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Review article

A review on green synthesis of zinc oxide nanoparticles – An eco-friendly approach

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ABSTRACT

Nanotechnology deals with the production and usage of material with nanoscale dimension. Nanoscale dimension provides nanoparticles a large surface area to volume ratio and thus very specific properties. Zinc oxide nanoparticles (ZnO NPs) had been in recent studies due to its large bandwidth and high exciton binding energy and it has potential applications like antibacterial, antifungal, anti-diabetic, anti-inflammatory, wound healing, antioxidant and optic properties. Due to the large rate of toxic chemicals and extreme environment employed in the physical and chemical production of these NPs, green methods employing the use of plants, fungus, bacteria, and algae have been adopted. This review is a comprehensive study of the synthesis and characterization methods used for the green synthesis of ZnO NPs using different biological sources.

1. Introduction

Nanomaterials are particles having nanoscale dimension, and nanoparticles are very small sized particles with enhanced catalytic reactivity, thermal conductivity, non-linear optical performance and chemical steadiness owing to its large surface area to volume ratio [1]. NPs have started being considered as nano antibiotics because of their antimicrobial activities [2]. Nanoparticles have been integrated into various industrial, health, food, feed, space, chemical, and cosmetics industry of consumers which calls for a green and environment-friendly approach to their synthesis [3].

1.1. Nanoparticle synthesis methods

Two approaches have been suggested for nanoparticle synthesis: Bottom up and top down approach. The top–down approach involves milling or attrition of large macroscopic particle. It involves synthesizing large-scale patterns initially and then reducing it to nanoscale level through plastic deformation. This technique cannot be employed for large scale production of nanoparticles because it is a costly and slow process [4]. Interferometric Lithographic (IL) is the most common technique which employs the role of top–down approach for nanomaterial synthesis [5]. This technique involves the synthesis of nanoparticles from already miniaturized atomic components through self-assembly. This includes formation through physical and chemical means. It is a comparatively cheap approach [6]. It is based on kinetic and thermodynamic equilibrium approach. The kinetic approach involves MBE (molecular beam epitaxy).

1.2. Different methods used in nanoparticle synthesis

In the physical method, physical forces are involved in the attraction of nanoscale particles and formation of large, stable, well-defined nanostructures. Its example includes nanoparticle synthesis through colloidal dispersion method. It also includes basic techniques like vapor condensation, amorphous crystallization, physical fragmentation and many others [7–10]. Nanoparticle synthesis is mediated by physical, chemical and green methods [11–13]. The physical method involves the use of costly equipment, high temperature and pressure [14], large space area for setting up of machines. The chemical method involves the use of toxic chemicals which can prove to be hazardous for the environment and the person handling it. The literature states that some of the toxic

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chemicals that we use in physical and chemical methods may reside in the NPs formed which may prove hazardous in the field of their application in the medical field [15]. Thus, we needed an environment-friendly and cost-effective method for nanoparticle synthesis. Physical process involves the use of high vacuum in processes like pulsed laser deposition, MBE (molecular beam epitaxy), thermal evaporation etc. [16] and chemical methods include chemical micro emulsion, wet chemical, spray pyrolysis, electrodeposition [16], chemical and direct precipitation and microwave assisted combustion [17]. Additional capping and stabilizing agent are needed in physical and chemical methods [18–21].

1.3. Green approach

Biosynthesis of nanoparticles is an approach of synthesizing nanoparticles using microorganisms and plants having biomedical applications. This approach is an environment-friendly, cost-effective, biocompatible, safe, green approach [22]. Green synthesis includes synthesis through plants, bacteria, fungi, algae etc. They allow large scale production of ZnO NPs free of additional impurities [23]. NPs synthesized from biomimetic approach show more catalytic activity and limit the use of expensive and toxic chemicals.

These natural strains and plant extract secrete some phytochemicals that act as both reducing agent and capping or stabilization agent; for example, synthesis of ZnO nanoflowers of uniform size from cell soluble proteins of *B. licheniformis* showed enhanced photocatalytic activity and photo stability clearly depicted by 83% degradation of methylene blue (MB) pollutant dye in presence of ZnO nanoflowers considering the fact that self-degradation of MB was null (observed through the control value) and through three repeated cycles of experiment at different time interval, degradation was found at 74% which clearly showed photo stability of ZnO nanoflowers produced [24]. Oblate spherical and hexagonal shaped ZnO NPs of size ranging from 1.2 to 6.8 nm have been synthesized using fungal strain Aspergillus fumigatus TFR-8 and these NPs showed stability for 90 days confirmed by measuring hydrodynamic diameter of NPs using particle size analyzer which showed agglomeration formation of NPs only after 90 days suggesting high stability of NPs formed using the fungal strain [25]. ZnO NPs of size 36 nm synthesized from seaweed *Sargassum myriocystum* (microalgae) obtained from the gulf of Mannar showed no visible changes even after 6 months clearly demonstrating the stability of NPs formed. From FTIR result studies, it has been confirmed that fucoidan soluble pigments secreted from microalgae were responsible for the reduction and stabilization of the NPs.

Plant parts like roots, leaves, stems, seeds, fruits have also been utilized for the NPs synthesis as their extract is rich in phytochemicals which act as both reducing and stabilization agent [26–32]. ZnO NPs synthesized from *Trifolium pratense* flower extract showed similar peaks in UV-Vis spectrophotometer after 24, 48, 72, 96 and 120 hours of NPs formation showing the stability of NPs formed [33]. Similarly, fruit extract of Rosa canina acted as both reducing and stabilizing agent for synthesized ZnO NPs, confirmed by FTIR studies. Bio-capping is done by carboxylic and phenolic acid present in fruit extract. Spherical shaped ZnO NPs were formed by Aloe Vera leaf extract where free carboxylic and the amino group of plant extract acted as both reducing and capping agent.

1.4. Zinc oxide nanoparticles

ZnO is an n-type semiconducting metal oxide. Zinc oxide NP has drawn interest in past two–three years due to its wide range of applicability in the field of electronics, optics, and biomedical systems [34–40]. Several types of inorganic metal oxides have been synthesized and remained in recent studies like TiO_2, CuO, and ZnO. Of all these metal oxides, ZnO NPs is of maximum interest because they are inexpensive to produce, safe and can be prepared easily [41]. US FDA has enlisted ZnO as GRAS (generally recognized as safe) metal oxide [42]. ZnO NPs exhibit tremendous semiconducting properties because of its large band gap (3.37 eV) and high exciton binding energy (60meV) like high catalytic activity, optic, UV filtering properties, anti-inflammatory, wound healing [43–49]. Due to its UV filtering properties, it has been extensively used in cosmetics like sunscreen lotions [50]. It has a wide range of biomedical applications like drug delivery, anti- cancer, antidiabetic, antibacterial, antifungal and agricultural properties [51–55]. Although ZnO is used for targeted drug delivery, it still has the limitation of cytotoxicity which is yet to be resolved [56]. ZnO NPs have a very strong antibacterial effect at a very low concentration of gram negative and gram positive bacteria as confirmed by the studies, they have shown strong antibacterial effect than the ZnO NPs synthesized chemically [57–59]. They have also been employed for rubber manufacturing, paint, for removing sulfur and arsenic from water, protein adsorption properties, and dental applications. ZnO NPs have piezoelectric and pyroelectric properties [60,61]. They are used for disposal of aquatic weed which is resistant to all type of eradication techniques like physical, chemical and mechanical means [62]. ZnO NPs have been reported in different morphologies like nanoflake, nanoflower, nanobelt, nanorod and nanowire [63–65].

2. Literature study

Due to the increasing popularity of green methods, different works had been done to synthesize ZnO NPs using different sources like bacteria, fungus, algae, plants and others (Fig. 1). A list of tables had been put to summarize the valuable work done in this field.

2.1. Green synthesis of ZnO NPs using plant extract

Plant parts like leaf, stem, root, fruit, and seed have been used for ZnO NPs synthesis because of the exclusive phytochemicals that they produce. Using natural extracts of plant parts is a very eco-friendly, cheap process and it does not involve usage of any intermediate base groups. It takes very less time, does not involve usage of costly equipment and precursor and gives a highly pure and quantity enriched product free of impurities [66]. Plants are most preferred source of NPs synthesis because they lead to large-scale production and production of stable, varied in shape and size NPs [67]. Bio-reduction involves reducing metal ions or metal oxides to 0 valence metal NPs with the help of phytochemicals like polysaccharides, polyphenolic compounds, vitamins, amino acids, alkaloids, terpenoids secreted from the plant [66,67].

Most commonly applied method for simple preparation of ZnO NPs from leaves or flowers is where the plant part is washed thoroughly in running tap water and sterilized using double distilled water (some use Tween 20 to sterilize it). Then, the plant part is kept for drying at room temperature followed by weighing and then crushing it using a mortar and pestle. Milli-Q H_2O is added to the plant part according to the desired concentration and the mixture is boiled under continuous stirring using a magnetic stirrer [66–70]. The solution is filtered using Whatman filter paper and the obtained clear solution was used as a plant extract (sample). Some volume of the extract is mixed with 0.5 Mm of hydrated Zinc nitrate or zinc oxide or zinc sulfate and the mixture is boiled at desired temperature and time to achieve efficient mixing [69,70]. Some perform optimization at

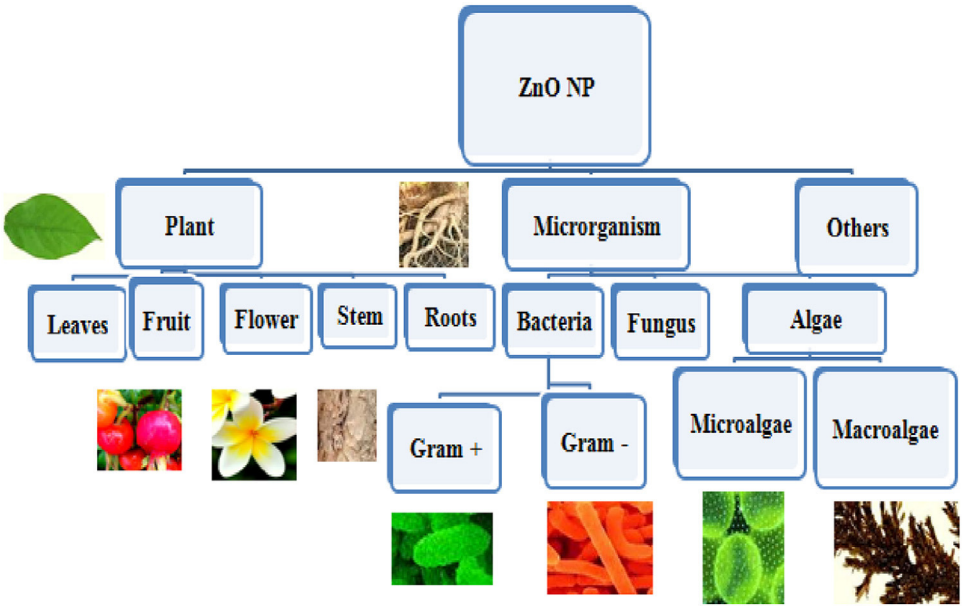

Fig. 1. Zinc oxide nanoparticle synthesis by using different sources.

this point using different temperature, pH, extract concentration and time. Incubation period results in a change of color of the mixture to yellow which is a visual confirmation of the synthesized NPs [69,70]. Then a UV-Vis spectrophotometry is employed to confirm the synthesis of NPs followed by centrifugation of mixture and drying the pellet in a hot air oven to get the crystal NPS [71]. Further, synthesized nanoparticles are further characterized using X-ray diffractometer (XRD), Energy Dispersion Analysis of X-ray (EDAX), Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Field Emission Scanning Electron Microscopy (FE-SEM), Atomic Force Microscopy (AFM), Thermal-gravimetric Differential Thermal Analysis (TG-DTA), Photoluminescence Analysis (PL), X-ray Photoelectron Microscopy (XPS), Raman Spectroscopy, Attenuated total reflection (ATR), UV-Visible Diffuse Reflectance Spectroscopy (UV-DRS), and Dynamic Light Scattering (DLS) [70–72].

An experiment conducted by Jafarirad et al. compared the results of NPs obtained through 2 different techniques—conventional heating (CH) and microwave irradiation (MI), and results clearly demonstrated that MI takes less time for NPs synthesis attributed to the high heating rate that MI provides and thus faster reaction rate [73].

Plants belonging to Lamiaceae family have been extensively studied like *Anisochilus carnosus* [74], *Plectranthus amboinicus* [75], and *Vitex negundo* [76] which showed NP formation of varied sizes and shapes like spherical, quasi-spherical, hexagonal, rod-shaped with agglomerates. Results clearly indicated that with the increasing concentration of a plant extract, the size of synthesized NPs decreases [74–76]. Results also compared the size ranges observed through different techniques like FE-SEM, TEM, XRD showed similar range values [75,76]. SEM and EDAX showed similar results different from results of XRD. NPs synthesized from *Vitex negundo* leaf and flower showed the similar size of 38.17 nm confirmed by XRD analysis calculated through Debye-Scherrer equation [76]. Leaves of *Azadirachta indica* of Meliaceae family have been most commonly used for the synthesis of ZnO NP [77,78]. All experiments showed NPs in similar size range confirmed by XRD and TEM analysis with spherical shape and hexagonal disc shape and Nano buds. These studies elucidated the involvement of alcohol, amide, amine, alkane, carboxylic acid and carbonate moieties in the formation of NPs confirmed through FTIR studies. Fresh leaf extract and leaf peel of Aloe vera belonging to Liliaceae family [79,80]. Synthesized NP showed the difference in size (NP synthesized from peel was greater in size confirmed by SEM and TEM analysis) but similar in shapes (hexagonal and spherical). NPs synthesized from extracts of *Agathosma betulina, Moringa oleifera, Pongamia pinnata, Plectranthus amboinicus, Nephelium lappaceum and Calatropis Gigantea* showed agglomerate formation. Table 1 is a comprehensive study of different plants used for the synthesis of ZnO NP till date.

2.2. Green synthesis of ZnO NPs using bacteria

NP synthesis using bacteria is a green approach but it has several disadvantages like screening of microbes is a time-consuming process, careful monitoring of culture broth and the entire process is required to avoid the contamination, lack of control on NP size, shape and cost associated with the media used to grow bacteria is also very high.

ZnO nanoflowers were synthesized by *B. licheniformis* through an eco-friendly approach which showed photocatalytic activity, degraded Methylene blue dye. These nanoflowers showed enhanced photocatalytic activity as compared to already present photocatalytic substances and it has been presumed that larger oxygen vacancy in the synthesized nanoparticles imparts it the property of enhanced photocatalytic activity. Photocatalysis generates active species by absorption of light which degrades the organic waste material and thus can be used as an effective bioremediation tool. Nanoflowers synthesized using *B. licheniformis* were 40 nm in width and 400 nm in height [83]. *Rhodococcus* is able to survive in adverse condition and it has the ability to metabolize hydrophobic compounds thus, can help in biodegradation [84]. Spherical shaped NPs had been synthesized using *Rhodococcus pyridinivorans* and Zinc Sulphate as a substrate which showed size range of 100–130 nm confirmed through FE-SEM and XRD Analysis. It also demonstrated the presence of Phosphorus compound, secondary sulphornamide, monosubstituted alkyne, β-lactone, amine salt, amide II stretching band, enol of 1-3-di ketone, hydroxy aryl ketone, amide I bending band, alkane, and mononuclear benzene band confirmed through FTIR analysis [85]. ZnO was used as a sub-

Table 1
Plant mediated synthesis of ZnO NP.

S. No	Plant (family)	Common Name	Part taken for extraction	Size (nm)	Shape	Functional group	Reference
1	*Azadirachta indica* (Meliaceae)	Neem	Fresh leaves	18 (XRD)	Spherical	Amine, alcohol, ketone, carboxylic acid	[48]
2	*Agathosma betulina* (Rutaceae)	Buchu	Dry leaves	15.8 (TEM), 12–26 (HRTEM)	Quasi-spherical agglomerates	O-H of hydroxyl group, Zn-O stretching band	[81]
3	*Aloe Vera* (Liliaceae)	Aloe Vera	Leaf extract	8–20 (XRD)	Spherical, oval, hexagonal	O-H of phenol, amines, O-H of alcohol and C-H of alkanes, the amide of protein and enzymes.	[80]
4	*Coptidis Rhizoma* (Ranunculaceae)	Coptis Rhizome	Dried Rhizome	2.9–25.2 (TEM)	Spherical, rod shaped	Primary& secondary amine, aromatic and aliphatic amine, alcohol, carboxylic acid, alkyl halide, alkynes.	[61]
5	*Phyllanthus niruri* (Phyllanthaceae)	Bhuiamla, stone breaker	Leaf extract	25.61 (FE-SEM & XRD)	Hexagonal wurtzite, quasi-spherical	O-H, C-H, C-O stretching, aromatic aldehyde.	[34]
6	*Pongamia pinnata* (Legumes)	Indian beech	Fresh leaves	26 (XRD), Agglomeration of 100 (DLS, SEM, TEM)	Spherical, hexagonal, nano rod	O-H stretching, C = O stretching of carboxylic acid or their ester, C-O-H bending mode.	[35]
7	*Trifolium Pratense* (Legumes)	Red clover	Flower	60–70 (XRD)	Spherical	Hydroxyl, -C-O, -C-O-C, C = C stretching mode.	[33]
8	*Rosa canina* (Rosaceae)	Dog rose	Fruit extract	[13.3 (CH), 11.3 (MI)] (XRD), [25–204 (CH), 21–243 (MI)] (DLS),	Spherical	C-O and C = O of esters, hydroxyl, C-H stretching.	[73]
9	*E. crassipes* (Pontederiaceae)	Water hyacinth	Leaf extract	32–36 (SEM & TEM), 32 (XRD)	Spherical without aggregation	-	[36]
10	*Ocimum basilicum L. var. purpurascens* (Lamiaceae)	Red Rubin basil	Leaf extract	50 (TEM, EDS), 14.28 (XRD)	Hexagonal (wurtzite)	-	[22]
11	*Solanum nigrum* (Solanaceae)	Black nightshade	Leaf extract	20–30(XRD and FE-SEM),29.79(TEM)	Wurtzite hexagonal, quasi-spherical	O-H, aldehydic C-H, amide III bands of protein, carboxyl side group, C-N of amine, carbonyl group	[28]
12	*Aloe vera* (Liliaceae)	Aloe vera	Freeze dried leaf peel	25–65 (SEM & TEM)	Spherical, hexagonal	-	[79]
13	*Anisochilus carnosus* (Lamiaceae)	Kapurli	Leaf extract	56.14 (30 mL of extract), 49.55 (40 mL), 38.59 (50 mL) [XRD], 20–40 (FE-SEM), 30–40 (TEM)	Hexagonal wurtzite, quasi-spherical	O-H of water, alcohol, phenol C-H of alkane, O-H of carboxylic acid, C = O of the nitro group.	[74]
14	*Azadirachta indica* (Meliaceae)	Neem	Leaf	9.6–25.5 (TEM)	Spherical	Amide II stretching band, C-N stretching band of aliphatic, aromatic amide, an aliphatic amine, alcohol, phenol, secondary amine, C-H of alkane and aromatics, C = C-H of alkynes, C = O, C-C of an alkane.	[77]
15	*Cocus nucifera* (Arecaceae)	Coconut	Coconut water	20–80 (TEM), 21.2 (XRD)	Spherical and predominantly hexagonal without any agglomeration	O-H of alcohol and carboxylic acid, C = O of ketones, C-N of aromatic and aliphatic amines,	[9]
16	*Gossypium* (Malvaceae)	Cotton	Cellulosic fibre	13 (XRD)	Wurtzite, spherical, nano rod	O-H, [C = O, C-O, C-O-C] (due to Zn precursor)	[8]
17	*Moringa oleifera* (Moringaceae)	Drumstick tree	Leaf	24 (XRD), 16–20 (FE-SEM)	Spherical and granular nano sized shape with a group of aggregates	O-H, C-H of alkane, C = O of alcohol, carboxylic acid	[10]
18	*Azadirachta indica* (Meliaceae)	Neem	Fresh leaves	10–30 (TEM), 9–40 (XRD)	Hexagonal disk, nanobuds	O-H between H2O and CO2, carbonate moieties	[78]
19	*Parthenium hysterophorus L.* (Asteraceae)	Santa maria feverfew, carrot grass, congress weed	Leaf extract	22–35 (50% plant extract), 75–90 (25% plant extract) (XRD, TEM)	Spherical, hexagonal	N-H bending & N-H stretching mode, phosphorus compound, secondary sulphornamide, monosubstituted alkyne, amine salt, vinyl cis-tri substituted	[82]
20	*Plectranthus amboinicus* (Lamiaceae)	Mexican mint	Leaf extract	50–180 (SEM)	Rod shape nanoparticle with agglomerates	Zn-O, C-O of C-O-SO3, phosphorus compound	[75]
21	*Vitex negundo* (Lamiaceae)	Nochi	Leaf	75–80 (SEM & EDX), 38.17 (XRD)	Spherical	OH, C-H, C = C stretching band.	[19]
22	*Vitex negundo* (Lamiaceae)	Nochi	Flowers	38.17 (XRD), 10–130 (DLS)	Hexagonal	-	[35]
23	*S. album* (Santalaceae)	Sandalwood	Leaves	100 (DLS & SEM), 70–140 (TEM)	Nano rods	N-H stretching of amide II, carboxylate group, carbonyl stretching, O-H of alcohol	[20]
24	*Nephelium lappaceum L.* (Sapindaceae)	Rambutan	Fruit peels	50.95 (XRD)	Needle-shaped forming agglomerate	O-H stretching, H-O-H bending	[23]
25	*Calatropis Gigantea* (Apocynaceae)	Crown flower	Fresh leaves	30–35 (SEM)	Spherical shaped forming agglomerates	-	[7]
26	*Sphathodea campanulata* (Bignoniaceae)	African tulip tree	Leaf extract	30–50 (TEM)	Spherical	O-H stretching of polyphenols, nitrile group, C-H, C = O group	[69]

Table 2
Bacteria-mediated synthesis of ZnO NP.

S. No	Bacterial strain	Family	Size (nm)	Shape	Functional group	Reference
1	*Aeromonas hydrophila*	Pseudomonadaceae	57.72 (AFM), 42–64 (XRD)	Spherical, oval	Phosphorus compound, vinyl cis-trisubstituted, monosubstituted alkyne	[41]
2	*Lactobacillus sporogens*	Bacillaceae	5–15 (TEM), 11 (XRD)	Hexagonal unit cell	-	[38]
3	*Pseudomonas aeruginosa*	Pseudomonadaceae	35–80 (TEM), 27 (XRD), 81 (DLS)	Spherical	O-H stretching vibration, -CH of aliphatic stretching vibration, ester carbonyl group.	[88]
4	*Rhodococcus pyridinivorans*	Nocardiaceae	100–120 (FE-SEM), 120–130 (XRD)	Hexagonal phase, roughly spherical	Phosphorus compound, secondary sulphornamide, monosubstituted alkyne, β-lactone, amine salt, amide II stretching band, enol of 1-3-di ketone, a hydroxy aryl ketone, amide I bending band, alkane, mononuclear benzene band.	[87]
5	*B.licheniformis*	Bacillaceae	200 with nanopetals 40 in width and 400 in length (TEM)	Nanoflowers	0-H, N-H,-C-O(carbonyl stretching in the amide I and amide II linkage of protein), C-N stretching bond.	[85]
6	*Serratia ureilytica* (HM475278)	Enterobacteriacea	170–250 (30 min), 300–600 (60 min), 185–365 (90 min) [SEM]	Spherical to nanoflower shaped	-	[15]

Table 3
ZnO nanoparticle synthesis using algae.

S. No	Algal strain	Family	Size (nm)	Shape	Functional group	Reference
1	*Chlamydomonas reinhardtii*	Chlamydomonaceae	55–80 (HR-SEM), 21 (XRD)	Nanorod, nanoflower, porous nanosheet	C=O stretching, N-H bending band of amide I and amide II, C=O stretch of zinc acetate, C-O-C of polysaccharide	[3]
2	*Sargassum muticum*	Sargassaceae	30–57 (FE-SEM), 42 (XRD)	Hexagonal wurtzite	Asymmetric stretching band of the sulfate group, an asymmetric C-O band associated with C-O-SO3 & -OH group, sulfated polysaccharides.	[90]
3	*S. myriocystum*	Sargassaceae	46.6 (DLS), 20–36 (AFM)	Spherical, radial, triangle, hexagonal, rod	O-H and C=O stretching band, carboxylic acid	[91]

strate to synthesize ZnO NP through *A. hydrophilla*. NPs synthesized showed size range of 42–64 nm, confirmed through AFM and XRD analysis with varied shapes like oval and spherical [86]. Singh et al. compared the antioxidant activity of bare ZnO NP and *Pseudomonas aeruginosa* rhamnolipid stabilized NPs and it had been found that rhamnolipid stabilizes the ZnO NP because it is tough to form micelle aggregates on surface of carboxymethyl cellulose [87] and it acts as a better capping agent because of its long carbon chain [88]. It showed the formation of spherical shaped NP with nano size of 27–81 nm confirmed through TEM, XRD, and DLS analysis [88]. Table 2 illustrates the characteristics of ZNO NP synthesized using bacterial strains.

2.3. Green synthesis of ZnO NPs using microalgae and macroalgae

Algae are a photosynthetic organism which ranges from unicellular forms (ex. *Chlorella*) to multicellular ones (ex. Brown algae). Algae lack basic plant structure like roots and, leaves. Marine algae are categorized based on the pigment present in them like Rhodophyta having red pigment, Phaeophyta with brown pigment and chlorophytes with green pigment. Algae have been used extensively for the synthesis of Au and Ag nanoparticles but its application for the ZnO nanoparticle synthesis is limited and reported in very less number of papers [81]. Microalgae draw special attention because of its ability to degrade toxic metals and convert them to less toxic forms [89]. *Sargassum muticum* and *S. myriocystum* belonging to Sargassaceae family have been used for ZnO NP synthesis. *Sargassum muticum* studied size of NPs using XRD and FE-SEM which showed similar ranges and hexagonal wurtzite structure with the presence of hydroxyl group and sulfated polysaccharides. *S. myriocystum* compared size using DLS and AFM which showed different size ranges with the presence of hydroxyl and carbonyl stretching in NPs which vary greatly in shape [82]. Table 3 represents some of the micro and macro algae that have been employed for the synthesis of ZnO NP.

2.4. Green synthesis of ZnO NPs using fungus

Extracellular synthesis of NPs from the fungus is highly useful because of large scale production, convenient downstream processing and economic viability [90]. Fungal strains are chosen over bacteria because of their better tolerance and metal bioaccumulation property [92]. ZnO NPs were synthesized from mycelia of Aspergillus fumigatus. DLS analysis revealed the size range of NPs to be 1.2 to 6.8 with the average size of 3.8. AFM confirmed the average height of NP to be 8.56 nm. Particle size was >100 nm for 90 days but after 90 days they formed an agglomerate of average size 100 nm which suggested the stability of formed NPs for 90 days [93]. NPs synthesized from *Aspergillus terreus* belonging to Trichocomaceae family had a size range of 54.8–82.6 nm confirmed by SEM and the average size of 29 nm calculated using Debye-Sherrer equation through XRD analysis results. It confirmed the presence of primary alcohol, primary or secondary amine, amide, aromatic nitro compounds in the NPs formed confirmed through FTIR studies [94]. NPs synthesized using *Candida albicans* showed similar size range 15–25 nm confirmed by SEM, TEM and XRD Analysis [95]. *Aspergillus* species have been widely employed for the synthesis of ZnO NPs and NPs synthesized from fungal strain were spherical shaped in most of the cases. Table 4 gives a brief account of commonly used fungus utilized for ZnO NP synthesis.

Table 4
Fungus mediated synthesis of ZnO NP.

S. No	Fungal strain	Family	Size (nm)	Shape	Functional group	Reference
1	*Aspergillus strain*	Trichocomaceae	50–120 (SEM)	Spherical forming aggregates	-	[93]
2	*Aspergillus fumigatus TFR-8*	Trichocomaceae	1.2–6.8 (DLS), 100 (agglomerate)	Oblate spherical and hexagonal forms aggregate	-	[83]
3	*Aspergillus terreus*	Trichocomaceae	54.8–82.6 (SEM), 29 (XRD)	Spherical	C-N bond of primary amine, C-O of primary alcohol, primary & secondary alcohol, N = O aromatic nitro compound, alkyl C = C, amide, open chain imino group	[14]
4	*Candida albicans*		25 (XRD), 15–25 (SEM), 20 (TEM)	Quasi-spherical, hexagonal phase (wurtzite structure)	-	[95]

Table 5
ZnO NP synthesis by protein.

S. No	Others	Size (nm)	Shape	Functional group	Reference
1	Egg albumin	16 (XRD), 10–20 (TEM), 8–22 (AFM)	Spherical, Hexagonal wurtzite	Hydroxyl group	[19]
2	Soluble starch	50 (SEM)	-	-	[96]
3	L-alanine	50–110 (TEM, SEM)	-	Hydroxyl group, C-O vibration of Schiff- base.	[97]

2.5. Green synthesis of ZnO NPs using other green sources

Biocompatible chemicals are used as some other green sources for the synthesis of nanoparticles. It is a fast, economic process which eliminates the production of any kind of side product in the nucleation and synthesis reaction of nanoparticles. It leads to the formation of controlled shape and size nanoparticles with their well-dispersed nature [91]. Nanoparticles synthesized through wet chemical method render them special properties like enhanced anti-bacterial efficiency up to 99.9% when coated on a cotton fabric [96]. Table 5 illustrated a few other green sources that have been employed for the synthesis of ZnO NP [91,96,97].

3. Conclusion

Biosynthesis of nanoparticles using eco-friendly approach has been the area of focused research in the last decade. Green sources act as both stabilizing and reducing agent for the synthesis of shape and size controlled nanoparticles. Future prospect of plant-mediated nanoparticle synthesis includes an extension of laboratory-based work to industrial scale, elucidation of phytochemicals involved in the synthesis of nanoparticles using bioinformatics tools and deriving the exact mechanism involved in inhibition of pathogenic bacteria. The plant-based nanoparticle can have huge application in the field of food, pharmaceutical, and cosmetic industries and thus become a major area of research.

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