Chapter 7
The Role of Green Synthesised Zinc Oxide Nanoparticles in Agriculture

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Abstract Nanotechnology is the most innovative field of the twenty-first century, as detailed research is underway to develop nanoproducts worldwide. Because of their unique properties, nanoparticles have grown considerably. These nanomaterials are used in photovoltaic systems, fuel cells and biomedical fields, with zinc oxide as an actual example. Concerning their synthesis, ZnO-NPs may be synthesised by numerous chemical techniques, including vapour transport, precipitation and hydrothermal processes. The green synthesis of ZnO-NPs is also popular nowadays because it is facile, safe, non-toxic and environmentally friendly. The green synthesis includes bacteria, fungi, yeast, algae, plants and their parts like seeds, fruits, leaves, stem and pulp. Among green synthesis, using plant extracts is the most popular as it is a single-step process. In this paper, we will discuss the role of plant-mediated synthesis of ZnO-NPs in crop production.

Keywords Nanotechnology · ZnO-NPs · Crop production · Green synthesis · Plant extracts

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7.1 Introduction

In modern days, due to their distinct and attractive applications, ZnO-NPs have received tremendous attention in many fields like physics, chemistry, biology, medicine, electronics, etc. These characteristics can be endowed with their large surface area, reduced scale and surface-specific binding position, availability and catalytic, electronic and thermal properties. There are different routes for the biosynthesis of ZnO-NPs using physical and chemical methods that involve different set-up, high-temperature and high-pressure conditions (Agarwal et al., 2018). Biosynthesis of nanoparticles via the green route is natural, environmentally friendly, cost-effective, safe and biocompatible (Abdul Salam et al., 2014). The green synthesis method involves the use of bacteria, fungi, algae, yeast, plant extracts, etc. They permit the mass production of ZnO-NPs without additional impurities (Yuvakkumar et al., 2014). The utilisation of nanotechnology in agriculture is one of the potential sectors that might enhance sustainable crop management. For example, the use of nano-based pesticides to release chemicals has been effectively deployed in a regulated and specifically tailored manner that makes for a cleaner and simpler pest control system. Nanoparticles that are essential for improving agricultural production are generally considered to improve productivity and sustainability. Zinc (Zn) is a significant micronutrient for the proper growth and development of plants and animals. In this regard, numerous studies have been carried out on the role of zinc in the growth and metabolism of plants. For crop nutrition, it is crucial since it is needed in numerous enzyme processes, metabolism and oxidation-reduction processes. Zinc is important for the proper functioning of many enzymes such as isomerases, dehydrogenases, transphosphorylases, aldolases and DNA and RNA polymerases used for a wide variety of essential physiological and metabolic processes. Zinc also takes part in tryptophan synthesis, cell division, photosynthetic maintenance and membrane structure. Besides, it also acts as an essential cofactor in controlling the biosynthesis of proteins (Lacerda et al., 2018). Appropriate Zn fertilisation, therefore, helps enhance cereal, vegetable and food production. Zinc deficiency is characterised by reduced leaf size, interveinal necrosis and ribbed leaf margins.

Under the extreme conditions of zinc shortage, SPAD values, low leaf area values and total N and NO3 are observed (Castillo et al., 2019). With the deteriorating deficiency, catalase, superoxide dismutase and glutathione peroxide activities often increase. Declines in cross-sectional area, yield and kernel percentages are also found with severe Zn shortage. Increased activity of the enzyme superoxide dismutase, catalase and peroxides is related to reactive oxygen detoxification (Ali et al., 2020).

7.2 Zinc Oxide Nanoparticles (ZnO-NPs)

In numerous cutting-edge applications such as communications, environmental biosafety, biology, medicine, cosmetics and electronics, ZnO-NPs have been used within the broad family of metal oxide nanoparticles. In addition, ZnO-NPs have immense potential in biomedical applications such as gene transfer, bio-labelling, nanomedicine and biological sensing (Bala et al., 2015). Zinc oxide is an n-type semiconductor metal oxide that has been extensively used for numerous applications like the manufacture of rubber and separation of arsenic and sulphur from water. It has an excellent property of protein adsorption and is also used in dental applications. It has been registered as GRAS (generally recognised as safe) among the other metal oxides by the US FDA. From the past years, ZnO-NPs gained tremendous attention in the area of research due to its wide bandgap and large excitation-binding energy (Anbuvannan et al., 2015; Jamdagni, Khatri, et al., 2018; Taranath & Patil, 2016; Pulit-Prociak et al., 2016; Sundrarajan et al., 2015). Due to its wide bandgap and high binding energy ZnoNPS have shown excellent antibacterial, antifungal, wound healing, antioxidant and optical properties. There are different methods available to synthesise ZnO-NPs like physical, chemical and biological or green synthesis. Due to the limitation of the physical and chemical methods, biological or green synthesis of ZnO-NPs is usually preferred. The physical and chemical methods are costly, time-consuming, employed on high pressure and temperature and generating large quantities of secondary waste products and toxic chemicals into the environment. As a result of these limitations, biogenic or green synthesis is the ideal method for nanoparticle synthesis as it is safer, cheaper and less toxic (Sharmila et al., 2019).

7.3 Nanoparticles Synthesis

For the development of nanomaterials of definite form and scale, two methods called top-down and bottom-up approaches (Fig. 7.1) are commonly used. The principle of synthesis for both approaches is different, but they produce nanomaterials with desired characteristics. In top-down approaches, the bulk material is crushed into small pieces leading to the formation of nanomaterials. The nanomaterial produced in this manner utilises the photolithographic techniques, sputtering, grinding and milling. The top-down approach is a relatively feasible nanoparticle production method that results in a large mass of nanomaterials being generated. The limitations associated with the top-down approach are surface imperfection of nanomaterials. Another approach is the bottom-down approach, in which assembly of atoms by atoms, molecules by molecules and clusters by clusters is done to produce a wide range of nanomaterials. The techniques employed for the development of nanomaterials through the bottom-up method are chemical or electrochemical nanostructural precipitation, chemical vapour deposition, laser pyrolysis, and bio-assisted

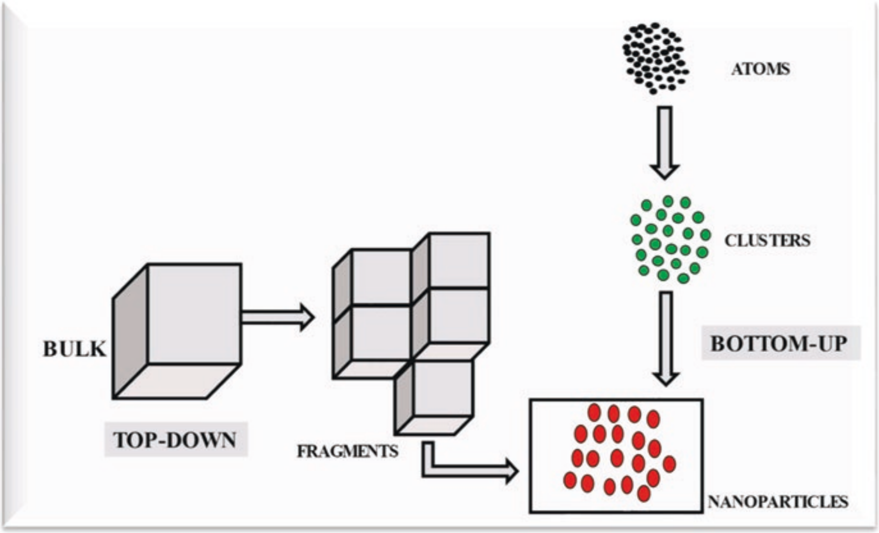

Fig. 7.1 Top-Down and Bottom-Up Approaches of Nanomaterial Synthesis

synthesis (Dhand et al., 2015; Gwo et al., 2016; Patil & Chandrasekaran, 2020) (Dhand et al., 2015; Gwo et al., 2016; Patil & Chandrasekaran, 2020).

7.4 Methods of Nonmaterial Synthesis

7.4.1 Physical Synthesis

The techniques like ball milling, sputtering and deposition are included in the physical synthesis of nanomaterials. The rate of production of nanomaterials through these techniques is meagre. In ball milling, the yield of nanomaterial synthesis is only 50%. In the case of laser ablation and plasma techniques, high consumption of energy is required. For most physical technologies that cannot be adopted for actual commercial applications, vast size distribution, slow production rate, waste by-products and significant energy consumption make it exceedingly costly (Seetharaman et al., 2018). (Seetharaman et al., 2018).

7.4.2 Chemical Synthesis

The chemical synthesis of nanomaterials includes various methods like sol-gel deposition, hydrothermal deposition, microemulsion and chemical vapour deposition (Król et al., 2017). Based on solid phases, wet chemical synthesis is one of the

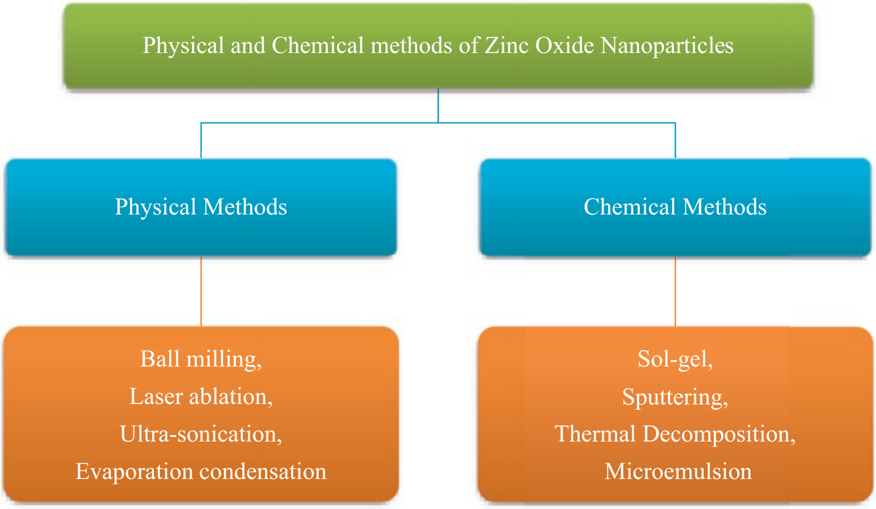

Fig. 7.2 Physical and chemical methods for nonmaterial synthesis

essential tools for the production of nanomaterials (Król et al., 2017; Malfatti et al., 2015). In industrial wet chemical synthesis, capping agents and stabilising agents are typically used to control the particles' size and prevent agglomeration due to toxicity. Triethylamine (TEA), thioglycerol, oleic acid and polyethylene glycol are significant capping or stabilising agents, even though they are apoptotic, immunogenic and necrotic (Naveed Ul Haq et al., 2017). In the microemulsion method, stable fluid droplets from immiscible hydrocarbons and waters are formed in a thermodynamically stable manner. A method to monitor the size (˂200 nm), structure (hexagonal crystal) and shape of ZnO-NPs based on minimum emulsion using TEA has been documented by Fricke et al. (2015). The chemical vapour deposition has also been used for the synthesis of ZnO-NPs, efficiently. Figure 7.2 shows the physical and chemical synthesis of nanomaterials.

7.4.3 *Biological Synthesis*

As biological methods are environmentally friendly, they provide exciting possibilities than physical and chemical synthesis (Agarwal et al., 2018). The biosynthesis of ZnO-NPs was systematically examined with microorganisms, proteins, DNA and plant extracts (Ishwarya et al., 2017; Raja et al., 2018). However, biological synthesis is not fully understood as the mechanical method for producing ZnO-NPs. By going through enzymatic and biological pathways, ZnO-NPs can be produced. A synthesis of ZnO-NPs (10–95 nm; rod, cubic, multiform, triangle, acicular) was performed with bacteria, including *Halomonas elongate* IBRC-M 10214 (Taran et al., 2018), *Sphingobacterium thalpophilum* (Rajabairavi et al., 2017) and

Staphylococcus aureus (Rauf et al., 2017). Fungal species such as Candida albicans (Mashrai et al., 2017) and Aspergillus niger (Kalpana et al., 2018) can also be used to synthesise ZnO-NPs. Fungal-mediated ZnO-NPs with a spherical and quasi-spherical form of 61 nm and 25 nm were used for steroidal pyrazoline synthesis and antimicrobial applications. As a yeast system, JA2 (Chauhan et al., 2014) can also synthesise ZnO-NPs from *Pichia kudriavzevii* (Moghaddam et al., 2017) and *Pichia fermentans*. The algae like *Chlamydomonas reinhardtii* and *Sargassum muticum* (Azizi et al., 2014) are also used to synthesise ZnO-NPs. Gelatin has also been helpful for the synthesis of 20 nm ZnO-NPs, which show excellent antibacterial and anti-angiogenic activity (Divya et al., 2018). By using egg albumin, spherical and hexagonal ZnO-NPs were synthesised, and the size was found to be 16 nm (XRD), 10–20 nm (TEM) and 8–22 nm (AFM) (Ambika & Sundrarajan, 2015). Plants are regarded as the bio-factories of nonmaterial synthesis (Table 7.1) due to many secondary metabolites like alkaloids, flavonoids and phenolics (Chakravorty et al., 2020). The synthesis of nonmaterial is started by adding the extracts obtained from the different plant components to the aqueous solution containing metal ions. The secondary metabolites present in the plant extract functions as reducing and capping agents to reduce metal ions into nanoparticles (Rather et al., 2020).

Nanoparticles, which have proven to be one of the critical needs for growth and development in the era of nanotechnology (Keat et al., 2015), can be used for a broad range of applications. Therefore, the study is going on to increase the efficiency of nanoparticles to make them more application-specific. However, the methods used to synthesise nanoparticles should be cost-effective and eco-friendly. This suggests that the method of NP synthesis should avoid the use of toxic chemicals, and there should be a negligible generation of any harmful by-products.

Table 7.1 Different Parts of Plants Used for Nanoparticle Synthesis

S. no.	Name of plant	Part of plant used	UV absorption peak (nm)	Shape of nanoparticles	References
1.	*Musa acuminate*	Peel	344	Triangular	Abdullah et al. (2020)
2.	*Melia azedarach*	Leaf	372	Spherical	Dhandapani et al. (2020)
3.	*Cassia alata*	Leaf	320	Spherical	Happy et al. (2019)
4.	*Coccinia abyssinica*	Tuber	365	Hexagonal	Safawo et al. (2018)
5.	*Azadirachta indica*	Leaf	375	Spherical	Singh et al. (2019)
6.	*Artemisia annua*	Bark	330	Spherical	
7.	*Ziziphus jujube*	Fruit	376	Spherical	Golmohammadi et al. (2020)
8.	*Berberis aristata*	Leaf	343	Needle	Chandra et al. (2019)
9.	*Codonopsis lanceolata*	Root	356	Flower	Lu et al. (2019)

The method of green synthesis (biosynthesis) uses basic methods, readily available raw materials and the atmosphere for the synthesis process, where the precursors used are healthy, with a small possibility of developing harmful by-products (Dizaj et al., 2014 (Hossain et al., 2019; Ogunyemi et al., 2019)). Biosynthesised NPs are observed and characterised using various methods, such as XRD, AFM, FT-IR, DLS, SEM, TEM, UV-Vis spectroscopy, zeta potential analysis, etc. (Salem & Fouda, 2021).

Plant sections including leaves, roots, flowers and stem have been utilised to synthesise zinc oxide nanoparticles (Azizi et al., 2016; Lingaraju et al., 2016; Raj, 2015; Suresh et al., 2018). They contain many phytochemicals that help stabilise and reduce zinc to zinc nanoparticles (Iqbal et al., 2019). The simple method used for synthesising zinc nanoparticles is that the plant part is collected and washed under tap water or double-distilled water. Then the plant part is shade dried for few days and finally ground to powder using mortar and pestle or electric grinder. Milli-Q water is used for the preparation of plant extract and the synthesis of nanoparticles. Some volume of plant extract is added to the zinc acetate, zinc oxide solution. The mixture is boiled at the desired temperature to ensure optimal mixing. Some optimisation such as pH, temperature and extract concentration in the process of synthesis may be required. The mixture is centrifuged at 7000–8000 rpm and oven-dried at 6–80 °C. The oven-dried material is calcined in a muffle furnace at 400–450 °C for 2 h to obtain a white powder containing zinc oxide nanoparticles (Alamdari et al., 2020; Demissie et al., 2020; Selim et al., 2020). Several studies have reported the synthesis of zinc nanoparticles from plants (Lakshmi, 2017; Selim et al., 2020).

Happy et al. (2019) reported the plant-mediated synthesis of Zn nanoparticles from *Cassia alata* leaf. Aqueous extract of *Eucalyptus* has also been exploited for the synthesis of zinc oxide nanoparticles of size ranging between 52 and 70 nm, confirmed by SEM and TEM analysis (Ahmad et al., 2020). Zinc oxide nanostructures have also been synthesised using the seed extract of *Nigella saliva*. Chemingui et al. (2019) reported the synthesis of zinc oxide nanoparticles using *Laurus nobilis* plant extract. Synthesised nanoparticles were of wurtzite hexagonal structure, and the average size of the nanocrystals was between 20 and 35 nm.

The synthesis of metal nanoparticles using microorganisms has recently been investigated and now accepted as an effective way to exploit microorganisms as cost-effective nanofactories. The biological synthesis of nanoparticles using microbes provides a benefit over plants because microbes are readily replicated. Nonetheless, several drawbacks like careful monitoring are required, culturing bacteria, and the media used for bacterial culture is also quite costly (Ahmed et al., 2017). The involvement of different enzymes, proteins and other biomolecules from microbes such as bacteria, fungi and yeasts plays a crucial role in the reduction process (Ali et al., 2018). These organic products secreted in suspension or growth medium result in multisite mono- and polydispersed nanoparticles and serve as capping agents to stabilise nanoparticles (Gahlawat & Choudhury, 2019).

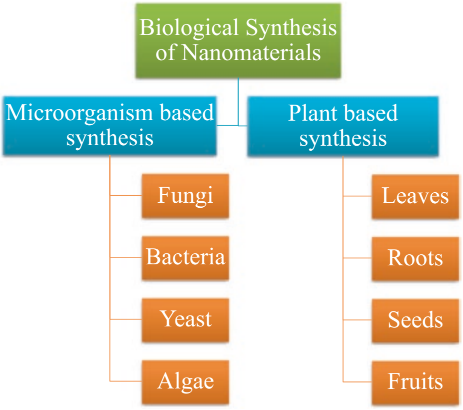

Fig. 7.3 Biological synthesis of nanomaterials

Lactic acid bacteria have raised interest in the wide-scale manufacturing of metal oxide nanoparticles because of their non-pathogenic features and the enormous synthesis of enzymes (Yusof et al., 2019). In addition, LAB has been acknowledged to have beneficial effects on human health. Moog et al. (2020) synthesised monodispersed zinc oxide nanoparticles utilising zinc-tolerant probiotic *Lactobacillus plantarum* strain TA4 with an average particle size of 124.2 nm, as validated by DLS analysis.

Fungi and yeasts have also been widely used to synthesise nanoparticles because of their high binding capacity, tolerance and better bioaccumulation ability (Boroumand Moghaddam et al., 2015a, 2015b; Pati et al., 2014). As study in which synthesis of ZnOnps was successfully conducted by using culture filtrates of Aspergillus niger have shown the size of ZnOnps were in the range of 84–91 nm as confirmed by SEM analysis. Extracellular mycosynthesis of zinc oxide nanoparticles using *A. alternata*, *A. tenuissima* (an endophytic fungi) and *Pichia kudriavzevii* (a yeast strain) has been reported in the scientific literature (Abdelhakim et al., 2020; Moghaddam et al., 2017; Sarkar et al., 2014), and the same have been confirmed by the SEM and TEM studies. Figure 7.3 shows biological methods of zinc oxide nanomaterials.

7.5 Limitations of Conventional Methods for ZnO Nanoparticle Synthesis

The physical methods for the synthesis of ZnO nanoparticles hold their limitations. The method microemulsion involves impacting the crystallisation process, due to which it is difficult to achieve a uniform size of nanocrystalline oxides. While in the sol-gel preparation method, the drawback is to purify the final products from residues of the solvents and polymers used. Meanwhile, the magnetron sputtering method holds a disadvantage involving the high cost of equipment relative complexity and technical implementation. The green synthesis, which provides a comparatively pollution-free mechanism, optimises reaction conditions to achieve improved performance, desirable features and instability. The stability of biosynthesised ZnO is unpredictable to calculate and could otherwise cause a significant harm to the biological systems. Thus, reaction mechanisms and technologies both for chemical and green syntheses must be properly built and optimised. In addition, most ZnO synthetic chemicals are classified as harmful chemical compounds, and the legal exhaust cap in most countries is well established. To assess the threat presented by ZnO, there is a clear need for environmental risk assessment. In addition, replication models should be built to parallel the growing usefulness, ZnO synthetisation quantity and contaminants expired during these operations.

7.6 Characterisation of ZnO Nanoparticles

In the past years, nanotechnology has gained immense popularity in science, be it medicine, electronics, agriculture and engineering. Nanomaterials can be characterised through different techniques like XRD, TEM, SEM, EDAX, FT-IR, DLS, AFM and UV-Vis spectroscopy (Fig. 7.4). Through these techniques, nanomaterial properties like morphology, composition, structure, form, physical and chemical properties can be studied. There is no single method that satisfies to analyse the properties of nonmaterial (Hasan, 2015; Nivetha et al., 2020).

7.6.1 UV-Visible Spectroscopy

UV-visible spectroscopy is one of the basic analytical techniques used to analyse nanomaterials. In UV-visible spectroscopy, light intensity is measured, and by this technique, the optical properties of nanomaterials can be studied. The nanomaterials like Au and Cu show normal UV-visible excitation spectrum due to the presence of a signal in the range of the visible portion of the spectrum (Hendel et al., 2014). With the help of UV-visible spectroscopy, the molar concentration of nanomaterials can be calculated (Paramelle et al., 2014).

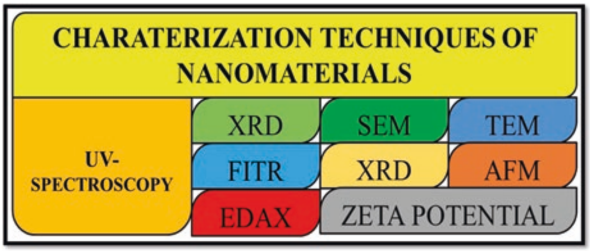

Fig. 7.4 Characterisation techniques of nanomaterial synthesis

7.6.2 *Transmission Electron Microscopy*

Transmission microscopy is one of the advanced methods used to characterise nanomaterials. By this technique, the actual size and images of the nanoparticles could be captured. During this technique, a uniform beam of electrons touches the specimen and spreads out through it. After the interaction between the electron beam and the specimen, an image is formed that is magnified and focused with the help of an imaging tool. The contact between the sample and beam depends on the density, elemental composition of the material, size and morphology. Compared to any other characterisation technique, TEM has significantly higher image resolution and can visualise extremely small atoms. TEM is one of the versatile techniques used to assess nanomaterials' in vitro absorption, size, shape, morphology and aggregation. With the help of TEM, it is possible to determine the degree of nanoparticles' penetration, their position inside the cell and the mechanism of cell death in cancerous cells. The dispersion of nanoparticles can also be analysed through TEM (Laborda et al., 2016; Yue et al., 2017).

7.6.3 *Scanning Electron Microscopy*

Scanning electron microscopy is one of the widely used characterisation method to measure the morphology of nanomaterials. Due to its high resolution, it is used to capture high-quality images of nanomaterials. The principle optical microscope and SEM are the same, but in SEM, the electron dispersion is quantified through electrical potential instead of photons. In this technology, the electrons are employed to make pictures, which further interacts and scans the surface of samples to create distinct signals to offer information on the type of interaction, composition and the arrangement of samples (Arun et al., 2020; Machado et al., 2015; Rajeev et al., 2019).

7.6.4 *Dynamic Light Scattering*

DLS is the most powerful technique employed to analyse the size of nanomaterials in colloidal solutions. The nanomaterials are in continuous Brownian motion in the aqueous form and produce both positive and destructive interfaces. By DLS, the light scattering amplitude causes the time-dependent oscillations, and hydrodynamic diameter is measured simultaneously for both nanomaterials and solvent molecule at the same rate. The average particle size can also be estimated (Chakravorty et al., 2020).

7.6.5 Energy-Dispersive X-Ray Spectroscopy

The energy dispersive x-ray spectroscopy (EDX) is used to evaluate nanomaterials' chemical characterisation and elemental composition. The composition of elemental analysis is achieved, as every element has its unique structure, and it can produce distinctive peaks on the x-ray spectrum. EDX is an essential tool for the examination and the extent of purity in ZnO-NPs. The plant extract acts as a source of reducing agents and elements like oxygen and carbon on EDX (Taziwa et al., 2017).

7.6.6 X-Ray Diffraction

X-ray diffraction (XRD) is one of the widely used techniques for the characterisation of nanomaterials. It is an advantageous and non-destructive method for the characterisation of nanomaterials. XRD gives information about the crystalline phase, structure, shape and pressures of nanomaterials. In this technique, the powdered samples are used, and by calculating the position and amplitude, the composition of nanomaterials can be analysed. The peaks are obtained by using the monochromatic beam of x-rays.

7.6.7 Fourier Transforms Infrared Spectroscopy

Fourier transform infrared spectroscopy (FTIR) is another flexible method used to analyse the composition of nanomaterials, their molecular structure, type of bonding and the existence of related functional groups. The principle of FTIR is based on the absorption spectrum of electromagnetic wavelength in the range of 4000–400 cm^{-1} (Blanco Andujar, 2014). With the help of the FTIR technique, characterisation of ZnO-NPs from plant extracts to determine the number of functional groups such as -OH, C=O, C=C and C-N present in the ZnO-NPs can be done (Shao et al., 2018).

7.6.8 Atomic Force Microscopy (AFM)

AFM, a type of microscopy, provides high-resolution 3D images. The main principle of this approach involves the force of attraction between the specimen and a fine probe. Because of attraction or repulsive forces, when AFM scans the sample between the tip and the sample surface, the information collected from the laser gap and the final result is decided by combining forces. When characterising the nanoparticles, the latter is the most common one. By this technique, topological characterisation of small nanoparticles (≤6 nm), such as ion-doped Y_2O_3, has been achieved without any special treatment (Krupa & Vimala, 2017).

7.7 The Role of Green Synthesised Zinc Oxide Nanoparticles (ZnO-NPs) in Agriculture

Agriculture is the primary sector or source of Third World economies. Still, unfortunately, it is facing numerous global challenges like drastic climate changes, urbanisation, environmental issues like runoff and the accumulation of pesticides and fertilisers. Metal oxide nanoparticles have shown excellent effects on the agriculture sector, including effective growth, increased yield and nutritional quality. Besides, they are acting as antipathogenic agents in plant protection. Being biologically important, Zn has played an essential role in plant systems, including its role in metal protein complexes. Zinc is required in very small amounts and serves a variety of activities in plants, including cell membrane stabilisation, protein synthesis, plant protection, cell elongation, and resistance to environmental stress (Kolenčík et al., 2019; Sabir et al., 2014). The positive effects of ZnO-NPs on the germination and development of pearl millet are also reported (Nandhini et al., 2019).

Similarly, the beneficial effects of ZnO-NPs on the quantitative and physiological parameters of *Zea mays* and *Triticum aestivum* L. have also been described (Singh et al., 2019). In corn and wheat, the chlorophyll formation is positively enhanced by ZnO-NPs (Rizwan et al., 2019). In *Solanum tuberosum* L., the usage of 100, 350 and 500 mgL-1 of ZnO-NPs has increased the common starch content (Raigond et al., 2017). The ZnO-NPs at lower concentrations increase seed germination (Ramesh et al., 2014). The foliar application of ZnO-NPs on coffee plants (*Coffea arabica* L.) demonstrated improved growth and physiology compared to Zn (ZnSO4) salt due to its greater leaf penetration (Rossi et al., 2019). The antioxidant and phenolic compounds in *Capsicum annum* L. have been boosted during seed germination by ZnO-NPs (García-López et al., 2018). In nursery phases with foliar spraying of ZnO-NPs, a significant increase in growth was observed in karanj, milk wood-pine and meem seedlings (Chaudhuri & Malodia, 2017). ZnO-NPs also promote embryogenesis, plantlet regeneration and certain enzymes in MS media that are allowed to survive in biotic tension (Helaly et al., 2014). The study conducted on *Fagopyrum esculentum* showed the presence of ZnO-NPs that had strengthened the antioxidant properties, photosynthetic efficacy and increased proline accumulation, providing plant stabilisation (Faizan et al., 2018). ZnO-NPs serve as new fertiliser for crop yield and food quality enhancement with unique physicochemical properties (Yusefi-Tanha et al., 2020). Studies performed on *Nicotiana benthamiana* have shown that it deactivates TMV (*Tomato mosaic virus*) and activates its immunity through the use of ZnO-NPs (Cai et al., 2019). Studies on ZnO-NPs have shown increased plant resistance to a wide range of microbes, increased crop production and decreased disease severity (Tripathi et al., 2017). Zinc oxide nanoparticles (ZnO-NPs) have shown excellent pesticide activity against the *Artemia salina* larva (Singh et al., 2018). In the growth of *Arachis hypogea* plant, the fertility study of ZnO-NPs was carried out. The results showed an increase in seed germination, rapid shoot growth, increased seedling vigour, enhanced root growth and rapid flowering and yield. In *Solanum lycopersicum* the fertility efficacy of ZnO-NPs was conducted, and the results showed increased seed germination and high protein content (Singh et al., 2016).

There was a significant rise in root growth and dry weight in onions after adding ZnO-NPs (Laware & Raskar, 2014). The photosynthetic pigment levels in millet were increased by applying ZnO-NPs (Tarafdar et al., 2014). The mechanism and behaviour of ZnO-NPs in plants are not well defined. Figure 7.5 shows the role of zinc oxide nanomaterials in agriculture.

Fig. 7.5 The role of green synthesised zinc oxide nanoparticles in agriculture

7.8 The Role of ZnO-NPs under Abiotic Stress

The application of ZnO-NPs mitigates the damaging effect of ROS on cells. The ZnO-NPs trigger antioxidant enzymes, free amino acids and nutrients, which play a major role in providing plant protection from different stresses (Fig. 7.6). It has shown successfully that the application of ZnO-NPs at reduced doses was very efficient in relieving various abiotic stresses and promoting plant growth and development (Venkatachalam et al., 2017; Wang et al., 2018).

The applications of nanoparticles have proven to be promising among the several other strategies implemented to combat drought-inducing damage to plants (Table 7.2). The application of ZnO-NPs to the wheat crop has minimised the adverse effects of drought stress and increased crop yield (Taran et al., 2017). According to Venkatachalam et al. (2017), the toxicity in *Leucaena leucocephala* seedlings by Cd and Pb has been reduced by applying ZnO-NPs. The foliar applications of ZnO-NPs have reduced salinity's adverse effects on the growth of sunflower

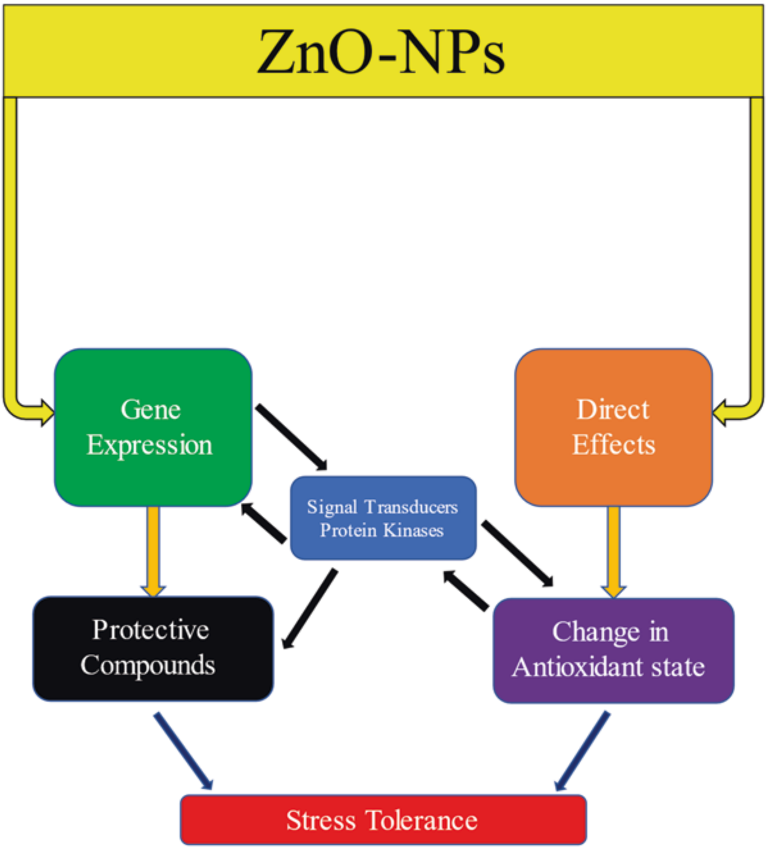

Fig. 7.6 The role of zinc oxide nanoparticles under abiotic stress

Table 7.2 Applications of green synthesised ZnO-NPs in the field of agriculture

S. no.	Type of nanoparticles	Plant	Source of nanoparticles	Size in nm	Application in agriculture	References
1.	Zinc oxide nanoparticles	*Aloe barbadensis*	Leaves	35 nm	Seedling (enhancing growth)	Singh et al. (2019)
2.	Zinc oxide nanoparticles	*Curcuma longa*	Tuber	20 nm	Seedling (root and shoot elongation)	Jayarambabu et al. (2015)
3.	Zinc oxide nanoparticles	*Nyctanthes arbor-tristis*	Flower	12–32 nm	Plant (antifungal activity)	Jamdagni, Khatri and Rana (2018, Jamdagni, Rana, et al., (2018)
4.	Zinc oxide nanoparticles	*Solanum lycopersicum*	Leaves	48.5 nm	Plant (antibacterial activity)	Ogunyemi et al. (2019)
5.	Zinc oxide nanoparticles	*Eucalyptus globules*	Leaves	52–70 nm	Plant (antifungal activity)	Ahmad et al. (2020)
6.	Zinc oxide nanoparticles	*Nigella sativa*	Leaves	20 nm	Plant (increases branching, growth)	Alaghemand et al. (2018)
7.	Zinc oxide nanoparticles	*Citrus limon*	Fruit extract	388 nm	Plant root (antibacterial effect)	Hossain et al. (2019)
8.	Zinc oxide nanoparticles	*Scadoxus multiflorus*	Leaves	31 nm	Plant (antilarval)	Al-Dhabi and Valan Arasu (2018)
9.	Zinc oxide nanoparticles	*Calotropis gigantea*	Leaf extract	1.5–8 nm	Seedling (acts as nanofertiliser and improves growth and development)	Chaudhuri and Malodia (2017)
10.	Zinc oxide nanoparticles	*Aloe barbadensis*	Leaf extract	35 nm	Enhances plant growth	Singh et al. (2019)
11.	Zinc oxide nanoparticles	*Elaeagnusan-gustifolia*	Flower extract	40 nm	Enhances growth and germination of seedling	Singh, Kim, et al. (2016); Singh, Singh, et al. (2016)

(continued)

Table 7.2 (continued)

S. no.	Type of nanoparticles	Plant	Source of nanoparticles	Size in nm	Application in agriculture	References
12.	Zinc oxide nanoparticles	*Nigella sativa*	Seed extract	24 nm	Enhances growth of the shoot and root and increases leaf chlorophyll content	Awan et al. (2020)
13.	Zinc oxide nanoparticles	*Nyctanthes arbor-tristis*	Flower extract	76 nm	Acts as fungicidal	Jamdagni, Khatri, & Rana (2018); Jamdagni, Rana, et al. (2018)
14.	Zinc oxide nanoparticles	*Solanum lycopersicum*	Plant extract	500 nm	Acts as strong antibacterial agent	Abdallah et al. (2020)
15.	Zinc oxide nanoparticles	*Azadirachta indica*	Leaf extract	27.8 nm	Plant (antimicrobial activity)	Mankad et al. (2016)
16.	Zinc oxide nanoparticles	*Mentha spicata*	Leaf extract	11–88 nm	Acts as antiviral agent against TMV	Abdelkhalek and Al-Askar (2020)
17.	Zinc oxide nanoparticles	*Psidium guajava*	Leaf extract	12 nm	Shows antibacterial activity and enhances fabric properties	Saha et al. (2018)

(Torabian et al., 2018). ZnO-NPs have led to the alleviation of soil salinity. About 60 mg/L of ZnO-NPs has shown to reduce the salt stress in *Moringa peregrina* plants (Soliman, 2015). Under stressful and stress-free conditions, ZnO-NPs act as essential materials for plant growth. ZnO-NPs have shown an increase in plant production as well as plant growth. Under stressful conditions like lipid peroxidation, ZnO-NPs have played an essential role in modulating the physiological parameters in plants. Due to their small size, ZnO-NPs have facilitated their easy penetration inside the plant cells and controlled the water channels that assisted plant growth and seed germination in plants (Faizan et al., 2018).

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