Green Synthesis, Characterization, and Applications of Selected Nanoparticles: A Review

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Abstract
Recently, nanobiotechnology has attracted a lot of attention, as it is a rapidly emerging field which is still growing and developing efficient and advanced therapeutic protocols under the umbrella of nanomedicine and environmental remediation. It can revolutionize solutions to biomedical problems by developing effective treatment protocols and therapeutics. In this review, we come across the green synthesised metal oxide nanoparticles such as iron oxide, copper oxide, zinc oxide and some other mixed metal oxides using different plant sources, their characterisation techniques and applications. The seasonal distributions of plants and their compositions as well as issues with low purity and poor yield were the major concerns. Anyhow, current environmental problems and problems associated with chemical synthesis, were also taken in mind and selected green synthesis as an alternative development prospect with potential applications. However, focus and research are still required to make these therapeutics more effective and safer to use.

Key words: Green synthesis, iron oxide, zinc oxide, copper oxide.

Introduction

Metal oxide nanoparticles have been widely used in antimicrobial agents, anticancer drugs, wastewater treatment, degradation of harmful organic dyes, and other fields. Metal oxide nanoparticles have exceptional properties due to their small size, including quantum confinement, surface-to-volume ratio, plasmon excitation, biocompatibility, and surface modifiability. The green synthesis method for nanoparticles is getting more attention globally, due to its lesser cost, non-hazardous, and eco-friendly nature. One of the most threatening factors to human health today, as in the past, is pathogens, which cause significant damage to health. Antimicrobial infectious diseases have been a fatal problem worldwide. In the era of increasing antimicrobial resistance towards conventional antibiotics, antimicrobial nanoparticles appeared as one of the best alternatives. Many materials are used to destroy such bacteria. One of the biggest challenges encountered by the current generation is the evolution of antibiotic resistant bacteria as a result of excessive and inappropriate use of antibiotics. One of the most promising and novel approaches to combat these pathogens is utilization of nanomaterials as antimicrobial agents.

The investigation of antibacterial properties of materials containing heavy metals produced with plant extracts also continues. Surface and underground water sources are threatened by various pollutants every day. Due to the fact that heavy metals do not disappear, their presence in the environment is very dangerous. To develop inexpensive and highly stable photocatalyst materials for dye degradation is of great significance today, inorder to resolve the global environmental problems caused by dye abuse. Environmental methodologies are gaining recognition in this modern world. Also, environmental nanotechnology plays a major role in improving modern fields of environmental engineering and science. The biosynthesis of nanoparticles using fungi, bacteria, and plants through various biotechnological techniques is currently a new paradigm for environmental protection.

Synthesis of nanoparticles through plant extract is good because it eliminates the dangers of toxic chemicals, it is environmentally friendly, simpler, and safer as the reaction time is reduced and it can also be increased in size for higher operation. Nanoparticles have developed as a promising medicinal delivery technique in the last 10 years. Excessive use of antimicrobial medications including antibiotics has led to the emerging menace of antimicrobial resistance, which, as per the World Health Organization, is among the top ten public health threats facing humanity, globally. This necessitates that innovative technologies be sought that can aid in the elimination of pathogens and hamper the spread of infections.

Zinc oxide has multifunctionality owing to its extraordinary physico-chemical properties and functionality in a range of applications. Environmentally friendly copper oxide nanoparticles were prepared with a green synthesis route without using hazardous chemicals. The studies of metal oxides in environmental remediation of chemical and biological

pollutants are gaining huge importance. Biosynthesis techniques for nanomaterials have advanced significantly, promoting eco-friendly synthesis chemistry as a sustainable alternative to conventional methods. Nanotechnology is becoming a promise for scientific advancement nowadays in areas like medicine, consumer products, energy, materials, and manufacturing.

With the intense development of nanotechnology, copper oxide nanoparticles have terrible immense applications in electrical, optical and bio-medical applications. Iron oxide nanoparticles, especially when doped with metals, have emerged as a promising avenue for combating microbial infections. Like IONPs, the antimicrobial activities of doped-IONPs are also linked to their surface charge, size, and shape. Doping metals on nanoparticles can alter the size and magnetic properties by reducing the energy band gap and combining electronic charges with spins. Furthermore, smaller metal-doped nanoparticles tend to exhibit enhanced antimicrobial activity due to their higher surface-to-volume ratio, facilitating greater interaction with bacterial cells. Moreover, metal doping can also lead to increased charge density in magnetic nanoparticles and thereby elevate reactive oxygen species generation. These ROS play a vital role to disrupt bacterial cell membrane, proteins, or nucleic acids.

Iron oxide nanoparticles

Lakshmnarayanan et al., 2021 synthesised iron oxide nanoparticles using the leaf extract of *Bauhinia tomentosa* and it was immobilized in porcine pancreatic lipase. This immobilized lipase was used for the synthesis of 1,3-diolein using enzyme-mediated esterification of oleic acid and 94% diolein yield was achieved. Iron oxide nanoparticles were synthesized using *Aloe vera* extract at different temperature conditions and their application for zinc removal from aqueous solution using the method of adsorption of heavy metals was studied by Ahmadi & Izanloo, 2023. The obtained particles were spherical in shape and the ones synthesised at higher temperature had a more uniform structure with higher adsorption efficiency.

Matar & Andac, 2023 synthesised iron oxide nanoparticles using the extract of Brown Egyptian Propolis and evaluated their antibacterial activity and dye degradation efficiency. The obtained spherical shaped particles are found to be effective against the gram negative bacteria Pseudomonas aeruginosa with the MB dye adsorption capacity of up to 92.7%. Ahmed et al., 2021 fabricated iron oxide nanoparticles in a sustainable way using the seed extract of Punica granatum and used it for the solar-light driven photocatalytic degradation of Congo red and Bromophenol blue dye. Experimental results indicated remarkable photocatalytic activity suggesting that the synthesized nanoparticles could effectually be applied to remove organic dyes from the wastewater.

According to Hussain et al., 2023 the iron oxide NPs synthesized through a green synthesis route from leaves of Ficus Palmata holds a promising future and could be used in treating diseases, and microbial pathogenesis and also could be used as a vector in drug delivery. Moreover, they can also eradicate persistent dyes and could be used as an alternative to remediate pollutants from the environment. Buarki et al., 2022 synthesised iron oxide nanoparticles from the flowers of *Hibiscus rosa sinensis* using the microwave method. The reactions are repeated by changing the precursor concentration for different time and the obtained products had an average size of 51 nm. These particles also proved to be good antibacterials.

Catharanthus roseus is one of the potential plants for biosynthesis of nanoparticles due to its easy availability. Roy et al., 2022, green synthesized iron nanoparticles from this plant extract which exhibited notable antibacterial activity against E.coli and demonstrated efficient dye degradation ability, indicating their potential application in environmental remediation and antimicrobial treatments. Gupta et al., 2023 used green tea extract for the rapid synthesis of iron oxide nanoparticles which were amorphous in nature with spherical shape. These particles act as catalysts for the removal of dyes and show significant reusability. They were good antioxidants and exhibited moderate antibacterial activity.

Adhikari et al., 2022, synthesized iron oxide nanoparticles using *Psidium guajava* leaf extract, which was further applied for its industrial dye degradation and anti-microbial activities. The degradation efficiency was 82.1% in 95 min and 53.9% in 205 min for MB and MO, respectively. Likewise, the synthesized IONPs showed good anti-bacterial and anti-fungal activity with a ZOI of 13 mm and 15 mm for both bacterial and fungal strains respectively. Thereby proving that the IONPs can combat harmful organic dyes, and they can terminate the pathogenicity of several human pathogens. Shabbir et al., 2023, synthesised iron oxide nanoparticles from *Madhuca indica* extract using green synthesis protocols. The nanoparticles were further characterized and biological assays were also performed for the synthesized nanoparticles. *In silico* analysis to assess the druglike properties was performed. The 81% DPPH inhibition confirmed the antioxidant activity, and the 96.20% inhibition of egg albumin protein confirmed the anti-inflammatory activity. Additionally, the 73.26% inhibition of α-amylase, which was more than that of the control used, confirmed the antidiabetic activity.

Clove and green Coffee (g-Coffee) extracts were used by Mohamed et al., 2023, to synthesize green iron oxide nanoparticles, which were then used to sorb Cd^{2+} and Ni^{2+} ions out of an aqueous solution. The characterizations performed revealed that the main component of iron nanoparticles was magnetite when the Clove extract was used but, both magnetite and hematite were included when the g-Coffee extract was used. Sorption capacity for metal ions was studied as a function of sorbent dosage, metal ion concentration, and sorption period. Different isotherm and kinetic adsorption models were used to fit experimental adsorption data. Adsorption of Cd^{2+} and Ni^{2+} on the iron oxide surface was found to be heterogeneous, and chemisorption is involved in the rate determining step. Antimicrobial study showed broad spectrum antibacterial activity with increased activity against Gram positive bacteria than Gram negative one and more activity for Green iron oxide nanoparticles prepared from Clove than g-Coffee one.

Awais et al., 2023, engineered iron oxide nanoparticles using the gum extract of Bombax malabaricum plant. TEM analysis indicated the particles were uniform round shaped. The particle exhibited good antibacterial, anti-fungal,

antioxidant and photocatalytic activities. The influence of the reaction variables on the response (i.e. degradation percentage; D%) was investigated by using two different optimization approaches designated as one-factor-at-a-time (OVAT) and response surface methodology (RSM) approaches. The RSM exhibited better D% results (98.721%) in comparison to OVAT (94.23%) indicating that rather than the conventional OVAT approach, the RSM should be utilized for the optimization of the MB dyes. Furthermore, it was observed that MB dose acted as the main rate-limiting factor for optimizing the reaction. These additional insights regarding photocatalysis can only be acquired by using the statistical modelling approach.

Malaikozhundan et al., 2022, synthesised Multifunctional iron oxide nanoparticles using Carica papaya fruit extract which acted as antibacterial, antioxidant and photocatalytic agents to remove industrial dyes. SEM analysis revealed the presence of agglomeration. The results suggested that the synthesized Fe_2O_3 NPs could be used to treat microbial infections and oxidative damage. Further, Fe_2O_3 NPs may be used as a better biocatalyst for the removal of harmful industrial dyes from the environment. Mahmoud et al., 2021, used the mint leaf extract and orange peels for the preparation of copper oxide nanoparticles. The particles are characterised and then used for the removal of metals like Pb, Ni and Cd from contaminated water. Various parameters of batch experiments were considered for the removal of Pb(II), Ni(II), and Cd(II) using the CuO NPs such as nano sorbent dose, contact time, pH, and initial metal concentration.

Copper oxide nanoparticles

Bibi et al., 2021, reported the facile synthesis of multifunctional copper oxide nanosheets (CuO NS) using an aqueous extract of *Rhazya stricta.* The phytochemical investigation of *R. stricta* indicated the presence of saponins, tannins, and reducing sugars, responsible for the reduction and stabilization. Interestingly these particles were aligned together in 3D cubical sheets layered above each other via self-assembly. It showed enhanced antibacterial potential and appreciable photocatalytic potential causing the degradation of MB dye on solar irradiation. The green synthesised copper oxide nanoparticles were also used for the degradation of the antibiotic rifampicin by Nzilu et al., 2023. The reducing and capping agent used here was *Parthenium hysterophorus* whole plant aqueous extract. The agglomerated nanoparticles were spherical with monoclinic crystalline structure. . From this study, it can be concluded that CuO NPs synthesized from *Parthenium hysterophorus* aqueous extract are promising in the remediation of environmental pollution from antibiotics.

In another study by Priya et al., 2023, also the green synthesis and anti bacterial and anti-fungal activities were explained. Here the nanoparticles were reduced using the plant *Morinda citrifolia*. Atri et al., 2023, synthesised copper oxide in an eco-friendly, simple, low-cost, and economical synthesis method using Ephedra Alata aqueous plant extract as a reducing and capping agent and a study of their antifungal, antibacterial activity and photocatalytic performance under sunlight was carried out. Also, the biosynthesised nanoparticles were compared with their chemically synthesised counterparts. The obtained results revealed that the biosynthesized CuO-NPs can play a vital role in the destruction of pathogenic bacteria, the degradation of dyes, and the activity of antifungal agents in the bioremediation of industrial and domestic waste.

Moudgil et al., 2022 used *Eichhornia crassipes*, an aquatic weed, for the one-pot quick synthesis of cuprous and cupric oxide nanoparticles. The synthesized nanoparticles have a spherical morphology with an average diameter of 10 nm. Antioxidant assay performed showed an increasing trend in a dose-dependent manner with the percentage radical scavenging activity up to 94.70% at a much higher concentration of 1000 µg/ml. A significant cytotoxic activity against HeLa (cervical cancer) and HCT 116 (colorectal carcinoma) cell lines was detected with noted IC_{50} values of 17.17 and 13.70 µg/ml respectively. These nanoparticles are used in biomedical areas specifically in anticancer treatment due to their high toxicities.

Kazmi et al., 2021 studied the physicochemical and functional characterization of phyto-mediated copper oxide nanoparticles using three plants viz. *Alternanthera pungens* (Ap), *Adiantum incisum* (Ai) and *Trichodesma indicum* (Ti). CuO NPs revealed UV–Vis spectra in the range of 350–450 nm with distinct effect of different plants on their morphological and chemical characteristics as analyzed via SEM and FTIR. However, nanoparticle sizes were not influenced by the plants selected. Additionally, Cu-Ap but not Cu-V disclosed outstanding performance revealing noticeable inhibitory concentrations IC_{50} for antioxidant (49.66 ± 3.7 µg/ml), antidiabetic (22.74 ± 4.2 µg/ml), anti-inflammatory (100.82 ± 3.3 µg/ml), antitumor (20.61 ± 2.5 µg/ml) and MTT cytotoxicity (3.98 ± 0.8 µg/ml against HeLa cells) assessments.

Mohammad & Shyam, 2023focused on the green synthesis of copper oxide nanoparticles (CuO Np) from the plant *Vitex negundo*. This plant has mainly utilized for its antioxidant activity and abundant flavonoids, terpenoids, and other secondary metabolites. The CuONps were observed as crystalline structure, absorbing UV reading was 378 nm wavelength, spherical as seen in SEM images, and size was approximately 100 nm. Antimicrobial activity exhibit an efficient inhibition zone of 8 mm for CuO Np and 6 mm inhibition zones for streptomycin against *B. subtilis*. Subsequently, the synthesized nanoparticles showed significant anticancer activity against HepG2 cell lines rather than HeLa cell lines. The IC_{50} of CuO Np was observed as 49 µg/ml and 82 µg/ml, respectively, in HepG2 and HeLa cells.

Theophil Anand et al., 2021 synthesized copper oxide nanoparticles (CuO NPs) by the microwave combustion method using moringa oleifera and punica grantum. From the DRS-UV analysis, bandgap of CuO NPs synthesized using moringa oleifera and punica grantum samples were found to be 2.8 eV & 2.18 eV respectively. The surface morphology of the samples was examined by scanning electron microscope. It was observed that the dielectric constants decreased with increase in frequency and increases as the increase in temperature. The antimicrobial activity of copper oxide nanoparticles extracted from moringa oleifera L. and punica granatum L. was determined for microorganisms. Sackey et al., 2021 reported the green synthesis and characterization of CuO nanoparticles using Mimosa hamata flower extracts as reducing

agents. The average particle size obtained from the XRD for both annealed and as-prepared samples varied with the concentrations. The energy band gap calculated from the diffuse reflectance was 1.5 eV, 1.3 eV, and 1.2 eV for the different cupric acetate concentrations used, i.e. 0.5, 1.0 and 1.5 g per 10 mL, respectively. The photoluminescence properties obtained at ambient temperature gave emission peaks at 417 and 437 nm which were ascribed to the near-band-edge emission peak of CuO. Furthermore, Anti-bacterial studies were performed on both the as-prepared and annealed CuO for direct application purposes. The as-prepared CuO (liquid form) was demonstrated to have better antimicrobial activity than the CuO powder formed after annealing at 500 °C.

Alhalili, 2022 synthesised copper oxide nanoparticles with leaf extract of Eucalyptus Globoulus. The results of scanning electron microscopy and dynamic light scattering revealed that the green synthesized copper oxide nanoparticles are spherical and have a mean particle size of 88 nm, with a negative zeta potential of −16.9 mV. The XRD graph showed the crystalline and monoclinic phases of CuO nanoparticles. The average crystalline size around 85.80 nm. The adsorption characteristics of the nano-adsorbents were investigated using methyl orange, and the adsorption efficiency at room temperature attained 95 mg/L. Prathap et al., 2023 used the leaf extract of *Indigofera linnaei Ali*, an Indian medicinal plant, in the synthesis of copper oxide nanoparticles (CuO-NPs). Green chemistry is a safe and cost-effective method for the synthesis of nanoparticles using plant extracts. The synthesis of CuO NPs was confirmed using ultraviolet–visible spectrum. Different functional groups were identified using Fourier-transform infrared spectroscopy. X-ray diffraction was used to confirm the crystalline structure of the CuO-nanoparticles. SEM and EDAX analyses were performed to examine the surface morphology and elemental composition of the biosynthesized CuO-NPs. Furthermore, the synthesized CuO-NPs exhibited antibacterial activity against *S. aureus*, *P. aeruginosa*, *E. coli*, and *E. faecalis*. Additionally, they exhibited a good insecticidal effect on *Culex quinquefasciatus* larvae. The CuO-NPs inhibited human breast cancer cells in a concentration-dependent manner, with an IC_{50} value of 63.13 µg/mL.

Han et al., 2023 studied the preparation of copper nanoparticles using leaf extract of *A. monanthum* (AM-CuNPs) via eco-friendly green synthesis. The synthesized AM-CuNPs had spherical shapes with sizes in the range of 30–80 nm and were crystalline in nature. Furthermore, the AM-CuNPs possessed good antibacterial properties against selected major disease-causing bacteria, such as *E. coli*, *S. typhi*, *P. aeruginosa* and *S. aureus*. The antioxidant activity of AM-CuNPs exhibited potent free radical scavenging activities in DPPH, ABTS and H_2O_2 radical assays. Vijayakumar et al., 2021 performed biogenic synthesis of copper nanoparticles using three different spices star anise, nutmeg and mace, and determine their antibacterial properties. They were then characterized by UV-Vis spectroscopy, FTIR, GC-MS, EDAX, and SEM analysis. The antibacterial activities of the three extracts from spices were analyzed using growth zone inhibition and TLC-bioautography methods. The results showed that star anise spice extract had the highest antibacterial activity. These results indicate that such CuNPs phyto-formulated with spice extracts having antibacterial properties could be used as potential therapeutics for microbial diseases.

Ali et al., 2023 used the leaves of the Aegle marmelos plant for the green synthesis of copper oxide nanoparticles. The UV-Vis showed a peak at 330 nm, which may be due to the Surface Plasmon Resonance phenomenon. XRD analysis showed the crystalline nature of copper oxide nanoparticles (CuO NPs). In contrast, SEM showed that nanoparticles were not aggregated or clumped, EDX showed the presence of elemental copper., and further, the TEM analysis revealed the average particle size of copper oxide nanoparticles to be 32 nm. The MIC for *E. coli* and *S. aureus* was found to be 400 µg/mL, whereas for *C. albicans* and *C. dubliniensis* it was 800 µg/mL. The zone of inhibition in the well diffusion assay showed the antimicrobial activity of copper oxide nanoparticles, and it also showed that as the concentration of copper oxide nanoparticles increased, the zone of inhibition also increased. The prepared CuO NPs showed significant photocatalytic degradation of organic dyes in the presence of sunlight. Alshammari et al., 2023 studied, the synthesis of copper nanoparticles (CuNP) using root extract of the medical plant Rhatany (*Krameria* sp.) as a reducing and capping agent and investigated the influence of microorganisms. The formation of nanoparticles was confirmed through UV-spectrophotometer, FTIR technique and Transmission Electron Microscopy, Scanning Electron Microscopy, and X-ray diffractometer analysis. In tests with a few drug-resistant pathogenic bacteria and fungus species, CuNP showed good antimicrobial efficacy and significant antioxidant capacity. Green synthesized CuNPs were cost-effective and nontoxic and can be applied in agriculture, biomedical, and other fields.

Rehman et al., 2022 synthesized copper oxide nanoparticles (CuO NPs) using *Bergenia ciliata* (*B. ciliate*) leaf extract. The X-ray diffraction analysis showed that the CuO NPs were found to be highly crystalline, while the irregular morphology and other structural properties were investigated by scanning electron microscopy and transmission electron microscopy, and the average particle size was found to be 50.05 nm. Energy dispersive X-ray spectroscopy was used to determine the percentage composition and purity, whereas Fourier transform infrared spectroscopy was utilized to examine the surface functional groups. CuO NPs were tested for their antibacterial properties against Gram-positive and Gram-negative bacteria, and the activity was found to increase with an increasing concentration of CuO NPs in the wells. The dose-dependent antioxidant potential is slightly higher than ascorbic acid. Tai et al., 2023 successfully prepared copper oxide nanoparticles (CuONPs) via a biological approach using Mangifera Indica aqueous extract as a reducing agent. The characterization of the as-prepared CuONPs was investigated via modern analytical methods. Accordingly, the CuONPs exhibited a particle size distribution ranging from 20 to 80 nm and high stability. In addition, the CuONPs photo-catalyst was deployed in the photocatalytic degradation of malachite green under visible illumination thanks to the notable bandgap energy of 1.62 eV. Furthermore, CuONPs showed effective antibacterial activities toward both E. coli and S. aureus strains under light conditions than in darkness. Therefore, the green synthesized CuONPs served as the role of a photo-catalyst can be a promising choice for applications in environmental remediation.

Zinc oxide nanoparticles

Son et al., 2023, reported the synthesis of zinc oxide nanoparticles using extracts of guava leaves in an ecofriendly method. The anticancer activity of the synthesized zinc oxide nanoparticles was evaluated against different cancer cell lines, including A549 (lung cancer), HeLa (cervical cancer), and MCF7 (breast cancer), as well as normal human dermal fibroblast (HDF) cells, which showed that the zinc oxide nanoparticles exhibited significant anticancer activity, especially against the MCF7 and HeLa cancer cell lines, along with relatively low toxicity toward HDF cells.

ZnO NPs synthesized by Tilahun et al., 2023, using the *Ocimum lamifolium* leaf have a potential electrocatalytic activity for diverse organic pollutant detection as well as a desirable material for such drug resistance antimicrobial strains as they strongly inhibit the bacterial activity. According to Maher et al., 2023, zinc oxide nanoparticles can precisely and captivatingly promote the apoptosis of cancer cells in cancer treatment. The zinc oxide nanoparticles was prepared using an alcoholic and aqueous extract of *Sisymbrium irio* (L.) (Khakshi) prepared using the Soxhlet method. These particles were rich in phenolic and flavonoid content and had a hexagonal wurtzite structure. Also these green synthesised particles possess potential anticancer activity.

Manojkumar et al., 2023, used leaf extract of Brassica oleracea var. botrytis for the synthesis of zinc oxide nanoparticles by co-precipitation and applied for photocatalytic/antibacterial activity. The particles had flower shaped morphology with hexagonal wurtzite structure. Akbar Jan et al., 2021, explored the environmental and therapeutic applications of Myrtus communis L. assisted synthesized zinc oxide and iron doped zinc oxide nanoparticles. The optical band gaps was calculated to be Eg = 3.4 eV and Eg = 3.2 eV for ZnO and Fe-ZnO nanoparticles respectively. SEM analysis showed that ZnO nanoparticles are granular size and have irregular spherical morphology while with Fe doping there is dispersion of nanoparticles with less agglomeration as well as regular distribution of ZnO NPs. The characterized nanoparticles were used as photo catalyst in the degradation of Acid Yellow-3 dye. Effect of different parameters i.e. irradiation time, initial dye concentration, catalyst dosage and temperature was also studied. Excellent antioxidant potential was shown by the prepared NPs. Good haemolytic activity was shown by undoped ZnO NPs and good antibacterial activity by doped ZnO nanoparticles.

Faisal et al., 2021 synthesised zinc oxide nanoparticles from aqueous fruit extracts of *Myristica fragrans* and are characterised by XRD, FTIR, SEM, UV, TEM, DLS and TGA. The nanoparticles were pure and are spherical in shape and exhibited a mean size of 41.23 nm. . These particles were found to be highly active against bacterial strains. *Klebsiella pneumoniae* was found to be the most sensitive strain (27 ± 1.73). ZnO-Nanoparticles displayed outstanding inhibitory potential against enzymes protein kinase (12.23 ± 0.42), α-amylase (73.23 ± 0.42), and α-glucosidase (65.21 ± 0.49). Overall, the synthesized NPs have shown significant larvicidal activity (77.3 ± 1.8) against *Aedes aegypti*, the mosquitoes involved in the transmission of dengue fever. Similarly, tremendous leishmanicidal activity was also observed against both the promastigote (71.50 ± 0.70) and amastigote (61.41 ± 0.71) forms of the parasite. The biosynthesized NPs were found to be excellent antioxidant and photocatalytic agents. Thus, these nanoparticles are potential candidates for biomedical and environmental applications.

Mohammed et al., 2023 synthesized zinc oxide nanoparticles from zinc nitrate hexahydrate, using *Cymbopogon citratus* extract as a green reducing agent. The particles had a size of 20–24 nm, a wurtzite structure with a high crystallinity, and hexagonal rod-like shape. UV–Vis spectroscopy and FTIR results revealed the formation of Zinc oxide nanoparticles. Negative values of the highest occupied molecular orbital–lowest unoccupied molecular orbital for ZnO NPs indicated the good potential to form a stable ligand–protein complex. Docking results indicated favorable binding interaction between ZnO and DNA gyrase subunit b with a binding energy of −2.93 kcal/mol. Zinc oxide nanoparticles are good antibacterial agents with MIC of 92.07 ± 0.13 and 88.13 ± 0.35 μg/mL, against *E. coli* and *S. aureus* respectively, at a concentration of 2 mg/mL. Thus, Zinc oxide nanoparticles, can be employed as alternatives to antibiotics and a tool to eliminate drug-resistant microbes in the future.

MalligArjuna Rao et al., 2021 reported the green synthesis of zinc oxide nanoparticles from the plant extract of Camellia sinensis by using the hot plate combustion method (HPCM). The hexagonal wurtzite structure and the spherical rod shape with size equal to 10-20 nm were reveealed using various structural conformations. Synthesized ZnO NPs photocatalytic activity was evaluated by degrading methyl orange (MO) dye and degradation of 80 % using 0.5 g ZnO NPs for 180 min irradiation time and the antibacterial property of ZnO NPs was evaluated against two different strains of bacteria like Staphylococcus aureus and Escherichia coli; however, the antibacterial efficiency of ZnO NPs effective against E. coli compared to S. aureus.

M. Arumugam et al., 2021 studied, the synthesis of zinc oxide nanoparticles using *Syzygium cumini (Java plum)* aqueous leaf extract as a stabilizing and reducing agent. The in vitro antioxidant and cytotoxic potential were also analysed. The beneficial effect of ZnO NPs on the growth dynamics of sesame plant was investigated. The zinc oxide nanoparticles exhibited significant antioxidant activity against DPPH and H2O2 radical scavenging activity. Also, these particles show concentration dependant anticancer activity too. Green synthesized ZnO NPs were given as the nutrient source for the growth of the sesame plant with different concentrations (1, 3, 5, 7, 9 mg/ml). At the concentration of 5 mg/ml of ZnO NPs reveals significant growth in root and shoot of the plant when compared to the control. In total, the ZnO NPs can be used in the field of nanomedicine and nanonutrient.

J. Arumugam et al., 2021 obtained zinc oxide nanoparticles through biological method using phytochemicals present in leaf extract of Ficus carica tree. The scanning electron microscope images have indicated formation of small spherical ZnO NPs in the form of clusters whose diameter ranges between 30 and 40 nm having mean diameter of 35 nm. The X-ray diffraction pattern has exemplified several sharp crystalline peaks that are indexed to ZnO with hexagonal wurtzite structure and its average crystallite size is 33.39 nm. The ZnO NPs have demonstrated high bactericidal activity against

E. coli and K. pneumoniae strains with inhibition zone value of 17 mm. The photocatalytic performance of the green synthesized ZnO NPs has showed significant decolorization of methylene blue dye at 60 min of natural sunlight irradiation. Hence, the F. carica leaf extract is viewed as an appropriate green resource to prepare ZnO NPs with bactericidal and photocatalytic application prospects.

Hussein & Mohammed, 2021 synthesized zinc oxide nanoparticles using a reduction agent from aqueous grape extract (Vitis vinifera). The X-ray diffraction pattern of ZnO NPS exhibited a wurtzite (hexagonal) crystalline structure. Fourier transform infrared spectroscopy exhibited a stretching vibration of Zn-O at 408.91 cm^{-1}. The bactericidal activity of ZnO NPs showed a significant inhibitory activity against pathogenic bacterial strains, which was investigated against Gram-negative bacterial strain *K. pneumoniae* and Gram-positive bacterial strain *S. aureus*. Furthermore, ZnO NPs showed significant cytotoxicity against human breast cancer and brain cancer cell lines. Therefore, the study reveals that grape extract is an effective reducing agent for the formation of ZnO NPs, which exhibits biological properties.

Kirubakaran et al., 2023 synthesised zinc oxide nanoparticles using *Clerodendrum heterophyllum.* The UV–visible spectrum analysis revealed a peak at 366 nm, indicating the presence of ZnONPs. FTIR analysis confirmed the presence of different functional groups in the nanoparticles, while XRD results confirmed their crystalline structure. SEM analysis showed the formation of spherical-shaped nanoparticles, and EDAX analysis confirmed the elemental composition of zinc and oxygen. TEM results indicated that the size of the ZnONPs ranged between 4.68 and 8.65 nm. The antibacterial activities of the ZnONPs were high and exhibited antioxidant as well as anticancer activity. In conclusion, this research highlights the biological properties of *C. heterophyllum*, particularly its potential as a viable resource for the synthesis of ZnONPs.

Ihsan et al., 2023synthesised zinc oxide nanoparticles from *Momordica charantia* and *Curcuma zedoaria* plant extracts, as well as evaluated their antibacterial properties. The synthesis of ZnO NPs was confirmed via UV-visible spectroscopy, showing clear peaks at 375 and 350 nm for *M. charantia* and *C. zedoaria*, respectively. Scanning electron microscopy analysis revealed crystals of irregular shapes for the majority of the nanoparticles synthesized from both plants. The existence of ZnO NPs was confirmed using X-ray diffraction while the particle size was 19.65 nm for *C. zedoaria* and 17.02 nm for *M. charantia*. Different functional groups were detected through Fourier transform infrared spectroscopy analysis. The antibacterial activity of the ZnO NPs at three different concentrations (250, 500, and 1000 µg/ml) was assessed against three different bacterial strains, using disc diffusion methods. The ZnO nanoparticles showed promising antibacterial activity against bacterial strains. The nanoparticles extracted using *C. zedoaria* exhibited higher antioxidant activity than *M. charantia*. Thus, greenly synthesized ZnO nanoparticles have remarkable antibacterial properties and antioxidant activity, making them a promising contender for future pharmaceutical application.

Ramesh et al., 2021 described the synthesis of biocompatible Zinc oxide nanoparticles from the zinc acetate through eco-friendly green process using leaf extract of Cassia auriculata leaf and their antibacterial activity. FTIR studies confirm the presence of bio molecules and metal oxides. The calculated optical band gap values of the material was found to be around 3.3 eV. PL spectrum study revealed the optical properties of ZnO NPs. The biosynthesized nanoparticle synthesized from leaf extract of Cassia auriculata exhibited strong antibacterial activity Bacillus subtilis, Klebsiella pneumonia, Pseudomonas aeruginosa and Proteus mirabilis. Thus, it may be used in the surface coating of food package to prevent the bacterial contamination.

Dappula et al., 2023 synthesized zinc oxide nano particles with the aid of an aqueous extract of whole plants of Andrographis alata. As a part of extensive characterisation, the UV–Vis spectrum manifested absorption maxim at 372 nm, characteristic for bio-reduced ZnO NPs. The XRD study demonstrated the hexagonal wurtzite structures for ZnO NPs. FTIR analysis has assured the role of phytoconstituents of A.alata in reduction and capping of ZnO NPs. Morphological studies via EDS, DLS, SEM and HR-TEM analysis illustrated crystalline flower shaped flakes like structures for ZnO NPs with size in the range of 35–53 nm. The photosynthesized ZnO NPs displayed strong anti-bacterial activities against various pathogenic bacterial strains. Moreover, bio-reduced ZnO NPs also had strong anti-oxidant, anti-Alzheimer and anti-diabetic potencies with IC_{50} values in micro gram ranges. All in all, the ZnO NPs synthesized using A.alata has substantial efficacy for further use in biomedical, pharmaceutical and food processing industries.

Alikord et al., 2023 investigated a biological method that is both new and effective for synthesis of zinc oxide nanoparticles using extract from fermented table olives (FTO), with the goal of reducing the environmental impact of the process. Phenolic compounds, which are considered an important group of known compounds in FTO extract, were also present in the volatile profile. XRD results revealed the formation of a hexagonal wurtzite structure with a crystallite size of 22.05 nm. FE-SEM and TEM analyses showed that the nanoparticles were spherical. The lattice parameter values were consistent with the standard values for zinc oxide nanoparticles, and the mesoporous structure. The antimicrobial properties of the synthesized zinc oxide nanoparticles were evaluated against both gram-positive and gram-negative bacterial strains as well as fungi. Zinc oxide nanoparticles demonstrated the highest bactericidal activity and antifungal effect. The highest DPPH free radical scavenging activities were obtained. The results of this study indicate that the green synthesis of zinc oxide nanoparticles using FTO extract is a promising and effective method. The synthesized zinc oxide nanoparticles exhibited significant antimicrobial and antioxidant properties, making them a potential candidate for use in both clinical and non-clinical studies.

Al-Askar et al., 2023 used the leaf extract of *Pluchea indica* to biosynthesize zinc oxide nanoparticles and evaluated antimicrobial and photocatalytic activities. Different experimental methods were used to characterize the biosynthesized zinc oxide nanoparticles. The biosynthesized zinc oxide nanoparticles showed maximum Ultraviolet–visible spectroscopy absorbance at a wavelength of 360 nm. The X-Ray diffraction pattern exhibits seven strong reflection peaks, and the average particle size was 21.9 nm. Fourier-transform infrared spectroscopy spectrum analysis reveals the presence of

functional groups that help in biofabrication. Antimicrobial studies showed that the biosynthesized zinc oxide nanoparticles have antimicrobial efficacy. Under both dark and sunlight irradiation, the photocatalytic activity of zinc oxide nanoparticles was evaluated. These results, suggest that zinc oxide nanoparticles synthesized by implementing environmentally friendly techniques can be employed for a variety of environmental and biomedical applications.

Mixed Metal Oxide Nanoparticles

Kamal et al., 2023, collected a fungus which was identified as *Daedalea* Mushroom and used for the first time to synthesise bimetallic Iron and ZnO nanoparticles. The characterizations revealed the synthesised Iron and ZnO NPs with an irregular shape. It was used against the most dangerous fungi Aspergillus niger. Preethi & Philominal, 2022, synthesised pure Ag doped copper oxide nanoparticles using Moringa Oleifera Leaf Extract, and it showed a good result towards antimicrobial activities. From XRD, the nanoparticles was found to be in the nanometre range and monoclinic. From the optical absorption spectrum, the bandgap for pure copper oxide was found to be 1.2 eV, while increasing the dopant concentrations shows enhancing results towards optical properties.

Adeyemi et al., 2022, reported the synthesis of copper oxide, zinc oxide nanoparticles, and their nanocomposite (CuO–ZnO) prepared using the phytochemical extracts from the leaves of *Dovyalis caffra*. The XRD confirmed the monoclinic and a hexagonal nanoparticles phase, which were both confirmed in the CuO–ZnO composite. The electron microscopy showed a mixture of nano-scale sizes and spherical/short-rod morphologies, with some agglomeration. Antioxidant properties of the nanoparticles was studied, and exhibited better scavenging potential than the individual metal oxide nanoparticles (CuO, and ZnO). Also the in vitro anticancer studies using MCF7 breast cancer cell lines indicated a concentration-dependent profile with the CuO–ZnO nanocomposite having the best activity over the respective metal oxides.

Atacan et al., 2021, studied the fabrication of silver on different metal oxide nanoparticles and evaluated their antibacterial and catalytic applications. The 4-nitroaniline reduction efficiencies of Ag-MO NPs are stronger than MO NPs at the end of 20 min and among the different metal oxides, copper oxide performed well. Ag-CuO demonstrated the highest antibacterial activity also compared with other Ag-MO NPs. Veisi et al., 2021, also fabricated a recyclable catalyst for the reduction of nitroarenes. The catalyst synthesised was pd doped magnetic iron oxide nanocomposite using *Fritillaria imperialis* flower extract. The nano catalyst was retrieved and reused several times without considerable leaching or loss of activity. This green, bio-inspired ligand-free protocol has remarkable advantages like environmental friendliness, high yields, easy workup and reusability of the catalyst.

Indhira et al., 2022 focused on synthesizing ZnO nanoparticles (NPs) and CuO NPs using Elaeagnus indica leaf extract as reducing and stabilizing agents. The size of synthesized zinc oxide nanoparticles and copper oxide nanoparticles were in the range of 20–30 nm and 30–40 nm, respectively. The antimicrobial activity of ZnO NPs at 75 µg concentration is superior against Salmonella typhimurium, Klebsiella pneumonia, Bacillus subtilis, Staphylococcus epidermidis, and Aspergillus niger. While CuO nanoparticles with 75 µg concentration effectively inhibited *S. typhimurium, B. subtilis, S. epidermidis, and A. niger*. The photodegradation of methylene blue by ZnO NPs and CuO NPs was 91% and 76%, respectively. CuO NPs and ZnO NPs have different intrinsic properties and phytochemical compositions; hence ZnO NPs photodegrade faster than CuO NPs even though ZnO has higher bandgap energy than CuO. Both the nanoparticles might be utilized as antimicrobials and photocatalysts in the future.

Arabkhani et al., 2023 prepared zinc oxide/carbon nanofiber nanocomposite and evaluated their photocatalytic and antimicrobial properties for wastewater treatment. For biosynthesis of ZnO-CNFs, plant extracts of Thymus daenensis (TD) and Stachys pilifera Benth (SB) were used as both green-reducing agents and aqueous carbon-rich sources. The antimicrobial activity was examined against Escherichia coli (E. coli) and Bacillus subtilis (B. subtilis) bacteria and Candida albicans (C. albicans) fungus. To this end, the antibacterial behaviors of ZnO-CNFs were studied based on minimal inhibitory concentration (MIC) ranges and diameter of inhibition zone, which indicated that the ZnO-CNFs exhibited superior antibacterial activity against Gram-positive (B. subtilis) and Gram-negative (E. coli) bacteria compared to ZnO nanoparticles. Also, the antifungal activity of ZnO-CNFTD with MIC range of 156.25–625 µg mL^{-1} was more potent than ZnO nanoparticles with MIC range of 156.25–2500 µg mL^{-1}. Overall, the synthesized ZnO-CNFTD exhibits excellent photocatalytic and antimicrobial potential compared to ZnO nanoparticles and therefore can be a promising candidate for effective treatment of water contaminated with microorganisms and organic compounds.

Conclusion

Biosynthesis of Fe-O, ZnO, Cu-O and some mixed metal oxides (MMO) are discussed. Studies on various biosynthesis show that the products formed are highly stable, non-uniform and mostly irregularly shaped particles. Since the availability of raw materials is not a difficult task, the focus should be on other aspects. The aspects such as high yield, more green, more uniform and more application oriented products must be focussed. Since the green synthesised nanoscale metals and their oxides have broad advantages and great potential, it needs to be more developed.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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