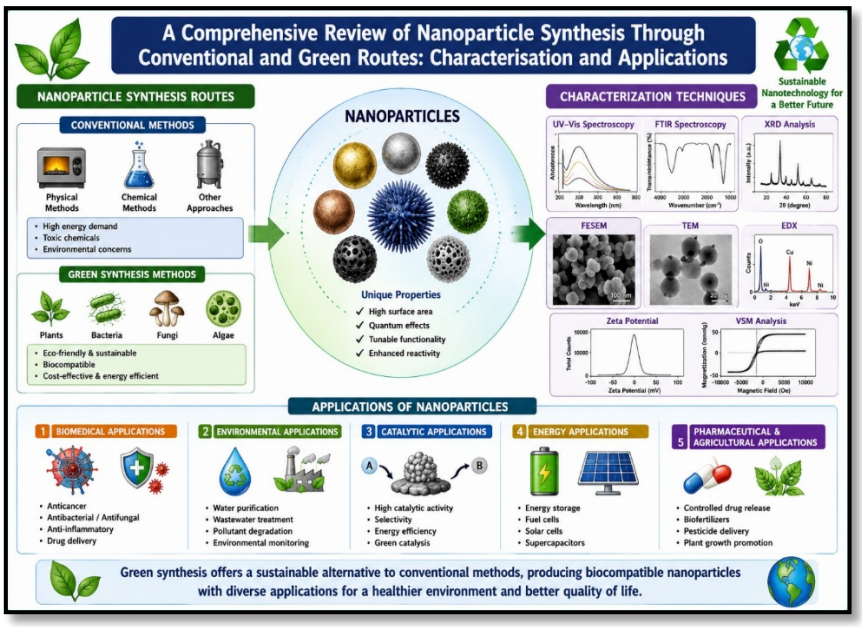
RESEARCH PAPER

A Comprehensive Review of Nanoparticle Synthesis Through Conventional and Green Routes: Characterisation and Applications

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ABSTRACT
Nanotechnology is a rapidly growing interdisciplinary field due to the unique properties of nanoscale materials. Nanoparticles exhibit exceptional optical, electronic, magnetic, catalytic and biological characteristics making them applicable in various domains. This review discusses both conventional and green methods for synthesizing nanoparticles including physical techniques, chemical methods approach. It emphasizes environmentally friendly green synthesis methods using biological sources like bacteria, fungi, algae and plants as sustainable alternatives. The review also covers essential characterization techniques to assess nanoparticle properties. Moreover, it explores recent advancements in nanoparticles applications across biomedical, environmental, catalytic and pharmaceutical fields. By comparing conventional and green synthesis strategies, the review offers insights into developing sustainable nanomaterials and highlights future opportunities for creating efficient, eco-friendly nanoparticles with improved functionality for various scientific and technological applications.
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Graphical abstract

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1. INTRODUCTION

Nanotechnology is the science and engineering of matter at the nanoscale, typically defined as dimensions between approximately 1 and 100 nanometres, where unique physical and chemical phenomena enable novel applications[1]. The term *nano* derives from the Greek word *nanos*, meaning dwarf, and denotes one billionth (10^{-9}) of a unit, such that one nanometre equals 10^{-9} meters. At this scale, materials exhibit size-dependent properties arising primarily from their high surface-area-to-volume ratio and quantum confinement effects resulting in unique optical, electrical, magnetic, mechanical and catalytic properties that differ significantly from those of their bulk counterparts[2].

The conceptual foundation of nanotechnology was first proposed by physicist Richard P. Feynman in his 1959 lecture *There's Plenty of Room at the Bottom* in which he envisioned manipulating atoms and molecules individually to fabricate materials and devices[3]. The term *nanotechnology* was later introduced by Norio Taniguchi in 1974 to describe manufacturing processes with nanometer-scale precision[4]. The field gained further recognition through K. Eric Drexler's 1986 book *Engines of Creation* which popularized molecular nanotechnology and stimulated extensive research in nanoscale science.

The rapid development of nanotechnology during the 1980s was accelerated by the invention of the Scanning Tunneling Microscope (STM) by Gerd Binnig and Heinrich Rohrer in 1981 enabling atomic-scale imaging and manipulation. Important milestones included the discovery of fullerenes (C_{60}) by Curl, Kroto and Smalley in 1985, Don Eigler's atomic manipulation experiment in 1990 the discovery of carbon nanotubes by Sumio Iijima in 1991 and the isolation of graphene by Andre Geim and Konstantin Novoselov in 2004. These discoveries established nanotechnology as a major interdisciplinary research field[5, 6].

Nanoparticles are particles having at least one external dimension between 1 and 100 nm. Owing to quantum confinement, localized surface plasmon resonance, superparamagnetic and their exceptionally high surface-area-to-volume ratio, nanoparticles exhibit remarkable physicochemical properties that are absent in bulk materials. They may consist of metals, metal oxides, semiconductors, carbon-based materials, polymers, ceramics or hybrid composites. Their optical, electronic, magnetic, catalytic and biological properties can be tailored by controlling particle size, shape, composition, crystallinity and surface chemistry making them valuable in catalysis, sensing, environmental remediation, energy conversion, agriculture, electronics and biomedical applications[7].

Nanomaterials are classified according to dimensionality based on the number of dimensions confined within the nanoscale (1-100 nm) as shown in Figure No. 1. Zero-dimensional (0D) nanomaterials have all three dimensions below 100 nm and include nanoparticles, nanoclusters, quantum dots and fullerenes. Their complete spatial confinement produces discrete electronic energy levels and size-dependent optical properties[8]. One-dimensional (1D) nanomaterials possess two nanoscale dimensions and one extended dimension including nanowires, nanorods, nanotubes and nanofibers. Their high aspect ratio facilitates efficient charge transport and enhanced mechanical properties making them suitable for nanoelectronics, sensors and energy-storage devices[9]. Two-dimensional (2D) nanomaterials possess nanoscale thickness with extended lateral dimensions and include graphene, transition-metal dichalcogenides (e.g., MoS_2) and other nanosheets. Their large surface area, exceptional electrical conductivity, mechanical strength and unique optical behaviour have attracted considerable attention for flexible electronics, catalysis, sensing and energy applications[10]. Three-dimensional (3D) nanomaterials are macroscopic materials assembled from nanoscale building blocks or containing nanoscale pores, grains or interfaces. Examples include nanoparticle assemblies, nanocomposites, porous nanostructures and multilayer nanofilms. These materials retain nanoscale interfacial effects that improve mechanical strength, thermal stability, electrical conductivity, catalytic efficiency and overall functional performance in engineering, environmental and energy-related applications[11].

2. METHODS OF SYNTHESIZING VARIOUS TYPES OF NANOPARTICLES AND ITS VARIOUS APPLICATIONS.

2.1 Physical methods-mediated nanoparticle synthesis.

Park, D. K. et al. (2010) Platinum nanoparticles were created by laser ablation of a Pt plate in water and the effect of polymeric stabilizers such as PVP, PVS and PEI was studied. The laser technique produced nanosized Pt particles and the polymer environment influenced their surface characteristics and catalytic behavior. The experiment established an electron-transfer catalytic reaction between ferricyanide ($Fe(CN)_6^{3-}$) and thiosulfate ($S_2O_3^{2-}$). PEI-stabilized Pt nanoparticles demonstrated the highest catalytic rate and the activity was dependent on pH and polymer concentration[12].

Huang, Z. et al. (2022) manufactured TiO_2 nanoparticles using pulsed laser ablation in liquid and optimized the laser-processing settings to enhance nanoparticle production and photocatalytic capabilities. Laser-processing parameters were optimized for TiO_2 nanoparticle manufacturing efficiency and photocatalytic performance. Experiments showed that controlling laser settings improved the photocatalytic performance of TiO_2 nanoparticles[13].

Hamad, A. et al. (2015) Picosecond laser ablation of a Ti/Ag alloy in deionized water resulted in the production of Ag- TiO_2 nanoparticles. The technique transformed the bulk alloy into spherical Ag- TiO_2 nanoparticles with an average size of 31 nm. The laser parameters and the alloy composition influenced nanoparticle production. The produced particles were experimentally examined for antibacterial activity including action against harmful microbes establishing their use as antibacterial nanomaterials[14].

Pandey, J. K. et al. (2014) produced silver nanoparticles in aqueous media using pulsed laser ablation and examined their antibacterial properties. The physical approach involved laser irradiation of a bulk Ag target without typical chemical reduction, with laser conditions governing nanoparticle production and size. The Ag nanoparticles were evaluated against human enteropathogenic Gram-positive and Gram-negative bacteria with inhibition zones, minimum inhibitory doses and growth curves determined. Thus, the proven application was antibacterial control of pathogenic microorganisms which is particularly relevant to antimicrobial systems[15].

Salavati-Niasari, M. et al. (2013) produced silica nanoparticles from rice husk ash using high-energy planetary ball milling. After 6 hours, mechanical impacts cracked and refined the initial silica resulting in roughly 70 nm spherical amorphous rice husk ash – SiO_2 nanoparticles. Increased milling time and rotational speed lowered particle size. The nanoparticles were subsequently loaded with Penicillin-G, and their release was monitored in simulated bodily fluid. A delayed-release profile was produced demonstrating their practical use as a controlled drug delivery carrier[16].

Li, J. et al. (2024) Ball milling was used to create porous boron nitride functionalized with Fe_3O_4 nanoparticles. Mechanical milling boosted the integration of Fe_3O_4 with porous boron nitride creating a magnetic composite with improved adsorption properties. Milling conditions had an impact on the structure and accessibility of surface sites. The material was utilized experimentally to remove cationic dyes from water and it outperformed the similar porous material in terms of adsorption. Therefore, the shown application is environmental wastewater cleaning via dye adsorption[17].

Giannakopoulos, K. et al. (2024) Spark-discharge aerosol production produces Cu and CuO nanoparticles. Electrical discharges between copper electrodes resulted in fast evaporation followed by condensation, resulting in aerosol nanoparticles measuring 10-20 nm. The metallic/oxide composition was determined by the electrical circuit parameters, discharge conditions, and the oxidation environment. Rather than simply describing the particles the researchers deposited the Cu/CuO aerosol onto face-mask air-filter materials experimentally proved antibacterial and antiviral efficacy against SARS-CoV-2[18].

Vons, V. A. et al. (2011) synthesised silicon nanoparticles using spark discharge was demonstrated. Electrical discharges were applied to silicon electrodes resulting in localized evaporation and fast gas-phase condensation. The electrical resistance, circuit behavior, carrier-gas conditions and discharge parameters all had an impact on nanoparticle creation. The work largely demonstrated regulated synthesis of semiconductor Si nanoparticles rather than addressing a specific biomedical or environmental use[19].

Huang, Y. et al. (2010) Bi_2WO6 porous microspheres were created using ultrasonic spray pyrolysis. An ultrasonically generated aerosol of the precursor solution was pushed thru a heated reaction zone where breakdown produced the oxide structures. Temperature, precursor concentration and aerosol droplet properties all had an impact on morphology and porosity. The material was directly tested for visible-light-induced photocatalytic removal of nitric oxide (NO) from air showing an environmental air-purification use[20].

Wu, Y. et al. (2021) CeO_2 nanoparticles were produced by spray pyrolysis a regulated aerosol-to-particle conversion technique. In the heated reactor, precursor droplets evaporated thermally decomposed and formed oxides resulting in CeO_2 nanoparticles with high surface area. Temperature, precursor concentration and aerosol conditions all had an impact on particle size and surface area. The work demonstrated the production of high-surface-area CeO_2 for catalytic/environmental material development[21].

Zhou, R. et al. (2017) produced Ag/TiO_2 nanoparticles thru continuous pulsed laser ablation and studied their photocatalytic properties. Laser irradiation created the nanostructured Ag/TiO_2 material, with laser-processing parameters affecting particle production and surface properties. The Ag/TiO_2 nanoparticles were examined for photocatalytic activity and shown increased performance[22].

Hmmoodi, A. M. et al. (2024) NiO nanoparticles were produced by pulsed laser ablation in liquid. A pulsed laser irradiated a Ni target in liquid and the laser energy density was adjusted to control nanoparticle production. Increasing laser energy density had an effect on the size and morphology of NiO nanoparticles highlighting the significance of laser fluence as a regulating factor. The generated NiO nanoparticles were then studied for a photodetector application as an optoelectronic device rather than a general NiO application[23].

Shaker, S. S. et al. (2026) produced MoS_2 nanoparticles in liquid using pulsed laser ablation and studied their applicability in photodetection. Molybdenum was laser-ablated in a thiourea-containing liquid, and the addition of SDS was employed to alter nanoparticle characteristics. The laser wavelength, pulse circumstances, liquid composition and surfactant content all had an impact on the final morphology and optical properties. The nanoparticles were experimentally included and tested for high-performance photodetection making the actual demonstrated application an optoelectronic photodetector rather than a suggested semiconductor application[24]. As per shown in Table No.01.

Table No. 01. Comparative Studies Physical Method Mediated Nanoparticles.

Sr. No.	Methods of Preparation	Name of Nanoparticles	Applications	Author Name and References
1	Laser ablation in liquid	Pt nanoparticles	Electron-transfer catalysis between ferricyanide and thiosulfate	Park, D. K. et al. (2010)[12].
2	Pulsed laser ablation in liquid	TiO_2 nanoparticles	Photocatalytic activity	Huang, Z. et al. (2022)[13]
3	Picosecond laser ablation of Ti/Ag alloy in deionized water	Ag–TiO_2 nanoparticles	Antibacterial activity	Hamad, A. et al. (2015)[14].
4	Pulsed laser ablation in aqueous medium	Ag nanoparticles	Antibacterial activity against pathogenic Gram-positive and Gram-negative bacteria	Pandey, J. K. et al. (2014)[15].
5	High-energy planetary ball milling	SiO_2 nanoparticles	Controlled drug delivery of Penicillin-G	Salavati-Niasari, M. et al.(2013)[16].
6	Ball milling	Fe_3O_4 functionalized porous boron nitride	Removal of cationic dyes from wastewater	Li, J. et al.(2024)[17].
7	Spark-discharge aerosol production	Cu/CuO nanoparticles	Antibacterial and antiviral activity against SARS-CoV-2	Giannakopoulos, K. et al. (2024)[18].
8	Spark discharge	Si nanoparticles	Controlled synthesis of semiconductor nanoparticles	Vons, V. A. et al. (2011)[19].
9	Ultrasonic spray pyrolysis	Bi_2WO_6 porous microspheres	Visible-light photocatalytic removal of nitric oxide (NO) from air	Huang, Y. et al. (2010)[20].
10	Spray pyrolysis	CeO_2 nanoparticles	Catalytic/environmental material development	Wu, Y. et al. (2021)[21].
11	Continuous pulsed laser ablation	Ag/TiO_2 nanoparticles	Photocatalytic activity	Zhou, R. et al. (2017)[22].
12	Pulsed laser ablation in liquid	NiO nanoparticles	Photodetector/optoelectronic application	Hmmoodi, A. M. et al. (2024)[23].
13	Pulsed laser ablation in liquid	MoS_2 nanoparticles	High-performance photodetection	Shaker, S. S.et al. (2026)[24].

2.2 Chemical methods-mediated nanoparticle synthesis.

Khan, M. F. et al. (2016) produced ZnO nanoparticles by hydrolyzing, condensing, drying and thermally treating a zinc precursor in a sol–gel process. Nucleation, crystallinity and particle shape were impacted by the sol-gel reaction conditions, precursor concentration, hydrolysis and calcination. According to reports, the produced ZnO nanoparticles were smaller than 50 nm and had a distinctive hexagonal wurtzite structure with a thorn-like appearance. Instead of only proposing a biological use the authors demonstrated the antimicrobial efficacy of the nanoparticles by empirically assessing their antibacterial activity against pathogenic microbes[25].

Behnajady, M. A. et al. (2011) using titanium tetra-isopropoxide as the titanium source and acetic acid as a hydrolysis/modifying reagent, low-temperature sol-gel is used to create titanium dioxide nanoparticles. The formation and crystallinity of TiO_2 were regulated by the hydrolysis conditions, acetic acid content and heat treatment. The anatase phase of nanoscale size predominated in the resultant nanoparticles. The chemically produced TiO_2 environmental photocatalytic functionality was demonstrated thru an experimental investigation of its activity using photocatalytic degradation[26].

Dillip, G. R. et al. (2015) created a ZnO/carbon-nanofiber nanohybrid by employing a modified three-step co-precipitation method with graphitic carbon nanofibers and a zinc precursor. Nucleation, dispersion and interfacial characteristics were influenced by the precipitation sequence, precursor concentration and ZnO-carbon nanofiber interaction. A heterogeneous nanostructure with enhanced interfacial charge-transfer properties was created by depositing nanosized ZnO particles on the carbon

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nanofiber surface. The ZnO/CNF interface contributed to better photocatalytic behavior when the materials photocatalytic activity was examined experimentally[27].

Brintha, S. et al. (2016) created Al- and Ni-doped ZnO nanoparticles utilizing a sol-gel method with zinc precursor and supplies of aluminum and nickel dopants. The primary factor influencing lattice distortion, crystallite size, optical properties and morphology was the dopant concentration. The hexagonal wurtzite ZnO structure was preserved in the resultant nanoparticles but the crystallite and surface properties were altered by the addition of Al and Ni. The produced doped ZnO nanoparticles showed antibacterial efficacy when tested experimentally against four harmful bacterial strains[28].

Rathore, M. S.et al. (2024) synthesized ZnO nanoparticles using a chemical sol-gel process, then heat treatment to produce crystalline ZnO. Crystallinity, crystallite size and optical emission properties were all impacted by the synthesis conditions and calcination. The nanoparticles were 21 nm in size and displayed the distinctive hexagonal ZnO crystal structure. The chemically produced ZnO nanoparticles had quantifiable antimicrobial action in addition to their optical characteristics, as demonstrated by the scientists experimental investigation of photoluminescence and antibacterial behavior[29].

Ismail, A. M. et al. (2019) created ZnO nanoparticles by a sol-gel chemical process and examined how calcination temperature affected the final nanomaterial. Crystallite growth, agglomeration and structural order were all affected by raising the calcination temperature. The size and crystallinity of the produced ZnO nanoparticles changed with heat treatment and their shape was primarily rod-like. The material produced under the ideal temperature conditions demonstrated significant inhibition against the identified bacteria when the nanoparticles antibacterial activity was subsequently assessed[30].

Khan, A. et al. (2016) produced zero-valent copper nanoparticles by chemical reduction with a copper precursor and ascorbic acid as the reducing agent; starch served as a stabilizing and protecting substance. The generation and stabilization of metallic Cu were regulated by the reducing-agent/stabilizer conditions during the synthesis, which was conducted in an aqueous solution at about 80°C. The resultant nanoparticles matched zero-valent crystalline copper and had a crystallite size of about 28.7 nm. Instead of designating an unproven biomedical application the work mainly illustrated the chemical synthesis and stability of Cu nanoparticles[31].

Wulandari, R. et al. (2024) produced copper nanoparticles by chemically reducing Cu^{2+} with sodium borohydride ($NaBH_4$) while CTAB was present as a surfactant. An ideal precursor/reductant/surfactant ratio was found to be roughly 1:20:4 after the concentrations of the Cu precursor, reducing agent and CTAB were methodically changed. Under the stated ideal conditions, the resultant nanoparticles showed the distinctive optical response of metallic Cu and had an average size of about 92 nm. The nanoparticles showed antibacterial efficacy when tested experimentally against *Staphylococcus aureus* and *Escherichia coli*[32].

Sharma, P. et al. (2022) using a reducing/stabilizing chemical method created chemically reduced copper nanoparticles and prepared numerous nanoparticle batches under regulated conditions. The synthesis conditions influenced colloidal stability and hydrodynamic particle size with reported hydrodynamic diameters in the 11-14 nm range. The nanoparticles had slightly steady colloidal behavior and typical copper-nanoparticle characteristics. Their biological performance was experimentally tested against *E. coli* and *Proteus vulgaris* utilizing MIC, MBC and cellular-damage measures which demonstrated bactericidal action linked with ROS production and membrane/cytoplasmic damage[33].

Chidurala, S. C. et al. (2016) copper nanoparticles were created utilizing surfactant-assisted chemical reduction, which involved combining a copper precursor, a chemical reducing agent and a stabilizing surfactant. The concentration of the surfactant and reducing agent influenced nucleation, particle growth and colloidal stability. The final substance was composed of nanoscale crystalline copper particles. The researchers evaluated the nanoparticles for antibacterial activity and found concentration-dependent suppression against the tested pathogens[34].

Tanna, J. A. et al. (2016) Copper nanoparticles were synthesized by chemical reduction with a copper precursor and diethylenetriamine as a protective/stabilizing reagent. The chemical environment and concentration of protective agents influenced the nucleation and stability of metallic Cu nanoparticles, resulting in crystalline nanoscale copper particles. Importantly, the authors used the produced Cu nanoparticles as a catalyst in a one-pot multicomponent synthesis of chromene derivatives revealing a practical organic-synthesis catalytic use. The antimicrobial activity of Cu nanoparticles was also examined[35].

Santhosh, M. V. et al. (2020) WO_3 nanoparticles were produced utilizing a hydrothermal technique with a tungsten precursor under controlled acidity conditions. Hydrothermal temperature, reaction duration, and solution chemistry all have an impact on phase formation and particle morphology. The produced material was composed of nanosized monoclinic WO_3 nanoparticles with a homogeneous particle distribution and a reported zeta potential of around −12.9 mV. The material was experimentally subjected to sono-catalytic degradation, confirming its ambient catalytic activity during ultrasonic irradiation[36].

Karunakaran, C. et al. (2014) created $BiVO_4$ nanoparticles using a hydrothermal chemical process and specifically looked into how pH affected phase and morphology. The reaction conditions were very pH-dependent: crystalline $BiVO_4$ was preferred at acidic circumstances about pH 5, whereas amorphous $BiVO_4$ was formed at about pH 12. Different optical and structural characteristics resulted from the variation in crystallinity. When the visible-light photocatalytic activity of the produced $BiVO_4$ materials was assessed experimentally, the amorphous material outperformed the crystalline equivalent[37].

Sun, Y. et al. (2009) created MoS_2 nanostructures using a solvothermal technique using precursors including sulfur

and molybdenum in an ethanol–water reaction media. Nucleation and anisotropic crystal formation were regulated by solvothermal temperature, reaction duration and solvent composition. The resultant material which was composed of nanoscale 10nm MoS_2 sheets organized into hierarchical structures, has a distinctive flower-like MoS_2 shape. Instead of providing a separate biomedical application, the work mainly showed controlled synthesis of flower-like MoS_2 nanostructures highlighting the connection between solvothermal conditions and morphology[38].

Nguyen, V. L. et al. (2010) created palladium nanoparticles using a polyol chemical process, where PVP acted as a stabilizer and a polyol was used as the reaction medium and reducing environment. Nucleation, growth and particle morphology were regulated by the Pd precursor concentration, PVP/Pd ratio and polyol reaction conditions. The size and shape of the produced nanoscale Pd nanoparticles could be adjusted by varying the chemical conditions. The study provided experimental evidence of chemical control over the size and shape of Pd nanoparticles[39].

Vivero-Escoto, J. L. et al. (2010) created mesoporous silica nanoparticles utilizing a silica precursor and surfactant template in a surfactant-directed sol-gel/Stöber-type chemical process. regulated particle size, pore diameter, mesostructural ordering, hydrolysis and condensation of the silica precursor, surfactant concentration and template removal. Mesoporous silica nanoparticles with organized pore channels and a large surface area made up the final product. The nanoparticles capacity to convey therapeutic compounds into cells was demonstrated thru experimental investigation as intracellular drug-delivery nanocarriers[40].

Kim, M. et al. (2023) Mesoporous silica nanoparticles were manufactured utilizing a modified Stöber chemical technique that included a silica precursor and a structure-directing surfactant. The nanoparticles ranged in size from 34.5 ± 2.3 to 216.0 ± 17.1 nm with a homogeneous spherical shape and regulated pore architecture[41].

Bouchoucha, M. et al. (2016) Functionalized mesoporous silica nanoparticles were created using a Stöber/sol-gel chemical method that included silica precursors, surfactants and surface-functionalization reagents. The particle size was purposefully regulated between 45 and 500 nm, while the surface chemistry and mesoporous structure were tailored using the chemical composition and synthesis conditions. The resultant nanoparticles have excellent dispersibility and regulated pore properties. The authors experimentally studied controlled drug release and antitumor activity, including cellular and biological evaluations demonstrating a biomedical nanocarrier application rather than simply recommending drug transport[42]. As per shown in Table No.02.

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Table No. 02. Comparative Studies Chemical Method Mediated Nanoparticles.

Sr. No.	Methods of Preparation	Name of Nanoparticles	Application	Author Name and References
1	Sol–gel	ZnO nanoparticles	Antibacterial activity	Khan, M. F. et al. (2016)[25].
2	Low-temperature sol–gel	TiO_2 nanoparticles	Environmental photocatalytic degradation	Behnajady, M. A. et al. (2011)[26].
3	Modified three-step co-precipitation	ZnO/carbon nanofiber nanohybrid	Photocatalytic activity	Dillip, G. R.et al. (2015)[27].
4	Sol–gel	Al and Ni-doped ZnO nanoparticles	Antibacterial activity	Brintha, S. et al. (2016)[28].
5	Chemical sol–gel followed by heat treatment	ZnO nanoparticles	Antibacterial activity	Rathore, M. S. et al. (2024)[29].
6	Sol–gel followed by calcination	ZnO nanoparticles	Antibacterial activity	Ismail, A. M.et al. (2019)[30].
7	Chemical reduction using ascorbic acid with starch stabilizer	Zero-valent Cu nanoparticles	Chemical synthesis and stability of Cu nanoparticles	Khan, A. et al. (2016)[31].
8	Chemical reduction using $NaBH_4$ with CTAB	Cu nanoparticles	Antibacterial activity against *S. aureus* and *E. coli*	Wulandari, R. et al. (2024)[32].
9	Chemical reduction with reducing/stabilizing agents	Cu nanoparticles	Bactericidal activity against *E. coli* and *Proteus vulgaris*	Sharma, P. et al. (2022)[33].
10	Surfactant-assisted chemical reduction	Cu nanoparticles	Antibacterial activity	Chidurala, S. C. et al. (2016)[34].
11	Chemical reduction using diethylenetriamine as stabilizer	Cu nanoparticles	Catalyst for one-pot multicomponent synthesis of chromene derivatives; antimicrobial activity	Tanna, J. A.et al. (2016)[35].

12	Hydrothermal	WO_3 nanoparticles	Sonocatalytic degradation	Santhosh, M. V. et al. (2020)[36].
13	Hydrothermal	$BiVO_4$ nanoparticles	Visible-light photocatalytic activity	Karunakaran, C. et al. (2014)[37].
14	Solvothermal	MoS_2 nanostructures	Controlled synthesis of hierarchical flower-like nanostructures	Sun, Y. et al. (2009)[38].
15	Polyol process	Pd nanoparticles	Controlled size and morphology of Pd nanoparticles	Nguyen, V. L. et al. (2010)[39].
16	Surfactant-directed sol–gel/Stöber process	Mesoporous silica nanoparticles	Intracellular drug delivery	Vivero-Escoto, J. L. et al. (2010)[40].
17	Modified Stöber method	Mesoporous silica nanoparticles	Controlled mesoporous structure and particle morphology	Kim, M. et al. (2023)[41].
18	Stöber/sol–gel chemical method	Functionalized mesoporous silica nanoparticles	Controlled drug release and antitumor activity	Bouchoucha, M. et al. (2016)[42].

2.3 Green synthesised mediated Nanoparticles.

2.3.1 Bacteria-mediated nanoparticle synthesis.

Huq, Md. A. et al. (2021) Silver nanoparticles were manufactured utilizing the culture supernatant of the bacterium *Paenarthrobacter nicotinovorans* MAHUQ-43 allowing for an extracellular pathway in which bacterial metabolites served as reducing and capping components. The reaction was tracked by the emergence of the characteristic brown color and an Ag surface-plasmon resonance band at 466 nm. FE-TEM revealed primarily spherical Ag nanoparticles with diameters ranging from 13 to 27 nm, while XRD proved their crystalline character and FTIR demonstrated the involvement of bacterial biomolecules in reduction and stabilization. The resultant AgNPs were tested against Gram-positive *Bacillus cereus* and Gram-negative *Pseudomonas aeruginosa* and showed antibacterial efficacy[43].

Rajora, N. et al. (2021) reported the fast extracellular production of Ag nanoparticles using *Pseudomonas stutzeri* isolated from textile-contaminated soil. Bacterial culture and reaction conditions were improved for faster reduction of Ag^+ ions with bacterial extracellular metabolites acting as reducing and stabilizing agents. The generated AgNPs were nanosized with physical attributes determined by the optimal biological reaction circumstances. The nanoparticles were experimentally examined for antibacterial activity and cytotoxicity, showing activity against tested pathogens and giving a biological use[44].

Alsamhary, K. I. et al. (2020) Ag nanoparticles were created utilizing Bacillus subtilis as a biological reduction system. Bacterial biomolecules reduced Ag^+ and stabilized nanoparticles resulting in an ecologically friendly extracellular/biogenic synthesis. TEM found primarily spherical or nearly spherical particles ranging in size from 3 to 20 nm. The synthesized AgNPs were tested against multidrug-resistant *Staphylococcus aureus* (MRSA), *S. epidermidis, Klebsiella pneumoniae*, *E. coli* and *Candida albicans*. MIC values were determined and strong antimicrobial activity was demonstrated including MICs of approximately 230 µg/mL for *MRSA*, 180 µg/mL for *S. epidermidis*, 200 µg/mL for *E. coli* and 100 µg/mL for *C. albican*[45].

Nadaf, N. Y. et al (2019) the catalytic characteristics of gold nanoparticles were examined after they were produced using the bacterium *Bacillus marisflavi*. The bacterial biomass/cell-free biological components converted Au^{3+} to Au^0 resulting in biologically capped Au nanoparticles. The synthesis parameters include the concentration of gold precursor and biological material, as well as the reaction conditions, controlled nanoparticle production and colloidal properties. The resultant AuNPs were tested as catalysts for the reduction of organic pigments. Biosynthesized AuNPs degraded Congo-red by 98% in 20 minutes with $NaBH_4$ with an estimated rate constant of 0.2192 min^{-1} indicating a direct environmental catalytic application for dye degradation[46].

Kora, A. J. et al. (2017) bacteriogenic production of selenium nanoparticles was reported using *Escherichia coli* ATCC 35218. The bacterial method physiologically reduced selenium precursor ions to produce elemental selenium nanoparticles by microbial reduction. UV-visible spectroscopy, DLS, XRD, Raman spectroscopy, FESEM, TEM and EDX were used to identify the particles elemental selenium content and nanoscale shape. The study demonstrated bacterial reduction of selenium oxyanions and synthesis of recoverable elemental Se nanoparticles thus developing a bacteriogenic pathway for selenium nanoparticle manufacturing[47].

Liu, P. et al. (2023) using *Bacillus paramycoides* 24522 discovered a high-efficiency biological method for selenium nanoparticle manufacturing. Sodium selenite was added to the bacterial culture and the effects of pH, temperature and shaking speed were carefully tuned. Maximum reduction efficiency was achieved at 37°C and pH 6, while a shaking speed of 150 rpm resulted in approximately 99.39% selenite-reduction efficiency before decreasing at higher speeds. The resultant SeNPs were generally regular and spherical, with diameters ranging from 100 to 180 nm and a mean DLS size of around 150 nm. XRD revealed mixed crystalline/amorphous properties.

The SeNPs were experimentally investigated for antioxidant and antibacterial uses[48]. As per shown in Table No.03.

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Table No. 03. Comparative Studies Bacteria Method Mediated Nanoparticles.

Sr. No.	Methods of Preparation	Name of Nanoparticles	Application	Author Name and References
1	Extracellular bacterial synthesis using culture supernatant	Ag nanoparticles	Antibacterial activity against *Bacillus cereus* and *Pseudomonas aeruginosa*	Huq, Md. A.et al. (2021)[43].
2	Extracellular bacterial synthesis using *Pseudomonas stutzeri*	Ag nanoparticles	Antibacterial activity and cytotoxicity	Rajora, N. et al. (2021)[44].
3	Biogenic/extracellular bacterial synthesis using *Bacillus subtilis*	Ag nanoparticles	Antimicrobial activity against MRSA, *S. epidermidis*, *K. pneumoniae*, *E. coli* and *C. albicans*	Alsamhary, K. I. et al. (2020)[45].
4	Bacterial biosynthesis using *Bacillus marisflavi*	Au nanoparticles	Catalytic degradation of Congo red dye	Nadaf, N. Y.et al. (2019)[46].
5	Bacterial reduction using *Escherichia coli* ATCC 35218	Selenium nanoparticles	Bacteriogenic production of elemental Se nanoparticles	Kora, A. J. et al. (2017)[47].
6	Bacterial synthesis using *Bacillus paramycoides* 24522	Selenium nanoparticles	Antioxidant and antibacterial activity	Liu, P. et al. (2023)[48].

2.3.2 Algae-mediated nanoparticle synthesis.

Muthusamy, G. et al. (2017) *microalga Spirulina* sp. was used to produce Ag nanoparticles via an algal-mediated reduction process. Biomolecules in the microalgal material reduced Ag^+ and stabilized the particles. Reaction variables such as silver precursor concentration, algae biomass and reaction duration all had an impact on nanoparticle production. The physicochemical features of the produced AgNPs were investigated and their efficacy against pathogenic bacteria was assessed. The work demonstrated the antibacterial efficacy of the *Spirulina*-mediated AgNPs[49].

Kumar, L. et al. (2024) produced Ag nanoparticles by methodically optimizing the biological synthesis using an aqueous extract of the freshwater microalga *Chlorella minutissima*. Important regulating factors included the reaction pH and the ratio of $AgNO_3$ precursor to algal extract; optimal synthesis was achieved at about pH 9, an $AgNO_3$ concentration of 10 mM and a ratio of 1:10. The nanoparticles had a zeta potential of −21.2 mV a mean diameter of roughly 73.13 nm, an SPR band at 426 nm and a mostly spherical shape. AgNPs produced distinct concentration-dependent inhibitory zones and shown a genuine antibacterial applicability when tested experimentally against *E. coli*, *Salmonella*, *Klebsiella*, *Staphylococcus aureus* and *Bacillus cereus*[50].

Raghuwanshi, N. et al. (2017) examined the antioxidant and anticancer effects of silver nanoparticles that were phyco-fabricated using the freshwater microalga *Chlorella minutissima*. While proteins and carbohydrates helped with stability and capping the aqueous algal extract decreased Ag^+ ions. XRD verified crystallinity while TEM showed mostly spherical particles with diameters between 10 and 30 nm. When tested against HepG2 liver-carcinoma cells the nanoparticles had greater radical-scavenging activity than the algal extract resulting in about 91.8% mortality at 120 μg/mL with an IC_{50} of 12.42 ± 1.096 μg/mL after 48 hours. Therefore, this study showed that algal-mediated AgNPs have direct anticancer and antioxidant applications[51].

Venkatesan, J. et al. (2014) created gold nanoparticles by converting chloroauric acid with algal macromolecules utilizing the sea brown algae *Ecklonia cava*. FTIR revealed that amine, hydroxyl and other functional groups contributed to the stability of the nanoparticles, and the reaction was remarkably quick finishing in about one minute at 80°C. Highly pure face-centered cubic Au was confirmed by XRD and microscopy showed spherical and triangular nanoparticles with an average size of 30 ± 0.25 nm. The artificial AuNPs utilized for cellular compatibility and biological activity[52].

Vijayan, S. R. et al. (2014) used an aqueous extract of the marine seaweed *Turbinaria conoides* to create both Ag and Au nanoparticles. In addition to providing biomolecules for stabilization, the biological extract decreased the corresponding metal ions. Spherical and triangular AgNPs of about 2–17 nm and AuNPs of about 2–19 nm was revealed by HRTEM. SPR bands occurred at around 421 nm for AgNPs and 538 nm for AuNPs. In contrast to AuNPs, AgNPs shown high action against marine biofilm-

forming bacteria with experimentally established MIC and MBC values and inhibition zones against *E. coli* that reached about 15.6 mm[53].

Elrefaey, A. et al. (2021) produced ZnO nanoparticles by utilizing an aqueous extract of *Cystoseira crinita* a brown sea algae. During the production of ZnO biomolecules like proteins and phenolic compounds served as reducing and capping agents. The produced particles had distinctive absorbance bands between 268 and 360 nm, whereas XRD verified crystallinity and TEM indicated multilayered rectangular particles between 23 and 200 nm. The nanoparticles showed both antibacterial and antioxidant properties when tested experimentally against *Bacillus cereus, Staphylococcus aureus*, *E. coli*, *Salmonella typhi*, *Candida albicans* and *Aspergillus niger*. They were also analyzed using the DPPH assay[54].

Fouda, A. et al. (2022) Magnesium oxide nanoparticles were produced utilizing the brown alga *Cystoseira crinita* and tested for various biological functions. Algal metabolites served as biogenic/capping components during MgO nanoparticle production, while synthesis conditions impacted particle size and morphology. The resulting MgO nanomaterial was physically and morphologically described and experimentally tested for antibacterial activity, in-vitro cytotoxicity, larvicidal activity and repellence demonstrating many biological applications rather than simply proposing them[55]. As per shown in Table No.04.

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Table No. 04. Comparative Studies Algae Method Mediated Nanoparticles.

Sr. No.	Methods of Preparation	Name of Nanoparticles	Application	Author Name and References
1	Algal-mediated biological synthesis using *Spirulina* sp.	Ag nanoparticles	Antibacterial activity against pathogenic bacteria	Muthusamy, G. et al. (2017)[49].
2	Algal-mediated synthesis using aqueous extract of *Chlorella minutissima*	Ag nanoparticles	Antibacterial activity against *E. coli*, *Salmonella*, *Klebsiella*, *S. aureus* and *B. cereus*	Kumar, L. et al. (2024)[50].
3	Phycofabrication using aqueous extract of *Chlorella minutissima*	Ag nanoparticles	Antioxidant and anticancer activity against HepG2 liver-carcinoma cells	Raghuwanshi, N. et al. (2017)[51].
4	Algal-mediated synthesis using *Ecklonia cava*	Au nanoparticles	Cellular compatibility and biological activity	Venkatesan, J. et al. (2014)[52].
5	Seaweed-mediated biological synthesis using *Turbinaria conoides*	Ag and Au nanoparticles	Antibacterial activity of AgNPs against marine biofilm-forming bacteria	Vijayan, S. R. et al. (2014)[53].
6	Algal-mediated green synthesis using aqueous extract of *Cystoseira crinita*	ZnO nanoparticles	Antibacterial and antioxidant activity	Elrefaey, A. et al. (2021)[54].
7	Algal-mediated biological synthesis using *Cystoseira crinita*	MgO nanoparticles	Antibacterial, in-vitro cytotoxicity, larvicidal and repellent activities	Fouda, A. et al. (2022)[55].

2.3.3 Fungi-mediated nanoparticle synthesis.

Mukherjee, P. et al. (2001) reported the first intracellular production of silver nanoparticles (AgNPs) utilizing *Verticillium sp*. Exposure to aqueous Ag^+ ions caused fungal cell-wall/membrane-associated biomolecules notably enzymatic components, to reduce Ag^+ to metallic silver. The production occurred intracellularly with nanoparticles developing beneath the fungal cell wall while the fungal cells remained alive and multiplying. The TEM investigation revealed nanoscale AgNPs with an average dimension of around 25 ± 12 nm. The study is significant because it showed that living fungal biomass may function as both a biological reduction system and a nanoparticle-forming matrix. The main shown contribution was the establishment of an intracellular fungal route for AgNP synthesis, rather than a discrete biomedical application[56].

Verma, V. C. et al. (2010) Extracellular AgNPs were produced utilizing the endophytic fungus *Aspergillus clavatus* (AzS-275). When exposed to 1 mM $AgNO_3$ the fungal system produced metallic Ag nanoparticles thru extracellular biomolecules. XRD, TEM and AFM validated the particle crystalline structure and nanoscale shape. The AgNPs were mostly spherical to hexagonal in shape and polydispersed measuring between 10 and 25 nm. The nanoparticles were tested against *Candida albicans*, *Pseudomonas fluorescens* and *Escherichia coli*. For *C. albicans*, the average MIC was 5.83 µg/mL and the MFC

was 9.7 µg/mL. Thus, the study established a antimicrobial biomedical use of fungal AgNPs[57].

Birla, S. S. et al. (2013) Optimized the fungal system physico-cultural parameters to study rapid AgNPs production by *Fusarium oxysporum*. The fungal filtrate was treated with $AgNO_3$ and parameters such as concentration, pH, temperature, fungal biomass and reaction time were tuned to accelerate nanoparticle formation. The produced AgNPs were crystalline and nanosized with the morphology determined by the biological reaction conditions. The study found that optimizing fungal culture conditions can significantly expedite mycosynthesis and boost nanoparticle output[58].

Wang, L. et al. (2016) generated AgNPs from the fungus *Arthroderma fulvum* and tested their antifungal efficacy. The fungal system was exposed to silver ions and fungal biomolecules helped to reduce and stabilize AgNPs. The resultant particle structure and morphology were determined using UV-visible spectroscopy, TEM, SEM, XRD and other techniques. The produced AgNPs were evaluated against pathogenic fungus from the genera *Candida*, *Aspergillus* and *Fusarium*. The study proved a direct antifungal application of *A. fulvum*-mediated AgNPs rather than simply hinting that they would be beneficial as antifungal materials[59].

Yassin, M. A. et al. (2021) produced AgNPs from the cell-free filtrate of *Penicillium verrucosum*. The fungal filtrate was treated with $AgNO_3$ which allowed extracellular fungal metabolites to decrease and stabilize silver nanoparticles. UV-visible spectroscopy, TEM, SEM, EDX and XRD were employed to determine nanoparticle production, elemental content, shape and crystallinity. The nanoparticles were polydisperse measuring roughly 10-12 nm. Their biological activity was tested directly against the phytopathogenic fungus *Fusarium chlamydosporum* and *Aspergillus flavus*. At 150 ppm, the AgNPs inhibited the growth of both fungal infections by around 50% suggesting antifungal action with possible application to plant-pathogen management[60].

Thakor, R. et al. (2022) AgNPs were produced utilizing cell-free filtrates from the marine fungus *Penicillium oxalicum* and *Fusarium hainanense* both individually and in a mixed fungal consortium. The cell-free filtrates were treated with silver nitrate under dark circumstances allowing extracellular fungal metabolites to decrease Ag and stabilize the nanoparticles. UV-visible examination revealed SPR maxima at around 438, 441 and 437 nm for AgNPs generated by *P. oxalicum*, *F. hainanense* and their consortia respectively. The nanoparticles were then examined for their antibacterial, antioxidant, larvicidal and anticancer effects[61].

Owais, M. et al. (2011) fungus *Candida albicans* was used to synthesize gold nanoparticles. The fungal system was subjected to gold precursor ions. Fungal biomolecules reduced Au^{3+} to Au^0 and stabilized the nanoparticles. TEM, AFM and spectroscopic methods were used to characterize the resultant AuNPs. AuNPs were studied in relation to liver cancer detection namely their interaction with cancer-associated molecular targets. As a result, this study presents an experimentally examined biomedical/diagnostic application of fungal-mediated gold nanoparticles[62].

Mishra, A. et al. (2012) Gold nanoparticles were manufactured using *Penicillium rugulosum* an industrial fungus. Both the supernatant broth and the live-cell filtrate were capable of creating AuNPs and even the potato-dextrose-broth growth media could create nanoparticles. Bio-TEM was used to measure nanoparticle size and morphology before/after purification and XRD FTIR, XPS and UV-visible spectroscopy validated the particles structural alongwith chemical properties. The study also evaluated the interaction of fungal AuNPs with genomic DNA extracted from *Escherichia coli* and *Staphylococcus aureus* revealing their use in nanoparticle-DNA interaction research and bio-nanotechnology[63].

Kitching, M. et al. (2015) derived fungal biosynthesis of gold nanoparticles was examined as well as the mechanism governing nanoparticle generation and scale-up. Fungal biomass and extracellular components were employed to decrease gold ions and released proteins helped to form and stabilize nanoparticles. The study focused on the interaction between fungal metabolism, Au ion reduction, nanoparticle generation and the feasibility of scaling up production from the laboratory to the wider scale. This is especially valuable for a literature review describing scale-up and mechanism of fungal nanoparticle synthesis even though the key contribution was nanoparticle creation rather than a separate biological assay[64].

Sharma, J. L. et al. (2021) Using a white-rot fungus produced zinc oxide nanoparticles and then integrated them into cellulose fibers. The fungal system provided biomolecules for ZnO nanoparticle creation while the synthesis conditions determined particle formation and surface properties. The generated ZnO nanoparticles were combined with cellulose to create antibacterial functional fibers. The composite fibers were experimentally tested for antibacterial efficacy, revealing a direct textile/materials use rather than simply reporting the biological activity of free nanoparticles. This research is very useful because it connects fungal-mediated nanoparticle production with a viable manufactured material[65].

Abdelhakim, H. K. et al. (2020) ZnO nanoparticles were produced from the culture filtrate of the endophytic fungus *Alternaria tenuissima*. The fungal culture filtrate served as the biological synthesis medium and nanoparticle production occurred quickly within about 20 minutes under the conditions described. The resultant ZnO exhibited a single-phase crystalline structure, but DLS revealed a substantially monodispersed solution with a reported PDI of around 0.311. The scientists experimentally examined many functions of the fungal ZnO nanoparticles including antibacterial, anticancer antioxidant and photocatalytic[66].

Hussein, H. G. et al. (2022) endophytic fungi were used to produce selenium nanoparticles which were then studied for biological activity. Selenium precursor ions were subjected to fungal biological systems, where fungal metabolites converted the selenium ions to elemental Se nanoparticles which helped to stabilize them. The generated SeNPs were structurally and morphologically described and the effect of fungal species and synthesis conditions on nanoparticle formation was studied. The produced selenium

nanoparticles were tested for antioxidant, antibacterial and antifungal properties[67]. As per shown in Table No.05.

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Table No. 05. Comparative Studies Fungi Method Mediated Nanoparticles.

Sr. No.	Methods of Preparation	Name of Nanoparticles	Application	Author Name and References
1	Intracellular fungal-mediated synthesis using *Verticillium* sp.	Ag nanoparticles	Demonstration of an intracellular fungal route for AgNP synthesis	Mukherjee, P. et al. (2001)[56].
2	Extracellular fungal-mediated synthesis using *Aspergillus clavatus* (AzS-275)	Ag nanoparticles	Antimicrobial activity against *Candida albicans*, *Pseudomonas fluorescens* and *Escherichia coli*	Verma, V. C. et al. (2010)[57].
3	Extracellular fungal-mediated synthesis using *Fusarium oxysporum* filtrate	Ag nanoparticles	Rapid and optimized mycosynthesis of AgNPs	Birla, S. S. et al. (2013)[58].
4	Fungal-mediated synthesis using *Arthroderma fulvum*	Ag nanoparticles	Antifungal activity against *Candida*, *Aspergillus* and *Fusarium* species	Wang, L. et al. (2016)[59].
5	Extracellular synthesis using cell-free filtrate of *Penicillium verrucosum*	Ag nanoparticles	Antifungal activity against phytopathogenic *Fusarium chlamydosporum* and *Aspergillus flavus*	Yassin, M. A. et al. (2021)[60].
6	Extracellular fungal synthesis using cell-free filtrates of *Penicillium oxalicum*, *Fusarium hainanense* and their consortium	Ag nanoparticles	Antibacterial, antioxidant, larvicidal and anticancer activities	Thakor, R. et al. (2022)[61].
7	Fungal-mediated biological synthesis using *Candida albicans*	Au nanoparticles	Biomedical/diagnostic application related to liver cancer	Owais, M. et al. (2011)[62].
8	Fungal-mediated synthesis using *Penicillium rugulosum*	Au nanoparticles	Nanoparticle–DNA interaction and bio-nanotechnology research	Mishra, A. et al. (2012)[63]
9	Fungal biomass/extracellular component-mediated synthesis	Au nanoparticles	Investigation of synthesis mechanism and scale-up feasibility	Kitching, M. et al. (2015)[64].
10	Fungal-mediated synthesis followed by incorporation into cellulose fibers	ZnO nanoparticles	Antibacterial functional textile/material	Sharma, J. L. et al. (2021)[65].
11	Culture-filtrate-mediated fungal synthesis using *Alternaria tenuissima*	ZnO nanoparticles	Antibacterial, anticancer, antioxidant and photocatalytic activities	Abdelhakim, H. K. et al. (2020)[66].
12	Fungal-mediated biological synthesis using endophytic fungi	Selenium nanoparticles	Antioxidant, antibacterial and antifungal activities	Hussein, H. G. et al. (2022)[67].

2.3.4. Plant Mediated Metal Nanoparticles.

2.3.4.a Synthesis of Iron Nanoparticles from Plant Extracts and It's Various applications.

Pattanayak, M. et al. (2013) described an eco-friendly approach for the synthesis of zero-valent iron nanoparticles utilizing the aqueous leaf extract of *Azadirachta indica* (Neem). In this study, naturally occurring phytoconstituents present in the plant extract functioned as both reducing and capping agents thereby avoiding the use of toxic chemical stabilizers and reducing agents commonly employed in conventional synthesis methods. The formation and physicochemical characteristics of the nanoparticles were

confirmed through UV–Visible spectroscopy, X-ray diffraction (XRD) and scanning electron microscopy (SEM). SEM observations indicated that the synthesized nanoparticles exhibited predominantly spherical to irregular morphology with particle sizes ranging from 50 to 100 nm. The investigation demonstrated that neem-assisted biosynthesis represents a cost-effective, sustainable and environmentally benign strategy for producing iron nanoparticles with potential utility in biomedical and environmental fields[68].

Saikia, I. et al. (2017) reported the green synthesis of silica-supported iron oxide nanoparticles using the fruit extract of *Zanthoxylum rhetsa*. The successful reduction of ferric ions and subsequent nanoparticle formation were visually indicated by the development of a brown coloration during the reaction process. Morphological and structural characterization was performed using scanning electron microscopy (SEM) and high-resolution transmission electron microscopy (HRTEM). SEM studies revealed a sheet-like morphology, whereas HRTEM analysis confirmed the presence of well-dispersed nanoparticles with particle sizes ranging between 5.0 and 21.0 ± 1.4 nm. The synthesized Fe_2O_3@SiO_2 nanoparticles exhibited remarkable catalytic activity and were effectively applied in the ipso-hydroxylation of boronic acid under aqueous conditions. The findings emphasized the efficiency of plant-mediated nanocatalysts as greener alternatives for catalytic organic reactions[69].

Devatha, C. P. et al. (2018) synthesized iron nanoparticles using the aqueous leaf extract of *Azadirachta indica* and investigated their antimicrobial efficacy against pathogenic bacterial strains. Different analytical techniques confirmed the successful formation of predominantly spherical nanoparticles with particle dimensions varying from 98 to 500 nm. The antibacterial potential of the synthesized nanoparticles was evaluated against *Escherichia coli*, *Pseudomonas aeruginosa* and *Staphylococcus aureus* using the agar well diffusion assay. The nanoparticles demonstrated considerable inhibitory activity against both Gram-positive and Gram-negative bacteria. This antimicrobial effect was attributed to membrane disruption, induction of reactive oxygen species (ROS)and interference with essential cellular metabolic functions. The study highlighted the possible application of green synthesized iron nanoparticles as effective antimicrobial nanomaterials[70].

Karpagavinayagam, P. et al. (2019) carried out the biosynthesis of iron oxide nanoparticles using flower extract of *Avicennia marina* for potential biomedical applications. The synthesized nanoparticles were characterized using UV–Visible spectroscopy, X-ray diffraction (XRD), scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Morphological analysis revealed a unique honeycomb-like architecture with particle sizes ranging from 30 to 100 nm. XRD results confirmed the crystalline nature of the nanoparticles, while electron microscopy demonstrated relatively uniform particle distribution. The authors proposed that bioactive phytochemicals present in the flower extract contributed significantly to nanoparticle reduction and stabilization. Due to their eco-friendly synthesis and favorable structural properties, the nanoparticles were considered promising candidates for biomedical and catalytic applications[71].

Patil, Y. Y. et al. (2020) investigated the green synthesis of magnetic iron nanoparticles using the leaf extract of the medicinal plant *Tridax procumbens*. The synthesized nanoparticles were analyzed using UV–Visible spectroscopy, XRD and SEM techniques, which confirmed the formation of spherical nanoparticles with an average particle size of approximately 72 nm. The antimicrobial activity of the nanoparticles was assessed against the Gram-negative bacterium *Escherichia coli* using agar well diffusion and Most Probable Number (MPN) methods. The synthesized nanoparticles exhibited substantial antibacterial activity, which was primarily associated with oxidative stress generation, damage to microbial cell membranes and disruption of metabolic pathways. The study demonstrated the importance of plant-mediated iron nanoparticles as sustainable antimicrobial agents with possible biomedical and environmental relevance[72].

Dowlath, M. J. H. et al. (2021) explored the biosynthesis of iron oxide nanoparticles using ethanolic leaf extract of *Cardiospermum halicacabum* and compared their characteristics with chemically synthesized counterparts. Vibrating Sample Magnetometry (VSM) analysis was employed to examine the magnetic behavior of the nanoparticles. The green synthesized FeONPs displayed a rhombohedral crystalline structure with particle sizes around 20.9 nm, whereas chemically synthesized nanoparticles exhibited larger particle sizes of approximately 42.3 nm. The biological properties of the nanoparticles were further evaluated through antibacterial and antioxidant studies. Antioxidant potential was measured using DPPH and ABTS radical scavenging assays, while antibacterial activity was tested against pathogenic bacterial strains. The biosynthesized nanoparticles showed enhanced antioxidant and antibacterial activities compared to chemically synthesized nanoparticles likely due to phytochemical capping molecules and increased surface reactivity. The investigation highlighted the biomedical significance of green synthesized iron oxide nanoparticles[73].

Aksu Demirezen, D. et al. (2022) synthesized iron oxide nanoparticles using aqueous extract of *Ceratonia siliqua* L. and evaluated their antibacterial efficacy against both Gram-positive and Gram-negative microorganisms. Antimicrobial activity was determined using the Kirby–Bauer well diffusion technique. Detailed characterization through SEM, TEM and UV–Visible spectroscopy demonstrated that the nanoparticles possessed monodispersed spherical morphology with an average particle size of 78 ± 22 nm. The nanoparticles exhibited strong antibacterial activity which was attributed to enhanced interaction between nanoparticles and bacterial cell walls, leading to oxidative stress and cellular damage. Additionally, optimization of synthesis conditions improved nanoparticle stability and dispersion behavior thereby increasing their suitability for biomedical applications[74].

Kirubavathy, S. J. et al. (2022) reported the green synthesis of magnetite iron oxide nanoparticles using aqueous leaf extract of *Coccinia grandis*. Various characterization techniques were employed to evaluate their structural, magnetic and morphological properties. The results confirmed the formation of cubic-shaped Fe_3O_4 nanoparticles with an average particle size of approximately 5.21 nm. In addition to physicochemical characterization, the in vitro anticancer activity of the synthesized nanoparticles was assessed using the MTT assay against cancer cell lines. The nanoparticles demonstrated significant cytotoxic activity which was mainly associated with oxidative stress induction, mitochondrial dysfunction and apoptotic cell death. The study suggested that plant-mediated magnetite nanoparticles may serve as promising candidates for future cancer therapeutics and nanomedicine applications[75].

Rauf, A. et al. (2025) developed an environmentally sustainable method for synthesizing iron oxide nanoparticles using aqueous extract of *Thevetia peruviana*. Comprehensive characterization of the synthesized nanoparticles was carried out using UV–Visible spectroscopy, Fourier Transform Infrared Spectroscopy (FTIR), scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Biological investigations demonstrated remarkable anticancer activity against multiple cancer cell lines, including HepG2, A498, NCI-H226, MDR and 2780AD. The nanoparticles induced cytotoxicity mainly through reactive oxygen species (ROS)-mediated oxidative stress and apoptotic pathways. Furthermore, the synthesized nanoparticles exhibited notable antidiabetic activity suggesting their multifunctional therapeutic potential. The study emphasized the importance of plant-mediated iron oxide nanoparticles as effective, sustainable and biocompatible nanomaterials for advanced biomedical applications[76]. As per shown in Table No.06.

Table No. 06. Comparative Studies of Plant Extracts Mediated Iron Nanoparticles.

Sr. No.	Methods of Preparation	Name of Nanoparticles	Application	Author Name and References
1	*Azadirachta indica* leaf extract green synthesis	Zero-valent iron nanoparticles (Fe^0 NPs)	Biomedical and environmental applications	Pattanayak, M. et al. (2013) [68].
2	*Zanthoxylum rhetsa* fruit extract green synthesis	Fe_2O_3@SiO_2 nanoparticles	Catalytic ipso-hydroxylation of boronic acids	Saikia, I. et al. (2017)[69].
3	*Azadirachta indica* leaf extract green synthesis	Iron nanoparticles	Antibacterial activity	Devatha, C. P. et al. (2018)[70].
4	*Avicennia marina* flower extract biosynthesis	Iron oxide nanoparticles	Biomedical and catalytic applications	Karpagavinayagam, P. et al. (2019)[71].
5	*Tridax procumbens* leaf extract green synthesis	Magnetic iron nanoparticles	Antibacterial activity	Patil, Y. Y. et al. (2020)[72].
6	*Cardiospermum halicacabum* leaf extract green synthesis	Iron oxide nanoparticles (FeONPs)	Antibacterial and antioxidant activities	Dowlath, M. J. H. et al. (2021)[73].
7	*Ceratonia siliqua* aqueous extract green synthesis	Iron oxide nanoparticles	Antibacterial activity	Aksu Demirezen, D. et al. (2022)[74].
8	*Coccinia grandis* leaf extract green synthesis	Magnetite iron oxide nanoparticles (Fe_3O_4 NPs)	Anticancer activity	Kirubavathy, S. J. et al. (2022)[75].
9	*Thevetia peruviana* aqueous extract green synthesis	Iron oxide nanoparticles	Anticancer and antidiabetic activities	Rauf, A. et al. (2025)[76].

2.3.4.b Green Synthesis of Nickel nanoparticles and its applications.

Mayedwa, N. et al. (2018) explored an environmentally benign approach for the biosynthesis of nickel oxide and palladium-based nanoparticles using aqueous leaf extract of *Aspalathus linearis* as a natural reducing and stabilizing medium. The phytoconstituents present in the plant extract, including polyphenols and flavonoids played a crucial role in the reduction of metal ions and stabilization of the resulting nanoparticles without the involvement of hazardous chemicals. Structural and morphological characterization was carried out using high-resolution transmission electron microscopy (HR-TEM) and selected area electron diffraction (SAED). The microscopic investigations revealed the formation of nanoparticles with diverse morphologies, predominantly semi-spherical and irregularly shaped structures, with an average particle size of approximately 31.8 ± 5 nm. Furthermore, the SAED

diffraction patterns confirmed the crystalline nature of the synthesized nanoparticles. The investigation demonstrated that *Aspalathus linearis*-mediated synthesis offers a simple, sustainable and eco-friendly strategy for the development of nanomaterials with promising catalytic and biomedical applications[77].

Iqbal, J. et al. (2020) developed a phytogenic method for the green synthesis of nickel oxide nanoparticles using fresh leaf extract of *Rhamnus triquetra* (Wall.) as a biological reducing and capping agent. During the reaction process, a visible color transformation from brown to dark green was observed indicating the successful bio-reduction of nickel ions and formation of nickel oxide nanoparticles. UV–Visible spectroscopic analysis further verified nanoparticle synthesis through the appearance of a characteristic absorption peak at 333 nm. Morphological analysis revealed predominantly spherical nanoparticles with an average particle size of nearly 65 nm. The biologically synthesized RT-NiONPs exhibited remarkable biomedical potential, particularly significant anticancer activity against human liver cancer cell lines HUH7 and HepG2 with IC50 values of 11.3µg/mL and 20.73µg/mL, respectively. In addition to anticancer effects the nanoparticles demonstrated potent antileishmanial activity against both promastigote and amastigote stages of *Leishmania* parasites highlighting their antiparasitic efficacy. Antioxidant potential was comprehensively assessed using CUPRAC, DPPH radical scavenging, total antioxidant capacity and total reducing power assays all of which confirmed excellent free radical neutralizing ability. The synthesized nanoparticles also showed pronounced antibacterial activity against pathogenic bacterial strains. The enhanced biological efficiency of RT-NiONPs was mainly attributed to the synergistic interaction between nickel oxide nanoparticles and phytochemical compounds adsorbed on the nanoparticle surface, which collectively enhanced oxidative stress induction and cellular disruption in pathogenic organisms and cancer cells[78].

Srihasam, S. et al. (2020) reported the biosynthesis of nickel oxide nanoparticles using *Stevia rebaudiana* leaf extract and evaluated their antibacterial and antioxidant properties under in vitro conditions. The phytochemicals present in the plant extract effectively acted as reducing and stabilizing agents during nanoparticle formation, thereby avoiding the use of toxic synthetic reagents. X-ray diffraction (XRD) studies confirmed the crystalline nature of the synthesized nanoparticles with particle sizes ranging between 20 and 55 nm. Morphological investigations demonstrated that the majority of nanoparticles were spherical in shape, although slight agglomeration was observed in some regions due to intermolecular interactions among particles. The antibacterial activity of the synthesized nanoparticles was tested against several Gram-positive and Gram-negative bacterial strains. Among the tested microorganisms, *Bacillus subtilis* and *Escherichia coli* showed higher sensitivity toward the nanoparticles indicating strong antimicrobial efficacy. The antibacterial mechanism was mainly associated with reactive oxygen species (ROS) generation, membrane disruption, protein denaturation and leakage of intracellular biomolecules. In addition, antioxidant activity was evaluated using the DPPH radical scavenging assay which demonstrated significant antioxidant potential due to the presence of phytochemical residues on the nanoparticle surface. The study highlighted the biomedical significance of *Stevia*-mediated nickel oxide nanoparticles as multifunctional therapeutic nanomaterials[79].

Taş, R. et al. (2021) synthesized nickel nanoparticles through a green and sustainable method using extract of *Peumus boldus* Koch as a natural reducing and stabilizing source. Bioactive compounds present in the plant extract effectively facilitated the reduction of nickel ions and prevented nanoparticle aggregation. Structural and morphological characterization was performed using scanning electron microscopy (SEM), UV–Visible spectroscopy, Fourier Transform Infrared Spectroscopy (FTIR) and X-ray diffraction (XRD) analyses. The synthesized nanoparticles predominantly exhibited round morphology with particle sizes ranging from 15 to 20 nm. FTIR studies confirmed the involvement of phenolic compounds, flavonoids and other phytochemicals in nanoparticle stabilization and surface capping. The antibacterial activity of the synthesized nickel nanoparticles was evaluated against pathogenic bacterial strains including *Escherichia coli* and *Staphylococcus aureus*. The nanoparticles demonstrated stronger inhibitory activity against *E. coli* than *S. aureus*, which may be attributed to differences in bacterial cell wall architecture and membrane permeability. The antimicrobial activity was mainly associated with oxidative stress induction, ROS generation and membrane damage caused by the nanoparticles. The study suggested that green synthesized nickel nanoparticles possess considerable potential for use in biomedical formulations, pharmaceutical products and antimicrobial surface coatings[80].

Uddin, S. et al. (2021) investigated the green synthesis of nickel oxide nanoparticles using stem extract of *Berberis balochistanica* a medicinal plant rich in biologically active phytochemicals. Prior to nanoparticle synthesis a detailed phytochemical screening of the stem extract was conducted to identify the compounds responsible for nanoparticle reduction and stabilization. X-ray diffraction analysis confirmed the crystalline nature of the synthesized nickel oxide nanoparticles with an average crystallite size of 31.44 nm, while scanning electron microscopy revealed rhombohedral agglomerated morphology. Additional characterization through FTIR and UV–Visible spectroscopy further validated nanoparticle formation and confirmed the presence of phytochemical functional groups on the nanoparticle surface. The biological properties of the synthesized nanoparticles were extensively investigated. Antioxidant activity assessed using the DPPH radical scavenging assay demonstrated strong free radical inhibition capacity. Cytotoxic potential was evaluated using the brine shrimp lethality assay, where the nanoparticles exhibited concentration-dependent toxicity. Antibacterial activity was examined against pathogenic bacteria such as *Proteus vulgaris* and *Staphylococcus aureus*, while antifungal activity was investigated against fungal pathogens including *Fusarium oxysporum*, *Aspergillus*

niger and *Alternaria alternata*. The synthesized NiO nanoparticles displayed significant inhibitory activity against both bacterial and fungal microorganisms. These biological effects were mainly attributed to oxidative stress induction, ROS generation, membrane disruption and interaction with intracellular proteins and nucleic acids. The study concluded that *Berberis balochistanica*-mediated nickel oxide nanoparticles provide a cost-effective, eco-friendly and biologically efficient approach for the development of multifunctional nanomaterials with potential biomedical and pharmaceutical applications[81]. As per shown in Table No.07

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Table No. 07. Comparative Studies of Plant Extracts Mediated Nickel Nanoparticles.

Sr. No.	Methods of Preparation	Name of Nanoparticles	Application	Author Name and References
1	*Aspalathus linearis* leaf extract biosynthesis	NiO NPs and Pd NPs	Catalytic and biomedical applications	Mayedwa, N. et al. (2018)[77].
2	*Rhamnus triquetra* leaf extract green synthesis	NiO NPs	Anticancer, antileishmanial, antioxidant and antibacterial activities	Iqbal, J. et al. (2020)[78].
3	*Stevia rebaudiana* leaf extract biosynthesis	NiO NPs	Antibacterial and antioxidant activities	Srihasam, S. et al. (2020)[79].
4	*Peumus boldus* extract green synthesis	Ni NPs	Antibacterial activity and potential biomedical/pharmaceutical applications	Taş, R. et al. (2021)[80].
5	*Berberis balochistanica* stem extract green synthesis	NiO NPs	Antioxidant, cytotoxic, antibacterial and antifungal activities	Uddin, S. et al. (2021)[81].

2.3.4.c Biosynthesis of Copper Nanoparticles and It's Applications.

Ghosh, S. et al. (2012) described an eco-friendly one-pot biosynthesis of copper nanoparticles employing extracts obtained from various parts of *Gnidia glauca* and *Dioscorea bulbifera*. In this investigation the leaves, flowers and fruits of *Gnidia glauca* together with the bulb extract of *Dioscorea bulbifera* acted as natural reducing and stabilizing agents during nanoparticle formation. The phytochemical constituents present in the extracts, particularly flavonoids, phenolics and other secondary metabolites, played a vital role in the bioreduction of copper ions and stabilization of the synthesized nanoparticles. The prepared copper nanoparticles were further evaluated for their antidiabetic potential through in vitro α-amylase and α-glucosidase inhibition assays. The nanoparticles demonstrated appreciable inhibitory activity against carbohydrate metabolizing enzymes, thereby suggesting their possible application in the regulation of postprandial hyperglycemia associated with diabetes mellitus. In addition, High-Performance Liquid Chromatography (HPLC) fingerprint analysis was performed to identify the bioactive phytochemicals responsible for nanoparticle synthesis and stabilization. The study emphasized that plant-mediated copper nanoparticles possess enhanced biological efficacy due to the synergistic interaction between copper ions and phytoconstituents present in the medicinal plants[82].

Harne, S. et al. (2012) reported a rapid and environmentally sustainable biosynthetic approach for the preparation of copper nanoparticles using aqueous latex extract of *Calotropis procera*. The latex extract served both as a reducing and capping agent thereby eliminating the requirement for hazardous chemical stabilizers and reducing agents. Characterization studies confirmed the formation of predominantly spherical copper nanoparticles with an average particle size of approximately 15 ± 1.7 nm. The smaller particle size provided a higher surface area which significantly enhanced their biological activity. The anticancer efficacy of the synthesized nanoparticles was investigated against several cancer cell lines including HeLa, A549and BHK21 using the MTT dye reduction assay. The copper nanoparticles exhibited significant cytotoxicity toward cancer cells, mainly through reactive oxygen species (ROS)-mediated oxidative stress, mitochondrial dysfunction, membrane damage and apoptosis induction. The study highlighted the therapeutic significance of green synthesized copper nanoparticles and suggested their potential utility in cancer nanomedicine and targeted drug delivery systems[83].

More P. et al. (2015) synthesized copper nanoparticles using the medicinal plant *Dioscorea bulbifera* through a simple green synthesis method and evaluated their biomedical applications. The phytochemicals present in the plant extract effectively reduced copper ions into stable nanoparticles and also acted as surface capping agents. Dynamic Light Scattering (DLS) analysis indicated nanoparticle sizes ranging from 12 to 16 nm while TEM analysis showed aggregated particles with sizes between 86 and 126 nm. The synthesized nanoparticles were investigated for antidiabetic activity using α-amylase inhibition assays and demonstrated effective enzyme inhibitory potential, suggesting their usefulness in glucose metabolism regulation. Furthermore, antioxidant activity

was assessed using DPPH, nitric oxide and superoxide radical scavenging assays where the nanoparticles exhibited remarkable free radical scavenging capacity. The enhanced antioxidant potential was mainly attributed to the combined action of copper nanoparticles and phytochemical molecules adsorbed on the nanoparticle surface. The study concluded that *Dioscorea bulbifera*-mediated copper nanoparticles could be utilized as promising therapeutic agents for diabetes management and oxidative stress-related disorders[84].

Sharmila, G. et al. (2016) carried out the green synthesis of copper oxide nanoparticles using leaf extract of *Tecoma castanifolia*. The phytochemical compounds present in the leaf extract facilitated the reduction of copper ions and simultaneously stabilized the nanoparticles formed during the reaction process. Morphological studies revealed the formation of predominantly circular nanoparticles with particle sizes below 100 nm. The antibacterial activity of the synthesized CuO nanoparticles was evaluated against pathogenic bacterial strains including *Escherichia coli* and *Staphylococcus aureus*. The nanoparticles demonstrated considerable bactericidal activity against both Gram-positive and Gram-negative bacteria. The antimicrobial mechanism was associated with membrane disruption, oxidative stress induction through ROS generation, leakage of intracellular constituents and inhibition of essential metabolic pathways within microbial cells. The study suggested that *Tecoma castanifolia*-derived copper oxide nanoparticles could serve as cost-effective and environmentally friendly antibacterial agents suitable for pharmaceutical formulations, food packaging materials, textile coatings and biomedical applications[85].

Ijaz, F. et al. (2017) synthesized copper oxide nanoparticles using aqueous leaf extract of *Abutilon indicum* and investigated their biomedical significance. The biosynthesized nanoparticles exhibited predominantly spherical morphology indicating uniform nanoparticle formation and stability. Antibacterial activity was assessed against several pathogenic microorganisms including *Staphylococcus aureus*, *Klebsiella pneumoniae* and *Bacillus subtilis* using the agar well diffusion method. The synthesized nanoparticles displayed effective antimicrobial activity against both Gram-positive and Gram-negative bacteria. Additionally, antioxidant activity was evaluated through DPPH radical scavenging assay, ferric reducing antioxidant power (FRAP), total antioxidant capacity and total phenolic content analysis. The nanoparticles demonstrated excellent free radical scavenging ability due to the presence of phytochemical capping molecules adsorbed on their surface. The study emphasized that plant-mediated CuO nanoparticles possess multifunctional therapeutic properties and may be useful in biomedical and pharmaceutical fields[86].

Mohindru, J. et al. (2017) reported the green synthesis of copper nanoparticles using aqueous tea leaf extract as a natural reducing agent, while starch and gelatin were employed as stabilizing agents to prevent nanoparticle aggregation. UV–Visible spectroscopy confirmed nanoparticle formation through characteristic absorption peaks in the range of 540–570 nm. Morphological analysis revealed that the synthesized nanoparticles possessed predominantly spherical morphology with particle sizes ranging from 50 to 100 nm. Magnetic characterization using a Vibrating Sample Magnetometer (VSM) demonstrated the paramagnetic behavior of the synthesized copper nanoparticles. The presence of unique optical and magnetic properties suggested that the nanoparticles may have potential applications in catalysis, magnetic devices, biomedical imaging, biosensors and nanotechnology-based electronic systems. The study highlighted the importance of environmentally benign synthesis approaches for the production of multifunctional copper nanoparticles[87].

Nagajyothi, P. C. et al. (2017) synthesized copper oxide nanoparticles using aqueous extract of b*lack bean* through an eco-friendly green synthesis method and evaluated their anticancer activity. Characterization studies confirmed the formation of spherical nanoparticles with an average particle size of approximately 26.6 nm. The smaller nanoparticle size and larger surface area significantly enhanced their interaction with biological systems. The synthesized CuO nanoparticles were investigated for cytotoxic activity against human cervical carcinoma cells under in vitro conditions. The nanoparticles demonstrated remarkable anticancer activity through ROS-mediated oxidative stress, mitochondrial dysfunction, DNA fragmentation and apoptosis induction in cancer cells. The enhanced cytotoxic efficiency of the nanoparticles was attributed to their nanoscale dimensions and improved cellular penetration capability. The study suggested that green synthesized copper oxide nanoparticles may serve as effective nanotherapeutic agents for cancer treatment[88].

Vaidehi, D. et al. (2018) synthesized copper oxide nanoparticles using leaf extract of *Solanum lycopersicum* through a green synthesis route and characterized them using several analytical techniques. TEM analysis revealed the formation of circular nanoparticles with particle sizes ranging from 20 to 40 nm. FTIR analysis confirmed the presence of phytochemical functional groups responsible for nanoparticle reduction and stabilization. The antibacterial efficacy of the synthesized CuO nanoparticles was evaluated against *Bacillus subtilis*, *Escherichia coli* and *Staphylococcus aureus*. Among the tested microorganisms, *Bacillus subtilis* exhibited greater susceptibility toward the nanoparticles. The antibacterial mechanism involved disruption of bacterial cell walls, ROS generation, oxidative stress induction and leakage of intracellular materials. The study highlighted the potential application of biosynthesized CuO nanoparticles as efficient antimicrobial agents for environmental and biomedical applications[89].

Tavakoli et al. (2019) performed a systematic green synthesis of copper oxide nanoparticles using *Aloe vera* extract and investigated their morphology-dependent antibacterial activity. The phytochemicals present in *Aloe vera* acted as natural reducing and stabilizing agents during nanoparticle synthesis. Characterization studies revealed the formation of rod-shaped as well as spherical nanoparticles with particle sizes ranging between 9 and 23 nm. Antimicrobial activity was assessed using the agar well diffusion method against several pathogenic bacterial

strains. The nanoparticles exhibited significant antibacterial efficacy mainly due to enhanced surface reactivity, oxidative stress generation and membrane disruption in microbial cells. The study demonstrated that nanoparticle morphology plays a crucial role in determining antimicrobial efficiency and emphasized the biomedical significance of green synthesized copper oxide nanoparticles[90].

Jamdade, D. A. et al. (2019) synthesized novel copper nanoparticles using extracts of *Gnidia glauca* and *Plumbago zeylanica* through a green synthesis approach. Characterization studies confirmed the formation of highly stable circular nanoparticles with extremely small particle sizes ranging from 1 to 5 nm. Various spectroscopic and microscopic techniques verified the crystalline nature and stability of the synthesized nanoparticles. The antidiabetic activity of the nanoparticles was evaluated using porcine pancreatic α-amylase and α-glucosidase inhibition assays. The synthesized nanoparticles demonstrated significant inhibitory activity against carbohydrate metabolizing enzymes suggesting their potential application in diabetes management. The enhanced biological activity was attributed to the synergistic interaction between copper nanoparticles and plant-derived phytochemicals acting as surface capping agents[91].

Tahvilian, R. et al. (2019) synthesized copper nanoparticles using leaf extract of *Allium saralicum* through an environmentally friendly synthesis method. Characterization studies confirmed the formation of spherical nanoparticles with particle sizes ranging between 45 and 50 nm. Antioxidant activity was evaluated using the DPPH radical scavenging assay, where the nanoparticles exhibited efficient free radical neutralization capacity. Antibacterial activity was investigated using agar well diffusion and disk diffusion methods against pathogenic bacterial strains. The synthesized nanoparticles displayed strong antimicrobial efficacy due to membrane damage, ROS generation, oxidative stress induction and inhibition of essential intracellular enzymes. The study suggested that phytochemical-coated copper nanoparticles possess improved biological compatibility and enhanced therapeutic applications[92].

Andualem, W. W. et al. (2020) synthesized copper oxide nanoparticles using leaf extract of *Catha edulis* and investigated their biomedical applications, particularly antibacterial activity. The biosynthesized nanoparticles exhibited spherical morphology with particle sizes ranging from 18.20 to 28.10 nm. Antibacterial efficacy was evaluated using the disk diffusion method against several pathogenic bacterial strains. The nanoparticles demonstrated effective inhibitory activity against microbial pathogens which was mainly attributed to membrane disruption, oxidative stress induction, ROS generation and interference with intracellular biomolecules. The study emphasized that plant-mediated copper nanoparticles provide an eco-friendly and sustainable alternative to conventional antimicrobial agents for biomedical applications[93].

Iqbal, J. et al. (2022) synthesized copper oxide nanoparticles using seed extract of *Silybum marianum* and evaluated their multifunctional biomedical properties. Antidiabetic activity was investigated through α-amylase inhibition, urease inhibition and lipase inhibition assays where the nanoparticles exhibited significant enzyme inhibitory potential. Antimicrobial activity was determined using disk diffusion methods against pathogenic microorganisms and the nanoparticles displayed strong inhibitory effects. Antioxidant activity was assessed using free radical scavenging assays and ferric reducing antioxidant power (FRAP) analysis, demonstrating remarkable antioxidant potential. The study also reported ROS/RNS inhibitory activities suggesting effective oxidative stress regulation by the nanoparticles. The enhanced therapeutic efficacy was mainly attributed to phytochemical-mediated stabilization and the increased surface reactivity of the synthesized CuO nanoparticles[94].

Bhuvaneswari, K. et al. (2023) synthesized copper nanoparticles using the medicinal plant *Leucas aspera* and explored their diverse biomedical applications. The synthesized nanoparticles demonstrated significant anticancer activity against MCF-7 breast cancer cells while showing comparatively lower toxicity toward normal Vero cells. Antidiabetic activity was evaluated using α-amylase and α-glucosidase inhibition assays where the nanoparticles exhibited promising glucose regulatory potential. Furthermore, anti-inflammatory activity was assessed using albumin denaturation and human red blood cell membrane stabilization assays, demonstrating effective suppression of inflammatory responses. The multifunctional biological activities were mainly associated with ROS modulation, oxidative stress induction in cancer cells and the presence of bioactive phytochemicals on the nanoparticle surface. The study highlighted the therapeutic significance of plant-mediated copper nanoparticles for cancer, diabetes and inflammatory disorders[95].

Ramasubbu, K. et al. (2023) synthesized copper oxide nanoparticles using leaf extract of *Sesbania grandiflora* through a green synthesis route and evaluated their multiple biomedical applications including antidiabetic, antioxidant, antimicrobial and anti-inflammatory activities. The synthesized nanoparticles exhibited circular morphology with an average particle size of approximately 33nm. Antidiabetic activity was evaluated using α-amylase and α-glucosidase inhibition assays where the nanoparticles demonstrated effective enzyme inhibitory properties. Antioxidant activity was determined through the DPPH radical scavenging assay, confirming strong free radical neutralization potential. Antimicrobial activity was evaluated against *Escherichia coli*, *Pseudomonas aeruginosa* and *Staphylococcus aureus* in the presence of streptomycin. The nanoparticles exhibited enhanced antibacterial activity due to synergistic interactions between CuO nanoparticles and antibiotics. The study suggested that biosynthesized CuO nanoparticles possess substantial therapeutic potential for biomedical applications[96].

Sankara Narayanan et al. (2023) synthesized copper nanoparticles using leaf extract of *Emilia sonchifolia* and investigated their broad-spectrum biotherapeutic applications. Characterization studies confirmed the formation of round-shaped nanoparticles with an average

particle size of approximately 45 nm. Antidiabetic activity was evaluated using α-glucosidase inhibition assays, where the nanoparticles demonstrated promising glucose regulatory activity. Antibacterial activity was investigated against both Gram-positive and Gram-negative pathogenic bacterial strains and the nanoparticles exhibited effective microbial inhibition. Anti-inflammatory activity was assessed using protein denaturation and egg albumin assays confirming their anti-inflammatory efficacy. Additionally, anticancer activity was evaluated against human keratinocyte cancer cells (HaCaT) and human breast cancer cells (MCF-7). The synthesized nanoparticles demonstrated considerable cytotoxicity through ROS-mediated oxidative stress, mitochondrial dysfunction and apoptosis induction. The study concluded that *Emilia sonchifolia*-mediated copper nanoparticles possess multifunctional therapeutic properties and significant potential for future nanomedicine and biomedical applications[97]. As per shown in Table No.08.

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Table No. 08. Comparative Studies of Plant Extracts Mediated Copper Nanoparticles.

Sr. No.	Methods of Preparation	Name of Nanoparticles	Application	Author Name and References
1	*Gnidia glauca* and *Dioscorea bulbifera* extract green synthesis	Cu NPs	Antidiabetic activity	Ghosh, S. et al. (2012)[82].
2	*Calotropis procera* latex extract biosynthesis	Cu NPs	Anticancer activity	Harne, S. et al. (2012)[83].
3	*Dioscorea bulbifera* extract green synthesis	Cu NPs	Antidiabetic and antioxidant activities	More P. et al. (2015)[84].
4	*Tecoma castanifolia* leaf extract green synthesis	CuO NPs	Antibacterial activity	Sharmila, G. et al. (2016)[85].
5	*Abutilon indicum* leaf extract biosynthesis	CuO NPs	Antibacterial and antioxidant activities	Ijaz, F. et al. (2017)[86].
6	Tea leaf extract green synthesis	Cu NPs	Catalytic, biomedical, biosensing and electronic applications	Mohindru, J. et al. (2017)[87].
7	Black bean extract green synthesis	CuO NPs	Anticancer activity	Nagajyothi, P. C. et al. (2017) [88].
8	*Solanum lycopersicum* leaf extract green synthesis	CuO NPs	Antibacterial activity	Vaidehi, D. et al. (2018)[89].
9	*Aloe vera* extract green synthesis	CuO NPs	Antibacterial activity	Tavakoli et al. (2019)[90].
10	*Gnidia glauca* and *Plumbago zeylanica* extract green synthesis	Cu NPs	Antidiabetic activity	Jamdade, D. A. et al. (2019)[91].
11	*Allium saralicum* leaf extract green synthesis	Cu NPs	Antioxidant and antibacterial activities	Tahvilian, R. et al. (2019)[92].
12	*Catha edulis* leaf extract biosynthesis	CuO NPs	Antibacterial activity	Andualem, W. W. et al. (2020)[93].
13	*Silybum marianum* seed extract green synthesis	CuO NPs	Antidiabetic, antimicrobial and antioxidant activities	Iqbal, J. et al. (2022)[94].
14	*Leucas aspera* extract green synthesis	Cu NPs	Anticancer, antidiabetic and anti-inflammatory activities	Bhuvaneswari, K. et al. (2023)[95].

15	*Sesbania grandiflora* leaf extract green synthesis	CuO NPs	Antidiabetic, antioxidant, antimicrobial and anti-inflammatory activities	Ramasubbu, K. et al. (2023)[96].
16	*Emilia sonchifolia* leaf extract green synthesis	Cu NPs	Antidiabetic, antibacterial, anti-inflammatory and anticancer activities	Sankara Narayanan et al. (2023)[97].

3. CONCLUSION

Nanoparticle synthesis has gained considerable attention due to its wide-ranging applications in biomedical, environmental and industrial fields. Although conventional physical and chemical methods enable the production of nanoparticles with controlled properties their reliance on high energy input, sophisticated equipment and hazardous chemicals limits their sustainability. Green synthesis has emerged as an eco-friendly and cost-effective alternative with plant-mediated synthesis being particularly advantageous because of its simplicity, scalability and utilization of naturally occurring phytochemicals as reducing and stabilizing agents. Compared with microbial approaches plant-based synthesis is faster, safer and more suitable for large-scale production. Among various nanomaterials plant-derived iron, copper and nickel nanoparticles have demonstrated excellent physicochemical characteristics, stability, biocompatibility and multifunctional applications. Therefore, plant-mediated synthesis represents a promising and sustainable strategy for developing advanced nanomaterials supporting the future growth of green nanotechnology and its practical applications.

Author contributions

Sumangal S. Kale was involved in conceptualization, investigation and writing original draft. Ajay P. Nikum, Dadaso B. Shinde and Vijay L. Gurav help in data curation and data analysis. Ghanasham B. Sathe contributed to conceptualization, writing review, editing and supervision.

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Declarations

Ethics approval and consent to participate

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Competing interests

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AI Usage Declaration

No AI tools were used in the preparation or writing of this manuscript

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