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Review Article

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Green Synthesis of Metal Oxide Nanoparticles and Studies of Their Antibacterial Efficacy against Common Pathogens

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Abstract

Green synthesis of metal oxide nanoparticles has been emerging highlight of the research owing to its unique properties that make them applicable in various fields of science and technology. The method of synthesis is simple, cost effective and environmental friendly. After review, we reported the phyto-synthesis of metal oxide nanoparticles using plant extract with an emphasis on recent developments. Biomolecules such as alkaloids, flavonoids, polyphenols etc. present in the plant extract can be used for the reduction of metal ions to nanoparticles in a single step process. These extract also act as a stabilizing agent. Although, a good number of work has been reported for the synthesis of gold and silver nanoparticles. However, limited no of work has been reported for the synthesis of copper, zinc and iron oxide nanoparticles. We have discussed the green synthesis of copper, zinc and iron oxide nanoparticles and potential of their antibacterial efficacy.

Keywords: Green synthesis, Metal Oxide Nanoparticles, Antibacterial Activity

Introduction

The word "*nano*" arises from "*nanos*", a Greek word meaning "*dwarf*". The concept of nanotechnology and nano materials come from the lecture entitled "There's plenty of room at the bottom" by Nobel Laureate Richard Feynman in 1959. Presently, nanoscience and nanotechnology are two peculiar words extensively used for broad range of research exploration around the world. Nanomaterials are defined as the materials with at least one dimension in the size range of 1-100 nm. Discoveries in the past have shown that the physical and chemical properties of materials change significantly once the size of the materials is reduced to nanoscale [1].

The development of nanotechnology has revolutionized every aspect of the science, engineering and technology. In the recent years, the multidimensional aspects of nanoparticles make them potential materials for application in a wide variety of fields. The properties of nanoparticles are significantly different from their bulk counterparts. Nanoparticles show some unique properties such as surface plasmon resonance (SPR), surface-enhanced Rayleigh scattering and surface-enhanced Raman scattering (SERS) properties that make them the potential materials for optoelectronics, electronics, chemical sensing and a wide variety of biological applications [2].

Among the various materials, metallic nanoparticles have extensively been used by researchers worldwide. The preparation of nanoparticles is done either through a top-down or a bottom-up approach. Various physical and chemical methods have also been employed for the preparation of nanoparticles by size reduction of bulk material by the top-down approach. A top-down synthesis method implies that the nanostructures are synthesized by etching out crystals planes (removing crystal planes) which are already present on the substrate. A top-down approach can thus be viewed as an approach where the building blocks are removed from the substrate to form the nanostructure [3].

However, the main drawback of this process is the imperfection of the surface structure. Besides this, the high energy consumption requirement during the preparation for maintaining high temperature and pressure is another limitation to this process.

A bottom-up synthesis method implies that the nanostructures are synthesized onto the substrate by stacking atoms onto each other which gives rise to crystal planes. The crystal planes further stack onto each other resulting into the synthesis of the nanostructures. A bottom-up approach can thus be viewed as a synthesis approach where the building blocks are added onto the substrate to form the nanostructures. The bottom–up approach commonly uses the wet chemical process for the preparation of nanoparticles. However, extensive use of toxic and hazardous chemicals is a matter of great concern towards the environment and living cells [4, 5].

Synthesis of Metal Oxide Nanoparticles

Metals are capable of forming a huge variety of oxide compounds.

Metal oxide nanoparticles (MONPs) reveal significant use in many areas such as physical science, chemical science and materials science [6]. The MONPs have released new boundaries in materials science and engineering such as nano-biotechnology, quantum dots technology cancer treatment [7-9] etc.

The MONPs may be synthesized by various methods generally divided into two approaches. As discussed earlier, they are primarily top-down approaches and bottom-up approaches [3]. The bottom-up approach is more advantageous than the top-down approach because the former has a better chance of producing nanostructures with fewer defects, more homogenous chemical composition and better short and long-range ordering. Figure 1 shows the methods of synthesis of nanoparticles. Chemical methods involved in the reduction of metal ions in a solution by chemical reducing agents such as $NaBH_4$, potassium tartrate [10] and ethylene glycols [11].

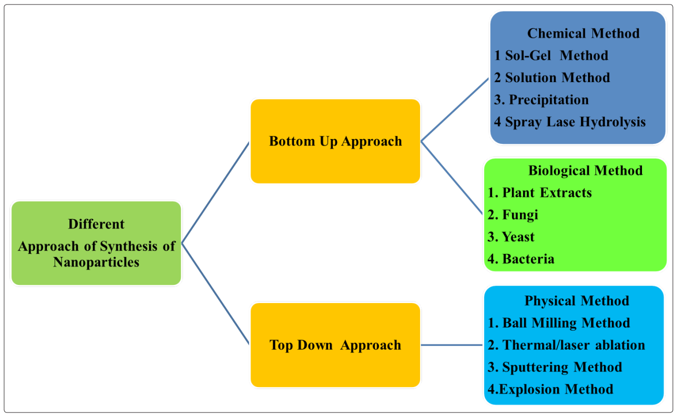

Figure 1: Methods of synthesis of nanoparticles

Although physical methods produce well defined nanoparticles than chemical methods, these methods are expensive and time-consuming but chemical methods require hazardous chemicals to synthesize nanoparticles and are also expensive. Therefore, there is a considerable interest in the development of an environmentally benign procedure for nanoparticle synthesis which avoids the use of toxic chemicals and solvents. Compared to all these methods, the bio-based methods utilizing plant extracts, fungi, yeast and bacteria are now gaining recognition for the synthesis of nanoparticles.

Green Synthesis

Green chemistry is the interdisciplinary branch of chemistry and engineering where chemists and engineers work to design chemicals, chemical processes and commercial products. The aim of green chemistry is to make better, safer chemicals while choosing the ecofriendly and most efficient ways to synthesize them and to reduce wastes. Green chemistry seeks synthesis and use of chemicals so that they are inherently environmentally benign and more efficient in use. The term "green chemistry" often use as synonyms with sustainable because it focuses on the broader sustainability movement.

It has been widely accepted worldwide that transition to a sustainable society necessity significant changes in resource and energy consumption. Trans-materialization and dematerialization must occur to efficiently use the limited resources of the planet. Trans-materialization is the process of shifting away from hazardous and non-renewable resources towards safer and reusable materials. Dematerialization seeks to minimize the material and energy inputs to society while maintaining its prosperity.

Green chemistry is becoming increasingly popular and is much needed as a result of worldwide problems associated with environmental contamination. It is the eco-friendly way to produce materials with reduced usage and generation of hazardous substances from biodegradable, safe materials and if not fully, few issues associated with nanotoxicology and hazards can be dealt up to a good extent with green approaches of synthesis. "Green synthesis" is a new platform to design novel products that are benevolent to human and environment health and has huge potential to revolutionize large scale nanosynthesis procedures [12].

These green synthesis approaches for nanomaterials are supposed to benefit environmental and biomedicine segments of nanotechnology applications in the future. This new concept can be seen as a benchmark for clean and sustainable nanomaterials. Basic pillars of green chemistry are:

1. Maximize utilization of raw material that ends up in the product
2. Safe, biodegradable and cost-effective sources
3. Energy efficient reactions and inherently safer chemistry
4. Avoiding the production of waste

Green synthesis methods eliminate the necessities of hazardous reagents and advance the efficiency in providing the necessary quantity of pure material in a cheap feasible manner. It also provides possible design schemes to ensure that the nanomaterials produced are effectively safer by evaluating the biological and environmental hazards.

Green Synthesis of Nanoparticles

The green synthesis of metal nanoparticles is the novel, environmentally friendly and a busy area of research in which the preparation of metal nanoparticles employs the use of bacteria, fungus and plants. Based on this approach, plant extract has been used for the preparation of the inorganic nanomaterials. Plant-mediated green synthesis of metal nanoparticles is a fast, economical, non-toxic and produces highly stable nanoparticles. Figure 2 represents biological synthesis approaches of metal oxide nanoparticles. It is one pot synthetic approach, eco-friendly and safe for human therapeutic use. In contrast to the traditional method of synthesis, plant-based protocols meet all the criteria for green synthesis [4, 5].

These methods are energy efficient and less time consuming and are suitable for ecosystem i.e. eco-friendly. Bio-fabrication of MONPs tenders a precious contribution to nanomaterials research emphasizing the opportunities of green chemistry pathways to produce technically significant nanomaterials [13].

In summary, the green synthesis of MONPs is based on three important steps.
(i) Choice of non-hazardous and biocompatible solvent medium.
(ii) Choice of environment friendly reducing agents.
(iii) Choice of non-hazardous stabilizing and size controlling agents.

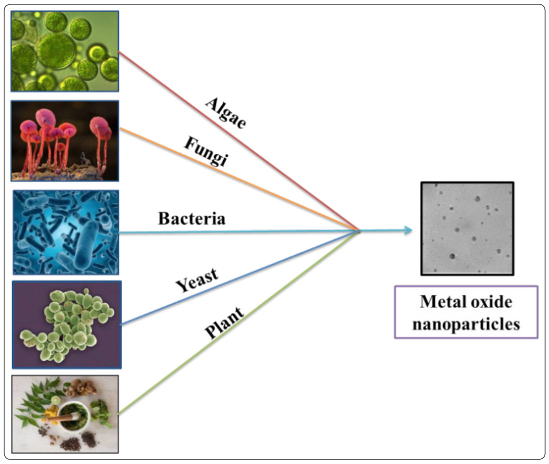

Figure 2: Biological synthesis approach of metal oxide nanoparticles

Synthesis of Metal Nanoparticles by using Plants

Green synthesis of nanoparticles applies "bottom-up" approach and it mainly relies on chemical and biological methods of production. Since ancient times different parts of the plants like root, stem, leaf, latex, seed etc. were used as a medicinal herb. To date, biological methods mainly rely on the plants for nanoparticles synthesis. The major classes of antibacterial compounds found in plants are phenolics, terpenoids, alkaloids, lectins, polypeptides and flavonoids. Medicinal plants mainly having high phenolic contents have drawn increasing attention due to their potent antioxidant properties. Recently, these plant parts have become the potential candidates for green synthesis of metal nanoparticles.

A good number of works have been reported for the green synthesis of metal oxide nanoparticles from different parts of the plants. The first step of the synthesis is extraction from different parts of the plants which can be done by the various methods like maceration, infusion, digestion, and decoction. Hot continuous extraction by soxhlet apparatus is a general method of extraction from the plants [14]. Nanoparticles are synthesized from plant parts by mixing plant extract with the metal salt solution.The reaction is complete within short period of time. Nanoparticles of silver, gold, iron, copper, palladium, platinum and many other metals have successfully been synthesized using plant extracts.

Green synthesis of gold and silver nanoparticles using different parts of the plant has been exploited extensively and their antibacterial efficacy has also been studied against various bacterial strains. However, a limited number of works has been reported for the synthesis of copper, zinc and iron oxide nanoparticles.

Antibacterial Activity of Copper Oxide Nanoparticles

Lee *et.al* synthesized CuNPs using *Magnolia kobus* leaf extract and observed UV-Visible absorption peak at around 560 nm [15]. The size of the prepared nanoparticle range in between 37-110 nm. Further antibacterial activity was observed against *Escherichia coli* (ATCC 25922). They showed that antibacterial activity of as-synthesized copper nanoparticles using *Magnolia kobus* extract is higher as compared to chemical method. Their results also showed that copper nanoparticles were stable even after 30 days.

In another experiment Subhankari *et al*. synthesized CuNPs using clove [16]. Copper ions were reduced by the biomolecules present in the extract. Besides, these extract also act as a stabilizing agent. The synthesized nanoparticles were spherical in shape as depicted by the micrograph of SEM and TEM.

Kulkarni *et al.* synthesized CuNPs using the extract of cloves and copper sulphate as a precursor [17]. They observed that the reaction was complete within 8 to 10 minutes after adding the extract to the salt solution. They reported that the average particle size of the nanoparticles was 77 nm. Kathad *et al*. describe the synthesis of copper nanoparticles using papaya extract as stabilizing and capping agent [18]. The reaction was carried out at 50 to 60°C and the complete reaction was observed by the colour change of the reaction. XRD spectra showed that the particles are FCC crystalline in nature. SEM and TEM spectra confirm that average particle size of the copper nanoparticles was around 20 nm. CuNPs were synthesized using papaya extract by Suresh *et al.* [19]. UV-Visible absorption peak was obtained at 560 nm [19]. The synthesized nanoparticles were found to be spherical and crystalline with the particle size of 20 nm. In this method, copper salts were used as basic precursors and papaya extract as stabilizer. Green synthesis of CuNPs using *Capparis zeylanica* leaf extract was reported by Renganathan *et al.* [20]. XRD analysis revealed that the particles were cubic cantered *Escherichia coli* with particles size approximately 5 nm. Antibacterial activity was evaluated against *Staphylococcus aureus, Escherchia coli* and *Pseudomonas aeruginosa*. They observed that on increasing the concentration of the nanoparticles suspension the zone of inhibition also increases. Furthermore, these nanoparticles were more pronounced against Gram-negative as compared to Gram-positive bacterial strains. In another experiment, Subbaiya *et al.* prepared CuNPs using precursor copper sulphate as a precursor and *Vitis vinifera* leaf extract [21]. They observed UV-Visible absorption characteristic peak of copper at 384 nm. FT-IR spectra reveal a peak at around 500 cm^{-1} confirming the presence of metal oxide bond. Besides, they also observed the antibacterial activity against *Escherichia coli*, *Staphylococcus aureus*, *Klebsiella pneumonia, Salmonella typhi* and *Bacillus subtilis* and found that zone of inhibition of *Staphylococcus aureus* is highest followed by *Escherichia coli*, *Klebsiella pneumonia*, *Bacillus subtilis* and *Salmonella typhi*. *Nerium oleander* mediated green synthesis of copper nanoparticles and its antibacterial activity was observed by Gopinath *et al.* [22]. They observed UV-Visible absorption peak at 350 nm. They also tested the antibacterial activity against *Staphylococcus aureus*, *Salmonella typhi, Klebsiella pneumonia*, *Bacillus subtilis* and *Escherichia coli.* They found that maximum zone of inhibition of copper nanoparticles was observed by *Salmonella typhi* (18 mm) followed by *Bacillus subtilus* (14 mm), *Staphylococcus aureus* (13 mm), *Klebsiella pneumoniae* (10 mm) and *Escherichia coli* (10 mm). Makwana *et al*. reported the synthesis and antibacterial activity of CuNPs using datura-metal leaf extract and $CuSO_4.5H_2O$ [23]. The particles were spherical in shape and size range in between 15-20 mm. They observed the antibacterial activity against *Staphylococcus aureus*, *Escherichia coli*, *Bacillus megaterium* and *Bacillus subtilis* and reported that copper nanoparticles are more susceptible to these bacterial strains as compared to plant extract. Furthermore, they concluded that the method of synthesis is cost effective and environmentally safe. Bhaskar *et al*. evaluated the green synthesis and antibacterial activity of CuNPs using *Ocimum sanctum* leaf extract [24]. The extract reduced the copper ions in copper nanoparticles. The characteristic peak was observed by UV-Visible absorption peak at 360-380 nm. It was observed that these nanoparticles possess antibacterial activity against *Staphylococcus aureus*, *Salmonella typhi*, *Vibrio cholera* and *Pseudomonas aeruginosa* with zone of inhibition of 8 mm, 10 mm, 12 mm and 10 mm respectively. In a study Karimi *et al*. evaluated the phytosynthesis of CuNPs using *Aloe vera* flower extract [25]. The reaction was complete within 30 minutes. The formation of copper nanoparticles was confirmed by the presence of the characteristic absorption peak at 578 nm. FESEM micrograph reveals the spherical nature of the particles with an average size 40 nm. FT-IR spectra recognized the biomolecules held responsible for the reduction of Cu^{2+} to Cu^0. There is a similar report on using the biomolecules of *Citrus medica Linn* (Idilimbu) juice for the synthesis of CuNPs by Rai *et al*. It was observed that average particle size of synthesized nanoparticles was 20 nm [26]. XRD result showed the FCC structure of crystallite and the size was calculated using Debye–Scherrer's equation about 20 nm. The as-synthesized nanoparticles possess antibacterial activity against *Escherichia coli*, *Klebsiella pneumoniae*, *Pseudomanas aeruginosa*, *Proponibacterium acnes* and *Salmonella typhi*. It was found that *Escherichia coli* were more susceptible to CuNPs followed by *Klebsiella pneumoniae*, *Pseudomanas aeruginosa*, *Proponibacterium acne* and *Salmonella typhi*. *Phyllanthus embilica* extract was used for the synthesis of CuNPs in the range of 15-30 nm by Caroling *et al.* [27]. XRD confirms the crystallinity and FCC structure of the synthesized nanoparticles. UV-Visible absorption peak was obtained at 294 nm. Zone of inhibition of CuNPs against *Escherichia coli* and *Staphylococcus aureus* were found to be 10 mm and 12 mm (1500μg) respectively. *Cassia auriculata* is a medicinal plant is also known as avaram. The extract of the plant is used to cure many diseases and is reported to possess antipyretic, hepatoprotective, antidiabetic, antiperoxidative, antihyperglycemic, microbicidal and antihyperlipidaemic activities. Valli *et al*. reported the synthesis of CuNPs using the leaf extract of *Cassia auriculata* [28]. UV-Visible absorption peak was observed at 488 nm. XRD peaks were in consistent to FCC structure. FESEM micrograph reveals the particles are spherical in shape with the size of about 38.1 nm. Vennila *et al*. used the leaf extract of *Ocimumteni florum* to reduce the copper ions to copper nanoparticles within 8-10 minutes in the size 72 nm [29]. XRD peaks show the characteristic FCC structure. SEM analysis showed the formation of sheet-like structure. EDX analysis confirms the composition of the prepared nanoparticles having copper and oxygen peak in the micrograph. Khatami *et al*. demonstrated the formation of copper/cuprous oxide (Cu/Cu_2O) nanoparticles using *Stachys lavandulifolia* both as a reducing and stabilizing agent [30]. XRD spectra reveal the formation of both copper and cuprous oxide entity. The size of the nanoparticles was reported to be 80 nm. Furthermore, these nanoparticles were susceptible to *Pseudomonas aeruginosa*. In a similar type of experiment Y.T. Prabhu *et al*. used *Garcinia mangostana* leaf extract for the synthesis of copper nanoparticles [31]. XRD confirms the cubic phase of the copper nanoparticles. The particle size was calculated from XRD was 26.51 nm. The morphology of the nanoparticles was depicted using SEM and TEM. The micrograph showed that the particles are spherical in shape. It was observed that copper nanoparticle is more susceptible to *Staphylococcus aureus* as compared to *Escherichia coli*. A. Pugazhendhi *et al*. showed that *Sida acuta* was also capable of reducing copper ions for the formation of copper oxide nanoparticles [32]. FE-SEM shows the presence of nano rods structure whereas TEM clearly confirm the crystalline nature of the particles with size around 50 nm. Antibacterial efficacy of synthesized nanoparticles was tested against both Gram-positive and Gram-negative bacterial strains. It was observed that the antibacterial efficacy of copper nanoparticles against Gram-negative bacteria is higher as compared to Gram-positive bacteria. Cloves are the aromatic flower buds of a tree in the family *Myrtaceae* and the bud extract of this plant reduced copper ions to spherical nanoparticles with an average diameter of ~15 nm. Reddy *et al.* records the UV-Visible characteristic peak of copper nanoparticles at ~ 580 nm [33]. Antibacterial activity of synthesized nanoparticles was tested against *Staphylococcus* spp., *Escherichia coli*, *Pseudomonas* spp. and *Bacillus* spp. The result showed that *Bacillus* spp.is more effective against copper nanoparticles as compared to other bacterial strains. Recently, in a comparative study iron, copper and silver nanoparticles was synthesized using green and black tea leaves extracts and their evaluation of antibacterial activity was done against *Staphylococcus aureus* strains. The antibacterial activity was in the order Ag-NPs > Cu-NPs > Fe-NPs both synthesized using green and black tea leaves extracts [34].

Green Synthesis of Zinc Oxide Nanoparticles and its Antibacterial Activity

Vidya *et al*. synthesized zinc oxide nanoparticles using *Calotropis gigantea* leaf extract and zinc nitrate as a precursor [35]. The average size of the nanoparticles was observed ~30-35 nm. SEM micrograph reveals the spherical nature of the particles with agglomeration. XRD spectra show the hexagonal structure of zinc oxide nanoparticles. Gnanasangeeta *et al*. reported a comparative study of chemical and green method for the synthesis of zinc oxide nanoparticles using the leaf extract of *Corriandrum sativum* [36]. They concluded that green synthesis of zinc oxide nanoparticles are more efficient as the process is eco-friendly and cost-effective. Senthilkumar *et al*. showed the green synthesis of zinc oxide nanoparticles using the aqueous extract of green tea *Camelia sinensis* [37]. The XRD pattern revealed hexagonal wurtzite structure of zinc oxide nano partilces. FT-IR spectroscopic analysis was used for the identification of possible biomolecules involved in the synthesis process. The as-synthesized nanoparticles were tested for the antibacterial efficacy against *Gram-negative Klebsiella pneumoniae*, *Pseudomonas aeruginosa* and *Escherichia coli* and the Gram-positive *Staphylococcus aureus*. They observed that the materials are susceptible to all the bacterial strains especially the Gram-negative strains. Similarly ethanolic and aqueous extract in the ratio 1:2 of fruit peels of rambutan reduced zinc ions to ZnO nanocrystals. XRD analysis showed a strong and narrow peak confirming the formation of highly crystalline nanocrystals. SEM analysis revealed that the ZnO nanocrystals form needle-like structure. They reported that cotton fabric coated with ZnO nanocrystals exhibited stronger antibacterial activity. Das *et al.* synthesized different sizes and shape zinc oxide nanoparticles using leaf extract of *Hibiscus subdariffa* leaf extract by annealing the nanoparticles at the different temperature [38-39]. They observed that the ratio of plant extract and precursor salt 20 ml/g. is sufficient for the synthesis of zinc oxide nanoparticles. XRD spectra revealed that on increasing the annealing temperature the crystallinity of the material also increases. UV-Visible spectra showed the absence of any peak of ZnO nanoparticles annealed at 30°C whereas particles annealed at 60°C and 100°C showed characteristic peak at 377 nm. FE-SEM micrograph showed irregular shape of nanoparticles annealed at 30°C whereas particles annealed at 60°C and 100°C showed spherical and dumbbell-shaped respectively. Antibacterial activity of zinc oxide nanoparticles annealed at 100°C are more susceptible to bacterial strains as compared to zinc oxide nanoparticles synthesized at 30°C and 60°C due to its smaller in size. Velmurugan *et al*. showed that *Azadirachta indica* which has antibacterial property was also capable of synthesizing zinc oxide nanoparticles [40]. 20 mL of the extract was allowed to react with 2g of zinc nitrate solution under constant stirring. The nanoparticles were recovered for further characterization. UV-visible result showed the characteristic peak at 370 nm. XRD analysis reveals the hexagonal structure of zinc oxide nanoparticles. FT-IR spectra showed absorption band at 497 cm^{-1} confirming the presence of zinc oxide linkage. EDX spectra showed the presence of zinc and oxygen which confirms the purity of zinc oxide nanoparticles. Furthermore, they reported that on increasing the concentration of the suspension of the zinc oxide nanoparticles increases the antimicrobial activity. Supraja *et al*. reported synthesis of zinc oxide nanoparticles using *Boswellia ovalifoliolata* stem bark-extract [41]. UV-Visible showed absorbance at 230 nm. FT-IR spectroscopic study reveals that primary and secondary amine present in the extract is responsible for the reduction of the zinc ions. XRD spectra confirm the presence of hexagonal phase of ZnO. It was observed that zone of inhibition of 170 ppm concentration was higher as compared to the 100 and 50 ppm. Moreover, zinc oxide nanoparticles showed the better antibacterial property as compared to antifungal activity. Phytosynthesis of zinc oxide nanoparticles was reported Dobrucka *et al*. wherein, an aqueous extract of *Trifolium pratense* was used for the synthesis of zinc oxide nanoparticles. TEM micrograph confirms the size of zinc oxide nanoparticles in the range of 60-70 nm [42]. FT-IR spectra show the bands at 515 cm^{-1} confirming the formation of zinc oxide nanoparticles. Zone of inhibition was observed to almost the same for the all bacterial strains. However, it was observed that the efficacy of the nanoparticles increases with increase in the concentration of the nanoparticles. The reduction of zinc nitrate by using the cumin seed as a reducing agent was carried out successfully for the synthesis of zinc oxide nanoparticles. The result showed that reaction parameters like concentration, time and pH affect the rate of the reaction. The characteristic UV-visible peak was observed in the range of 370 nm. TEM result revealed the spherical nature of the zinc oxide nanoparticles with an average size of 7 nm. Antibacterial efficacy was done using the disk diffusion method. The efficacy of the Gram-negative bacteria was more as compared to the Gram-positive bacteria [43]. Maaza *et al*. studied an eco-friendly method for the synthesis of zinc oxide nanoparticles using leaf extract of *Sageretia thea* which act as a reducing as well as a stabilizing agent [44]. XRD peak was found in consistency to hexagonal zincite white pattern. Average size of crystal annealed at 400°C was 15.2 nm while 12.4 nm for crystal annealed at 500°C. The multifunctional zinc oxide nanoparticles have promising activity against both Gram-positive and Gram-negative bacteria. It was observed that these nanoparticles are most susceptible against *Klebsiella pneumoniae* while least efficacy against Pseudomonas aeruginosa. Swaminathan *et al*. studied the green synthesis of zinc oxide nanoparticles using *Tabernaemontana divaricata* leaf extract [45]. XRD spectra confirm the formation of hexagonal crystalline structure. TEM images showed the formation of spherical shape nanoparticles with size range from 20 to 50 nm. FT-IR confirms the possible biomolecules responsible for the reduction of zinc ions. They reported that these nanoparticles showed antibacterial efficacy against *Salmonella paratyphi*, *Escherichia coli* and *Staphylococcus aureus*. Moreover, *Escherichia coli* and *Staphylococcus aureus* were reported to be more susceptible as compared to *Salmonella paratyphi*. Vaseeharan *et al.* reported synthesis of zinc oxide nanoparticles using extract of *Ulva luctuca* [46]. TEM result revealed the size of nanoparticles in the range of 10-50 nm. XRD studies confirm the crystalline nature of the as prepared particles. UV-visible spectrum show absorbance at 325nm. Zinc oxide nanoparticles showed excellent antibacterial activity against both Gram positive (*Bacillus licheniformis* and *Bacillus pumilis*) and Gram negative (*Escherichia coli* and *Proteus vulgaris*) bacteria.

Green Synthesis of Iron Oxide Nanoparticles and its Antibacterial Activity

Tridax procumbens leaves extract mediated facile green synthesis of iron nanoparticles was reported by Senthi M *et al*. The as prepared nanoparticles were irregular spheres with size 80-100 nm [47]. Iron nanoparticles exhibit antibacterial activity against *Pseudomonas aureginosa*. Daniel *et al*. synthesizes iron nano particles using leaf extract of *Dodonaea viscosa* [48]. They studied the effect of temperature, pH and concentration on rate of synthesis. FT-IR spectroscopy reveals the possible biomolecules responsible for the reduction of zinc ions. The as-synthesized nano particles were evaluated against *Escherchia coli, Klebsiella pneumoniae, Pseudomonas fluorescens*, *Staphylococcus aureus* and *Bacillus subtilis*. They reported that at a very low concentration these nanoparticles show effective antibacterial property. Biomolecules of *Azadirachta indica* contains phenolic compound which are responsible for reduction ferric ions to spherical nanoparticles with an average diameter of ~100 nm. UV-visible absorbance was observed at 216-265 nm. They reported that the process of synthesis is cost effective and eco-friendly in nature [49]. In another study, Latha *et al*. synthesized Fe_3O_4 nanoparticles using *Carica papaya* leaves extract [50]. The characteristic peak occurs at wavelength in the range 190-250 nm. FT-IR spectra reveal the possible polyphenols for the reduction and the stabilizing agent. SEM micrograph showed agglomeration of the particles with spherical in shape. EDX spectra show the strong signal of iron, oxygen supporting the presence of Fe_3O_4. XRD analysis reveals orthorhombic structure of Fe_3O_4. The average size of iron nanoparticles was found to be 33 nm. Naseem *et al*. studied the green synthesis of iron nanoparticles using *Lawsonia inermis* and *Gardenia jasminoides* leaves extract and evaluated its antibacterial activity [51]. XRD spectra of both the nanoparticles reveal the cubic nature of Fe. SEM and TEM micrograph of iron nanoparticles synthesized using *Lawsonia inermis* showed distorted hexagonal appearance with size of ~21 nm whereas synthesis using *Gardenia jasminoides* was observed to be shattered rock-like appearance with size 32 nm. They reported that iron nanoparticles synthesized using *Gardenia jasminoides* are more susceptible to *Staphylococcus aureus* as compared to *Lawsonia inermis*. Zone of inhibition of iron nano particles synthesized using *Lawsonia inermis* and *Gardenia jasminoides* against *Escherichia coli*, *Salmonella enterica* and *Proteus mirabilis* was 14 mm and 15 mm, 9 mm and 12 mm, 11mm and 13 mm respectively. Musa peel is rich in polyphenols, carotenoids and other bioactive compounds which were exploited for the synthesis of iron nanoparticles. UV-vis study reveals the absorbance at 207 nm. FT-IR confirms the biomolecules held for the synthesis of iron nanoparticles. The particles size range from 100-200 nm. Sudha *et al*. reported Citrus maxima peel extracts discarded waste material for the fabrication of iron nanoparticles due to their reduction and stabilising property [52]. *Citrus maxima* peel extracts a discarded waste material was used for the fabrication of iron nanoparticles due to their reduction and stabilising property. The nanoparticles were further characterized using various techniques like TEM, EDS, XPS, FT-IR, DLS and Zeta potential. TEM results showed irregular shape particles with size ranging 10-100 nm. The zeta potential of iron nanoparticles was found to be +19.4 mV. EDX peak showed the presence of Fe, N, C and oxygen. They claimed that the as-synthesized nanoparticles mainly help in the removing of Cr (VI) [53]. Shameli *et al.* synthesized magnetite (Fe_3O_4) using *Kappaphycus alvarezii* extract. XRD confirms the formation of highly crystalline iron nanoparticles [54]. FT-IR spectra showed peak at 556 and 423 cm^{-1} which are consistence to the formation of Fe_3O_4. TEM image displayed the spherical nature of the nanoparticles with an average size of 14.7 nm. Selveraj *et al*. reported green synthesis of iron oxide nanoparticles using leaf extract of *Cynometra ramiflora* [55]. SEM micrograph showed spherical shape nanoparticles. XRD analysis revealed the crystalline nature of the nanoparticles. The adsorption band ~800 cm^{-1} correspond to the vibration is in consistence of Fe-O bonds. Antibacterial activities of as-synthesized nanoparticles were tested using well diffusion method against *Escherichia coli* and *Staphylococcus epidermidis*. Zone of inhibition was clearly observed confirming the presence of antibacterial efficacy of iron oxide nano particles. Li *et al*. demonstrated a facile bottom up approach for synthesis of iron oxide nanoparticles using the *Punica granatum* peel extract as reducing and stabilizing agent [56]. They reported that 40 ml extract helps in the formation of small and better morphology iron oxide nanoparticles. UV- Visible spectral analysis showed absorbance at 300 nm a characteristic peak of metal iron. FT-IR study showed the presence of peak ~500 cm^{-1} confirming formation of metal oxide linkage. XRD spectra reveal the amorphous nature of the particles. The antibacterial activity of as synthesized nanoparticles was evaluated against *Pseudomonas aeruginosa*. The efficacy of the nanoparticles depends on the morphology and size of the nanoparticles. They reported that iron oxide nanoparticle synthesized using 40 ml extract show higher activity as compared to others concentration. *Piliostigma thonningii* mediated green synthesis of iron nanoparticles was studied by Igwe *et al*. UV–visible and XRD result. UV–Visible and XRD result confirm the amorphous nature of the particles. FT-IR spectra reveal the possible biomolecules responsible for the synthesis of nanoparticles. Iron oxide nanoparticles exhibit antibacterial efficacy against both Gram-positive and Gram-negative bacteria [57]. However, efficacy against Gram-negative bacteria was higher as compared to Gram-positive bacterial strains. *Glycosmis* belongs to family *Rutaceae* comprising about 40 species having various biological activities such as antimicrobial and antioxidant activities. The aqueous leaf extract was exploited for the green synthesis of iron nanoparticles. The absorbance peak was observed in the range of 40-450 nm. XRD peak are in consistence to *rhombohedral* structure. The surface morphology and size of the nanoparticles was reported to be of spherical shape with core diameter of 20 nm [58].

Advantage of green synthesis of metal nanoparticles from plant parts

1. Omnipresent: Plants are rich source of biomolecules and are easily available throughout the earth surface in bulk quantity.
2. Simple reaction: The reaction is performed without requiring high temperature, pressure and energy.
3. Rate of reaction is fast: The rate of the reaction is quite fast as compared to other physicochemical method.
4. Use of Nontoxic chemicals: It does not require any hazardous chemicals for synthesis.
5. Act as both reducing as well as stabilizing agent: The plant extract act as both reducing as well stabilizing agent.
6. Free from toxic by-product: The final product is free from toxic by-product as compared to physiochemical methods.

Conclusions

Green synthesis of metal nanoparticles is a blooming area of research worldwide because it is one-pot, rapid and eco-friendly. A great deal of effort has been employed to study the application of these metal nanoparticles. However, it finds immense application in the in medicine where it shows a prompt antibacterial efficacy against the resistant superbugs. Further research is required to investigate the mechanism of antimicrobial action of metallic nanoparticles. As plants are the repository of biomolecules therefore the need of the hour is to know the exact molecules responsible for the reduction of the metal salts. Being a panacea of all technical ills, the metal nanoparticles find its wide applications in electronics, agriculture, food packaging, waste water treatment etc. It is expected that traditional medicines along with nanocarriers will overcome the existing problem of bioavailability, beside increasing the prolonged circulation of the drug into the blood.

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