Plant-mediated green synthesis of nanoparticles

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Abstract

Nanoparticles are an inspiring group of nanostructured materials with broad-spectrum applications in different fields such as catalysis, antimicrobial treatment, drug delivery, nanomedicine, environmental remediation, electronics, and chemical sensors. Nevertheless, the techniques used for preparation are environmentally unfriendly. Aiming to promote the greener synthesis of nanoparticles, this chapter spotlights plant-mediated eco-friendly and sustainable development of nanoparticles. Naturally occurring plant extracts are enriched with a plethora of various biologically active biomolecules and secondary metabolites, including alkaloids, terpenoids, flavonoids, enzymes, and phenolic substances. These bioactive compounds can catalyze the reduction of metal ions into biogenic nanoparticles in an eco-sustainable single-step biosynthetic process. Additionally, the utilization of plant extracts and their derived compounds circumvents the necessity for capping and stabilizing agents and generates bioactive size and shape-dependent green nanoparticles. Herein, we have made an effort the describe the synthesis of a wide range of metal-based nanoparticles (platinum, gold, zinc oxide, silver, and titanium dioxide nanoparticles) by using plant extract as a green synthesis matrix. In addition, different parts of plants that have widely been utilized for the biosynthesis of these NPs with several sizes and shapes by biological methodologies are briefly described. In conclusion, the greener synthesis approaches are safer and easier to exploit the massive preparation of nanostructured particles.

Keywords; Nanotechnology; Metal nanoparticles; Green chemistry; Plant extract; Secondary metabolites

1. Introduction

Nanotechnology may be described as the modification of matter by different physical or chemical tactics for the formation of substances with particular applications [1]. It can also be defined as the microscopic-sized particle that has at least, one dimension much lesser than one hundred nanometers in size [2]. Nanoparticles (NPs) possesses many interesting applications and multi-functional properties in diverse fields which includes nutrition energy and medicine [3, 4] because of their significant surface to volume ratio and abundance of surface atoms. Other considerable advantageous features of plant-based nanoparticles are shown in Figure 1. The biogenic synthesis of monodispersed nanoparticles with particular sizes and shapes was an undertaking in biomaterial science. Also, it has garnered prodigious interest within the industry of pharmacology for the cure of viral and bacterial infections [5]. The biological synthesis strategies are prospective alternative as compared to other classical methods of synthesis due to the usage of extra-biological compounds. The easy accessibility and rich biodiversity of natural material had been enormously studied for the biosynthesis of nanomaterials (NMs) [6]. Recently, the green synthesis of nanosized tubes, particles, wires, and flowers was described. These biosynthesized NMs exhibit great prospective in many diverse fields like diagnosis, treatment, commercial product manufacturing, and improvement surgical nanodevices [7]. Nanomedicines had made a great influence in the healthcare sector by curing numerous chronic ailments. Therefore, green biosynthesis of NPs is taken into consideration as the building blocks of the coming near generations by controlling various health issues [8].

Nowadays, nanotechnology has attracted great interest as a promptly growing scientific field. Manipulation, characterization, fabrication of NPs are the foremost aims observed in this new technology [4, 9, 10]. Plant crude extracts of plants consist of unique secondary metabolites like phenolic acid, terpenoids, flavonoids, and alkaloids, wherein these metabolites are known to be the reason for ions reduction during the biosynthesis of NPs from different metals

[11]. These plant metabolites are frequently used for redox reactions for the preparation of eco-friendly NPs. Many earlier reviews are revealing that these synthesized nanoparticles are efficiently controlling the apoptosis, genotoxicity, and oxidative stress associated changes [12]. Moreover, NPs possess a wider range of applications in plant sciences and the agriculture industry. For example, with the help of bioprocessing technology, nanoparticles can convert agricultural wastes and food into energy and many other useful products.

2. Methods for metallic nanoparticle biosynthesis

Numerous procedures are utilized for the formation of different nanoparticles like chemical, biological, physical as well as enzymatic. Chemical protocols are utilized to prepare nanoparticles by way of the sol-gel, electrodeposition, and vapour deposition [13], moist chemical, and co-precipitation techniques [14], hydrolysis, catalytic route, Langmuir Blodgett approach and soft chemical technique [15]. Likewise, physical techniques that are being used include ball milling, plasma arcing, thermal evaporate, ultra-thin films, spray pyrolysis, lithographic techniques, pulsed laser desorption, layer by using layer growth, molecular beam epistaxis, sputter deposition and diffusion flame [16]. Chemical and physical techniques are using stabilizing agents, highly concentrated reductants, and high radiations that are toxic and unsafe for humans and the environment. Therefore, the biosynthesis of NPs is a single step bio-reduction procedure that uses lesser energy for the synthesis of eco-friendly nanoparticles [17]. Plant extracts, enzymes, fungi, bacteria, and microalgae are the different resources that are being used for the biosynthesis of nanoparticles [18]. Table 1 depicts a recent list of biosynthesis of metallic nanoparticles from various plant sources.

3. Green biosynthesis of metallic NPs

The procedures for acquiring NPs through different naturally occurring compounds like sugars, plant extracts, vitamins, micro-organisms, and biodegradable polymers might be considered as appealing for nanotechnology. This biological synthesis has led to the fabrication of a confined variety of inorganic NPs (particularly metallic NPs, though numerous salts and metal oxides also are described). Among the material noted above, primarily plant-based substances are to be the greatest source and are appropriate for the large-scale formation of NPs [18]. For the biological synthesis of metallic NPs, different parts of plants like root, stem, leaf, seed, and latex are being utilized. Polyphenols that are present in plants for example in wine, tea, red grape pomace, and winery waste are supposed to be the active and important agent required for the synthesis. Green biosynthesis of nanoparticles offers advancement as compared to other strategies as it is cost-efficient, comparatively reproducible, simple and it results in more stable products [19]. Generally, biological material offers an environmentally friendly and green chemical protocol for the production of valuable materials as the biomaterial-based routes reduce the usage of toxic chemicals [20]. Figure 2 shows a schematic illustration of the biosynthesis of metallic nanoparticles using various parts of the plant. Few different types of synthesis for metallic NPs are as follows:

3.1. Gold nanoparticles

Gold (Au) nanoparticles have been stated as an extensive research tool in different fields of agriculture, medicine, and health center due to their stability and biocompatibility [21]. Au is considered as one of the extraordinary metals having a melting and boiling point of 1064 °C and 2808 °C, respectively. Numerous properties of Au, like its incapability to react with oxygen and water and its exceptional conductive properties, have made it very beneficial for mankind. During the 5th millennium BC, gold extraction began close to Bulgaria and is assumed that “soluble” Au come to be seen approximately the 4th or 5th centuries BC in China. The spectacular statue of Touthankamon that was built in this time, is proof. Earlier, gold was known with various terms, like drinkable and soluble Au, Graham [22] coined the term “colloid”. The colloids of Au and the stunning ruby-red color have attracted people for lots of eras [23, 24]. Gold was widely utilized for medicinal, cosmetic, and ornamental purposes [25, 26]. Drinkable Au was also used for the cure of several health problems like arthritis, heart diseases, tumors, dysentery, epilepsy, and venereal disease [27].

Gold nanoparticles (AuNPs) fascinated some researchers inside the area of plant-based biosynthesis due to their exceptional applications and properties in biomedical, nanodevices, nonlinear optics, catalysis, and nanodevices [28]. Gold nanoparticles offer promising scaffolds for gene and drug delivery [29]. These nanoparticles possess many useful features such as monodispersity, tunable core size, tunning, and transport of delivery processes and the large surface-volume ratio [30]. The AuNPs can be formed by green synthesis [11, 31], however, the number of gold synthesis reports is considerably lesser as compared to AgNPs. The size of AuNPs varies within a range of 20-300 nm. For example, gold nanoparticles (100 nm) have been prepared from the peel extract of banana (*Musa paradisiaca*) by using simple, eco-friendly, and non-toxic material [32]. The crushed, boiled, acetone-precipitated and dried powder of banana peel was used for the reduction of chloroauric acid. In this study, the enlargement of NPs into microwire and microcubes networks to the periphery of the banana sample was seen. The contribution of amine, hydroxyl, carboxyl groups was observed during the synthesis. Using tea extracts, nanocomposites of gold nanoparticles can be prepared. The extract was made in the solution of 1-methyl-2-pyrrolidinone during the process of nanoparticles (20 nm) formation [33]. The AuNPs formation in the polyaniline matrix was confirmed through TEM. In another research by Wu and Chen [34], a facile and green route was reported, by mixing rice wine, soda, and Au (III) at pH 6.5 at a temperature of 25-55 °C without the use of any protective agent. No precipitation occurred, and the resultant solution was stable after a few months.

Shankar et al. [35] described the formation of AuNPs by using the leaves of *Pelargonium graveolens*. It was stated that present terpenoids in geranium leaves act as reducing and capping material for a quick reduction of chloroaurate ions towards the AuNPs of different sizes. Later on, these research groups determined the formation of gold nanoparticles by using different plants like *Azadirachta indica* [36] and lemongrass [37]. Prism-, trapezoid-, rod- and sphere-shaped gold nanoparticles were formed from the black tea leaf extract. The tea phenols and flavonoids are known to be the reason for efficient reduction caused by the extract [38]. Song et al. [39] stated that leaf extracts of *Diospyros kaki* and *Magnolia kobus* successfully synthesize the extracellular gold nanoparticles within a range of 5-300 nm having pentagonal, triangular, spherical and hexagonal shapes at the temperature of 95 °C within few minutes. Babu et al. [40] cited that leaves of *Mentha arvensis* (ethanolic extract) formed AuNPs of spherical and hexagonal shapes having approximately a size of 39 ± 15 nm. Extract of peer fruit biosynthesized hexagonal and triangular nanoparticles at room temperature of 200-500 nm [41]. The reason for the synthesis of AuNPs is the presence of organic acids, proteins, peptides, amino acids, and saccharides in pear fruit extract. Rajan et al. [42] used *Garcinia combogia* (fruit extract) for the biosynthesis of AuNPs of anisotropic and spherical shapes. It was concluded that the shape of nanoparticles relies on the reaction temperature and quantity of extract. In 2015, Islam [43] and his research group stated that *Pistacia integerrima* (leaf galls) reduces ions into the gold nanoparticles. Carboxylic acid and hydroxyl groups of polyphenols were known to be the reason for the process of reduction. These polyphenols capped the NPs and making then more stable in varied pH solution and at high temperatures. These synthesized Au nanoparticles showed great potential in antimicrobial, enzyme inhibition, muscle relaxant, and antinociceptive activities. The mechanism of antimicrobial activity of nanoparticles is shown in Figure 3.

3.2. Platinum nanoparticles

Noble metallic nanoparticles like silver, gold, platinum, and palladium, possess a wider range of different applications, such as material science, medicine, pharmaceuticals, and chemistry [44, 45]. Amongst them, platinum has few specific properties like good resistance towards chemical attacks and corrosion, and high surface area. For the synthesis of platinum nanoparticles (PtNPs) till now numerous methods have been used such as sol-gel route, vapour deposition, and chemical precipitation. Though, these protocols have few limitations such as usage of toxic and unsafe chemical, high cost and energy requirements, multistep for preparation. To overcome these limitations, recently different plant-based synthesis of these metallic nanoparticles, especially platinum nanoparticles have gained great attention because of their simple usage, eco-friendly, and non-toxic nature.

Platinum (Pt) is one of the expensive, rare, and high-density metal. Platinum nanoparticles are mostly used in the form of suspension or colloid. The antioxidant ability of PtNPs is one of the reasons for their extensive research [46]. The main application areas of PtNPs are cancer therapy, polymer membranes, catalytic converters, plastics, textiles, and nanofibers. PtNPs are being extensively utilized as catalysts and in the different biomedical applications [47]. In comparison with silver, gold, platinum NPs are notably limited. The reaction between an aqueous solution of Pt and plant extracts leads to the following mechanism:

$$H_2Pt^{+}6Cl^{-} \cdot 6H_2O + \text{Plant molecule} \rightarrow Pt^{0} \text{ nano- particles}$$

Specifically, the interest in PtNPs is because of their unique structural, catalytic, and optical properties making them a promising nanoparticle in catalysis and biomedical applications [48, 49]. Biological approaches for the biosynthesis of PtNPs with the help of plant extracts has not been extensively used. According to literature survey, the plants that have been used for the green synthesis for PtNPs are; *Diospyros kaki* [50], *Ocimum sanctum* [51], *Anacardium occidentale* [52], *Cacumen platycladi* [53], *Bidens Tripartitus* [54], *Punica granatum* [55], *Cochlospermum gossypium* [56], *Azadirachta indica* and *Quercus glauca* [57]. Jae et al. [58] prepared PtNPs (2-12 nm) from a solution of $H_2PtCl_6 \cdot 6H_2O$, where leaves extract of *Diopyros kaki* were used as the agent for reduction of ions. At a temperature of 95 °C with an extract concentration of more than 10%, around 90% of platinum ions were successfully converted into PtNPs. Zheng et al. [53], biologically synthesize PtNPs (2.4 ± 0.8 nm) by using an extract of *Cacumen platycladi* at 90 °C having an extract of 70% and reaction time of 25 h. During this reaction, the flavonoids and reducing sugars performed an important part in the reduction of the platinum ion as compared to proteins. Likewise, Soundarrajan et al. [51] used the leaves of *O. sanctum* that acts as the reducing agent during the biosynthesis of PtNPs of size 23 nm, whereas the solution of $H_2PtCl_6 \cdot 6H_2O$ was used. Different compounds of plants such as gallic acid, ascorbic acid, proteins, and terpenoids acted as agents for reduction during the formation of PtNPs. Kumar et al. [59] isolated polyphenols from the extract of *Terminalia chebula* that causes the one single step synthesis of platinum nanoparticles. They demonstrated that the reduction of platinum (IV) to platinum (0) was due to the presence of polyphenols in the *T. chebula* extracts.

Platinum nanoparticles, which were synthesized form tea polyphenol act as both capping and reducing agents. These PtNPs were crystalline in nature, having a particle size of 30-60 nm, with a structure of face-centered cubic. Transmission electron microscopy determines that the NPs were of flower-shaped. The polyphenols present in tea include an amount of different phenolic components that form the complexes with the ions and quickly reduce them into metallic nanoparticles of various sizes and shapes [60-62]. The usage of different extracts from plant extracts for the green biosynthesis of PtNPs relies on the fact that the procedure is easier, faster, reliable, cost-effective, and eco-friendly and forms more stable nanoparticles as compared to other classical methods [63].

3.3. Silver nanoparticles

Usually, silver (Ag) is used as a catalyst for the oxidation of ethylene to ethylene oxide and methanol to formaldehyde [64]. Some of the features of Ag are good conductivity, catalytic, antibacterial potential, and chemical stability [65]. In the era of the Roman Empire, silver nanoparticles were utilized by the founders of glass, for the creation of the Lycurgus cup (4th century AD), now this cup is in British Museum [64, 66]. Before the 1980s, silver nanoparticles (AgNPs) were used for isolated supports that were utilized for signals in Raman spectroscopy for practical and scientific concern [65], revealing that AgNPs exhibits a unique organization of high electrical double layer capacitance [67]. Currently, the formation of AgNPs is one of the most actively rising development in the colloid chemistry and continuous increase in the scientific publications in around the last 20 years.

The mechanism of AgNPs synthesis is due to the occurrence of the polyphenols in the extracts of different plants, which causes the reduction of NPs. This reduction is carried out by the removal of hydrogen due to the OH groups present in polyphenols. The formation of silver nanoparticles is being performed by various biological systems [68-71]. Numerous plants and their respective parts have been utilized for the formation of silver nanoparticles. This formation involves the reaction of AgN salt with the plant. The presence of a brownish-yellow colour confirms the formation of AgNPs.

At present, AgNPs have gained great attention and are being considered as the most capable and useful NP for different biological applications, including biomolecular detection, therapeutics goals, food production and preservation, agricultural purposes, antibacterial agents, drug delivery [72], bio-labeling, wound healings, sensing, cosmetics and water purifications [73]. These NPs can be formed through protocols [74]. Though the method of chemical reduction is a common one for the formation of silver nanoparticles, the usage of precarious and expensive chemicals has diverted the attention of researchers for the search of new and alternative methods [75]. Some potential health risks were another reason for the search for new methods and had attracted the attention of researchers worldwide [2, 76].

Recently, plant-based green biosynthesis of AgNPs is rising into an important subdivision of nanotechnology, as it gained importance and is developed due to its cost-effectiveness and lesser toxicity [77]. Silver has been considered and studied very extensively for plant-based synthesis and it has been known as a more rapid and easier process as compared to the monotonous and time taking microbial synthetic methods [47]. Shankar et al. [78] used leaves extract of *Pelargonium graveolens* for the extracellular formation of AgNPs. Through mixing AgN solution and plant extract, a quick reduction of Ag ions take place followed by the synthesis of crystalline and highly stable AgNPs (16–40 nm) in solution. Later on, in 2007, Huang [79] displayed that spherical or triangular-shaped silver nanoparticles of size 55-80 nm can be prepared from the leaf extract of *Cinnamomum camphora*. He discovered that water-soluble heterocyclic and polyol compounds in the leaves of *C. camphora* are responsible for silver ions reduction. Leela and Vivekanandan [80] compared the leaves extract of some different plants such as *Sorghum bicolar, Basella alba, Helianthus annus, Saccharum officinarum, Zea mays, Oryza sativa and* for the formation of AgNPs and determined that *H. annus* showed a speedy reduction of silver ions. Similarly, Ahmad et al. [81] used broth of *Ocimum sanctum* for the biosynthesis of AgNPs and observed highly stable

NPs with a size of 5 ± 1.5 nm to 10 ± 2. In a research conducted by Jeyaraj et al. [82] the biological preparation of silver nanoparticles from the leaves extract of *Podophyllum hexandrum* was described. The complete reduction of silver ions was completed in 2.5 h at the temperature of 60 °C and pH 4.5 with the formation of spherical shaped nanoparticles in the range of 12 to 40 nm. Saratale et al. [83] biosynthesized spherically and monodispersed silver nanoparticles (15 nm) by using the leaf extract of *Taraxacum officinale*. The presence of flavonoids, terpenoids, and triterpenes are known to be the active compounds present in extract for the synthesis of silver nanoparticles.

By using the aqueous extract of *Alternanthera dentate* a rapid and green synthesis of AgNPs having spherical shaped with a size of 50–100 nm was prepared. Within 10 min, the silver ions were reduced into silver nanoparticles by the leaf extract. These prepared AgNPs showed antibacterial potential against *Escherichia coli*, *Klebsiella pneumonia*, *Enterococcus faecal* and *Pseudomonas aeruginosa* [84]. For the formation of AgNPs, *Acorus calamus* was also used and its antibacterial, anticancer, and antioxidant effects were determined [85]. In 2014, Nakkala [86] and his research members used the extract of *Boerhaavia diffusa* plant as the reducing material for the formation of AgNPs. It was revealed from TEM and XRD that the prepared NPs possess a particle size of 25 nm, spherical shape with a face-centered cubic structure. The antibacterial potential was determined against *Flavobacterium branchiophilum*, *Aeromonas hydrophila*, and *Pseudomonas fluorescens*, the highest sensitivity was observed toward *F. Branchiophilumin* as compared to the two other bacteria. Similarly, Nabikhan et al. [87] prepared spherical AgNPs (5-20 nm) by using the callus extract of *Sesuvium portulacastrum* L. a salt marsh plant.

The fruit of *Tribulus terrestris* L was dried and reacted with Ag nitrate for the formation of silver nanoparticles. The newly synthesized AgNPs possess a size of 16-28 nm with spherical shape and were used to determine their antibacterial potential against few multi-drug resistant bacteria like *Streptococcus pyogens, Staphylococcus aureus, Pseudomonas aeruginosa, Escherichia coli* and *Bacillus subtilis* [88]. Methanolic and Ethyl acetate extracts of *Cocous nucifera* were used for the successful synthesis of Ag nanoparticles (22 nm) and exhibited good antimicrobial activity towards different bacterial strains such as *Klebsiella pneumoniae, Bacillus subtilis, Salmonella paratyphi and Pseudomonas aeruginosa* [89]. Another spherical shaped and stable AgNPs were synthesized from *Abutilon indicum* which also possesses good antimicrobial potential against *E. coli*, *S. typhi*, *B. substilus*, and *S. aureus* [90]. Leaves of *Ziziphoratenuior* were also utilized for the preparation of AgNPs and the nanoparticles were characterized through different techniques. TEM analysis reveals the spherical shape and size of 8 to 40 nm, and FTIR showed carbonyl, hydroxyl, amine, and some other stabilizing functional groups [91]. By using the leaves of *Acalypha indica*, a rapid and green protocol for the formation of nanoparticles was reported by Krishnaraj et al. [92], where a successful formation of nanoparticles was completed in 30 min [92]. A weed *Chenopodium album* was reported in a rapid and facile biosynthesis of AgNPs. Its leaf extract was used for the synthesis and results in NPs of the size range of 10-30 nm and its shape was spherical that was inferred through TEM analysis [93]. Similarly, silver nitrate was reduced by *Azadirachta indica* (leaf extract) that results in the biosynthesis of silver nanoparticles (10-35 nm) with spherical shape [94].

3.4. Zinc oxide nanoparticles

Zinc oxide (ZnO) is an n-type semiconducting metallic oxide. ZnO nanoparticles (ZnONPs) have diverted the attention of researchers in the past few years because of its wider variety of applications in the field of optics, biomedical systems, and electronics [95, 96]. Different categories of inorganic metallic oxides have been prepared in some latest findings such as CuO, ZnO, and TiO_2. Of all these metallic oxides, ZnONPs have gained much interest as they are not costly to synthesize, safe, and easily prepared [97]. ZnO as a metal oxide has been registered as GRAS (generally recognized as safe) by FDA US [98]. These nanoparticles possess great semiconducting features due to the large bandgap and high exciton binding energy such as catalytic potential, wound healing, UV filtering, and optics [99, 100]. ZnONPs have been widely utilized in different cosmetics such as sunscreen lotion, depending on its UV filtering potential [101]. It also has extensive use in biomedical fields like anticancer, antifungal, antibacterial, antidiabetic, and drug delivery [102, 103]. While ZnO is being utilized in targeted drug delivery and still have the constraint of cytotoxicity, which has to be solved [104]. Nanoflower, nanoflake, nanorod, nanowire, and nanobelt are different morphologies of ZnONPs that have been reported [105, 106]. The different parts of plants like leaf, fruit, stem, seed, and root, have been used for the formation of ZnONPs, as they contain a sufficient quantity of phytochemicals. The usage of natural extracts for biosynthesis is an eco-friendly and cheap process that does not require any intermediate base groups [107]. Plants produce large scale synthesis of stable nanoparticles with various sizes and shapes, it is one of the reasons that plants are the preferred source for the formation of NPs [108]. The synthesis of ZnO nanoparticles is achieved by bio-reduction, which involves the reduction of metallic ions into 0 valences metallic NPs. This process is assisted by different phytochemicals such as polyphenolic compounds, amino acids, vitamins, polysaccharides, terpenoids, and alkaloids secreted from several plants [107, 108].

Jafarirad [109] and his research team experimented and compared the results of zinc oxide nanoparticles that were synthesized through two different methods- microwave irradiation (MI) and conventional heating (CH) and results proved that MI took lesser time and faster reaction rate for the formation of nanoparticles [109]. Plants of family Lamiaceae have been widely used like *Plectranthus amboinicus* [110], *Vitex negundo* [111], and *Anisochilus carnosus* [112] showed NPs of different shapes and sizes like quasi-spherical, rod-shaped, spherical, and hexagonal. The findings demonstrate that an increase in the concentration of the plant extract causes a decrease in the size of nanoparticles [110-112]. *Azadirachta indica* (leaf extract) of family Meliaceae have been commonly used for the ZnONP biosynthesis [113, 114]. Sangeetha et al. [115] synthesized spherical and highly stable ZnONPs of size 25-40 nm from the leaf extract of *Aloe barbadensis*. It was described that the synthesized NPs were polydispersed and their particle size can be controlled by changing the concentration of extract. Similarly, spherical and highly stable NPS were synthesized using *Parthenium hysterophorus* leaf extracts. Additionally, *Plectranthus amboinicus* (leaf extract) was utilized for the formation of zinc oxide NPs by Vijayakumar et al. [116]. The synthesis of ZnONPs has also been performed by using *Sedum alfredii* [108], *Physalis alkekengi* [117], *Pongamia pinnata* [118], flowers of *Trifolium pretense* [119], *Cassia Auriculata* [120, 121]. Qu et al. [117] synthesized crystalline ZnO nanoparticles (72.5 nm) from *Physalis alkekengi*, it can grow in soils with high levels of Zn and can incorporate zinc in its aerial parts.

3.5. Titanium dioxide nanoparticles

Titanium dioxide (TiO_2) is the oxide form of Ti and occurs naturally. It can be obtained from different minerals as brookite, rutile, and anatase. The manufacturing and utilization of TiO_2 only in the US have stayed is 1100 thousand tons since 1997, and it has been categorized as a possible carcinogen for humans (Group 2B) by International Agency for Research on Cancer [122]. TiO_2 is a main and vital metallic oxide nanoparticle that is being extensively used in industrial photocatalytic processes, printing ink, paints, paper, rubber, sunscreens, cosmetics, air cleaning products, and car materials because of its biological, chemical and physical features [123]. The nanoparticles of TiO_2 are being utilized in a wide variety of applications such as sunscreens, drug delivery systems, food preparation, and cosmetics [124-126].

Due to its bright, white pigment and high refractive index titanium dioxide is an ideal material used as a whitening agent in different applications. Discovery of the super-hydrophilicity and photocatalytic properties of TiO_2 has also led to applications in some industries by producing self-cleaning products as well as enhancing sterilization and deodorizing processes. The biomedical applications of nanoparticles synthesized from titanium dioxide have greatly developed in recent few years. Research is being conducted on these NPs to attenuate the effects of chemotherapy by making cancer therapy more efficient and targeted [127, 128]. Additionally, food-grade titanium dioxide nanoparticles (TiO_2NPs) are present in a range of food products like gum, candy, donuts, marshmallows, cookies, and some others. Toothpaste, shaving creams, deodorants, conditioners, shampoos, and sunscreens are some personal care products also containing food-grade TiO_2NPs [129].

Sundrarajan and Gowri [130] synthesized titanium nanoparticles by using titanium isopropoxide solution and leaf extract of *Nyctanthes arbortristis* with a size range of (100-150 nm). Similarly, TiO_2NPs (25–100 nm) were also biosynthesized from *Jatropha curcas* (aqueous extract) [131]. An enzyme, curcain, and cyclic peptides were recognized as the possible capping and reducing compound in latex of *J. curcas*. Spherical shaped (23 ± 2 nm) nanoparticles were synthesized from the fruit peel of *Annona squamosa* at room temperature with a time of 6 h [132]. At room temperature, *Solanum trilobatum* (leaves) were used for the formation of titanium NPs that were having pediculicidal and larvicidal activities [123] (Rajakumar et al., 2013). Velayutham et al. [133] use leaves extract of *Catharanthus roseus* for the synthesis of TiO_2NPs, the synthesized nanoparticles were having rough shape and size of 25-110 nm. These NPs possess great adulticidal and larvicidal potential against *Bovicola ovis* and *Hippobosca maculate.* Similarly, the synthesis of TiO_2NPs from plant *Eclipta prostrata* was reported by Rajakumar et al. [134]. Santhoshkumar et al. [135] biosynthesize TiO_2NPs from *Psidium guajava* (aqueous leaf extract), antibacterial, and antioxidant potential of these nanoparticles was explored. By using 20 μg/mL of nanoparticles the highest zone of inhibition was recorded against *E. coli* and *S. aureus*. In another research conducted by Priyadarshani et al. [136], TiO_2NPs of *Cissus quadrangularis* having significant bactericidal potential against *Staphylococcus* and *E. coli* were also reported. Kumar et al. [137] compared the antibacterial potential of two types of biosynthesized titanium dioxide nanoparticles one from extracts of *Hibiscus rosa sinensis* and one chemically synthesized. The author concluded that nanoparticles synthesized from plant extract showed higher activity as compared to chemically synthesized ones.

4. Different parts used for the synthesis of metallic nanoparticles

Recently, green plant-based nanotechnology has diverted the attention because of its wide applications in many different fields. The metallic NPs like gold, zinc, silver, platinum, nickel, copper, titanium oxide, and magnetite were biosynthesized by using various plant parts and are being studied extensively. Stem, fruit, root, seed, peel, callus, flower, and gums are the different parts that are utilized for the synthesis of nanoparticles with various sizes and shapes by biological methodologies [138].

4.1. Fruit

Fruit bodies of *Tribulus terrestris* and solution of silver nitrate were utilized for the eco-friendly biosynthesis of silver NPs [88]. The presence of different phytochemicals in the plant extracts causes the formation of nanoparticles in only one step of reduction. The shape of synthesized NPs was spherical and exhibit excellent antimicrobial potential against the multidrug-resistant human pathogens. Similar research was performed by Amarnath et al. [139] in which polyphenol from grapes was utilized for the formation of palladium NPs and these nanoparticles act very efficiently against different bacterial diseases. Fruit extracts of *Rumex hymenosepalus* act as reducing and stabilizing agents in the biosynthesis of silver nanoparticles.

4.2. Stem

The methanolic extract of *Callicarpa maingayi* (stem) was used for the biosynthesis of AgNPs [140]. The prepared extract consists of a group aldehyde that mainly involves in the process of reduction of Ag into silver nanoparticles. The functional groups such as amide I and polypeptides are considered as the responsible groups for the capping of ions to metallic NPs. The molecular findings on the synthesis of Ag crystals are complicated and still not completely known. According to some latest studies, AgNPs bind with the proteinaceous outer cell of fungi and bacteria that results in the breakage of lipoproteins of the microbial cell wall. This is followed by the blockage of cell division and leads to cell death. Vanaja et al. [141] stated the photosynthesis of silver nanoparticles by using extracts of *Cissus quadrangularis*. The functional groups mainly the amine, phenolics, and carboxyl are directly involved in the reduction reaction. The synthesized NPs possess good antibacterial potential towards *Bacillus subtilis* and *Klebsiella planticola* (pathogenic bacteria).

4.3. Seeds

The seed extract of fenugreek contains many naturally occurring bioactive compounds like lignin, saponin, vitamins, and high content of flavonoids. In the presence of reducing agents, this extract of seed acts as a good surfactant in the process of reduction of chloroauric acid for the formation of nanoparticles. Seed extracts of different plants contain some functional groups such as COO^- group, C,C, and C,N. This functional group serves as a surfactant of AuNPs and flavonoids easily stabilizes the electrostatic stabilization during the synthesis of AuNPs [74]. *Macrotyloma uniflorum* (aqueous extract) increases the rate of reduction of Ag ion in the biosynthesis of AgNPs. Caffeic acid present in the seed extracts is recognized to be the reason for the increase in the reduction rate. Hence, the present caffeic acid completes the reduction reaction of nanoparticle synthesis within a minute.

4.4. Flowers

Petals of rose were utilized for the formation of gold nanoparticles through an eco-friendly method by Noruzi et al. [142]. This extract contains an ample amount of proteins and sugars that are considered to be the main constituents during the reduction of salt tetrachloroaurate into the bulk of gold nanoparticles. Likewise, flowers of *Clitoria ternatea* and *Catharanthus roseus* are also utilized for the biosynthesis of different metallic nanoparticles of desired sizes and shapes. Vankar and Bajpai, [143] also synthesize AuNPs by using the flower extract of *Mirabilis jalapa*.

4.5. Leaves

Extracts of plant leaves also serve as a facilitator in the biosynthesis of different metallic nanoparticles. Leaves of several plants like *Alternanthera sessilis*, *Murraya koenigii*, and *Centella asiatica* have been used for the said purpose. Recently, *Piper nigrum* leaves were utilized for successful biosynthesis of silver nanoparticles through an eco-friendly protocol, as they contain important bioactive products. The silver nanoparticles have an effective role in cancer medicine for the treatment of different dreadful diseases. The presence of piper longminine and longumine in *Piper nigrum*, acts as the agent for capping in preparation of silver nanoparticles and can also improve the cytotoxic effects of the tumour cells [144]. Another green preparation of AgNPs from *Artemisia nilagirica* (leaves extract) was described by Vijayakumar et al. [145]. These metallic nanoparticles serve as a significant antimicrobial agent. Similarly, AgNPs formed from the different plant leaves can control many pathogenic problems in humans.

5. Conclusions

In this chapter, we have summarized information about the green and environmentally responsive production of various metal nanoparticles. The presence of biologically active molecules and secondary metabolites in plant extracts is responsible to reduce metal ions to nanostructures in a rapid single-step synthetic strategy. A large number of plant species, their parts, and derived extract has been effectively employed for the preparation of numerous kinds of nanoparticles and other nanostructured materials due to the occurrence of abundant metabolic compounds, including phenols, alkaloids, carbohydrates, terpenoids, and bio-enzymes. It is worth noting that the utilization of plant sources for nanoparticle biosynthesis obviates the requirement for capping and stabilizing agents. Taking into consideration the inescapable applications of nanotechnology and nanoscience in a range of modern everyday life, additional research is necessary to explore the unique physical and chemical attributes of newly-synthesized nanostructures. From the future development perspective, Figure 4 shows the involvement of nanotechnology to further advance the characteristics features and functionalization of nanoparticles [146,147].

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