A Review on Green Synthesis of Nanoparticles Leading to Sustainable Development

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Abstract

Nanoparticles (NPs) are significant to technological progress due to their versatile characteristics and improved performance over original materials. They are usually created by reducing metal ions into uncharged nanoparticles using harmful agents. Nanoparticles are known for their small size and wide range of applications. However, the synthesis process plays a crucial role in determining their size and properties. Traditional methods for nanoparticle synthesis often rely on harmful chemicals and consume a lot of energy. In contrast, green synthesis provides a sustainable, cost-effective, efficient production and eco-friendly alternative. The green synthesis of nanoparticles holds many potential uses in environmental and biomedical fields. Its main goal is to reduce the use of toxic chemicals. Using biological materials like plants is generally safe. Plants contain reducing and capping agents, which are helpful in this process. Here, we discuss the principles of green chemistry and review how plants mediate the synthesis of nanoparticles and their recent applications. This review also evaluates the latest developments in the green synthesis of nanoparticles like gold (Au NPs), silver (Ag NPs), palladium (Pd NPs), copper (Cu NPs), zinc oxide (ZnO NPs), titanium dioxide (TiO2 NPs) and iron along with its oxide (Fe NPs).

Keywords: Nanoparticles, Green Synthesis, Sustainable, Reducing and Capping Agent

Introduction

Nano-metallic materials refer to metals/alloys that contain nanocrystalline grains with a size ranging from 5 nm to 100 nm. Compared to regular or non-nano metals, nanoscale metals contain a high surface area. However, because of the size effect, surface effect, interface effect, and quantum effect, nanoscale metals possess distinctive physical and chemical properties. Currently, there is an increasing number of studies on the preparation of nanoscale metals using chemical, physical, and green chemical syntheses. Compared to green chemical syntheses, physical and chemical syntheses are slowly being replaced because they involve high energy consumption and the release of non-biodegradable and toxic chemicals (Ying **et al.,** 2022).

Green synthesis follows a clean, safe, economical, and ecologically friendly method of producing nanomaterials. The microorganisms used include bacteria, yeast, fungi, algae, and some plants which serve as a substrate for the synthesis of nanomaterials using the green method. Varying active compounds, such as metal salts, influence the shape and size of the nanoparticle. In addition, the nanomaterial produced using the green method offers the sections of the green substance used during the synthesis of nanomaterials may include certain enzymes, amino acid regions, proteins, or a chemical structure (Huston et al., 2021). The biosynthesis method not only improves the particle size and shape of the nanoparticle but is also more environmental than other traditional physicochemical processes. The biological origin of nanomaterials, which may include plant extracts, provides a stabilizing agent during the synthesis of nanomaterials. The nanomaterials produced using this method are safer and more stable than nanomaterials produced using traditional methods (Abuzeid et al., 2023).

Green Approach for Synthesis of NPs

Traditional methods from the past many years have been used, but researches have proved that the green methods are more effective for the generation of NPs with the advantage of less chances of failure, low cost and ease of characterization. Green synthesis refers to processes that utilize the organic parts of natural products to synthesize nanostructured materials through biological pathways such as oxidation/reduction, chelation and precipitation. Several biological systems can reduce metal ions to metal NPs, including various plants, algae, yeast, fungi, microbes, bacteria, actinomycetes, viruses and biowaste. Plant-based synthesis of NPs is absolutely not a troublesome procedure; a metal salt is synthesized with plant extract and the response is completed in minutes to couple of hours at typical room temperature. This strategy has attracted much more attention amid the most recent decade particularly for silver and gold NPs, which is more secure as contrasted with other metallic NPs. Generation of NPs from green techniques can be scaled up effortlessly and they are fiscally smart too. Green methods of synthesis are significantly appealing on account of their potential to diminish the toxicity of NPs. In this manner, the utilization of vitamins, amino acids and plants extracts is being extremely popularized (Gour and Jain, 2019).

Green Synthesis of NPs from Plant Extracts

Plants and their preparations have been used for ancient purposes and have thus gained significant importance for human life through their knowledge obtained from various experiences. Plants are defined as medicinal when they present some important role within the curing and treatment of diseases. In various parts of the world, these plants represent the only alternative for curing certain pathologies. Bio-nanotechnology represents a successful combination of the important properties of various plant extracts, as those obtained through the aforementioned approaches, with the strong properties of nanostructures. In this context, a preparation with strong medicinal properties and a high level of antioxidant activity provides a perfect supportive medium for nanoparticle stabilization due to their bioactivity with simultaneous action of properties, which results in an enhancement of actions towards their targets. In this case and for example, the preparation of a plant will possess antibacterial activity (Filho et al., 2023).

Green Synthesis of NPs from Biogenic Wastes

The potential advantages of synthesizing nanoparticles from biowaste can be quite beneficial compared with the chemical method of synthesis. This green method of synthesis is more environmentally friendly, cheaper, and simpler. In this green method of synthesis, the precursor used from natural sources can be reused, recycled, and reduced. Moreover, having plenty of natural precursors helps in constructing large-scale-up technologies. The green method of synthesis helps avoid additional capping and stabilizing agents, thus reducing the cost and ease of synthesis since the natural precursor has polyphenols, proteins, and pigments that can serve as a reducing and capping agent. There are quite a number of uses of biosynthesized nanoparticles in energy companies, helps increase efficiency in solar cells, fuel cells, and batteries, and companies in different sectors related to nanotechnology since it will be needed for making materials like aerogels, nanotubes, and nanoparticles needed in making different products, and this is another area that can benefit from nanotechnology and its applications because these nanotechnology materials are more sturdy, stronger, and lighter (Aswathi et al., 2022).

Green Synthesis from Enzymes

Microbiologically prepared nanoparticles are more beneficial than chemically prepared nanoparticles because the former does not require very stringent conditions such as using a pure substance. The presence of different types of interaction pathways in the bacterial cells causes the synthesis of metallic NPs. The enzymes like NADH-dependent reductase were causing the synthesis of metallic NPs. The enzyme Nitrate reductase present in Fusarium oxysporum along with the compounds Anthraquinones was causing the reduction of silver ions. In another mechanism, the extracellular NADH-dependent nitrate reductase along with quinolones in the fungi was causing the synthesis of AgNP. The NADH-dependent oxidoreductase in fungi also causes AuNPs synthesis (Lahiri, 2021).

Green Synthesis from Vitamins

Vitamins are necessary not only for normal cellular processes but also play prominent roles as catalysts in organic reactions, particularly in organocatalysis. In view of the growing importance of ecofriendly and sustainable organic reaction procedures, there has been rising interest in organocatalysis based on biocompatibility and ease of availability and use with excellent efficiency. Being ecofriendly and inexpensive organocatalysts with low toxicity and very high efficiency, vitamins VB1, VB2, and VB12 have found successful applications as catalysts in various organic reactions. The catalysts were highly effective in different C-C bond-forming reactions ranging from multicomponent reactions to cross-coupling reactions (Paul, 2024). The bacterial/yeast/microalgae-mediated fermentative production of vitamins has numerous advantages over chemical procedures. In regard to safety parameters and aspects such as bioactivity and absorption rate, vitamins produced by fermentative procedures may prove to be more suitable for use either internally and as well as externally. Although fermentative procedures for VB2 and VB12 have attained technological maturity and have successfully been implemented at an industrial scale for production purposes, fermentative procedures have still to emerge for the others with B-group vitamins (Wang, 2021).

Bio-based Methods

The green method proves to be a sustainable way of synthesizing metallic nanoparticles (MNPs) via biological agents like plants, algae, bacteria, yeast, and fungi. The plants make use of polyphenols and sugars, while algae use pigments such as chlorophylls and carotenoids. The bacteria use enzymes such as nitrate reductase to reduce metal ions both inside and outside the cells. The yeast, for example, makes use of enzymes like nitrate reductase for reducing metal ions outside the cells and metallothionein proteins for reducing metal ions within the cells, while fungi use enzymes such as laccase and reductase to reduce metal ions. It is divided into sections discussing the reaction conditions like solvent, pH, concentration of precursors, and temperatures that influence the MNPs size, shape, and stability (Cardoso et al., 2025). Bacteria-mediated green synthesis of AgNPs provides a very effective and eco-approachable method over chemical methods. The different biomolecular content of bacterial cells, such as enzymes and polysaccharides with reducing and stabilizing properties, add to this eco-friendliness. AgNP synthesis can also be started with different strains of bacteria, enabling various physicochemical properties such as size and shape, which are very necessary for different applications. Fungus-mediated green synthesis, known as mycosynthesis, is observed to be one of the mainly used methods for synthesizing AgNPs through green routes. This process provides a mechanism by which reduction of silver ions (Ag+) to elemental silver (Ag0) is done with the assistance of fungal biomolecules such as enzymes, secondary metabolite compounds, and proteins. These NPs have various applications due to their unique physicochemical and biological properties (Akdaşçi et al., 2025).

Metals Synthesized from Green Synthesis

Metal nanoparticles (MNPs) are the anchoring point in the field because of their extraordinary optical, electrical, and chemical abilities that are far more efficient compared to regular-sized nanoparticles. Metal nanoparticles are small-sized particles measuring 1–100 nm in diameter. These particles possess desirable properties that ensured the replacement of regular-sized particles in different industrial applications. They can be synthesized through chemical, physical, and/or biological processes. Biological synthesis of metal nanoparticles, also called green synthesis, involves the use of different microorganisms and plants. It's more advantageous than its counterparts in the synthesis process, as it's found to be economical and safe for the environment. The use of biologically synthesized metal nanoparticles, or biogenic metal nanoparticles, attains anticancer and antimicrobial properties because of the production of ROS. Biogenic metal nanoparticles possess desirable morphologies that increase their biological properties. AuNPs, AgNPs, ZnO-NPs, CuO-NPs, TiO2-NPs, and biogenic IONPs extracted from different biologic materials possess remarkable antimicrobial, anticancer, and antioxidant activities. Biogenic SeNPs are potential therapeutic materials that can be used alone or in conjunction with different sources of radiation. Biogenic PtNPs extracted from different fungal biomaterials possess remarkable physiochemical properties for different therapeutic applications (Morgan and Aboshanab, 2024).

Ag Nanoparticles

To create silver nanoparticles through green synthesis, you need a solution of silver metal ions and a reducing biological agent. The simplest and most cost-effective way to produce silver nanoparticles is to reduce and stabilize silver ions using a mix of biomolecules, including polysaccharides, vitamins, amino acids, proteins, saponins, alkaloids, terpenes, and phenolics (Tolaymat et al., 2010). Silver nanoparticles can come from various medicinal plants such as Saccharum officinarum (Chaudhari et al., 2012), Helianthus annus (Dubchak et al., 2010), Cinamomum camphora (Huang et al., 2008), *Oryza sativa* (Dar et al., 2016), *Aloe vera* (Chandran et al., 2006b), Capsicum annuum (Li et al., 2007), *Medicago sativa* (Lukman et al., 2011), Zea mays (Rajkumar et al., 2019), and *Magnolia Kobus* (Lee et al., 2014) in both biological and pharmaceutical fields. Eco-friendly bio-organisms found in plant extracts serve as capping and reducing agents for creating shape-controlled and stable silver nanoparticles. Modifying silver nanoparticles with polymers and surfactants showed significant microbial activity against Gram-negative and Gram-positive bacteria (Sharma et al., 2009).

Some researchers synthesized silver nanoparticles using the methanolic extract of *Eucalyptus hybrida* (Dubey et al., 2009). You can obtain silver nanoparticles by boiling 10 g of *Nelumbo lucifera* leaves in 100 ml of distilled water. The filter solution (12 ml) is then treated with 1 mM aqueous solution of AgNO3 (88 ml) and kept in the dark at room temperature. A brownish-yellow solution indicates the formation of silver nanoparticles (AgNPs) (Santhoshkumar et al., 2011). By adding the leaf extract of *Hibiscus rosasinensis* to a 10−3 M solution of AgNO3 (25 ml) and stirring for 5 minutes, reduction occurs at 300 K and completes in 30 minutes, resulting in light brown silver nanoparticles (Philip 2010). Silver nanoparticles were also synthesized by adding a 5 ml seed extract of *Jatropha curcas* to a 10−3 M aqueous solution of AgNO3 (20 ml) and heating the mixture at 80 °C for 15 minutes, which turned the solution reddish, indicating the synthesis of silver nanoparticles (Bar et al., 2009). Kumar and his colleagues demonstrated the biosynthesis of silver nanoparticles from silver precursors using bark extract from the *Cinnamon zeylanicum* plant. They noted that using plant materials is a form of green technology since it avoids harmful chemicals. The reduction of silver ions to nanosized silver particles primarily results from water-soluble organics found in these plant materials.

Other factors also influenced the biosynthesis, such as the pH of the medium, which affected the size of nanoparticles. The bark extract of *Cinnamon zeylanicum* produced more silver nanoparticles compared to its powder form, showing a rich availability of reducing agents in the bark extract. Zeta potential studies indicated a highly negative charge on the surface, with EC50 values of 11 ± 1.72 mg/L against the Escherichia coli BL-21 strain. Therefore, the bark extract from this plant is an excellent source for synthesizing silver nanoparticles with strong antimicrobial activity (Sathishkumar et al., 2009).

Au Nanoparticles

Gold nanoparticles have gained considerable interest among all metallic nanoparticles due to their potential for various uses in medicine and biology (Jain et al., 2006), biocompatibility (Sperling et al., 2008), tunable surface plasmon resonance (Huang and El-Sayed 2010), low toxicity (Jeong et al., 2011), and strong scattering and absorption (El-Sayed et al., 2005). They can be synthesized easily and have straightforward surface functionalization (Ghosh et al., 2008). In the synthesis of gold nanoparticles, various chemical compounds in biogenic complexes act as reducing agents, reacting with gold metal ions to form nanoparticles. Some studies show that biomolecules like flavonoids, phenols, and proteins in plant extracts play a significant role in reducing metal ions and stabilizing gold nanoparticles.

The first study on gold nanoparticle synthesis was conducted in 2003 by Shankar and his team using geranium leaf extract as a reducing and capping agent. This reaction took place over 48 hours, utilizing the terpenoids in the leaf extract to reduce gold ions to gold nanoparticles. Morphological studies showed that these nanoparticles formed various shapes, including triangular, spherical, decahedral, and icosahedral (Shankar et al., 2003). They also synthesized gold nanoparticles using leaf extract from *Azadirachta indica* in a reaction time of 2.5 hours. The neem extract, abundant in terpenoids and flavanones, likely adhered to the surfaces of the nanoparticles, enhancing their stability for 4 weeks. Morphological studies indicated that the nanoparticles were mostly spherical and planar, with a majority being triangular and some hexagonal (Shankar et al., 2004). To control the shape and size of gold nanoparticles, researchers used *Aloe vera* leaf extract (Chandran et al., 2006a). The shape and size depended on the amount of leaf extract used, producing triangles measuring 50–350 nm. Using lower amounts of leaf extract resulted in larger nanoparticle triangles, while increasing the extract quantity also led to spherical nanoparticles, reducing the ratio of nanotriangles to nanospherical particles.

When using a small amount of mushroom extract, some anisotropic gold nanoparticles were formed in the shapes of triangles and prisms, with fewer hexagons and spheres. As the amount of mushroom extract increased, the number of hexagons and spheres also increased, resulting in smaller nanoparticles and fewer nanotriangles. At the highest concentration of extract, nanoparticles measured 25 nm. The nanoparticles' morphology was also influenced by temperature. Hexagons were produced at a temperature of 313 K with the highest extract quantity, while dendritic shapes appeared at 353 K (Philip 2009).

Song et al. (2009) noted that in the biosynthesis of gold nanoparticles using *Diospyros kaki* and *Magnolia kobus* leaf extracts, higher extract concentrations and temperatures resulted in smaller spherical nanoparticles, while lower concentrations and temperatures yielded larger nanoparticles with varied morphologies. Leaf extract from *Terminalia catappa* served as a reducing and capping agent for synthesizing gold nanoparticles. Rapid reduction of chloroaurate ions to gold nanoparticles occurred when treated with chloroauric acid solutions and leaf extract. Morphological studies using transmission electron microscopy showed that nanoparticles ranged from 10–35 nm (Ankamwar 2010). High-resolution transmission electron microscopy analysis of gold nanoparticles synthesized from coriander leaf extract revealed shapes such as triangles, truncated triangles, spheres, and decahedra, with sizes ranging from 6.75–57.91 nm and an average size of 20.65 nm. These nanoparticles remained stable in solution at room temperature for one month (Narayanan and Sakthivel 2008).

Zhang and his colleagues used chloroplasts from *Trifolium* leaves collected at Shanghai Jiao Tong University, China. They employed these chloroplasts as a reductant and stabilizer. The resultant nanoparticles showed high crystallinity with a dominant (111) orientation and had a size of 20 nm in diameter. Toxicology assays against GES-1 gastric mucous cell line and MGC-803 gastric cancer cell line using the MTT method indicated the nontoxic nature of these nanoparticles. SERS (surface-enhanced Raman spectroscopy) studies showed that gold nanoparticles significantly enhanced the Raman signals of rhodamine 6G without any treatment. Thus, these nanoparticles are biocompatible and highly promising for sensitive detection of biomarkers in vivo and in vitro (Zhang et al., 2011).

Recently, Islam and his coworkers synthesized gold nanoparticles using *Salix alba* leaf extract. Scanning electron microscopy and atomic force microscopy studies revealed nanoparticle sizes of 50–80 nm and 63 nm, respectively. FTIR studies confirmed the involvement of amine, amide, and aromatic groups in the effective reduction and capping of gold nanoparticles. These nanoparticles exhibited high stability across various pH levels and salt concentrations but showed instability at elevated temperatures. Gold nanoparticles synthesized from *Salix alba* leaf extract are suitable for various pharmaceutical and biomedical applications due to their strong antifungal activity and excellent antinociceptive and muscle relaxant properties (Islam et al., 2019). Gold nanoparticles have also been synthesized recently from different plant extracts, including *Coffea Arabica* (Keijok et al., 2019), *Croton Caudatus* Geisel leaf extract (Kumar et al., 2019), *Bacillus marisflavi* (Nadaf and Kanase 2019), *Croton sparsiflorus* leaves extract (Boomi et al., 2020), *Citrus limonum* leaf extract (Bhagat et al., 2020), and *Aeromonas hydrophila* (Fernando and Judan Cruz 2020).

Pd Nanoparticles

Palladium is a silvery-white expensive metal having high density. Biosynthesis of this nanoparticle from plants has attracted wide attention of many researchers due to eco-friendly, sustainable, and economical nature. Green synthesis of Pd nanoparticles has been reported using various plant extracts such as *Cinnamomum camphora, Gardenia jasminoides, Pinus resinosa, Anogeissus latifolia, Glycine max, Ocimum sanctum, Curcuma longa, Musa paradisica, Cinnamom zeylanicum, Pulicaria glutinosa, Diospyros kaki,* and many more (Siddiqi and Husen, 2016).

When a methanolic extract of *Catharanthus roseus*, which is a mixture of eight compounds comprising –OH groups and responsible to reduce the metal ion to metal nanoparticles, was stirred for 1 h with an aqueous solution of [Pd(OAc)2] at 60 °C, solution color was changed, revealing the formation of Pd nanoparticles which showed the absorption peak at 360–400 nm range and morphological studies also supported the formation of spherical nanoparticles of 40 nm size (Kalaiselvi et al., 2015).

Palladium nanoparticles were also fabricated using protein-rich soybean leaf extract containing amino acids. Confirmation of nanoparticles formation was done by ultraviolet–visible, Fourier transform infrared spectroscopy, and morphology was confirmed by transmission electron microscopy revealing 15-nm size nanoparticles. Spherical particles of 5 nm size were derived by leaf extract of *Anacardium occidentale* (Sheny et al., 2012). Renewable and nontoxic black tea leaves (*Camellia sinensis*) extract were also used as reducing and stabilizing agent in Pd nanoparticles preparation (Lebaschi et al., 2017). These nanoparticles were applicable in the reduction of 4-nitrophenol as well as in heterogeneous & effective catalysts in the Suzuki coupling reaction along with phenylboronic acid and aryl halides. The recycling capability of the catalyst was found 7 times without losing its catalytic activity (Lebaschi et al., 2017). By using the extract of *Anogeissus latifolia* and palladium chloride, palladium nanoparticles were developed via the green route which was confirmed by intense brown color appearance and broad absorption spectrum in the ultraviolet–visible region. The average particle size of these was 4.8 ± 1.6 nm and spherical (Kora and Rastogi 2018). Arsiya et al. (2017) fabricated 5–20-nm average-sized Pd nanoparticles by extract of *Chlorella vulgaris* in only 10-min duration. Fourier transform infrared spectroscopy (FTIR) studies suggested the involvement of polyol and amide group of *Chlorella vulgaris* in the reduction of metal ions to the nanoparticle.

Cu Nanoparticles

Copper nanoparticles are synthesized by various plant extracts such as *Aloe vera* flower extract via the reduction of aqueous copper ions. The formation of an average size of 40 nm Cu nanoparticles was confirmed by 578-nm peak at UV–Visible spectrometer (Karimi and Mohsenzadeh 2015).

Green synthesis of Cu nanocomposite was performed by leaf extract of *Cuscuta reflexa* which is a rich source of numerous antioxidant phytochemicals such as Myricetin, Myricetin glucoside, Kaempferol-3-Oglucoside (Astragalin), Kaempferol-3-O-galactoside, Kaempferol, Quercetin, Quercetin-3-O-glucoside, Quercetin 3-O-galactoside, Oleic acid, Palmitic acid, Linoleic acid, Linolenic acid, Stearic acid, Isorhamnetol, Cuscutin, Cuscutalin, Azaleatin, Amarbelin, Dulcitol, Bergenine, Beta-sitosterol, Luteolin, Maragenin, and Coumarin. The above constituents are responsible for the conversion of plant extract to a rich source of antioxidants for nanoparticle synthesis (Rahmatullah et al., 2010; Vijikumar et al., 2011; Naghdi et al., 2018).

The Cu nanoparticles were immobilized on graphene oxide/MnO2 nanocomposites surface via the reduction of Cu+2 ions to Cu nanoparticles by using *Cuscuta reflexa* leaf extract. These nanocomposites with Cu nanoparticles were used as the heterogeneous and recoverable catalyst for the reduction of rhodamine B, congo red, methylene blue, methyl orange, 4-nitro phenol, and 2,4-DNPH by NaBH4 in an aqueous medium (Naghdi et al., 2018). Cheirmadurai and labmates prepared copper nanoparticles on a large scale by using henna leaves extract as a reductant. They prepared nanobiocomposites conducting film by these Cu nanoparticles and collagen fibers which were left away from leather industries. The film was suitable for numerous electronic device applications (Cheirmadurai et al., 2014). Large-scale synthesis of 20–50-nm-sized Cu nanoparticles was also done by using tamarind and lemon juice (Sastry et al., 2013).

In situ synthesis of Cu nanoparticles on reduced graphene oxide/Fe3O4 was performed by using barberry fruit extract as a stabilizing and reducing agent and found useful in the active catalyst for the reaction of phenol with aryl halides to get O-arylation of phenol under the ligand-free condition as well as it was recoverable and used for multiple times without losing any catalytic activity (Nasrollahzadeh et al., 2015a).

ZnO Nanoparticles

Zinc oxide nanoparticles have drawn considerable attention from researchers and scientists in the past 4–5 years due to their wide applications in the biomedical field as well as in optics and electronics. ZnO nanoparticles are of great interest due to their inexpensive, safe, and easy method of synthesis. These nanoparticles possess high exciton binding energy of 60 meV and a large bandgap of 3.37 eV, and due to this, these show various semiconducting properties such as high catalytic activity, wound healing, anti-inflammatory, ultraviolet filtering properties and are extensively used in various cosmetics such as sunscreen. These nanoparticles revealed various biomedical applications too such as antifungal, antibacterial, drug delivery, antidiabetic, and anticancer. Up to now, numerous works have been reported for ZnO synthesis and utilization by plants, microorganisms, and others. Plant parts like flower, root, seed, leaves, etc., are used for the synthesis of ZnO nanoparticles.

ZnO nanoparticles can be synthesized by mixing of plant extract clear solution with 0.5 mM solution of hydrated zinc sulfate/zinc oxide/zinc nitrate and boiling the above mixture at desired time and temperature to get effective mixing. The reaction showed the change in color, revealing confirmation of ZnO nanoparticles. These nanoparticles were characterized by various techniques for spectral, morphological, and thermal analysis. Energy dispersive X-ray analysis (EDAX) and scanning electron microscopy studies revealed different results from X-ray diffraction (XRD). For the synthesis of ZnO, the leaves of *Azadirachta indica* of Meliaceae family have been of utmost use (Bhuyan et al., 2015). Flower and leaf of *Vitex negundo* plant attributed similar size nanoparticles of 38.17 nm by the Debye–Scherrer equation of XRD (Ambika and Sundrarajan 2015). A functional group such as alcohol, alkane, carbonate, amide, carboxylic acid, and amine is confirmed by FTIR studies in the involvement of nanoparticle synthesis. Some ZnO nanoflowers were synthesized by *B. licheniformis* which were uniform in size and revealed highly enhanced photostability and photocatalytic activity for methylene blue (MB) dye degradation. These nanoflowers degrade 83% dye, while self-degradation of methylene blue was null, and at a different time interval, three repeated cycles of the experiment showed 74% degradation which undoubtedly exhibited photostability of ZnO nanoflowers formed (Auld 2001). *Lactobacillus plantarum* was used in the synthesis of ZnO nanoparticles, which were found moderately stable with zeta potential value of −15.3 mV (Selvarajan and Mohanasrinivasan 2013).

TiO_2 Nanoparticles

Titanium oxide nanoparticles are of great interest as these exhibit exclusive morphologies and surface chemistry. These nanoparticles are very useful in the preparation of textiles, plastics, papers, tints, cosmetics, foodstuffs, etc. TiO2 nanoparticles in the colloid form are vigorously used in the reduction of various toxic chemicals such as pollutants and dyes from water. Green synthesis of TiO2 nanoparticles from plants is a better choice for toxic-free synthesis. Up to now, numerous plants have been used for its synthesis and applications. The synthesis starts with the reaction of a plant extract with TiO2 salt. Initially, preparation of nanoparticle can be confirmed by the change in color of the reaction mixture, after that the morphological and spectroscopic studies confirmed their formation. These nanoparticles are reported in light green to dark green color. TiO2 nanoparticles in spherical shape were synthesized by the reaction of leaf extract of *Annona squamosa* L. and an aqueous solution of TiO2 salt at room temperature (Roopan et al., 2012). The reason for choosing mainly leaf extracts to synthesize TiO2 nanoparticles is that leaf extracts are always a rich source of metabolites. TiO2 nanoparticles were synthesized by Goutam et al. (2018) by leaf extract of *Jatropha curcas* which was confirmed by ultraviolet–visible, Fourier transform infrared spectroscopy (FTIR), X-ray diffraction, scanning electron microscopy, energy-dispersive spectroscopy, dynamic light scattering, and Brunauer–Emmett–Teller analysis. Likewise, *Catharanthus roseus* leaf extract was used to synthesize 25–110 nm TiO2 nanoparticles with irregular morphologies. In the leaf extract, the presence of aliphatic amines and alcohols was responsible for nanoparticle synthesis (Velayutham et al., 2012). Irregular shaped and size of 100-nm TiO2 nanoparticles were synthesized by *Moringa oleifera* leaf extract having superior wound healing capability (Sivaranjani and Philominathan 2016). Similarly, nanoparticles were achieved in 6 h by using *Calotropis gigantea* leaf extract. Primary amines in the extract were responsible for high bioreduction. These nanoparticles revealed outstanding acaricidal activity against the larvae of *Haemaphysalis bispinosa* and *Rhipicephalus microplus* (Marimuthu et al., 2013). The uniform spherical size nanoparticles were fabricated by using *Cucurbita pepo* seeds extract (Abisharani et al., 2019).

Conclusion

Over the past few decades, the rising demand for green chemistry and nanotechnology has led to a push for greener ways to create nanomaterials using plants, microorganisms, and other sources. Researchers have focused on the green synthesis of nanoparticles in recent years, taking an eco-friendly approach. Much of the research has centered on using plant extracts to create nanoparticles and exploring their potential uses in various fields. This approach is appealing because it is cost-effective, non-toxic, easy to access, and gentle on the environment.

Nanoparticles have a range of applications, including catalysis, medicine, water treatment, dye degradation, textile engineering, bioengineering, sensors, imaging, biotechnology, electronics, optics, and other biomedical areas. Additionally, plants contain unique compounds that aid in the synthesis process and increase the rate of production.

Using plants for the green synthesis of nanoparticles is an exciting and growing area of nanotechnology. It significantly contributes to sustainability and advancements in nanoscience. Looking ahead, we expect that applications for these nanoparticles will increase rapidly. However, we must consider the long-term effects on animals and humans, as well as the accumulation of these particles in the environment. These biogenic nanoparticles could be effective in combating plant pathogens and in purifying water for environmental cleanup. In drug delivery systems, these nanoparticles may become a key focus for the biomedical field.

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