# Chapter 10
# ZnO Nanoparticles: Sustainable Plant Production

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## 1 Introduction

Nanoparticles (NPs), because of their unique properties, have been extensively used in agriculture as fertilizer, pesticide, insecticide, and biosensors (Duhan et al., 2017; Chhipa, 2019; Hu & Xianyu, 2021). NPs have been suggested as beneficial agents in agriculture because of their implicit use as nanofertilizers, which have a greater capacity to saturate soil than ordinary fertilizers and are more easily taken up by plants (Morales-Díaz et al., 2017). NPs of metal oxide have attracted attention because of their large surface area, good adsorption, numerous reactive sites, more catalytic activity, and chemical stability. This has considerable effects on various species. Owing to their unique characteristics, NPs greatly influence higher plants' intake, accumulation, alteration, and movement in both terrestrial and aquatic environments. (Jebel et al., 2016).

Because of characteristics like small size, greater energy, high surface-to-volume ratio, superior transport, and catalyst capabilities, nanotechnology has recently garnered considerable interest. Most significantly, it was found that NPs of the same metals displayed different properties from bulk molecules (Ahmed et al., 2022). Special characteristics of NPs lead them to numerous applications, such as in the culinary, pharmaceutical, and agricultural industries (Naveed Ul Haq et al., 2017). It is quite concerning that the growing world population will lead to higher food demands and reduced output because of factors including the prolificacy of soil, climate change, and strains of biotic as well as abiotic bacteria, which will have substantial consequences on the yield of crops (FAO, 2019). Therefore, the production of food should rise in the same proportion (Kumar et al., 2006). Manures,

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insecticides, cultivars, and genetically modified organism crops have all been extensively used to combat the problem (Yadav et al., 2013). Synthetic fertilizers play a key role in boosting crop output, but their excessive and careless usage has negative outcome on food standards and soil conditions (Zamir, 2011; Conley et al., 2009; Bai et al., 2020).

Recently, chemical and engineered nanoparticles (ENPs) are being used more and more frequently as fertilizers and for pest control. Researchers are attempting to use a biological and more environmentally responsible way to create NPs to mitigate the environmental effects of chemical fertilizers and ENPs in soil systems. The biological extract explored in biosynthesis comes from many plants and microorganisms, and it is secure, economical, and contains natural capping and reducing agents as well as various photochemicals (Senthamarai & Malaikozhundan, 2022). That's why scientists are looking at different plant extracts, fruit and flower components, and cellular and microbial parts for the environmentally friendly prepared NPs. Eco-friendly and sustainable nanoparticles (NPs) are used for various purposes, such as medication transport, electrochemical and photo decomposition performances, wastewater treatment, and biofertilizers (Alshehri et al., 2018). The phytochemicals extracted from plants have been found to play a role in the synthesis of NPs (Alshameri & Owais, 2022).

ZnO NPs are presently obtaining a great deal of attention due to their benign nature, higher necessity for plant improvement, and Zn's deficit in soil (Itroutwar et al., 2020). ZnO NPs have been employed as foliar fertilizers in several studies because they improve the agromorphological characteristics, photosynthesis, biomass, and production of plants (Munir et al., 2018). Wheat germination and growth have been shown to be significantly impacted by ZnO NPs, according to a previous report (Du et al., 2017). $Zn^{+2}$ is a crucial trace element that takes part in both human and plant metabolism. The FDA has deemed the ZnO NPs to be safe because they are far less harmful (Senthamarai & Malaikozhundan, 2022).

Zinc is a vital micronutrient for plants, and its deficiency will reduce crop yields (Rudani et al., 2018). NPs of ZnO have been explored because of their strong antimicrobial and biocompatible nature. The production of ROS, free radicals, and the deliverance of $Zn^{2+}$ ions are all components of the process underlying its bactericidal effect (Gharpure & Ankamwar, 2020). Priyanka and Venkatachalam investigated ZnO NPs and found that they exhibit enormous potential in their application for powerful catalysis in agriculture (Priyanka & Venkatachalam, 2016). The incorporation of ZnONPs, in the presence of Cd and Pb ions, provides protective effects on cotton seedlings by mitigating heavy metal-induced phytotoxicity and enhancing physiochemical properties. This is accomplished by modulating the photosynthetic machinery and antioxidative defense mechanisms in cotton seedlings in a distinct manner (Priyanka et al., 2021). Keerthana et al. (2021) observed that the co-exposure of ZnO NPs to stressed plants with some heavy metals profoundly increased the expansion of the roots and shoots.

This chapter investigates on ZnO NPs for their application in sustainable plant production. The chapter addresses the importance of ZnO NPs and different fabrication techniques for the manufacture of ZnO NPs. It also demonstrates nanofertilization, the use of ZnO NPs in sustainable plant production, and future trends in the use of ZnO nanofertilizers.

## 2 Importance of ZnO Nanoparticles

ZnO NPs play a very important role in the growth of plants due to the following:

(i) Antimicrobial activity
(ii) Biosafety
(iii) Seed germination
(iv) Translocation

Jiang et al. (2016) studied the interactions among ZnO NPs, released $Zn^{2+}$ and ROS, and *Escherichia coli* cells and concluded that ZnO NPs are "biosafe material" for organisms. ZnO NPs have been reported to induce the germination of seeds and growth of plants, as well as conquering of disease and preservation of plants, because of their antimicrobial activity. It is known that the uptake, translocation, and accumulation of ZnO NPs by plants depend upon the properties of the ZnO NPs and the physiology of the host plant (Faizan et al., 2020). Alharby et al. investigated how ZnO NPs could reduce salt stress in tomato plants. Lower concentrations of NPs (15 mg $L^{-1}$) were shown to be more successful in their application than larger concentrations when it came to reducing the impacts of NaCl (30 mg $L^{-1}$). They concluded that more research into ZnO NPs for usage as helpful stress-reducing agents in crop production was necessary. With ZnO NPs, diverse tomato cultivars showed varying degrees of salt resistance (Alharby et al., 2016). Rizwan et al. reported that ZnO NPs increased the growth of wheat plants and reduced the oxidative stress and cadmium concentration in them (Rizwan et al., 2019). They found that ZnO NPs played a prime function in the enhancement of biomass and nutrients and the reduction of cadmium toxicity in wheat. ZnO, in addition to other metal oxide NPs, is a potential tool to combat salinity stresses, according to Rizwan et al. (Zia-ur-Rehman et al., 2023).

ZnO material is selected for usage in biomedical and for the growth of plants among the several metal NMs now accessible (Hussain et al., 2016). This is due to ZnO's special properties, which include its large availability in nature, being cheap and nonpoisonous, and its ability to generate grains with a variety of forms and possible applications (Nagajyothi et al., 2015; Hussain et al., 2016). ZnO semiconductors have an extensive direct bandgap energy (3.37 eV) and a high excitation energy of binding (Nagajyothi et al., 2015). There is a lot of evidence to support the good antibacterial, antifungal, anticancer, and oxidation-resistance performances of ZnO NPs, prepared via green synthesis (Hussain et al., 2016; Kedi et al., 2018; Sharma et al., 2016; Aquisman et al., 2020; Bala et al., 2015; Senthamarai & Malaikozhundan, 2022; Khorrami et al., 2019). ZnO plays a variety of crucial physiological roles. ZnO functions as an essential part of enzymes like alkaline phosphatase. It supports structure integrity in biomembranes and is a part of ribosomes. ZnO deficiency symptoms include (1) rosetting (slowed growth due to short internodes), (2) tiny leaves, and (3) its severe deficiency results in the death of shoot apices (Aouada & de Moura, 2015).

## 3 Preparation of ZnO NPs

Different authors have reported the synthesis procedures of ZnO NPs using different methods. Sahoo et al. (2021) prepared ZnO NPs using green and chemical methods, and the as synthesized materials were characterized by them. Their prepared NPs of ZnO revealed a better uniform size distribution with a mean diameter that was 57% smaller. They set up a pot experiment to evaluate the effectiveness of both NP types on the green gram (*Vigna radiata* (L.) Wilczek). Green synthesized ZnO NPs were found to enhance the green gram's growth and yield factors. Compared to normal ZnO NPs, green NPs showed that seeds had a 13.3% greater seed production, a 5.6% higher protein content, and a 3.2% higher Zn content. Up to a ZnO NP concentration of 20 mg $L^{-1}$, the growth of seeds was found to be significantly improved. The enhanced seed production was 56.2%; zinc content was 15.6% and 25.2%, and seed protein was 25.2% when compared to the control. These findings indicate that synthesizing and employing green NPs of ZnO have a great deal of potential for increasing enhanced nutrient utilization. ZnO NPs were created with *Aloe barbadensis* Mill (Singh et al., 2019). The NPs were characterized with microscopic devices. The size of the as-prepared ZnO NPs were estimated to be of 35 nm, which is smaller compared to those obtained from the traditional method (around 48 nm). Also, these NPs have a stronger capacity to reduce and cap leaf extracts. They examined the ZnO NPs at various NP concentrations that were sufficient for wheat seedling emergence and germination (0, 15, 62, etc.). They discovered that ZnO NPs promoted superior growth compared to control seeds. Thus, they recognize the capabilities of ZnO NPs in agriculture. *Piper betleas* leaf extract, a reducing-stabilizing negotiator, was used by Goyal et al. (2022) in preparing ZnO NPs, through the green method. They calculated the band gap as 3.41 eV, which is larger compared to the bulk ZnO ($E_g = 3.37$ eV). Photocatalytic activity analysis inferred that green ZnO-NPs were effective for degrading harmful reactive red dye (efficiency of degradation = 96.4%). They observed the as-prepared ZnO NPs to be effective photocatalysts and antimicrobial species. Sharma et al. (2022) studied the synthesis and antimicrobial performance of ZnO NPs using *Azadirachta indica* leaf. The prepared nanoparticles exhibit good crystallinity, with an average crystallite size of 60-65 nm as determined by XRD. The average grain size, as observed through SEM, ranges from 100-200 nm. The authors investigated whether fabricated ZnO NPs are a superior choice for biological dealings. Swarna Bharathi et al. (2022) conducted the study and found that brown seaweed algae are used in the fabrication of two different metal NPs. They biomedically investigated the $SiO_2$–ZnO nanocomposite for antioxidant, antibacterial, and anticancer properties. The as-synthesized $SiO_2$–ZnO nanocomposites were found to be a promising possible treatment agents for colon cancer's HT29 cancer cell line. They concluded that the $SiO_2$–ZnO nanocomposite produced by seaweed may be a source for the treatment of adenorectal colon cancer cells. Their research demonstrated that the formation of $SiO_2$–ZnO nanocomposites, mediated by seaweed extract, exhibits excellent antioxidant activity. Using various plant parts as manufactured particles, Gharpure et al. (2022) worked on the preparation of hexagonal wurtzite-based ZnO NPs. Abel et al. (2021) used the extraction of moringa leaves. Their process is cost-effective and environmentally friendly. Their results showed a large bandgap at 350 nm wavelength. Significant antibacterial properties were observed by the authors for the as-prepared ZnO NPs. Chikkanna et al. (2019) prepared ZnO using agricultural waste products, such as sheep and goat feces. Prepared NPs were characterized to have a sponge-like texture and a flower-like structure and to have effective antibacterial action against *Bacillus subtilis* and *Salmonella typhimurium*. ZnO NPs and Mn-doped ZnO NPs were synthesized by Priyadharsini et al. (2021) through a green synthesis process applying Carica papaya extract with a wurtzite crystal structure. It is inferred by them that Mn-doped ZnO NPs showed good antibacterial performance. Al Awadh et al. (2022) synthesized ZnO NPs from *R. sativus* leaf extract through the precipitation method, with a particle size of 66.47 nm and a wurtzite structure. The prepared NPs were effective on gram-positive and gram-negative bacteria and breast cancer cells. Green-synthesized ZnO NPs by Hassan et al. (2019) from olive and marjoram leaf extract showed alternate antifungal efficacy.

Recently, *Aegle marmelos* unripe fruit extract was used to fabricate the NPs of ZnO, and the as-prepared materials were characterized via biophysical methods (Senthamarai & Malaikozhundan, 2022). ZnO NPs produced through biological means have a 19.8 -nm crystallite size. The stability of NPs was aided by the presence of several functional molecules, which were detected by FTIR at 3657, 3486, 2316, 2183, 2032, 1978, 858, 564, and 442 cm. A hexagonal wurtzite structure is observed in the SEM micrograph (particle size 22.5 nm). According to the results of the EDX, 77.91% Zn was detected. Kyene et al. prepared the nanomaterial ZnO (Kyene et al., 2023) from *Cassia sieberiana extract* (Kyene et al., 2023). Characterization of ZnO NPs was performed employing EDX and other tools. The antibacterial performance of ZnO NPs was also assessed by them. Triterpenes, polyphenols, saponins, and anthracenosides are available from the plant extract. The average particle size determined was 12.9 nm and had a spherical appearance. NPs of ZnO were made with *Tavernier glabra*, a medicinal plant, through biogenic techniques by Khan et al. (2023). It was evidenced that ZnO NPs were produced through biosynthesis, and the functioning of biomolecules has also been demonstrated by FTIR. ZnO nanostructures were examined for the inhibition of microbes and antioxidant applications. High antileishmanial activities were exhibited by the ZnO NPs, with half-maximal inhibitory concentration values of 76.3 ± 2.08 and 90.4 ± 1.031.

ZnO's manufacturing with plant use is gaining momentum. Because it doesn't require hazardous chemicals, it is regarded as an environmentally benign method (Nagajyothi et al., 2015). ZnO NPs that had been synthesized were examined by relevant tools. It is known that plants appear to be the greatest means for the large-scale use of the green production of metal-oxide NPs through plant-mediated synthesis (Naseer et al., 2020; Rajabi et al., 2020; Dobrucka & Długaszewska, 2016; Alnehia et al., 2022). Plant extract is used to create these NPs because it is ecologically friendly, cost-effective, and easy to scale up (Dobrucka & Długaszewska, 2016; Ramesh et al., 2014). Due to their distinctive characteristics and many applications, ZnO NPs are extremely important to study among metal oxide NPs. Many techniques, including chemicals (solvothermal/sol-gel), can be used to create ZnO NPs. The chemical technique is not preferred in the manufacture of NPs as dangerous compounds are generated that may be absorbed on the NPs' surface. Similar problems are connected to physical approaches, such as their high cost and need for extreme conditions of reaction (Khan et al., 2020; Yuvakkumar et al., 2014). Due to its ease, cheapness, and significant antibacterial action, biosynthesis offers an appealing approach (Gunalan et al., 2012). Aside from being straightforward, biosynthesis of pure materials frequently requires no specialized knowledge or expensive equipment. Plant use has a precious impact on the morphology of the NPs formed (Xu et al., 2021). Synthesis methods, characterizations, and property development of the nanosized ZnO material are illustrated in Table 10.1.

Among the different procedures applied for the preparation of NPs of ZnO, green synthesis, biosynthesis, and plant-mediated synthesis methods have become more popular. In these methods, different plant extracts and plant parts are used for the preparation of pure ZnO NPs. Table 10.2 demonstrates some of the plants that were used for fabricating the NPs of zinc oxide.

It can be inferred that the green synthesis and biosynthesis methods have been mostly followed recently. Figure 10.1 presents a summary of the status of the synthesis, characterization, properties, and application of ZnO NPs for sustainable plant production.

## 4 Nanofertilization

Nanofertilizers are fertilizer substances with a nanometer-sized dimension that are applied to plants in a regulated manner (Bedi & Singh, 2022). NPs that enhance the yield of plants are considered nanofertilizers (Liu & Lal, 2015). NPs that enable conventional fertilizers to perform better but do not directly supply nutrients to crops are also considered nanofertilizers. The former are collectively referred to as nanofertilizers. Also, there are two subcategories of nanofertilizers: macronutrients and micronutrients. Meijas and coworkers inspected the implicit use of nanofertilizers (Mejias et al., 2021). Nanofertilizers are utilized to boost soil fertility as well as plant nutrition and nutrient efficiency (Toksha et al., 2021). The physicochemical

**Table 10.1** Synthesis, characterization, and property development of ZnO NPs

| Material | Method | Characterization | Property development | References |
|---|---|---|---|---|
| ZnO NPs | Green synthesis | XRD, SEM, EDX, UV–vis | (i) Green ZnO NPs had a mean diameter that was 57% smaller in compare to normal ZnO.<br>(ii) Compared to normal ZnO NPs, green NPs had a greater seed output of 13.3%, a higher protein content of 5.6%, and a higher Zn content of 3.2%. | Sahoo et al. (2021) |
| ZnO NPs | Green route (extract of *Aloe barbadensis Mill leaf*) | Optical spectroscopy, electron microscopy | (i) Particle size of ZnO NPs = 35 nm<br>(ii) Spherical shaped particle<br>(iii) Ability of strong reducing and capping | Singh et al. (2019) |
| ZnO NPs | Green route (leaf extract of *Piper betleas* explored) | XRD, FTIR, UV-vis, EDX | (i) Band gap energy of the prepared ZnO NPs = 3.41 eV<br>(ii) Photocatalytic activity = 96.4% (for red dye)<br>(iii) Rate constant = $1.6 \times 10^{-2}$ $\text{min}^{-1}$<br>(iv) Better antimicrobial | Goyal et al. (2022) |
| Triangular ZnO NPs | *Azadirachta indica* leaves extract | XRD, FTIR | (i) Grain size = 60–65 nm | Sharma et al. (2022) |
| $SiO_2$ ZnO nanocomposite | (i) Biosynthesis method<br>(ii) Brown seaweed algae were used | UV-vis, SEM, FTIR, XRD | (i) Therapeutic for colon cancer's HT29 cancer cell line<br>(ii) Exhibits excellent antioxidant activity | Swarna Bharathi et al. (2022) |
| ZnO NPs | (i) Biosynthesis<br>(ii) Plant parts of *Bixa orellana* utilized | UV-vis, XRD | (i) Hexagonal wurtzite structures<br>(ii) Band gap obtained = 3.636 eV | Gharpure et al. (2022) |
| ZnO NPs | (i) Biosynthesis<br>(ii) Extraction of moringa leaves used | UV-vis, XRD | Significant antibacterial activity | Abel et al. (2021) |
| ZnO NPs | (i) Green synthesis<br>(ii) Sheep/goat faecal matter were used | UV-vis, XRD, SEM | (i) Spongy-like and flower-shaped granules with irregular structures<br>(ii) Showed effective antibacterial activity | Chikkanna et al. (2019) |
| ZnO and Mn NPs | (i) Co-precipitation method<br>(ii) Carica papaya extract used | XRD | (i) Red shift in the absorbance spectrum observed<br>(ii) Mn-doped ZnO NPs revealed better antibacterial performance than that with ZnO NPs | Priyadharsini et al. (2021) |

(continued)

**Table 10.1** (continued)

| Material | Method | Characterization | Property development | References |
|---|---|---|---|---|
| ZnO NPs | (i) Precipitation method<br>(ii) *R. sativus* leaf extract | XRD, SEM, EDX | (i) Particle size of 66.47 nm<br>(ii) Wurtzite structure<br>(iii) Effective with bacteria | Al Awadh et al. (2022) |
| ZnO NPs | (i) Green synthesis<br>(ii) Leaves extract of olive and marjoram were used | XRD | (i) Antifungal activity of ZnO NPs were tested on sweet bell pepper | Hassan et al. (2019) |
| ZnO NPs | (i) Biological method<br>(ii) *A. marmelos* unripe fruit extract | XRD, SEM, FTIR | (i) Hexagonal wurtzite structure<br>(ii) Crystallite size = 19.8 nm, particle size = 22.5 nm<br>(iii) Prepared NPs were stable<br>(iv) Am-ZnO NPs had better antibacterial and antibiofilm effects on Gram-negative bacteria | Senthamarai and Malaikozhundan (2022) |
| ZnO NPs | (ii) Green synthesis method<br>(ii) Root bark extract of *Cassia sieberiana* | XRD, SEM, EDX, TEM, FTIR | (i) TEM measured particle size as 12.9 nm<br>(ii) Particles were spherical in shape<br>(iii) ZnO NPs showed good antioxidant property | Kyene et al. (2023) |
| ZnO NPs | (i) Biogenic techniques<br>(ii) Aqueous extract of *Tavernier glabra* | UV-vis, XRD, SEM, EDX, FTIR | (i) Surface plasmon resonance peak at 288 nm<br>(ii) As formed ZnO NPs are antimicrobial<br>(iii) As prepared ZnO NPs showed strong antileishmanial activities | Khan et al. (2023) |
| ZnO NPs | (i) Green synthesis method<br>(ii) Usage *Polygala tenuifolia* root extract | FTIR, UV-vis, TGA, EDX, SEM, and TEM | (i) Anti-inflammatory activity<br>(ii) Antioxidant<br>(iii) Anti-inflammatory | Nagajyothi et al. (2015) |
| ZnO NPs | (i) Green synthesis method<br>(ii) *Hibiscus subdariffa* leaf extract | XRD | Anti-bacterial activity | Bala et al. (2015) |
| ZnO NPs | (i) Green synthesis<br>(ii) *Phyllanthus embilica* stem extract | XRD, SEM | ZnO NPs showed antibacterial activity | Joel and Badhusha (2016) |

(continued)

**Table 10.1** (continued)

| Material | Method | Characterization | Property development | References |
|---|---|---|---|---|
| ZnO NPs | (i) Biological synthesis route<br>(ii) Leaf/bark of carica papaya | UV-vis, FTIR, EDX, TEM, SEM | (i) Absorption peaks obtained at 365 and 370 nm<br>(ii) Flower/petal shaped<br>(iii) Particle diameter = 141–168 nm | Droepenu et al. (2019) |
| ZnO NPs | (i) Biosynthesis<br>(ii) *Anacardium occidentale* leaf | FTIR, SEM, TEM, EDX | (i) ZnO structures were flake-like<br>(ii) TEM measured particle size 107 nm<br>(iii) Strong antibacterial | Droepenu et al. (2021) |
| ZnO NPs | Bio synthesis (leaf extract-assisted) | HRTEM, XRD | (i) Hexagonal wurtzite structure<br>(ii) Particle size = 15.6 nm<br>(iii) Zeta potential = −12.14 mV | Malaikozhundan et al. (2020) |
| ZnO NPs | Biosynthesis | XRD, UV-Vis, EDX, TEM, FTIR | (i) Hexagonal morphology<br>(ii) SPR peak value = 370 nm | Sharmila et al. (2018) |
| ZnO NPs | Green synthesis | XRD, FTIR, SEM/EDX, TGA, TEM/SAED | (i) Particle size = 2.90–25.20 nm<br>(ii) Shape: spherical/rod | Nagajyothi et al. (2014) |
| ZnO NPs and ZnO/CuO nanocomposite | Green synthesis | TGA, XRD, EDX, FE-SEM, TEM, FTIR, DRS, and BET | (i) Obtained size of ZnO = 12 nm<br>(ii) Specific surface areas: (a) ZnO (W) = 29.3 $m^2/g^{-1}$, and (b) ZnO/CuO = 18.0 $m^2/g^{-1}$ | Mohammadi-aloucheh et al. (2018) |

qualities and soil microbial symbiosis are affected by several factors. Nanofertilizers are anticipated to considerably increase crop growth and yields, increase fertilizer usage efficiency, limit nutrient losses, and minimize negative environmental effects (Liu & Lal, 2015). NPs possess a “smart delivery strategy”. Techniques like targeted distribution and controlled release of nanostructured fertilizers can improve the efficiency of nutrient usage. According to reports, nanofertilizers can increase agricultural output by speeding up photosynthesis, nitrogen metabolism, and the generation of proteins and carbohydrates.

Techniques that are used in crops through conventional fertilizers are spraying or broadcasting. This is based on the fertilizer concentration required for the plants. The repeated use of chemical fertilizers skeptically affects the balance of inherent nutrients in the soil. So, the optimal use of chemical fertilization is required for the crop, thereby minimizing the threat of pollution in the environment. Thus, to keep the environment clean and the soil structure in good shape, there is a need for alternative methods for fertilizing the soil with improved plant growth (Miransari, 2011).

With the help of nanotechnology, the fabrication of smart fertilizers with less pollution is feasible (Chinnamuthu & Boopati, 2009). The utilization of nanotechnology in agriculture is valuable for the delivery of agricultural chemicals like fertilizers that meet the required nutrients. Due to their tiny size, elevated mobility,

**Table 10.2** Plant extracts used for the ZnO NPs's fabrication

| Plants used | References |
|---|---|
| Aloe vera extract | Mandal et al. (2018) |
| Olive and marjoram | Hassan et al. (2019) |
| *R. sativus* leaf extract | Al Awadh et al. (2022) |
| Carica papaya extract used | Priyadharsini et al. (2021) |
| Extraction of moringa leaves | Abel et al. (2021) |
| *Aloe barbadensis Mill* | Singh et al. (2019) |
| *Piper betleas* | Goyal et al. (2022) |
| *Azadirachta indica* leaves extract | Sharma et al. (2022) |
| Brown seaweed algae were used | Swarna Bharathi et al. (2022) |
| *Bixa orellana* | Gharpure et al. (2022) |
| *A. marmelos* unripe fruit extract | Senthamarai & Malaikozhundan (2022) |
| (i) Extract of root bark of *Cassia sieberiana*<br>(ii) The bark was used for the purpose of capping as well as stabilizing | Kyene et al. (2023) |
| *Tavernier glabra extract, a medicinal plant* | Khan et al. (2023) |
| *Polygala tenuifolia* | Nagajyothi et al. (2015) |
| Organic extract of *Cola nitida* and *Cola acuminata* leaf | Aquisman et al. (2020) |
| *Hibiscus subdariffa* | Bala et al. (2015) |
| *Phyllanthus embilica* stem | Joel and Badhusha (2016) |
| Carica papaya | Droepenu et al. (2019) |
| *Anacardium occidentale* | Droepenu et al. (2021) |
| Watercress (*Nasturtium officinale*) extract (medicinal plant) | Bayrami et al. (2019) |
| *Syzygium cumini* | Arumugam et al. (2021) |
| Leaf extract of *Sambucus ebulus* | Alamdari et al. (2020) |
| *Withania somnifera* | Malaikozhundan et al. (2020) |
| *Bauhinia tomentosa* | Sharmila et al. (2018) |
| Utilizing *Coptidis Rhizoma* | Nagajyothi et al. (2014) |
| *Albizia lebbeck* | Umar et al. (2019) |
| Applying *Vaccinium arctostaphylos* L. Fruit extract | Mohammadi-aloucheh et al. (2018) |
| *Tecoma castanifolia* | Sharmila et al. (2019) |
| *Thymus vulgaris* leaf | Zare et al. (2019) |
| *Solenostemon monostachyus* leaf extract | Karu et al. (2020) |
| *Nasturtium officinale* | Bayrami et al. (2019) |

decreased toxicity, large surface-to-volume ratio, and raised solubility, NPs possess the characteristics required for plants (Sasson et al., 2007; DeRosa et al., 2010; Brady & Weil, 1999). Because of their large particle size and low solubility, normal fertilizers are not very bioavailable to plants. While nanofertilizers have more solubility, their larger surface areas show more bioavailability to plants. Also, the use of nanostructured formulations may improve fertilizer effectiveness and soil nutrient absorption ratios during crop production.

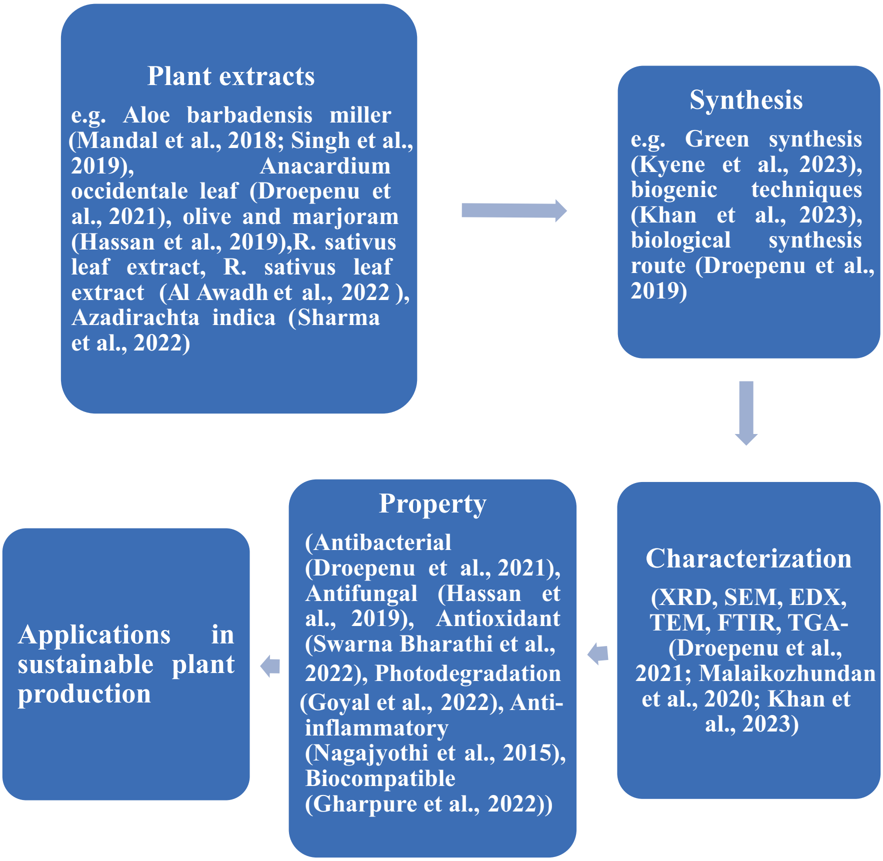


**Fig. 10.1** Summary of the status of synthesis, characterization, property, and application of ZnO NPs for sustainable plant production

## 5 Use of ZnO NPs in Sustainable Plant Production

Nanotechnology promotes sustainable plant production and development in agriculture. Priyanka and Venkatachalam utilized ZnO NPs as fresh micronutrient catalysts to promote cotton plant development (Priyanka & Venkatachalam, 2016). The cadmium and lead phytotoxicity in cotton seedlings was mediated using ZnO NPs (Priyanka et al., 2021). The biogenesis of ZnO NPs was investigated for the revolution in agriculture by focusing on plant growth stimulation and anti-contagion (Keerthana et al., 2021). The biocompatible nature of ZnO NPs and their potential as a promising material in biomedical applications are also reported (Gharpure et al., 2022). With their biocompatible nature, ZnO NPs can be utilized as carrier molecules in applications involving medication delivery. Being antibacterial, NPs of ZnO rupture membranes and produce reactive free radicals. ZnO NPs have excellent antioxidant effects in healthy mammalian cells.

A novel, environmentally friendly approach for the treatment of filthy water is needed (Shannon et al., 2008). Since pesticides and herbicides are very toxic, chemically stable, and resistant to biodegradation, using them on agricultural land results in poisoning (Mestankova et al., 2011; Sanches et al., 2010; Tizaoui et al., 2011; Kamble et al., 2006). Water pollution is also a result of the textile industry's use of colors and the enormous amounts of dye that are discharged into the water during the production and dyeing processes as textile effluent (Zhang & Zeng, 2012). Through acts like hydrolysis and related chemical reactions that occur in wastewater, hazardous compounds are created during the breakdown of these colors. The amount of oxygen that is soluble in colored wastewater decreases, which is essential for aquatic life because of the dyes present. Moreover, it stops sunlight from entering aquatic bodies. Hence, releasing these pigments into the wastewater without proper processing results in pollution problems (Zhang et al., 2010, 2011). Eliminating these dangerous dye-containing effluents is thus becoming more and more popular.

Salt stress is a major issue in tomato and other plants. ZnO nanoparticles (NPs) have been treated with tomatoes and other plants to enhance their properties and have been observed to effectively mitigate diseases (Faizan et al., 2021a, b, c; Ahmed et al., 2022). The stress resulting from Cd has also been overcome in *Oryza sativa* (Faizan, 2021b) by the NPs of ZnO. Chilling stress in rice (Song et al., 2021) and drought-induced oxidative stress in tomato (El-Zohri et al., 2021) have been examined to be cured with ZnO NPs. Figure 10.2 depicts all these stresses in plants, and a few valuable uses of ZnO NPs are presented in Fig. 10.3.

Table 10.3 and Fig. 10.4 demonstrate the use of ZnO NPs in sustainable plant production.

Mandal et al. (2018) investigated the photodecomposition of methylene blue (MeB) using NPs of ZnO that were obtained via green synthesis. Toxic industrial effluents have prompted a lot of focus on methods to remove dangerous contaminants from wastewater. Because these contaminants affect the cultivation and reduce plant development, they cause plant diseases. Reported research by Mandal and his group supports the use of ZnO NPs for the plant's sustainable production. Figure 10.5 indicates the decrease in absorbance, that is, the concentration of pollutant MeB in water, through the ZnO photocatalyst that was prepared by Mandal et al. using aloe vera (Mandal et al., 2018).

## 6 Future Trends

Great challenges are associated with nanofertilizers for practical application in future crop production, biosafety, and ethical issues. The creation of affordable, nontoxic NPs is highly demanded for the efficacious implementation of nanotechnology in agriculture's future. The aim of nanoagriculture will be higher plant growth with magnificent yields. The practice of using ZnO-based and other nontoxic nanofertilizers will increase the sustainable development of plant growth and

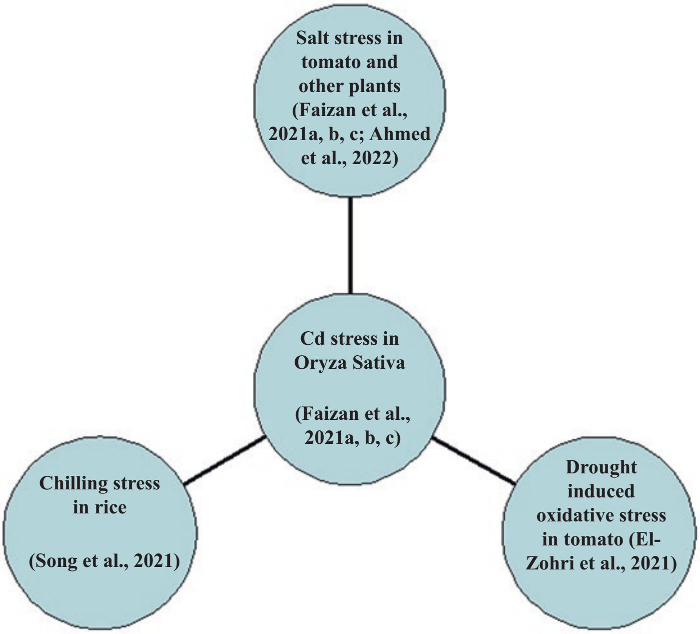
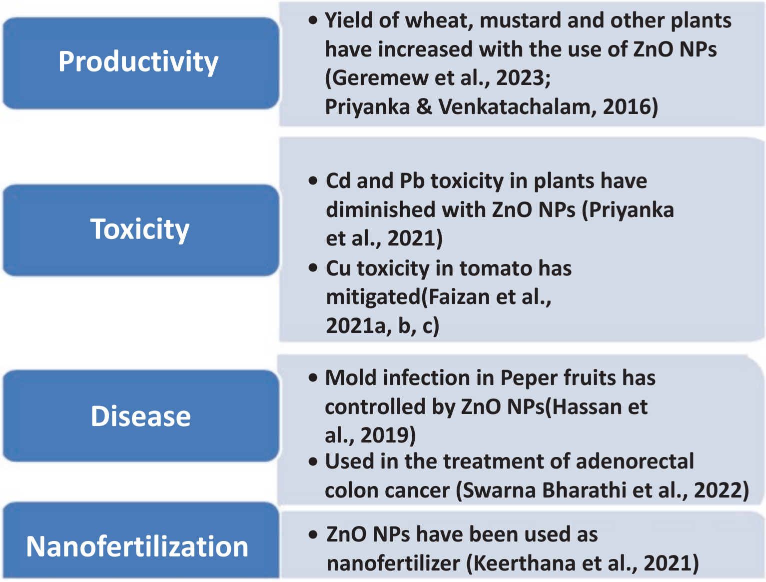


**Fig. 10.2** ZnO NPs to mitigate the different stresses in plant production



| | |
|---|---|
| Productivity | • Yield of wheat, mustard and other plants have increased with the use of ZnO NPs (Geremew et al., 2023; Priyanka & Venkatachalam, 2016) |
| Toxicity | • Cd and Pb toxicity in plants have diminished with ZnO NPs (Priyanka et al., 2021)<br>• Cu toxicity in tomato has mitigated(Faizan et al., 2021a, b, c) |
| Disease | • Mold infection in Peper fruits has controlled by ZnO NPs(Hassan et al., 2019)<br>• Used in the treatment of adenorectal colon cancer (Swarna Bharathi et al., 2022) |
| Nanofertilization | • ZnO NPs have been used as nanofertilizer (Keerthana et al., 2021) |

**Fig. 10.3** Some applications of ZnO NPs

**Table 10.3** The use of ZnO NPs in sustainable plant production

| Material | Property | Application | References |
|---|---|---|---|
| ZnO NPs | Micronutrient catalyst | Surge of cotton crop productivity | Priyanka and Venkatachalam (2016) |
| ZnO NPs | Catalyst | Mediates cadmium and lead toxicity tolerance | Priyanka et al. (2021) |
| ZnO NPs | Antimicrobial | Antimicrobial activity as well as nanofertilizers | Keerthana et al. (2021) |
| ZnO NPs | Antifungal | Postharvest control of grey and black mold infections on pepper fruits | Hassan et al. (2019) |
| Triangular ZnO NPs | Antimicrobial | Antimicrobial performance – (i) *Escherichia coli* (ii) *Bacillus subtilis* | Sharma et al. (2022) |
| $SiO_2$ ZnO nanocomposites | Antioxidant activity | Shows function on adenorectal colon cancer cell | Swarna Bharathi et al. (2022) |
| ZnO NPS | Biocompatible | Carrier molecules used in delivery of medicine | Gharpure et al. (2022) |
| ZnO | Antimicrobial activity | Antimicrobial – (i) *Salmonella typhimurium* (ii) *Bacillus subtilis* | Chikkanna et al. (2019) |
| Mn-doped ZnO NPs | Antimicrobial | Applied for – (a) Gram positive – (b) Gram negative bacteria | Priyadharsini et al. (2021) |
| ZnO NPs | Photocatalysis | Degraded MB (ZnO NPs + sunlight) | Mandal et al. (2018) |
| ZnO NPs | Increased chlorophyll contents | Yield of wheat was increased | Adil et al. (2022) |
| ZnO NP (green synthesized and cow-dung mediated) | Agriculture | Germination potential of Mung bean seeds have been examined | |
| ZnO NP (engineered) | Agronomic productions | Production of large food and protection of environmental | Liu and Lal (2015) |
| ZnO NPs | Antioxidant, antimicrobial | Effective action of antimicrobial action: (a) *S. typhi* (b) *S. aureus* | Kyene et al. (2023) |
| ZnO NPs | Antimicrobial and antioxidant | Detected antimicrobial performances: (i) niger and (ii) subtilis, etc. | Khan et al. (2023) |
| ZnO NPs | Antimicrobial and antioxidant | (i) Antibacterial agents (ii) Antioxidant (normal mammalian cells) | Singh et al. (2021) |

(continued)

**Table 10.3** (continued)

| Material | Property | Application | References |
|---|---|---|---|
| ZnO NPs | Antimicrobial and antioxidant | (i) Anti-inflammatory activity: in RAW 264.7 macrophages<br>(ii) Antioxidant activity: 2,2-Diphenyl-1-picrylhydrazyl assay | Nagajyothi et al. (2015) |
| ZnO NPs | (i) Antimicrobial<br>(ii) Antioxidant | Antibacterial activity of ZnO NPs | Aquisman et al. (2020) |
| ZnO NPs | Antimicrobial, antioxidant | Antibacterial activity of ZnO NPs | Bala et al. (2015) |
| ZnO NPs | (i) Antimicrobial<br>(ii) Antioxidant | Antibacterial activity of ZnO | Joel and Badhusha (2016) |
| ZnO NPs | Antimicrobial | Antibacterial efficacy | Droepenu et al. (2019) |
| ZnO NPs | Antibacterial | Strong effect with infectious bacteria (Gram positive and Gram negative microbes) | Droepenu et al. (2021) |
| ZnO NPs | Antibacterial | ZnO NPs was treated on the *Staphylococcus aureus* and *Escherichia coli* | Bayrami et al. (2019) |
|  | Antioxidants, nanonutrient, cytotoxic | Tested on – *Sesamum indicum* | Arumugam et al. (2021) |
|  | Good antimicrobials, and insecticides for fighting storage pests | At 100 g mL$^1$, ZnO NPs had a stronger activity with – (i) *E. faecalis* (ii) *S. aureus*. | Malaikozhundan et al. (2020) |
| ZnO NPs | Suitable bactericidal species for biological uses | Effectively combated (i) *P. aeruginosa*, (ii) *E. coli*. | Sharmila et al. (2018) |
| ZnO NPs | Antibacterial | (i) Gram-positive (ii) Gram-negative bacteria | Nagajyothi et al. (2014) |
| (i) ZnO NPs<br>(ii) ZnO/CuO nanocomposite | Antibacterial | Anti-bacterial (i) *Escherichia coli*, etc. | Mohammadi-aloucheh et al. (2018) |

crop production. There will be a trend toward the development of green synthesis techniques for ZnO NP production. In future, there will be a trend toward producing a large number of plants with fewer disturbances to the environment and yielding huge amounts of crops with less environmental pollution.

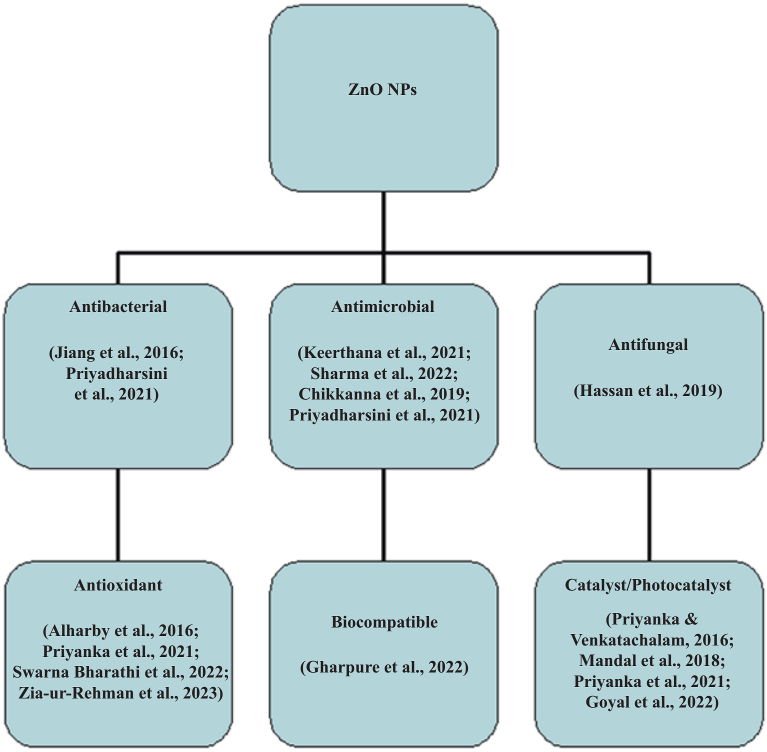


**Fig. 10.4** The execution of zinc oxide nanoparticles in sustainable plant production

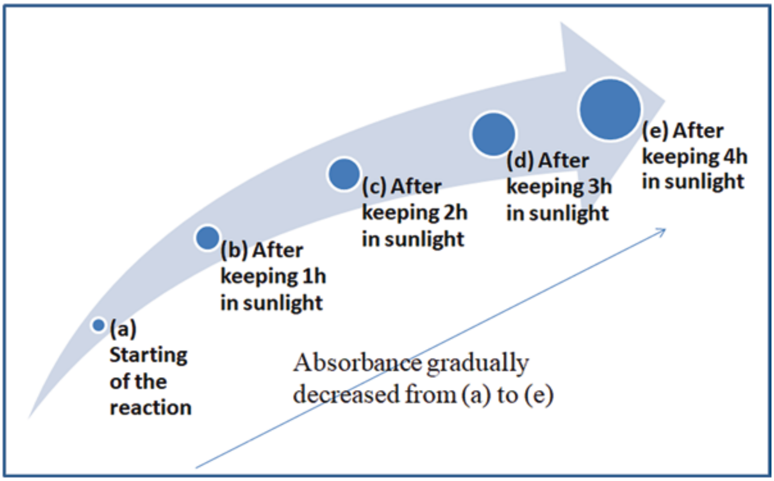


**Fig. 10.5** Treatment of zinc oxide nanoparticles with methylene blue through the photocatalytic reaction. (**a**) Reaction's beginning and on keeping in the sun, for (**b**) 1 h, (**c**) 2 h, (**d**) 3 h and (**e**) 4 h

## 7 Conclusion

ZnO NPs could be used for sustainable agriculture, plant disease control, and crop production. However, as the properties of NPs adversely affect plants and the environment, the dose of NPs used should be well monitored. ZnO-based nanofertilizers will be able to overcome the issues of rapid degradation of ordinary fertilizers that result from photolysis, hydrolysis, and decomposition reactions. They enable the soil's gradual absorption of crucial nutrients. ZnO-based nanofertilizers can encounter challenges related to higher fertilizer consumption and soil pollution in agriculture. Nanofertilizer's application has amplified the soil's nutrient absorption and increased the productivity of crops. The influence of ZnO-based and other nanofertilizers varies with the dose, morphology, structure, duration, and solubility of the associated NPs. It is obligatory to perceive the importance of NPs of green ZnO, which have better qualities and are more environmentally benign.

More research is required to produce sustainable plants using ZnO and other NPs. Environment-friendly green synthesis routes should be explored on a large scale to produce ZnO NPs, which will increase plant production, decrease diseases in plants, and reduce the crisis in the environment. The green synthesized ZnO NPs can be used to address the inadequacies of Zn in soil for agricultural use in a cost-effective, environmentally safe, and sustainable manner.

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