, Ni–Fe	Cowpea mosaic virus (CPMV)	≤ 35 nm	One-pot method for synthesis	[228]

antimicrobial and immunoassay activities [223, 242]. Various types of NPs, including metals and metal oxides such as Ag, Au, Ag_2O, ZnO, TiO_2, CaO, CuO, MgO, and SiO_2, are developed by different researchers to use in medical applications [4, 8, 20, 299–303]. Plant- and different microbe-mediated biosyntheses of NPs are suitable candidates for a novel production of antimicrobial nanomaterials [19, 183].

Recently, the green-synthesized ZnO-NPs showed antimicrobial activities against different pathogenic Gram-negative and Gram-positive bacteria such as *E. coli*, *Pseudomonas aeruginosa*, *Salmonella typhimurium*, *Listeria monocytogenes*, *Staphylococcus aureus*, and *Bacillus subtilis* [19, 276]. On the other hand, Au-NPs and Ag-NPs exhibit highly antibacterial activity toward pathogenic Gram-negative bacteria such as *E. coli*, *Klebsiella pneumonia*, *Salmonella typhimurium*, *Pseudomonas aeruginosa*, *Proteus mirabilis*, *Shigella dysenteriae*, *Enterobacter aerogenes*, and *Citrobacter* sp. Also, the biosynthesized Au-NPs and Ag-NPs have activities against pathogenic Gram-positive bacteria such as *Staphylococcus epidermidis*, *Staphylococcus aureus* including MRSA, *Streptococcus pyogenes*, *Enterococcus faecalis*, and *Bacillus subtilis* [105, 117, 242, 245]. The activities of NPs as antifungal agents for different pathogenic fungi have been widely evaluated [107, 148]. Several studies have reported the activities of biosynthesized Ag-NPs as antifungal agents against multicellular and unicellular fungi such as *Trichophyton mentagrophytes*, *Aspergillus flavus*, *Candida glabrata*, *Aspergillus fumigatus*, *Candida parapsilosis*, *Cryptococcus neoformans*, *Candida krusei*, *Fusarium solani*, *Trichophyton rubrum*, *Cryptococcus gattii*, *Candida tropicalis*, *Sporothrix schenckii*, *Epidermophyton floccosum*, *Candida albicans*, and *Mucor hiemalis*. In the same regard, Ag-NPs showed activities against plant pathogenic fungi such as *Aspergillus niger*, *Colletotrichum* sp., *Fusarium* sp., *Culvularia lunata*, and *Rhizoctonia solani* [19, 103, 304–306]. Recently, cancer diagnosis and treatment have received more attention. A large multiplicity in nanomaterials has been evaluated to improve its efficacy in cancer therapy as well as to reduce negative impacts compared with conventional therapies [251]. The toxicity impact of NPs synthesized by green methods is evaluated mainly by changes in viability and cell morphology, as well as metabolic activities [8, 141]. NPs have been localized in the mitochondria, inducing functional damage and structural as well as oxidative emphasis [307]. The physicochemical properties of NPs have a critical important role in cytotoxicity effect. The nature and size of NPs, its surface area, and its surface functionalization (capping agents) are important factors that affect their toxicity [5]. The small-sized NPs are more toxic compared with the bigger ones [305].

There are three defined prospective mechanisms that explain the antimicrobial activity of metal NPs: firstly, damage of the cell wall and cell membrane; secondly, damage of intracellular microbial components after penetration of the cell wall; and finally, oxidative stress mechanism (Fig. 5).

The cell wall and cell membrane protect microbes against external harmful condition and remain a transport mechanism of nutrients in/out of the cell. According to cell wall components, Gram-positive bacteria possess a thick layer of peptidoglycan, while Gram-negative contain thin layer of peptidoglycan [308, 309]. The metallic NPs exhibit higher antibacterial activity against Gram-negative bacteria more than those recorded for Gram-positive bacteria [310]. This activity may be attributed to the negative charge of lipopolysaccharides (LPS) in Gram-negative bacteria that permit adhesion of NPs to bacterial cell wall. The metallic NPs interact with bacterial cell wall through attraction between the microbial cell wall's negative charge and NPs' positive charge [311]. Due to this interaction, the permeability function of the cell membrane changes and, hence, the bacterial integrity disrupts and causes cell death [312]. Interestingly, the cellular components such as protein, nucleic acid, ions, and enzymes escape out of the cell membrane and adversely influence cellular activity [313]. Therefore, the degradation of bacterial cell wall and cell

Table 5 A representative list of size and applications of different NPs synthesized by plant extracts

NPs	Synthesized by	Size (nm)	Applications	Reference
Ag	Mulberry fruit (*Morus alba* L.)	80–150	Antibacterial activity	[242]
	Annona reticulata	7–8	Bactericidal activities	[243]
	Camellia sinensis	2–4	Cytotoxicity evaluation and antibacterial activity	[244]
	Persea americana	20–40	Antimicrobial properties	[245]
	Aqueous extract of *E. scaber*	37.86	Environmental and biological applications	[246]
	Panax ginseng	5–15	Anticancer and antiviral activities	[247]
	Dolichos lablab	4–16	Antimicrobial and anticancer activities	[248]
	Alternanthera bettzickiana	5–15	Antimicrobial and anticancer activities	[249]
	Ethanolic extract of *Thymus vulgaris*	30	Anticancer and antioxidant activities	[250]
Au	Red cabbage extracts	~ 25 18–30 5–70 27	Catalytic activity	[251]
	Tribulus terrestris	~ 7	Anti-*Helicobacter pylori*, cytotoxicity and catalytic activities	[252]
	Camellia sinensis	10	Antibacterial activity	[253]
	Nigella arvensis	3–37	Antibacterial, antioxidant, cytotoxicity, and catalytic activities	[254]
	Anacardium occidentale	10–30	In vitro antimicrobial and anticancer properties	[255]
	Alternanthera bettzickiana	80–120	Evaluation of bioactivities	[256]
	Rhazya stricta Decne	40	Biological activities against bacteria and *Leishmania*	[257]
	Elettaria cardamomum	15	Biological activities	[258]
Cu	Mulberry fruit (*Morus alba* L.)	50–200	Antibacterial activity	[242]
	Crotalaria candicans	30	Antibacterial activity	[259]
	Ziziphus spinachristi	5–20	Adsorption of tri-phenyl methane dye and antibacterial assay	[260]
	(*Syzygium aromaticum*) clove	~ 15–20	Antimicrobial properties	[261]
Fe	Tea leaves extract	30–100	Wastewater remediation	[262]
	Moringa oleifera	2.6–6.2	Removal of nitrate from water and antibacterial activity	[263]
	Trigonella foenum-graecum	~ 11	Dye degradation and antibacterial applications	[264]
Se	Plant extract of *O. tenuiflorum*	15–20	Medical and pharmaceutical applications	[265]
	Murraya koenigii	50–150	Larvicidal and bacteriostatic properties	[266]
	Zinziber officinale	100–150	Evaluation on antimicrobial and antioxidant activities	[267]
Pt	*Xanthium strumarium*	22	Biological studies	[268]
	Taraxacum laevigatum	2–7	Antibacterial activity	[269]
Pd	Mulberry fruit (*Morus alba* L.)	50–100	Antibacterial activity	[242]
	Couroupita guianensis Aubl.	5–15	Antibacterial and cytotoxicity activities	[270]
	Filicium decipiens	2–22	Antibacterial efficacy	[271]
Ni	*Calotropis gigantea* leaves	~ 60	Catalytic and antimicrobial potentials	[272]
Mn	*Cinnamomum verum*	50–100	Photocatalytic and antimicrobial activities	[273]
ZnO	*Calliandra haematocephala*	19.45	Photocatalytic dye degradation	[274]
	Aloe socotrina	15–50	Drug delivery approach	[275]
	Olive leaves	40.5–124	Antibacterial activity	[276]
	Tecoma castanifolia	70–75	Antioxidant, bactericidal, and anticancer activities	[277]
	Rhamnus virgata	~20	Evaluation of cytotoxic, antimicrobial, and antioxidant potentials	[278]
	Artocarpus gomezianus	30–40	Cytotoxicity, antibacterial, and antifungal activities	[279]
	Passiflora caerulea	30–50	Active against urinary tract infection pathogen	[280]
TiO_2	(*Citrus reticulata*) tangerine peels	50–150	Reduced environmental impact	[281]
	Glycyrrhiza glabra	69	Antibacterial activity	[282]
	Trigonella foenum graecum	20–90	Antimicrobial properties	[283]
	Artemisia haussknechtii	92.85	Antimicrobial and antioxidant activities	[284]
CuO	*Cymbopogon citratus*	11.4–14.5	Antibacterial and antibiofilm agents	[285]

Table 5 (continued)

NPs	Synthesized by	Size (nm)	Applications	Reference
	Citrofortunella microcarpa (calamondin)	54–68	Dye removal from wastewater	[234]
	Cordia sebestena	20–35	Photodegradation and antibacterial activities	[286]
FeO	*Avicennia marina*	10–25	Antibiofilm activity and in vitro toxicity	[287]
	Skimmia laureola	56–350	Antibacterial efficacy	[288]

membrane due to NPs adhesions is considered the first monitor for antimicrobial activity. On the other hand, Ghosh and co-authors [314] reported that the ability of NPs to interact with proteins in bacterial outer membrane causes harmful change in the bacterial cell wall.

Table 6 The most common instruments used for NPs characterizations

Characterization tool	Function
UV–visible spectrometry	Detection of surface plasmon resonance (SPR) which is attributed to reverberation of electron band on the surface of metal NPs with light wave
Fourier transformation infrared spectroscopy (FT-IR)	Detect functional groups which are responsible for reducing, capping, and stabilizing of metal NPs
Transmission, high-resolution, and scanning electron microscope (TEM, HR-TEM, and SEM)	Clarify the size, aggregation, and morphological shapes of NPs
Energy-dispersive spectroscopy (EDX)	Study the elemental composition and purity of green synthesized NPs
Dynamic light scattering (DLS)	Detect distribution and size of NPs in colloidal solution, detect agglomerations of NPs
Zeta potential	Detect surface charge of NPs which responsible for stability
Powder X-ray diffraction (XRD)	Detect the crystallographic shape of NPs, crystalline particle size
Atomic force microscope (AFM)	Study the 2D and 3D shape of NPs
X-ray photoelectron spectroscopy (XPS)	Study the surface chemistry, elemental composition, electronic and chemical state of elements within metal NPs
Vibrating sample magnetometer (VAM)	Study the hysteresis loops and the magnetic properties of the magnetic NPs
Thermogravimetric analysis (TGA)	Thermal behavior analysis
Brunauer–Emmett–Teller (BET)	Used to detect NPs surface area
Low-energy ion scattering (LEIS)	Give information about thickness of self-assembled monolayer
Photoluminescence (PL) spectroscopy	Used for fluorescence NPs characterizations such as quantum dots and metal nanoclusters
Nanoparticle tracking analysis (NTA)	Used to detect NPs size and NPs size distribution in liquid dispersion, analyze the capping efficiency in colloidal suspensions, determine the refractive index which explains the interaction between NPs and lights
Differential centrifugal sedimentation (DCS)	Detect NPs size based on sedimentation rates
Mass spectrometry (MS)	Study the elemental and molecular compositions and chemical state of NPs, study the bioconjugation of NPs with target biomolecules
Inductively coupled plasma-MS (ICP-MS)	Assessment of NPs chemical compositions, size distributions, and NPs concentrations
Ferromagnetic resonance (FMR)	Detect NPs size and their distribution, NPs shape, surface composition, magnetic anisotropic constant, demagnetization field

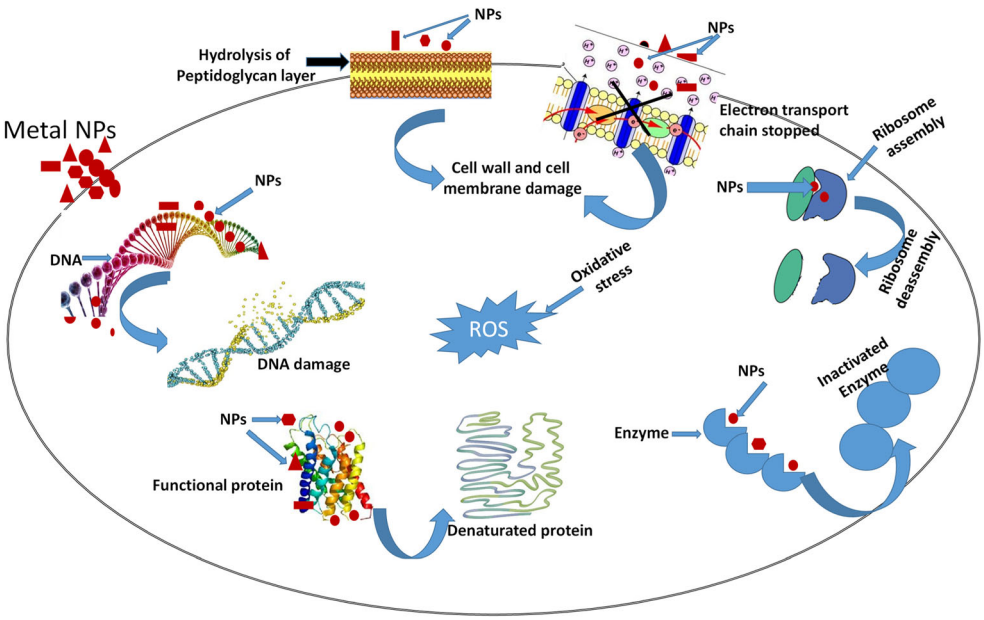

Fig. 5 Prospective mechanisms for antimicrobial activity for metallic NPs

According to the degree of damage in the cell wall, metallic NPs permeate the cell and cause irreversible effect in DNA and protein. Once NPs enter the bacterial cell, it interacts with DNA and converts it from normal state to condensed state, and hence, DNA loses replication ability [315]. Moreover, NPs cause enzyme inactivation due to reaction with a thiol group which is found in cysteine amino acid.

Antitumor Activities

Despite the availability of medications, millions of people die due to cancer every year. Additionally, the survival of patients is subjected to negative side effects due to consumption of available antineoplastic medicines. Therefore, the development of new NP-based drugs has received more attention due to its being more effective, providing little negative impacts and targeting cancer cells. These activities may be attributed to the large surface area of NPs that facilitate the combination of high drug doses [316]. Several types of NP-sized drug carriers such as polymeric micelles, liposomes, dendrimers, and inorganic NPs have been checked in cancer therapy to reduce the negative impacts of conventional anticancer drugs and improve the antitumor drug efficacy of target therapies [185, 265]. Inorganic nanomaterials, including metal oxides and metal (zinc oxide, iron oxide, titanium dioxide, gold, silver, and nickel particles), are promising materials applicable in medicine, such as in cell imaging, biosensing, gene or drug delivery, and cancer therapy [205, 247, 255].

Textile Industry

The incorporation of NPs to textiles during manufacture has increased in recent times because NPs improve the performance of finished fabrics. For example, Ag-NPs have been expended for enhanced antibacterial properties, self-cleaning properties, and UV blocking of finished fabrics [42, 124]. Also, ZnO-NPs are added to the textile industry for increasing UV locking and antibacterial properties [5, 8]. UV blockers due to the addition of inorganic NPs to the textile industry are preferable than UV blockers due to organic NPs [317]. In fact, the most common NPs, which are chemically stable and nontoxic when exposed to UV and high temperature, are TiO_2 and ZnO. Furthermore, NPs have a large surface area to volume percentage that consequentially results in a significant rise of the efficacy in UV blocking radiation compared to bulk materials [5, 8, 318, 319]. Recently, our published study is concerned with the different shapes of ZnO-NPs (hexagonal and nanorod) synthesized by *Fusarium keratoplasticum* A1-3 and *Aspergillus niger* G3-1 and characterized by FT-IR, TEM, XRD, and DLS. The hexagonal and nanorod ZnO-NP shapes exhibit antibacterial and cytotoxicity effects against normal and cancer cell lines. The safe dose of two NP shapes is loaded on cotton fabrics to enhance their properties such as antimicrobial activity against Gram-positive and Gram-negative bacteria and UV blocking activity [5].

Wastewater Treatment

Water is the greatest vital core in our life. Nowadays, overpopulation, lack of aquatic sustainability resources, and pollution are considered the most common problems facing human essentials. Nanotechnology provides a new strategy for solving most issues concerning water deficiency and quality [160]. Recently, nanotechnology-based wastewater treatment is able to provide high-performance treated water containing less impurities and less toxic substances and the removal of heavy metals [71]. A wide variety of nanomaterials are used in

the removal of toxic metals and inorganic and organic pollutants, disinfection, and detection of pathogens [160, 214]. The photocatalytic activities of Pd composite with ZnO-NPs allow the removal of pathogenic microbes from wastewater [200, 206]. A variety of metals in nanoscales, such as Ag, CuO, ZnO, TiO_2, and carbon nanotubes, have high potential to be used in the disinfection of wastewater and water [165, 234, 281]. According to an economic perspective, nanotechnology is accepted as a new strategy for utilizing the challenges of energy conservation and water resources. Unfortunately, the budget of this new nanotechnology should be properly achieved due to competition besides traditional technologies of wastewater treatment [262].

Food Industry

In the food industry, NPs applications are represented in nanoparticulate delivery systems, packaging, and food safety and security. In the pending future, it is clear that nanotechnology will provide specific characteristics in two key areas of food processing which are food packaging and food additives/ingredients [3, 320]. Some nanometal oxides, such as ZnO-NPs, were introduced to polymeric materials used in the manufacture of packaging tissue in order to improve their antimicrobial properties [321]. The nanomaterials were used in packaging operations, taking into account food safety. The researchers suggested producing nutritional covers and containers with the incorporation of ZnO-NPs, which offered antibacterial properties [322, 323]. Consequently, the usage of packaging containers that are treated by nanomaterials is a critical step and a good way to keep food fresh for a long time, reducing contamination and preventing food changes due to food-borne pathogens. Interestingly, Ag-NPs have the ability to penetrate and destroy bacterial biofilms which increase bacterial resistance during cleaning and decontamination processes [62, 324]. According to a biotechnological view, the availability of these NPs in the food industry would be of benefit in microbial biocontrol especially for those microbes that survive via biofilm formation [325].

NPs and Agriculture

Agriculture is the main process for providing human food, animal feed, desirable products, and necessary basic materials for different industries such as fibers and leathers and chemicals for industries such as starch, xylan, and sugars. Improving the agricultural system will have good effects on other sectors. Nanotechnology has positive impacts on different sectors of agriculture. These advantages include controlling plant pathogenic microbes, and NPs can be used as nanopesticides, nanoinsecticides, and nanofertilizers.

Nanofungicides

Fungi are the most common plant pathogens as compared to bacteria, viruses, and insects [103, 326]. There are many fungal genera, which are widespread phytopathogens such as species of *Fusarium* spp., *Phytopthora* spp., *Phoma* spp., *Aspergillus* spp., and *Phyllosticta* spp. [327]. Plant pathogenic fungi can be controlled by nanomaterials. Recently, Cu-NPs and CuO-NPs were synthesized by endophytic *Streptomyces* spp. and exhibited antifungal activity against plant pathogenic fungi represented as *Fusarium oxysporum*, *Alternaria alternata*, *Aspergillus niger*, and *Pythium ultimum* [4, 20].

Nanofertilizers

The major problems associated with the agricultural sector are represented in excessive and continuous use of chemical fertilizers, deficiency of water resources, and decrease of soil fertility which eventually affect crop production. The applicability of nanofertilizers leads to an increase in nutrient efficiencies, reduces soil toxicity, and reduces the negative effects related with overtreatment of chemical fertilizers. Hence, nanotechnology has a high efficacy for accomplishing sustainable agriculture, exceptionally in growing countries [328]. The presence of crystals or minerals, such as zeolites and nanoclays, can be practically used as nanofertilizers [329]. In another investigation, Subbarao et al. [330] developed strategies for the slow release of potash fertilizer with coating of plaster of Paris, wax, etc. It helps in the slow release of fertilizers and minimizes fertilizer loss [331, 332].

Nanopesticides

Nanopesticides include a great change of products that consist of inorganic ingredients (metal oxides) and/or organic ingredients (polymers) in numerous forms (particles, micelles). Recently, new formulations with nanoparticles have been accomplished and used in pesticides. Those metallic nanoparticles have good effectiveness against phytopathogens, pests, and insects that threaten the agricultural field in various countries around the world [326, 333–335]. Wang and co-authors [336] accomplished a new emulsion based on nanoparticles for used as pesticides against various pests that retard the agriculture process. On the other hand, Goswami et al. [333] concluded that the ability of different synthesized NPs, such as Ag-NPs, Al_2O_3-NPs, TiO_2-NPs, and ZnO-NPs, have the ability to control diseases in silkworm (*Bombyx mori*) caused by *Sitophilus oryzae* and baculovirus *B. mori* nuclear polyhedrosis virus. Recently, materials that depend on natural resources have been turned to green alternatives that are used in the formation of many types of promising and suitable nanoparticles to control many pests in various fields [334]. Recently, our published study revealed that, the ability of Se-NPs

synthesized by *Penicillium corylophilum* to control of 3rd instar of malaria vector *Anopheles stephensi* with low LC_{50} value (25.0 ppm) [337]

Bioremediation

Nowadays, biotreatment of pollutants such as dyes including azo dyes, acid dyes, cationic dyes, and others has received more attention due to their highly persistent and xenobiotic nature. Once these pollutants are disposed in water bodies such as rivers, lakes, and other water streams, this leads to an increase in water pollution and alteration in aquatic life [338]. NPs represent the green approach for treatment of these pollutants. Various studies reported the evaluation of the catalytic characteristic of some nanomaterials in reducing the hazards of environmental materials by using biological treatment processes combined with nanoscience [339, 340]. Interestingly, nanoscale silver exhibits good catalytic efficacy in decolorization of some organic dyes, which indicates that the nanocatalyst has an industrial role in the degradation process of organic dyes due to high efficiency and reaction rate [338]. Both Au-NPs and Ag-NPs act as catalysts in the degradation process of dyes, which increases the rate of reaction and, hence, reduces the time needed for the dye-removing process [341, 342]. Bastus et al. [343] postulated that the efficacy of NPs in dye reduction consists of two steps: first, inclusion of the accumulation of borohydride electrons on the surface of NPs, while the second step involved the diffusion of organic dye through its molecules on the surface of NPs and their subsequent reduction induced by superficial electrons. Reaction receipts are located on the surface of the surrounding nanocatalyst consequent to the properties of the capping molecules affected and the presence of reaction kinetics. Bhargava et al. [344] hypothesized that the surface proteins of the Au-NPs formed by the fungus *Cladosporium oxysporum* AJP03 may improve the process of adsorption of organic dyes (rhodamine B) such as amino acids that are attached to aromatic rings to form hydrophobic spaces that can improve the interaction with the dye by the nanocatalyst.

Conclusion and Future Challenges

Recently, metals and metal oxide NPs are widely synthesized for different biotechnological applications such as in biomedical, agricultural, industrial sectors and treatment of environmental pollutants. The green synthesis of NPs using biological entities such as bacteria, actinomycetes, fungi, algae, and plants has been developed as a significant part of biotechnology. The synthesis of NPs using the green approach has different advantages such as ease of synthesis and being cost-effective, eco-friendly, and easy to scale-up, hence overcoming the disadvantages of conventional methods. Therefore, increasing knowledge about green chemistry as greener routes for NPs synthesis opens the way for numerous biotechnological applications. Fundamentally, the green production of metal/metal oxide NPs using green methods has different uses, such as for antimicrobial and antitumor activity, controlling of different phytopathogens, the bioremediation process, the food industry, the textile industry, and wastewater treatment.

The major challenges that were observed during the green synthesis of NPs can be summarized as follows:

- The synthesis of a specific size and shape by the green method requires more optimization studies. Also, the production of NPs with specific physicochemical characteristics requires more studies especially for biomedical applications.
- The mechanistic aspect used for the fabrication of NPs by green methods requires more investigation.
- The metabolites involved in biological biomass filtrate should be completely analyzed to detect the role of each compound in NPs biofabrication.
- Scaling-up production of NPs by green methods is considered another challenge encountered in its commercialization.
- The stability of NPs with high yields correlated with optimizing factors such as pH, salt concentration, contact time, and temperature. These factors differ according to biological entities used.

Data Availability The data used to support the findings of this study are available from the corresponding author upon request.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

List of Abbreviations *NPs,* nanoparticles; *FT-IR,* Fourier transformation infrared spectroscopy; *TEM,* transmission electron microscopy; *SEM,* scanning electron microscopy; *AFM,* atomic force microscope; *DLS,* dynamic light scattering; *XRD,* powder X-ray diffraction; *EDX,* energy-dispersive spectroscopy; *SPR,* surface plasmon resonance; *XPS,* X-ray photoelectron spectroscopy; *Ag-NPs,* silver nanoparticles; *Cu-NPs,* copper nanoparticles; *CuO-NPs,* copper oxide nanoparticles; *Cu_2S-NPs,* chalcocite nanoparticles; *ZnO-NPs,* zinc oxide nanoparticles; *ZnS-NPs,* zinc sulfide nanoparticles; *Au-NPs,* gold nanoparticles; *Pt-NPs,* platinum nanoparticles; *Pd-NPs,* palladium nanoparticles; *Si-NPs,* silicon nanoparticles; *Ni-NPs,* nickel nanoparticles; *FeO-NPs,* iron oxide nanoparticles; *MgO-NPs,* magnesium oxide nanoparticles; *TiO_2-NPs,* titanium dioxide nanoparticles; *ZrO_2-NPs,* zirconium oxide nanoparticles; *TeO_3-NPs,* tellurium oxide nanoparticles; *SeO_3-NPs,* selenite nanoparticles; *Cd-NPs,* cadmium nanoparticles; *CdS-NPs,* cadmium sulfide; *Te-NPs,* tellurium nanoparticles; *Co_3O_4-NPs,* cobalt oxide nanoparticles; *Se-NPs,* selenium nanoparticles; *PbS-NPs,* lead sulfide nanoparticles; *MoS-NPs,* molybdenum sulfide nanoparticles; *Al_2O_3-NPs,* aluminum oxide nanoparticles; *CoO-NPs,* cobalt oxide nanoparticles; *CdTe-NPs,* cadmium telluride nanoparticles; *SiO_2-NPs,* silicon dioxide nanoparticles; *$BaTiO_3$-NPs,* barium titanium oxide nanoparticles; *Mn-NPs,* manganese nanoparticles; *MRSA,* methicillin-resistant *Staphylococcus aureus*; *LSP,* lipopolysaccharides

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