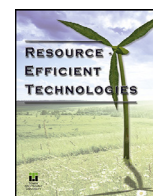


Contents lists available at [ScienceDirect](http://ScienceDirect)

# Resource-Efficient Technologies

journal homepage: [www.elsevier.com/locate/refit](http://www.elsevier.com/locate/refit)

## Review article

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



Happy Agarwal, S. Venkat Kumar, S. Rajeshkumar\*

School of Bio-Sciences and Technology, VIT University, Vellore, TN 632014, India

## ARTICLE INFO

### Article history:

Received 14 February 2017

Revised 1 March 2017

Accepted 3 March 2017

Available online 18 April 2017

### Keywords:

Zinc oxide nanoparticles

Biosynthesis

Plant

Microbes

Algae

## 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.

© 2017 Tomsk Polytechnic University. Published by Elsevier B.V.

This is an open access article under the CC BY-NC-ND license.

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>)

## 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

\* Corresponding author. School of Bio-Sciences and Technology, VIT University, Vellore, TN 632014, India. Tel.: +91 9629739263.

E-mail address: [ssrajeshkumar@hotmail.com](mailto:ssrajeshkumar@hotmail.com) (S. Rajeshkumar).

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<sub>2</sub>, 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 (60 meV) 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, anti-diabetic, 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<sub>2</sub>O 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

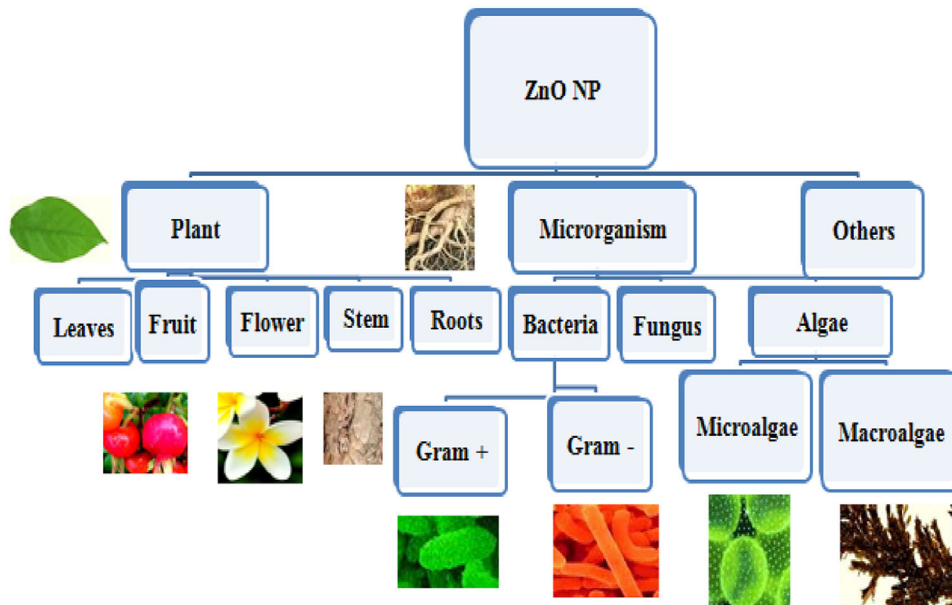


Fig. 1. Zinc oxide nanoparticle synthesis by using different sources.

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 for-

mation 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 sulphoramidate, monosubstituted alkyne,  $\beta$ -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	<i>Azadirachta indica</i> (Meliaceae)	Neem	Fresh leaves	18 (XRD)	Spherical	Amine, alcohol, ketone, carboxylic acid	[48]
2	<i>Agathosma betulina</i> (Rutaceae)	Buchu	Dry leaves	15.8 (TEM), 12–26 (HRTEM)	Quasi-spherical agglomerates	O-H of hydroxyl group, Zn-O stretching band	[81]
3	<i>Aloe Vera</i> (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	<i>Coptidis Rhizoma</i> (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	<i>Phyllanthus niruri</i> (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	<i>Pongamia pinnata</i> (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	<i>Trifolium Pratense</i> (Legumes)	Red clover	Flower	60–70 (XRD)	Spherical	Hydroxyl, -C-O, -C-O-C, C=C stretching mode.	[33]
8	<i>Rosa canina</i> (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	<i>E. crassipes</i> (Pontederiaceae)	Water hyacinth	Leaf extract	32–36 (SEM & TEM), 32 (XRD)	Spherical without aggregation	-	[36]
10	<i>Ocimum basilicum L. var. purpurascens</i> (Lamiaceae)	Red Rubin basil	Leaf extract	50 (TEM, EDS), 14.28 (XRD)	Hexagonal (wurtzite)	-	[22]
11	<i>Solanum nigrum</i> (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	<i>Aloe vera</i> (Liliaceae)	Aloe vera	Freeze dried leaf peel	25–65 (SEM & TEM)	Spherical, hexagonal	-	[79]
13	<i>Anisochilus carnosus</i> (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	<i>Azadirachta indica</i> (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	<i>Cocos nucifera</i> (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	<i>Gossypium</i> (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	<i>Moringa oleifera</i> (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	<i>Azadirachta indica</i> (Meliaceae)	Neem	Fresh leaves	10–30 (TEM), 9–40 (XRD)	Hexagonal disk, nanobuds	O-H between H2O and CO2, carbonate moieties	[78]
19	<i>Parthenium hysterophorus L.</i> (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 sulphoramide, monosubstituted alkyne, amine salt, vinyl cis-tri substituted	[82]
20	<i>Plectranthus amboinicus</i> (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	<i>Vitex negundo</i> (Lamiaceae)	Nochi	Leaf	75–80 (SEM & EDX), 38.17 (XRD)	Spherical	OH, C-H, C=C stretching band.	[19]
22	<i>Vitex negundo</i> (Lamiaceae)	Nochi	Flowers	38.17 (XRD), 10–130 (DLS)	Hexagonal	-	[35]
23	<i>S. album</i> (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	<i>Nephelium lappaceum L.</i> (Sapindaceae)	Rambutan	Fruit peels	50.95 (XRD)	Needle-shaped forming agglomerate	O-H stretching, H-O-H bending	[23]
25	<i>Calatropis Gigantea</i> (Apocynaceae)	Crown flower	Fresh leaves	30–35 (SEM)	Spherical shaped forming agglomerates	-	[7]
26	<i>Spathodea campanulata</i> (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	<i>Aeromonas hydrophila</i>	Pseudomonadaceae	57.72 (AFM), 42–64 (XRD)	Spherical, oval	Phosphorus compound, vinyl cis-trisubstituted, monosubstituted alkyne	[41]
2	<i>Lactobacillus sporogens</i>	Bacillaceae	5–15 (TEM), 11 (XRD)	Hexagonal unit cell	-	[38]
3	<i>Pseudomonas aeruginosa</i>	Pseudomonadaceae	35–80 (TEM), 27 (XRD), 81 (DLS)	Spherical	O-H stretching vibration, -CH of aliphatic stretching vibration, ester carbonyl group.	[88]
4	<i>Rhodococcus pyridinivorans</i>	Nocardiaceae	100–120 (FE-SEM), 120–130 (XRD)	Hexagonal phase, roughly spherical	Phosphorus compound, secondary sulphoramidate, monosubstituted alkyne, $\beta$ -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	<i>B.licheniformis</i>	Bacillaceae	200 with nanopetals 40 in width and 400 in length (TEM)	Nanoflowers	O-H, N-H, -C=O(carbonyl stretching in the amide I and amide II linkage of protein), C-N stretching bond.	[85]
6	<i>Serratia ureilytica</i> (HM475278)	Enterobacteriaceae	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	<i>Chlamydomonas reinhardtii</i>	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	<i>Sargassum muticum</i>	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-SO <sub>3</sub> & -OH group, sulfated polysaccharides.	[90]
3	<i>S. myriocystum</i>	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-Scherrer 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	<i>Aspergillus strain</i>	Trichocomaceae	50–120 (SEM)	Spherical forming aggregates	-	[93]
2	<i>Aspergillus fumigatus TFR-8</i>	Trichocomaceae	1.2–6.8 (DLS), 100 (agglomerate)	Oblate spherical and hexagonal forms aggregate	-	[83]
3	<i>Aspergillus terreus</i>	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	<i>Candida albicans</i>		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.

### References

- [1] S. Tabrez, J. Musarrat, A.A. Al-khedhairi, Colloids and surfaces B: biointerfaces countering drug resistance, infectious diseases, and sepsis using metal and metal oxides nanoparticles: current status, Colloids Surf. B Biointerfaces 146 (2016) 70–83, doi:10.1016/j.colsurfb.2016.05.046.
- [2] M. Sastry, A. Ahmad, M. Islam Khan, R. Kumar, Biosynthesis of metal nanoparticles using fungi and actinomycete, Curr. Sci 85 (2003) 162–170, doi:10.1016/S0927-7765(02)00174-1.
- [3] M.D. Rao, P. Gautam, Synthesis and characterization of ZnO nanoflowers using chlamydomonas reinhardtii: a green approach, Environ. Prog. Sustain. Energy (2016) 1–7, doi:10.1002/ep.
- [4] T. Arasu, Stable silver nanoparticle synthesizing methods and its applications, J. Biosci. Res 1 (2010) 259–270.
- [5] G. Vitor, T.C. Palma, B. Vieira, J.P. Lourenço, R.J. Barros, M.C. Costa, Start-up, adjustment and long-term performance of a two-stage bioremediation process, treating real acid mine drainage, coupled with biosynthesis of ZnS nanoparticles and ZnS/TiO<sub>2</sub> nanocomposites, Miner. Eng 75 (2015) 85–93, doi:10.1016/j.mineng.2014.12.003.
- [6] M. Imtiaz, T. Shahzad, M. Shahid, I.M.I. Ismail, G. Mustafa, T. Almeelbi, Zinc oxide nanoparticles affect carbon and nitrogen mineralization of phoenix dactylifera leaf litter in a sandy soil, J. Hazard. Mater 324 (2017) 298–305, doi:10.1016/j.jhazmat.2016.10.063.
- [7] C. Vidya, S. Hiremath, M.N. Chandrababha, M.A.L. Antonyraj, I.V. Gopala, A. Jain, et al., Green synthesis of ZnO nanoparticles by Calotropis gigantea, Int J Curr Eng Technol 1 (2013) 118–120.
- [8] R. Aladpoosh, M. Montazer, The role of cellulosic chains of cotton in biosynthesis of ZnO nanorods producing multifunctional properties: mechanism, characterizations and features, Carbohydr. Polym 126 (2015) 122–129, doi:10.1016/j.carbpol.2015.03.036.
- [9] A.N.D. Krupa, R. Vimala, Evaluation of tetraethoxysilane (TEOS) sol-gel coatings, modified with green synthesized zinc oxide nanoparticles for combating microfouling, Mater. Sci. Eng. C. 61 (2016) 728–735, doi:10.1016/j.msec.2016.01.013.
- [10] K. Elumalai, S. Velmurugan, S. Ravi, V. Kathiravan, S. Ashokkumar, Green synthesis of zinc oxide nanoparticles using Moringa oleifera leaf extract and evaluation of its antimicrobial activity, Spectrochim. Acta A Mol. Biomol. Spectrosc 143 (2015) 158–164, doi:10.1016/j.saa.2015.02.011.
- [11] M. Afifi, O.A. Almaghribi, N.M. Kadasa, Ameliorative effect of zinc oxide nanoparticles on antioxidants and sperm characteristics in streptozotocin-induced diabetic rat testes, Biomed. Res. Int 2015 (2015), doi:10.1155/2015/153573.
- [12] J. Chen, X. Liu, C. Wang, S.S. Yin, X.L. Li, W.J. Hu, et al., Nitric oxide ameliorates zinc oxide nanoparticles-induced phytotoxicity in rice seedlings, J. Hazard. Mater 297 (2015) 173–182, doi:10.1016/j.jhazmat.2015.04.077.
- [13] B.M.L. Vitosh, D.D. Warncke, R.E. Lucas, Secondary and micronutrients of vegetables and field crops Secondary and Micronutrients, 1994.
- [14] R. Chandrasekaran, S. Gnanasekar, P. Seetharaman, R. Keppanan, W. Arockiaswamy, S. Sivaperumal, Formulation of Carica papaya latex-functionalized silver nanoparticles for its improved antibacterial and anticancer applications, J. Mol. Liq 219 (2016) 232–238, doi:10.1016/j.molliq.2016.03.038.
- [15] P. Dhandapani, A.S. Siddarth, S. Kamalasekaran, S. Maruthamuthu, G. Rajagopal, Bio-approach: ureolytic bacteria mediated synthesis of ZnO nanocrystals on cotton fabric and evaluation of their antibacterial properties, Carbohydr. Polym 103 (2014) 448–455, doi:10.1016/j.carbpol.2013.12.074.
- [16] S. Mitra, P. Patra, S. Pradhan, N. Debnath, K.K. Dey, S. Sarkar, et al., Microwave synthesis of ZnO@mSiO<sub>2</sub> for detailed antifungal mode of action study: understanding the insights into oxidative stress, J. Colloid Interface Sci 444 (2015) 97–108, doi:10.1016/j.jcis.2014.12.041.
- [17] R. Yuvakkumar, J. Suresh, B. Saravanakumar, A. Joseph Nathanael, S.I. Hong, V. Rajendran, Rambutan peels promoted biomimetic synthesis of bioinspired zinc oxide nanochains for biomedical applications, Spectrochim. Acta A Mol. Biomol. Spectrosc 137 (2015) 250–258, doi:10.1016/j.saa.2014.08.022.
- [18] B. Kumari, S. Sharma, N. Singh, A. Verma, V.R. Satsangi, S. Dass, et al., ZnO thin films, surface embedded with biologically derived Ag/Au nanoparticles, for efficient photoelectrochemical splitting of water, Int. J. Hydrogen Energy 39 (2014) 18216–18229, doi:10.1016/j.ijhydene.2014.09.025.
- [19] S. Ambika, M. Sundarajan, Green biosynthesis of ZnO nanoparticles using Vitex negundo L. extract: spectroscopic investigation of interaction between ZnO nanoparticles and human serum albumin, J. Photochem. Photobiol. B Biol 149 (2015) 143–148, doi:10.1016/j.jphotobiol.2015.05.004.
- [20] K. Kavithaa, M. Paulpandi, T. Ponraj, K. Murugan, S. Sumathi, Induction of intrinsic apoptotic pathway in human breast cancer (MCF-7) cells through facile biosynthesized zinc oxide nanorods, Karbala Int. J. Mod. Sci 2 (2016) 46–55. <http://dx.doi.org/10.1016/j.kijoms.2016.01.002>.

- [21] S. Ravikumar, R. Gokulakrishnan, P. Boomi, In vitro antibacterial activity of the metal oxide nanoparticles against urinary tract infections bacterial pathogens, *Asian Pacific J. Trop. Dis* 2 (2012) 85–89, doi:10.1016/S2222-1808(12)60022-X.
- [22] H. Abdul, R. Sivaraj, R. Venkatesh, Green synthesis and characterization of zinc oxide nanoparticles from *Ocimum basilicum* L. var. *purpurascens* Benth-lamiaceae leaf extract, *Mater. Lett* 131 (2014) 16–18, doi:10.1016/j.matlet.2014.05.033.
- [23] R. Yuvakkumar, J. Suresh, A.J. Nathanael, M. Sundrarajan, S.I. Hong, Novel green synthetic strategy to prepare ZnO nanocrystals using rambutan (*Nephelium lappaceum* L.) peel extract and its antibacterial applications, *Mater. Sci. Eng. C* 41 (2014) 17–27, doi:10.1016/j.msec.2014.04.025.
- [24] D.S. Auld, Zinc coordination sphere in biochemical zinc sites, *Biometals* 14 (2001) 271–313, doi:10.1023/A:1012976615056.
- [25] J.D. Holmes, D.M. Lyons, K.J. Ziegler, Supercritical fluid synthesis of metal and semiconductor nanomaterials, *Chem. - A Eur. J.* 9 (2003) 2144–2150, doi:10.1002/chem.200204521.
- [26] Y. Zong, Z. Li, X. Wang, J. Ma, Y. Men, Synthesis and high photocatalytic activity of Eu-doped ZnO nanoparticles, *Ceram. Int* 40 (2014) 10375–10382, doi:10.1016/j.ceramint.2014.02.123.
- [27] V. Nachiyar, S. Sunkar, P. Prakash, Biological synthesis of gold nanoparticles using endophytic fungi, *Der Pharma Chem* 7 (2015) 31–38.
- [28] M. Ramesh, M. Anbuvarannan, G. Viruthagiri, Green synthesis of ZnO nanoparticles using *Solanum nigrum* leaf extract and their antibacterial activity, *Spectrochim. Acta A Mol. Biomol. Spectrosc* 136 (2015) 864–870, doi:10.1016/j.saa.2014.09.105.
- [29] L. Xiao, C. Liu, X. Chen, Z. Yang, Zinc oxide nanoparticles induce renal toxicity through reactive oxygen species, *Food Chem. Toxicol* 90 (2016) 76–83, doi:10.1016/j.fct.2016.02.002.
- [30] S. Rajeshkumar, Anticancer activity of eco-friendly gold nanoparticles against lung and liver cancer cells, *J. Genet. Eng. Biotechnol* 14 (2016) 195–202, doi:10.1016/j.jgeb.2016.05.007.
- [31] P.C. Nagajyothi, T.N. Minh An, T.V.M. Sreekanth, J. Il Lee, D.L. Joo, K.D. Lee, Green route biosynthesis: characterization and catalytic activity of ZnO nanoparticles, *Mater. Lett* 108 (2013) 160–163, doi:10.1016/j.matlet.2013.06.095.
- [32] G. Gnanajobitha, K. Paulkumar, M. Vanaja, S. Rajeshkumar, C. Malarkodi, G. Annadurai, et al., Fruit-mediated synthesis of silver nanoparticles using *Vitis vinifera* and evaluation of their antimicrobial efficacy, *J. Nanostruct. Chem* (2013), doi:10.1186/2193-8865-3-67.
- [33] R. Dobrucka, J. Długaszewska, Biosynthesis and antibacterial activity of ZnO nanoparticles using *Trifolium pratense* flower extract, *Saudi J. Biol. Sci* 23 (2016) 517–523, doi:10.1016/j.sjbs.2015.05.016.
- [34] M. Anbuvarannan, M. Ramesh, G. Viruthagiri, N. Shanmugam, N. Kannadasan, Synthesis, characterization and photocatalytic activity of ZnO nanoparticles prepared by biological method, *Spectrochim. Acta A Mol. Biomol. Spectrosc* 143 (2015) 304–308, doi:10.1016/j.saa.2015.01.124.
- [35] M. Sundrarajan, S. Ambika, K. Bharathi, Plant-extract mediated synthesis of ZnO nanoparticles using *Pongamia pinnata* and their activity against pathogenic bacteria, *Adv. Powder Technol* 26 (2015) 1294–1299, doi:10.1016/j.apt.2015.07.001.
- [36] P. Vanathi, P. Rajiv, S. Narendhran, S. Rajeshwari, P.K.S.M. Rahman, Biosynthesis and characterization of phyto mediated zinc oxide nanoparticles: a green chemistry approach, *Mater. Lett* 134 (2014) 13–15, doi:10.1016/j.matlet.2014.07.029.
- [37] P. Jamdagni, P. Khatri, J.S. Rana, Green synthesis of zinc oxide nanoparticles using flower extract of *Nyctanthes arbor-tristis* and their antifungal activity, *J. King Saud Univ. - Sci* (2016), doi:10.1016/j.jksus.2016.10.002.
- [38] K. Prasad, A.K. Jha, ZnO nanoparticles: synthesis and adsorption study, *Nat. Sci* 1 (2009) 129–135, doi:10.4236/ns.2009.12016.
- [39] B.N. Patil, T.C. Taranath, *Limonia acidissima* L. leaf mediated synthesis of zinc oxide nanoparticles: a potent tool against *Mycobacterium tuberculosis*, *Int. J. Mycobacteriology* 5 (2016) 197–204, doi:10.1016/j.ijmyco.2016.03.004.
- [40] S. Gunalan, R. Sivaraj, V. Rajendran, Green synthesized ZnO nanoparticles against bacterial and fungal pathogens, *Prog. Nat. Sci. Mater. Int* 22 (2012) 693–700, doi:10.1016/j.pnsc.2012.11.015.
- [41] C. Jayaseelan, A.A. Rahuman, A.V. Kirthi, S. Marimuthu, T. Santhoshkumar, A. Bagavan, et al., Novel microbial route to synthesize ZnO nanoparticles using *Aeromonas hydrophila* and their activity against pathogenic bacteria and fungi, *Spectrochim. Acta A Mol. Biomol. Spectrosc* 90 (2012) 78–84, doi:10.1016/j.saa.2012.01.006.
- [42] J. Pulit-prociak, J. Chwastowski, A. Kucharski, M. Banach, Applied surface science functionalization of textiles with silver and zinc oxide nanoparticles, *Appl. Surf. Sci* 385 (2016) 543–553, doi:10.1016/j.apsusc.2016.05.167.
- [43] H. Mirzaei, M. Darroudi, Zinc oxide nanoparticles: biological synthesis and biomedical applications, *Ceram. Int* 43 (2017) 907–914, doi:10.1016/j.ceramint.2016.10.051.
- [44] V. Patel, D. Berthold, P. Puranik, M. Gantar, Screening of cyanobacteria and microalgae for their ability to synthesize silver nanoparticles with antibacterial activity, *Biotechnol. Reports* 5 (2015) 112–119, doi:10.1016/j.btre.2014.12.001.
- [45] M. Stan, A. Popa, D. Toloman, A. Dehelean, I. Lung, G. Katona, Enhanced photocatalytic degradation properties of zinc oxide nanoparticles synthesized by using plant extracts, *Mater. Sci. Semicond. Process* 39 (2015) 23–29, doi:10.1016/j.mssp.2015.04.038.
- [46] E.D. Sherly, J.J. Vijaya, N.C.S. Selvam, L.J. Kennedy, Microwave assisted combustion synthesis of coupled ZnO-ZrO<sub>2</sub> nanoparticles and their role in the photo-catalytic degradation of 2,4-dichlorophenol, *Ceram. Int* 40 (2014) 5681–5691, doi:10.1016/j.ceramint.2013.11.006.
- [47] G. Sangeetha, S. Rajeshwari, R. Venkatesh, Green synthesis of zinc oxide nanoparticles by aloe barbadensis miller leaf extract: structure and optical properties, *Mater. Res. Bull* 46 (2011) 2560–2566, doi:10.1016/j.materresbull.2011.07.046.
- [48] K. Elumalai, S. Velmurugan, Green synthesis, characterization and antimicrobial activities of zinc oxide nanoparticles from the leaf extract of *Azadirachta indica*, *Appl. Surf. Sci* 345 (2015) 329–336, doi:10.1016/j.apsusc.2015.03.176.
- [49] Z. Sheikhloo, M. Salouti, F. Katiarae, Biological synthesis of gold nanoparticles by *Fungus Epicoccum nigrum*, *J. Clust. Sci* 22 (2011) 661–665, doi:10.1007/s10876-011-0412-4.
- [50] D. Wodka, E. Bielańska, R.P. Socha, M. Elzbiaciak-Wodka, J. Gurgul, P. Nowak, et al., Photocatalytic activity of titanium dioxide modified by silver nanoparticles, *ACS Appl. Mater. Interfaces* 2 (2010) 1945–1953, doi:10.1021/am1002684.
- [51] M.H. Sangani, M.N. Moghaddam, M. Mahdi, Inhibitory effect of zinc oxide nanoparticles on *Pseudomonas aeruginosa* biofilm formation, *Nanomed. J.* 2 (2015) 121–128.
- [52] A.S. Hameed, C. Karthikeyan, A.P. Ahamed, N. Thajuddin, N.S. Alharbi, S.A. Alharbi, et al., In vitro antibacterial activity of ZnO and Nd doped ZnO nanoparticles against ESBP producing *Escherichia coli* and *Klebsiella pneumoniae*, *Sci. Rep* 6 (2016) 24312, doi:10.1038/srep24312.
- [53] F. Movahedi, H. Masrouri, M.Z. Kassaei, Immobilized silver on surface-modified ZnO nanoparticles: as an efficient catalyst for synthesis of propargylamines in water, *J. Mol. Catal. A Chem*, 395 (2014) 52–57, doi:10.1016/j.molcata.2014.08.007.
- [54] L. Martínková, B. Uhnáková, M. Pátek, J. Nešvera, V. Křen, Biodegradation potential of the genus *Rhodococcus*, *Environ. Int* 35 (2009) 162–177, doi:10.1016/j.envint.2008.07.018.
- [55] N. Jain, A. Bhargava, J. Panwar, Enhanced photocatalytic degradation of methylene blue using biologically synthesized “protein-capped” ZnO nanoparticles, *Chem. Eng. J.* 243 (2014) 549–555, doi:10.1016/j.cej.2013.11.085.
- [56] H. Ma, P.L. Williams, S.A. Diamond, Ecotoxicity of manufactured ZnO nanoparticles – a review, *Environ. Pollut* 172 (2013) 76–85, doi:10.1016/j.envpol.2012.08.011.
- [57] K. Vimala, S. Sundarraj, M. Paulpandi, S. Vengatesan, S. Kannan, Green synthesized doxorubicin loaded zinc oxide nanoparticles regulates the Bax and Bcl-2 expression in breast and colon carcinoma, *Process Biochem* 49 (2014) 160–172, doi:10.1016/j.procbio.2013.10.007.
- [58] P. Venkatchalam, M. Jayaraj, R. Manikandan, N. Geetha, E.R. Rene, N.C. Sharma, et al., Zinc oxide nanoparticles (ZnONPs) alleviate heavy metal-induced toxicity in *Leucaena leucocephala* seedlings: a physicochemical analysis, *Plant Physiol. Biochem* 110 (2016) 59–69, doi:10.1016/j.plaphy.2016.08.022.
- [59] C. Hazra, D. Kundu, A. Chaudhari, J. Tushar, Biogenic synthesis, characterization, toxicity and photocatalysis of zinc sulfide nanoparticles using rhamnolipids from *Pseudomonas aeruginosa* BSc01 as capping and stabilizing agent, *J. Chem. Technol. Biotechnol* (2013), doi:10.1002/jctb.3934.
- [60] A.K. Jha, Microbe-mediated nanotransformation: cadmium, *Nano* 2 (2007) 239–242.
- [61] P.C. Nagajyothi, T.V.M. Sreekanth, C.O. Tetey, Y.I. Jun, S.H. Mook, Characterization, antibacterial, antioxidant, and cytotoxic activities of ZnO nanoparticles using *Coptidis Rhizoma*, *Bioorg. Med. Chem. Lett* 24 (2014) 4298–4303, doi:10.1016/j.bmcl.2014.07.023.
- [62] S. Rajeshkumar, Synthesis of silver nanoparticles using fresh bark of *Pongamia pinnata* and characterization of its antibacterial activity against gram positive and gram negative pathogens, *Resour. Technol* 2 (2016) 30–35, doi:10.1016/j.refit.2016.06.003.
- [63] K. Paulkumar, S. Rajeshkumar, G. Gnanajobitha, M. Vanaja, C. Malarkodi, G. Annadurai, et al., Biosynthesis of silver chloride nanoparticles using *Bacillus subtilis* MTCC 3053 and assessment of its antifungal activity, *ISRN Nanomater* 2013 (2013) 1–8, doi:10.1155/2013/317963.
- [64] K. Paulkumar, G. Gnanajobitha, M. Vanaja, S. Rajeshkumar, C. Malarkodi, K. Pandian, et al., Piper nigrum leaf and stem assisted green synthesis of silver nanoparticles and evaluation of its antibacterial activity against agricultural plant pathogens, *ScientificWorldJournal* 2014 (2014) 829894, doi:10.1155/2014/829894.
- [65] S. Rajeshkumar, C. Malarkodi, K. Paulkumar, M. Vanaja, G. Gnanajobitha, G. Annadurai, Algae mediated green fabrication of silver nanoparticles and examination of its antifungal activity against clinical pathogens, *Int. J. Met* 2014 (2014) 1–8, doi:10.1155/2014/692643.
- [66] M. Heinlaan, A. Ivask, I. Blinova, H.C. Dubourguier, A. Kahru, Toxicity of nano-sized and bulk ZnO, CuO and TiO<sub>2</sub> to bacteria *Vibrio fischeri* and crustaceans *Daphnia magna* and *Thamnocephalus platyurus*, *Chemosphere* 71 (2008) 1308–1316, doi:10.1016/j.chemosphere.2007.11.047.
- [67] J. Qu, X. Yuan, X. Wang, P. Shao, Zinc accumulation and synthesis of ZnO nanoparticles using *Physalis alkekengi* L., *Environ. Pollut* 159 (2011) 1783–1788, doi:10.1016/j.envpol.2011.04.016.
- [68] J. Qu, C. Luo, J. Hou, Synthesis of ZnO nanoparticles from Zn-hyperaccumulator (*Sedum alfredii* Hance) plants, *Micro Nano Lett* 6 (2011) 174, doi:10.1049/mnl.2011.0004.
- [69] P.E. Ochieng, E. Iwuoha, I. Michira, M. Masikini, J. Ondiek, P. Githira, et al., Green route synthesis and characterization of ZnO nanoparticles using *Spathodea campanulata*, *Int. J. Biochem. Phys* 23 (2015) 53–61.
- [70] S. Rajeshkumar, C. Malarkodi, M. Vanaja, G. Annadurai, Anticancer and enhanced antimicrobial activity of biosynthesized silver nanoparticles against clin-

- ical pathogens, *J. Mol. Struct* 1116 (2016) 165–173, doi:[10.1016/j.molstruc.2016.03.044](https://doi.org/10.1016/j.molstruc.2016.03.044).
- [71] A. Yasmin, K. Ramesh, S. Rajeshkumar, Optimization and stabilization of gold nanoparticles by using herbal plant extract with microwave heating, *Nano Convergence* (2014), doi:[10.1186/s40580-014-0012-8](https://doi.org/10.1186/s40580-014-0012-8).
- [72] Y. Ali, S. Benjakul, T. Prodpran, P. Sumpavapol, Food hydrocolloids properties and antimicrobial activity of fish protein isolate / fish skin gelatin film containing basil leaf essential oil and zinc oxide nanoparticles, *Food Hydrocoll* 41 (2014) 265–273, doi:[10.1016/j.foodhyd.2014.04.023](https://doi.org/10.1016/j.foodhyd.2014.04.023).
- [73] S. Jafarirad, M. Mehrabi, B. Divband, M. Kosari-Nasab, Biofabrication of zinc oxide nanoparticles using fruit extract of *Rosa canina* and their toxic potential against bacteria: a mechanistic approach, *Mater. Sci. Eng. C* 59 (2016) 296–302, doi:[10.1016/j.msec.2015.09.089](https://doi.org/10.1016/j.msec.2015.09.089).
- [74] M. Anbuvaran, M. Ramesh, G. Viruthagiri, N. Shanmugam, N. Kannadasan, *Anisochilus carnosus* leaf extract mediated synthesis of zinc oxide nanoparticles for antibacterial and photocatalytic activities, *Mater. Sci. Semicond. Process* 39 (2015) 621–628, doi:[10.1016/j.mssp.2015.06.005](https://doi.org/10.1016/j.mssp.2015.06.005).
- [75] L. Fu, Z. Fu, *Plectranthus amboinicus* leaf extract-assisted biosynthesis of ZnO nanoparticles and their photocatalytic activity, *Ceram. Int* 41 (2015) 2492–2496, doi:[10.1016/j.ceramint.2014.10.069](https://doi.org/10.1016/j.ceramint.2014.10.069).
- [76] S. Ambika, M. Sundrarajan, Antibacterial behaviour of *Vitex negundo* extract assisted ZnO nanoparticles against pathogenic bacteria, *J. Photochem. Photobiol. B Biol* 146 (2015) 52–57, doi:[10.1016/j.jphotobiol.2015.02.020](https://doi.org/10.1016/j.jphotobiol.2015.02.020).
- [77] T. Bhuyan, K. Mishra, M. Khanuja, R. Prasad, A. Varma, Biosynthesis of zinc oxide nanoparticles from *Azadirachta indica* for antibacterial and photocatalytic applications, *Mater. Sci. Semicond. Process* 32 (2015) 55–61, doi:[10.1016/j.mssp.2014.12.053](https://doi.org/10.1016/j.mssp.2014.12.053).
- [78] H.R. Madan, S.C. Sharma, Udayabhanu, D. Suresh, Y.S. Vidya, H. Nagabhusana, et al., Facile green fabrication of nanostructure ZnO plates, bullets, flower, prismatic tip, closed pine cone: their antibacterial, antioxidant, photoluminescent and photocatalytic properties, *Spectrochim. Acta A Mol. Biomol. Spectrosc* 152 (2016) 404–416, doi:[10.1016/j.saa.2015.07.067](https://doi.org/10.1016/j.saa.2015.07.067).
- [79] Y. Qian, J. Yao, M. Russel, K. Chen, X. Wang, Characterization of green synthesized nano-formulation (ZnO-A. vera) and their antibacterial activity against pathogens, *Environ. Toxicol. Pharmacol* 39 (2015) 736–746, doi:[10.1016/j.etap.2015.01.015](https://doi.org/10.1016/j.etap.2015.01.015).
- [80] K. Ali, S. Dwivedi, A. Azam, Q. Saquib, M.S. Al-said, A.A. Alkhedhairi, et al., Aloe vera extract functionalized zinc oxide nanoparticles as nanoantibiotics against multi-drug resistant clinical bacterial isolates, *J. Colloid Interface Sci* 472 (2016) 145–156, doi:[10.1016/j.jcis.2016.03.021](https://doi.org/10.1016/j.jcis.2016.03.021).
- [81] F.T. Thema, E. Manikandan, M.S. Dhlamini, M. Maaza, Green synthesis of ZnO nanoparticles via *Agathosma betulina* natural extract, *Mater. Lett* 161 (2015) 124–127, doi:[10.1016/j.matlet.2015.08.052](https://doi.org/10.1016/j.matlet.2015.08.052).
- [82] P. Rajiv, S. Rajeshwari, R. Venkatesh, Bio-Fabrication of zinc oxide nanoparticles using leaf extract of *Parthenium hysterophorus* L. and its size-dependent antifungal activity against plant fungal pathogens, *Spectrochim. Acta A Mol. Biomol. Spectrosc* 112 (2013) 384–387, doi:[10.1016/j.saa.2013.04.072](https://doi.org/10.1016/j.saa.2013.04.072).
- [83] R. Raliya, J.C. Tarafdar, ZnO nanoparticle biosynthesis and its effect on phosphorous-mobilizing enzyme secretion and gum contents in cluster-bean (*Cyamopsis tetragonoloba* L.), *Agric. Res* 2 (2013) 48–57, doi:[10.1007/s40003-012-0049-z](https://doi.org/10.1007/s40003-012-0049-z).
- [84] S.V. Otari, R.M. Patil, N.H. Nadaf, S.J. Ghosh, S.H. Pawar, Green biosynthesis of silver nanoparticles from an actinobacteria *Rhodococcus* sp, *Mater. Lett* 72 (2012) 92–94, doi:[10.1016/j.matlet.2011.12.109](https://doi.org/10.1016/j.matlet.2011.12.109).
- [85] R.M. Tripathi, A.S. Bhadwal, R.K. Gupta, P. Singh, A. Shrivastav, B.R. Shrivastav, ZnO nanoflowers: novel biogenic synthesis and enhanced photocatalytic activity, *J. Photochem. Photobiol. B Biol* 141 (2014) 288–295, doi:[10.1016/j.jphotobiol.2014.10.001](https://doi.org/10.1016/j.jphotobiol.2014.10.001).
- [86] S.K. Mehta, S. Kumar, S. Chaudhary, K.K. Bhasin, M. Gradzielski, Evolution of ZnS nanoparticles via facile CTAB aqueous micellar solution route: a study on controlling parameters, *Nanoscale Res. Lett* 4 (2009) 17–28, doi:[10.1007/s11671-008-9196-3](https://doi.org/10.1007/s11671-008-9196-3).
- [87] D. Kundu, C. Hazra, A. Chatterjee, A. Chaudhari, S. Mishra, Extracellular biosynthesis of zinc oxide nanoparticles using *Rhodococcus pyridinivorans* NT2: multifunctional textile finishing, biosafety evaluation and in vitro drug delivery in colon carcinoma, *J. Photochem. Photobiol. B Biol* 140 (2014) 194–204, doi:[10.1016/j.jphotobiol.2014.08.001](https://doi.org/10.1016/j.jphotobiol.2014.08.001).
- [88] B.N. Singh, A.K.S. Rawat, W. Khan, A.H. Naqvi, B.R. Singh, Biosynthesis of stable antioxidant ZnO nanoparticles by *Pseudomonas aeruginosa* Rhamnolipids, *PLoS ONE* 9 (2014), doi:[10.1371/journal.pone.0106937](https://doi.org/10.1371/journal.pone.0106937).
- [89] S.M. Bird, O. El-Zubir, A.E. Rawlings, G.J. Leggett, S.S. Staniland, A novel design strategy for nanoparticles on nanopatterns: interferometric lithographic patterning of Mms6 biotemplated magnetic nanoparticles, *J. Mater. Chem. C* (2015) in press, doi:[10.1039/C5TC03895B](https://doi.org/10.1039/C5TC03895B).
- [90] S. Azizi, M.B. Ahmad, F. Namvar, R. Mohamad, Green biosynthesis and characterization of zinc oxide nanoparticles using brown marine macroalga *Sargassum muticum* aqueous extract, *Mater. Lett* 116 (2014) 275–277, doi:[10.1016/j.matlet.2013.11.038](https://doi.org/10.1016/j.matlet.2013.11.038).
- [91] S. Nagarajan, A.K. Kuppusamy, Extracellular synthesis of zinc oxide nanoparticle using seaweeds of gulf of Mannar, India, *J. Nanobiotechnology* 11 (2013) 39, doi:[10.1186/1477-3155-11-39](https://doi.org/10.1186/1477-3155-11-39).
- [92] R. Pati, R.K. Mehta, S. Mohanty, C. Goswami, A. Sonawane, Topical application of zinc oxide nanoparticles reduces bacterial skin infection in mice and exhibits antibacterial activity by inducing oxidative stress response and cell membrane disintegration in macrophages, *Nanomedicine Nanotechnology, Biol. Med* 10 (2014) 1195–1208, doi:[10.1016/j.nano.2014.02.012](https://doi.org/10.1016/j.nano.2014.02.012).
- [93] K.V. Pavani, N. Sunil Kumar, B.B. Sangameswaran, Synthesis of lead nanoparticles by *Aspergillus* species, *Polish J. Microbiol* 61 (2012) 61–63.
- [94] M.R. Hoffmann, S. Martin, W. Choi, D.W. Bahnemann, Environmental applications of semiconductor photocatalysis, *Chem. Rev* 95 (1995) 69–96, doi:[10.1021/cr00033a004](https://doi.org/10.1021/cr00033a004).
- [95] A. Shamsuzzaman, H. Mashrai, R.N. Khanam, R.N. Aljawfi, Biological synthesis of ZnO nanoparticles using *C. albicans* and studying their catalytic performance in the synthesis of steroidal pyrazolines, *Arab. J. Chem* (2013), doi:[10.1016/j.arabj.2013.05.004](https://doi.org/10.1016/j.arabj.2013.05.004).
- [96] S. Anita, T. Ramachandran, C.V. Koushik, R. Rajendran, M. Mahalakshmi, Preparation and characterization of zinc oxide nanoparticles and a study of the anti-microbial property of cotton fabric treated with the particles, *JTATM* 6 (2010) 1–2.
- [97] M. Gharagozlu, Z. Baradaran, R. Bayati, A green chemical method for synthesis of ZnO nanoparticles from solid-state decomposition of Schiff-bases derived from amino acid alanine complexes, *Ceram. Int* 41 (2015) 8382–8387, doi:[10.1016/j.ceramint.2015.03.029](https://doi.org/10.1016/j.ceramint.2015.03.029).