Strategic significance: Nanotechnology in plant development and improved crop protection

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ABSTRACT

Agriculture faces numerous challenges such as pests, diseases, nutritional deficiencies, and the impacts of climate change, which can adversely affect crop quality and production. Nanotechnology has the potential to revolutionize the agricultural sector and address various biotic and abiotic stresses that crops encounter with the help of nano based insecticides, fertilizers, early disease diagnostics and herbicides. Biotic and abiotic stresses adversely influence plant growth and development and disturbs the biochemical, physiological as well as molecular processes within plants, leading to reduced productivity and crop losses. However, recent research has shown that nanoparticles can be employed to mitigate the adverse impacts of biotic and abiotic stresses on plants, offering potential benefits in agriculture. Despite the potential benefits of nanomaterials, their complete application in the agricultural industry has not yet been achieved. This is partly because of worries about the absorption, translocation, bioavailability, and eco-toxicity of nanoparticles. Using molecular methods, we can comprehend the underlying mechanisms and reactions brought on by nanoparticles and it is important in determining the biological potential of nanomaterials. The current chapter discusses the potential application of nanotechnology to mitigate biotic and abiotic stress in commercially significant crops, and its positively impact on growth and development of plants, there is growth, absorption, and transfer.

Keywords: Nanoparticles, Stress, Translocation, Phytotoxicity, Alleviation.

I. INTRODUCTION

In developing countries, more than 60% of the population depends on agriculture for their livelihood reflects the importance of the agricultural sector in these regions [1]. Agriculture not only provides food but also serves as a source of income and employment for a large portion of the population. Looking towards the future, the challenges become even more pressing. With a projected global population of over nine billion by 2050, it is estimated that food production will need to increase by 50-70% to meet the growing demand. This requires substantial efforts to enhance agricultural productivity and ensure sustainable food systems [2]. The natural surroundings of plants indeed consist of various environmental stresses that can significantly affect crop production. Factors such as limited agricultural land, diminishing water resources, global warming, and climate change are expected to further contribute to a decline in crop production soon [3]. Several biotic as well as abiotic factors cause negative impacts on plant growth, yield, and development of crops. The abiotic factors include soil salinity, drought, temperature, heat, cold, heavy metal, excessive water, UV stress, etc. affect the production of crops both quantitatively and qualitatively [5]. The biotic factors or stressors include several bacteria, fungi, viruses, insects, nematodes, weeds, arachnids, etc. [6]. Among these [7] found drought stress over time has caused a large portion of the world's grain production to decline by more than 5%. Approximately 51-82% of the annual obtainable crop yield in world agriculture is typically lost due to environmental or abiotic stress, as mentioned in a study by [8], in 2012. According to FAO estimates, pests cause up to 40% of the world's crop yield to be lost each year. Over $220 billion is lost annually to plant diseases and at least $70 billion to invasive insects in the global economy [9]. These diseases can affect a wide range of crops and can result in reduced yields, lower-quality produce, and increased costs for farmers. Addressing and mitigating the effects of environmental or abiotic stress as well as biotic stress on crop production is a significant challenge for farmers and agricultural scientists worldwide. There are several conventional methods available to control such stressors like the use of integrated pest management (IPM), sanitation, genetic breeding, chemical pesticides, crop rotation, trap cropping system, etc. [10]. But these methods have some disadvantages/drawbacks like time-consuming, laborious, frequent application, requiring higher doses, and creating resistance in the target organism. To date, for control of such insects, pests, and diseases farmers use different chemicals such as fungicides, insecticides, herbicides, etc, and try to enhance crop protection, growth, and also ultimately crop production. Fungicides are widely used in agriculture to protect crops, such as grains, fruits, and vegetables, from fungal diseases [11]. They are also commonly applied in postharvest packaging plants, urban parks, and protected forest areas. The use of fungicides has seen a significant increase over the past decade. Globally, around 400,000 tons of fungicides are applied, accounting for approximately 17.5% of total pesticide applications [12]. In the European Union, fungicide sales make up more than 40% of total pesticide sales. Inorganic fungicides constitute 54% of the sales, while organic fungicides make up the remaining 46%. Among the organic fungicides, (dithiol) carbamates account for 14.1% of sales, imidazoles, and triazoles for 6.7%, benzimidazoles for 1.3%, morpholines for 0.8%, and other fungicides and bactericides for 23.1% [13]. The extensive and continuous use of chemical fungicides can pose risks to public health, natural waters, aquatic animals, the environment, animal health, and non-target organisms [14]. Hence, to tackle such detrimental condition alternative to such methods are necessary and nanotechnology plays a crucial role in controlling such situations. Nanotechnology is indeed an emerging field that holds significant potential in various sectors, including agriculture. It involves the manipulation and control of matter at the nanoscale, typically at the level of individual atoms or molecules. In agriculture, nanotechnology can be applied to improve crop production, enhance plant protection, and develop more efficient nutrient delivery systems [15]. According to [16], nanoparticles (NPs), which are substances with dimensions between 1 and 100 nm, are utilized in nanotechnology. They are bioactive by nature and exhibit hybrid quantum effects. Nanotechnology aims to understand and control matter at the atomic and molecular levels to create new materials, devices, and systems with unique properties and functionalities. Controlled conveyance strategies in agriculture aim to ensure the precise and efficient application of agrochemicals over a specific period. These methods are designed to optimize the delivery of essential and appropriate quantities of agrochemicals while minimizing losses and adverse effects on the environment [17]. Nanotechnology has the potential to revolutionize agriculture and address various challenges in the food industry. It offers innovative solutions to enhance food production, improve crop yield, reduce environmental impact, and increase food security. To reduce the use of toxic chemicals and their impacts many nano-based agricultural products are now developed. Nanotechnology plays a crucial role in several aspects of food security, significant delivery systems and packaging materials, disease treatment, and new tools for the detection of pathogens [18]. Nano-based products have multiple effects on plants such as increasing biomass and grain yield by altering the metabolism on one side but phytotoxicity on the other side [21]. Sensors based on nanomaterials have shown promise as diagnostic tools in agriculture for detecting various parameters such as plant infection, nutrient and moisture content, pesticide residue, temperature, and soil condition. These sensors utilize the unique properties of nanomaterials to enable highly sensitive and selective detection. One of the advantages of using nanomaterial-based sensors is their high surface-to-volume ratio, which enhances their sensitivity to target analytes. They can be designed to specifically interact with certain molecules or ions, allowing for the detection of specific plant pathogens or nutrient levels [21].

II. MODE OF ACTION, TRANSLOCATION & MOVEMENT OF NPS

The uptake, translocation, and accumulation of nanomaterials can depend on various factors, including their size, concentration, and suspension medium. Additionally, the response of plants toward the absorption of nanomaterials can vary, leading to acceptance or rejection [20]. Plant cell walls restrict the entry of foreign material hence the entry of NPs in plant cells is difficult and it depends on the chemical composition, stability, and size of NPs, and plant species. NPs entry is also affected by the stability of NPs. Metal oxide and carbon-based NPs can enter plant cells by different modes such as aquaporins, endocytosis ion channels, and carrier proteins and it acts as entry points for NPs. Once NPs have entered plant tissue, they can be moved via apoplastic or symplastic means. NPs can be brought from plasmodesmata, which are found between the two cells, allowing one cell to communicate with another [22]. When NPs are present in the soil, they can interact with plant roots and undergo a series of transformations. The first step in the process is the adsorption of NPs by plant roots. Adsorption refers to the attachment or binding of NPs to the surface of the root. This interaction between NPs and roots is influenced by several factors, including the physicochemical properties of the NPs (such as size, shape, and surface charge) and the characteristics of the root surface. Over time, some of the NPs that have been adsorbed by plant roots can be taken up and translocated to other parts of the plant, including the aerial portions such as leaves and stems. This translocation can occur through various mechanisms, such as diffusion, active transport, or through the plant's vascular system. Once inside the plant, NPs may accumulate in cellular compartments or even subcellular organelles. Adsorption of NPs by plant roots is considered the initial step in the process of bioaccumulation, and subsequent bio/transformations play a crucial role in determining the fate and potential impacts of NPs in the soil-plant system [21]. Hydrophobicity of plant surface, particle size, and charge play crucial roles in the uptake and translocation of NPs [25]. The penetration of small nanoparticles (NPs) into plant roots can occur through various mechanisms, including osmotic pressure, capillary forces, and direct passage through root epidermal cells. NPs with diameters ranging from 3 to 5 nm are considered small and have the potential to enter the plant root system. Movement of NPs from one cell to another through plasmodesmata is internalized in the cytoplasm [21]. The potential effects of nanoparticles (NPs) on nutrient absorption in plants. [27], suggested that NPs that are not taken up by the roots of soil aggregates can still influence nutrient absorption. Also, [20], mentioned that NPs can be directly absorbed by seeds through the coat, specifically by entering the coat through parenchymatic intercellular spaces and diffusing into the cotyledon. The stomata or cuticles of the leaves are two ways that NPs applied by the leaves can enter the leaves. The cuticle serves as the principal leaf barrier, limiting the size of NPs that can enter to less than 5 nm. The NPs larger than 10 nm enter through the plant's stomata, and their cellular transport moves along apoplastic and symplastic pathways into its vascular system [27]. The cytoplasm of the neighboring cell is preferred for the transfer of NPs (between 10 and 50 nm) (symplastic pathway). Therefore, larger NPs (50–200 nm) are transported between cells by the apoplastic pathway. Through the phloem sieve tubes, internalized NPs are carried alongside the sugar flow. Because these organs act as powerful sap sinks, NPs can flow in both directions and accumulate in roots, stems, fruits, grains, and young leaves to various degrees as a result of vascular transport by phloem [21]. The interaction of nanomaterials with the soil, the nature and stability of the NPs, and the physiology and structure of the plant cells all affect how the NPs move and accumulate in the plant [29]. Plants' cell walls act as a specialized barrier that controls how NPs enter the cell and determines whether they can be solubilized and passed through the cell depending on their nature [30].

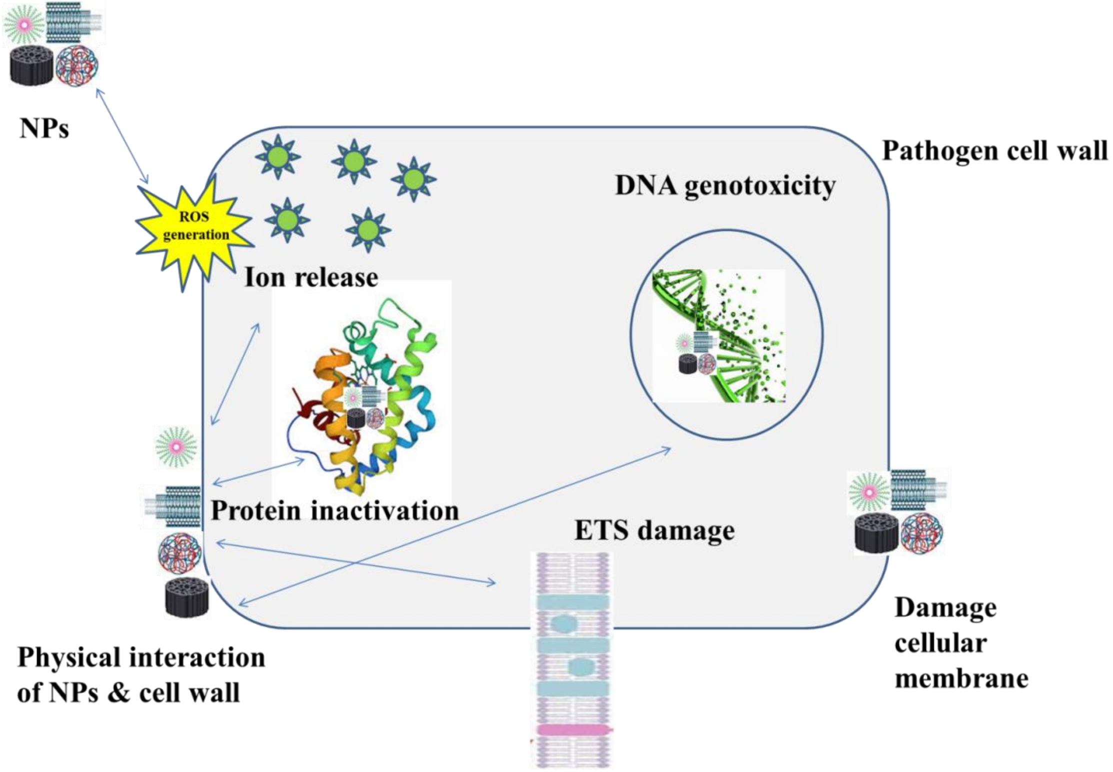

Fig. 1. Mode of action of nanoparticles

Table 1. NPs accumulation in different plant tissues

Sr. No.	Name of NPs	Concentration of NPs (mg/L)	Crops	Accumulation (mg/kg)		References
				Roots	Shoots	
1	Ag	4000	*Glycine max*	2102	1135	[31]
2	Ag	1000	*Oryza sativa*	20	5	[32]
3	ZnO	1000	*Solanum lycopersicum*	_	250	[33]
4	TiO_2	1000	*Solanum lycopersicum*	_	250	[33]
5	ZnO	100	*Zea mays*	10	30	[34]
6	Cu	1500	*Brassica juncea*	190.4	_	[35]
7	Cu	1000	*Oryza sativa*	1544.1	17.27	[36]
8	Cu	20	*Cajanus cajan*	5.82	19.06	[37]
9	Cu	250	*Lactuca sativa*	3773	_	[38]
10	Cu	100	*Phaseolus vulgaris*	800	_	[39]
11	Cu	125	*Vigna radiata*	_	18.46	[40]

12	$Mg(OH)_2$	1000	*Zea mays*	103	131	[41]
13	Ag	250	*Solanum lycopersicum*	_	50	[42]

III. ROLE OF NANOPARTICLES IN THE GROWTH AND DEVELOPMENT OF PLANT

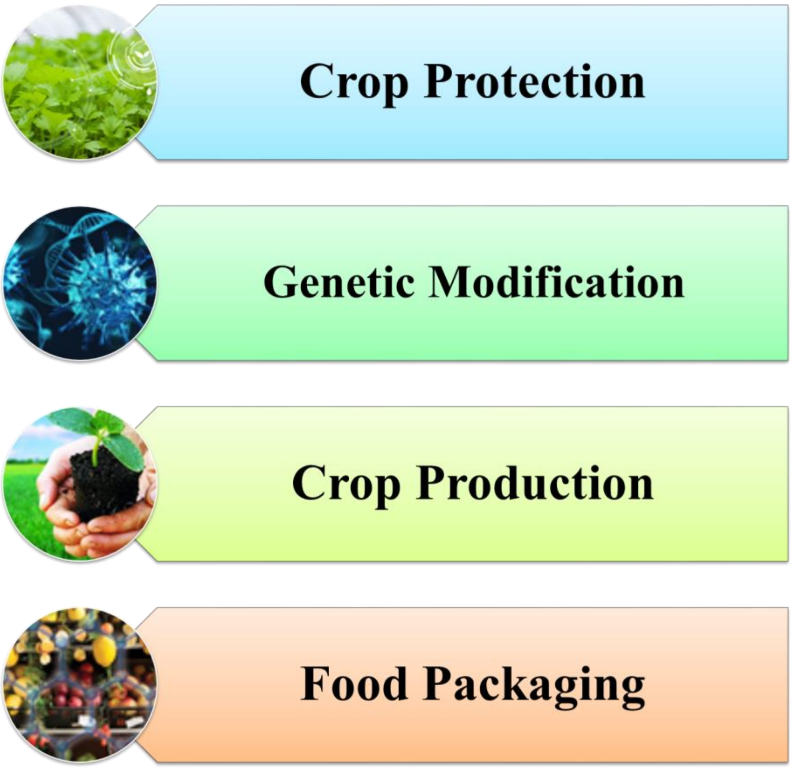

Fig. 2. Role of nanotechnology in crop improvement and crop protection

A. NANOPARTICLES IN SEED GERMINATION, CROP GROWTH, AND QUALITY ENRICHMENT

In the life cycle of a plant seed germination is the sensitive phase that plays a crucial role in the development of seedlings, population, and survival dynamics. Due to the availability of moisture content, genetic traits, fertility of the soil, and environmental factors seed germination is affected [43]. Several studies have reported that the treatment of nanoparticles or nanomaterials showed positive effects on the germination of seeds, growth, and development of plants. For example, Seed germination of many crops such as soybean, garlic, barley, peanut, corn, maize, tomato, and wheat has been improved by using multiwalled carbon nanotubes (MWCNTs) [48]. The application of Zeolite, TiO_2 NPs, and SiO_2 NPs positively stimulated the germination of seeds in crops [49]. Nanoparticles have the potential to enhance absorption ability and water utilization by penetrating seed coat results in stimulation of the enzymatic system and ultimately improving germination and growth of seedlings [49]. However, the mechanism of water uptake caused by nanomaterials inside the seed is still mainly not understood [50]. In addition to germination, nanomaterials like MWCNTs, TiO_2, FeO, ZnFeCu-oxide, ZnO, and hydroxy fullerenes have been shown to improve crop quality including growth and development in a variety of crop species, including mustard, onion, soybean, spinach, tomato, wheat, potato, and mungbean, peanut [18]. The capacity of nanomaterials to absorb more nutrients and water, which in turn helps to increase the vigor of root systems with increased enzymatic activity, may at least partially explain the promotion of plant growth and enriched quality, even though the precise mechanism underlying this is unknown [18]. Nano Fe/SiO_2 at a concentration of 15 mg/kg enhanced the length of shoot of maize (20.8%) and barley (8.25%) however, a concentration of 25 mg/kg negatively affects shoot length which means that the growth of crop depends on the concentration of applied nanoproduct [53]. On the other hand, there is mixed information regarding the beneficial effects of nanomaterials on seed germination and crop growth, according to various research. Such variation may result from a variety of nanomaterial features, including size, shape, surface coating, electrical properties, dose, application method, and the plant species under study [54].

Metal-based NPs play an important role in the enhancement of physiological activities and growth, fertilizer, and water use efficiency, seed germination, stimulation of nodule formation, and inhibit abscission of reproductive organs of plants. Soil application of silver nanoparticles in wheat at concentrations of 25-50 ppm resulted in enhancement of fresh and dry weight, and height of the plant as compared to control and this might be due to inducing changes at molecular as well as physiological levels [55]. No. of seminal roots at lower concentrations such as 25 ppm results in an increase in yield by enhancing the number of grains/spikes [56]. In aromatic rice (cultivar KDML105) application of TiO_2 NPs showed a positive effect on the efficiency of regeneration [57]. Concentration, type of plant species, and mode of application determine the effects on NPs. Singh *et al*., 2018 reported the application of CuO NPs at different concentrations such as 2, 4, 8, and 16 ppm, and results were found that at effective enhancement of the level of antioxidant and efficiency of photosynthesis at an optimum level of concentration such as 4 ppm. Metal oxide NPs such as Fe_2O_3, SiO_2, TiO_2, ZnO, and CeO_2 have been utilized for the improvement of crops in various plants. They found it effective in improving plant growth and yield, and seed germination [56]. The germination rate of pearl millet was significantly increased with the application of Au NPs as compared to that of untreated plants [58]. Application of ZnO NPs to wheat seed increased the efficiency of seed germination with comparison to control plants [59]. The ZnO NPs treated seedlings were executed to transcriptomic analysis and results showed that upregulation of several metal accumulation-related genes such as *ZINC TRANSPORTER 9 (ZIP9), BASIC HELIX-LOOP-HELIX 38 (Bhlh38), bHLH100, bHLH39 and IRON-REGULATED TRANSPORTER 1 (IRT1)* as compared to with those treated with only normal Zn ions [60]. Gene expression related to the signaling pathway of auxin has been induced with foliar application of Ag NPs to two varieties of common beans i.e. Nebraska and Bronco which leads to higher content of auxin in plants [61]. NPs can have a positive effect on plant growth by mediating crop antioxidant enzyme activity. The application of ZnO NPs on cucumber plants resulted in improvements in plant chlorophyll content and leaf fresh/dry weight. Furthermore, the activities of antioxidant-related enzymes such as superoxide dismutase (SOD) and catalase (CAT) increased significantly in the treated cucumber leaves compared to the untreated control. This indicates that the NPs influenced the plant's antioxidant defense system, leading to enhanced enzyme activity and subsequently improving plant growth [62]. Silver nanoparticles (AgNPs) have been widely studied for their potential applications in various fields, including agriculture. When applied to plants, AgNPs can have both positive and negative effects depending on their concentration and exposure duration. In the case of fenugreek plants, it has been observed that different concentrations of AgNPs can enhance IAA (indole-3-acetic acid) contents, photosynthetic pigments, plant growth, and yield quantity and quality at 40 mg/L of concentration [63].

B. THE ROLE OF NANOTECHNOLOGY IN THE DEVELOPMENT OF SECONDARY METABOLITES

The NPs not only act as elicitors of secondary metabolites but also as a source of micronutrients and sometimes as stimulators and antimicrobial agents of organogenesis, root initiation, callus induction and shoot growth [64]. NPs can be directly utilized in precise concentration either through soil or seed treatment or foliar application to enhance the production of secondary metabolite both in vivo and in vitro conditions. Nowadays NPs can be used as elicitors to increase levels of expression of genes that are related to secondary metabolite production [65]. Cu and Au NPs also increased flavonoids and phenolics production in milk thistle plants [30]. Application of AgNPs to *Trigonella foenum-graecum* L. (fenugreek) seedlings increased diosgenin biosynthesis and plant growth [66]. AgNPs act as positive elicitors of the rebaudioside A and glycosides stevioside in *Stevia rebaudiana* (B) after treatment of spraying at a concentration of 40 mM found to be most effective at which maximum enhancement occurred [67]. In *Citrus reticulata* (Kinnow Mandarin) synthesis of total phenolics and flavonoids increased by treatment of AgNPs at a concentration of 30 ppm which ultimately increases its anti-oxidant capacity and provides resistance against brown spot disease caused by *Alternaria alternate* [68]. The application of AgNPs at a concentration of 4-40 mg/plant in cucumber resulted in an enhancement of phenolics content which activates oxidative defense response [69]. Foliar application of AgNPs at 200 ppm to hydroponically grown *Rosmarinus officialis* L. (Rosemary) for 12 days resulted in an increase in the content of carnosic acid by more than 11% along with that of total flavonoids [70]. Cu or CuO NPs act as effective elicitors of secondary metabolism in plants. In vitro, plantlets of *Citrus reticulata* treated with CuO NPs and ZnO NPs with 30 µg/ml offered an effective increase in the total content of flavonoid and phenolic as well as antioxidant capacity [71]. Foliar application of CuNPs with 1.0 g/L to *Mentha piperata* L. (peppermint) was reported to increase the percentage of essential oil (20%) and chlorophyll content (35%) and content of menthon (25%), menthol (15%), menthofuran (65%) higher as compared to control [72]. CuO NPs were found to have significant effects on the flavonoid, polyphenol, and tannin content, as well as the antioxidant capacity, in the roots of two Indian medicinal plants like *Withania somnifera* L. Dunal (Ashwagandha) [73] and *Chicorium* *intybus* L. (chicory) [73]. Foliar application of CuO NPs with 250 mg/L was applied to *Solanum lycopersicum* (tomato) plants. The study found that this application of CuO NPs enhanced the quality of the fruits. The enhanced fruit quality was attributed to the stimulation of a greater accumulation of bioactive compounds such as total phenols, vitamin C, flavonoids, and lycopene, and antioxidant enzymes like SOD, CAT in the fruits. These bioactive compounds are known for their beneficial effects on human health [74]. Under salt stress conditions, the application of a CuO NP at a concentration of 250 mg/L resulted in several effects on tomato plants. Firstly, it enhanced the concentration of Cu in the plant tissues. Additionally, it caused an increase in phenols by 16% in the leaves and elevated the content of vitamin C by 80%, glutathione (GSH) by 81%, and phenols by 7.8% in the fruit, as compared to the control group. Moreover, these changes were accompanied by increased activities of various antioxidant enzymes in the leaf tissue. The activity of phenylalanine ammonia-lyase (PAL), an enzyme involved in phenolic compound synthesis, increased by 104%. Ascorbate peroxidase (APX), an enzyme responsible for the breakdown of hydrogen peroxide, showed a 140% increase in activity. Glutathione peroxidase (GPX), which helps in the detoxification of reactive oxygen species, exhibited a 26% increase in activity. Superoxide dismutase (SOD), an enzyme that scavenges superoxide radicals, showed an 8% increase in activity. Catalase (CAT), an enzyme involved in the breakdown of hydrogen peroxide, exhibited a significant 93% increase in activity [75].

Table 2: Growth promoting NPs

Sr. no.	Name of NPs	Dose of Application	crop	Enhancement of	References
1	ZnO	100 mg/L	*B. napus*	Pectin content, flavonol content, peroxidase activities	[76]
2	ZnO	25-200 mg/L	Cotton	Chlorophyll a & b, carotenoids, total soluble proteins	[77]
3	Se	10 mg/L	Wheat	Expression of heat shock factor A4A	[78]
4	CNT	10-40 µg/ml	Tomato	Increased germination & growth rate	[46]
5	Ag	25 mg/L	Wheat	Increased seminal roots, root biomass, leaf area & weight	[56]
6	Fe_3O_4	-	*Arachis hypogaea*	Enhanced shoot & root length, biomass	[79]
7	Fe_3O_4	-	Wheat	Increased germination rate, root & shoot length	[80]
8	Fe_3O_4	50 mg/L	*Daucus carota*	Increased yield	[81]
	ZnO	100 mg/L			
9	TiO_2		Wheat	Improved radicle & plumule growth	[82]
10	ZnO	8 mg/L	Wheat	Increased growth & photosynthetic efficiency, antioxidant & enzymatic activity	[82]
11	Ag	50 mg/L	*Brassica juncea*	Increased fresh weight, shoot & root length	[83]
12	TiO_2	1500 mg/L	*Tanacetum parthenium*	Increased the amounts of main compounds & oxygenated monoterpene in essential oils, enhanced quantity & quality of essential oils	[84]
13	CNTs, fullerols, MWCNTs, Ag NPs	25-50 ppm	*Triticum aestivum*	Increased yield and growth	[56]
14	CuO	100 ppm	*Bacopa monnieri* L.	Increased content of saponins, alkaloids, flavonoids, and antioxidant capacity	[85]
15	Cu	-	*Solanum lycopersicum*	Increased vitamin C, phenol, glutathione, flavonoid	[86]
16	Cu, Ni, Zn	-	*Solanum melongena* L	Enhancement of secondary	[87]

				metabolites anthocyanin, phenolics, flavonoids	
17	TiO_2	100 & 150 mg/L	*Mentha piperita* L	Increased content of essential oil & content & yield of menthol	[88]
18	TiO_2	90 mg/L	*Vetiveria zizanioides*	Increased content & yield of essential oil & khusimol, chlorophyll content, photochemical efficiency of PSII	[89]
19	TiO_2 & SiO_2	25 mM	*Tanacetum parthenium*	Upregulated expression of parthenolide synthesis genes like TpCarS, COST, TpGAS	[90]
20	ZnO & FeO	-	*Raphanus sativus* cv. Champion	Significant increase in anthocyanins, tannins, flavonoids, and phenols concentration	[91]

IV. APPLICATION OF NANOMATERIALS IN THE DETECTION AND DIAGNOSIS/MANAGEMENT OF PLANT DISEASES

A. NANOTECHNOLOGY IN THE ALLEVIATION OF STRESS

There are various types of NPs have been useful for the protection of crops in different ways such as mitigation of different stress, detection, and management of disease, and suppression of attack of insects, pests, and viruses in an eco-friendly and cost-effective manner which is illustrated below. The application of NPs plays a dual role such as developing resistance towards disease and also increasing the production of agriculture. NPs also help in the supply of nutrients and also effective against various pathogenic microorganisms [92]. The studies reported that disease management with the help of NPs showed positive impacts such as increased grain yield and promoted growth of plants [93].

B. NANOPARTICLES IN THE ALLEVIATION OF ABIOTIC STRESS

Recent studies indicated that NPs acts as nano enzymes and they penetrate plant cell wall resulting into scavenge ROS [94]. Salinity, which refers to the presence of excessive salts in the soil or water, is indeed a significant abiotic stress that can have detrimental effects on plant growth and crop production [95]. When the concentration of salts, particularly sodium chloride (NaCl), exceeds tolerable levels, it can negatively impact various physiological and biochemical processes in plants. According to [96], the accumulation of soluble salts like chloride, sodium, magnesium, and potassium resulted in increased salinity of soil by 3.5% because of the utilization of seawater for irrigation. Plant growth can be hindered due to soil salinity by disturbing nutrient and water uptake, plant metabolic processes, and higher solute accumulation results in the reduction of leaf surface area osmotic potential, decreases the content of chlorophyll, blocks stomatal conductance then finally resulted in the death of plant cell tissues [97], reported ZnO NPs to have the potential to decrease total sugar content and accumulation of proline in salinity-affected plants. In a study conducted by [98], it was observed that tomato plants grown in a NaCl-stressed environment exhibited stunted seedling growth and lower protein contents. However, these negative effects were subsequently improved through the foliar application of ZnO-NPs (zinc oxide nanoparticles) at various application rates ranging from 10 to 100 mg/L. Zinc oxide nanoparticles (ZnO-NPs) boost plant antioxidant defenses and protect against oxidative damage caused by the imbalance and accumulation of reactive oxygen species (ROS) and free radicals under salinity stress [99]. ZnO nanoparticles (ZnO-NPs) have been studied extensively for their diverse applications in various fields, including photosynthesis and increasing the synthesis of sucrose for the synthesis of LP, GB, and TSP which might be because of tryptophan synthesis [100]. Many researchers observed salinity stress can be mitigated with the help of ZnO NPs treatment at a lower dose of application in various crops such as brassica species [101]; tomato [102], mango [103], yellow and white lupine it may be because of antioxidant activities of enzymes improvement, Chlorophyll pigments improvement, maintenance of the integrity of the cell membrane as well as the balance of nutrients in cell. [104], reported that chilling stress was reduced by using NPs such as silicon dioxide, zinc oxide, selenium, graphene, etc. were applied through foliar spray on leaves of sugarcane and significantly resulted in reduced negative effects of chilling stress on photosynthesis and improved photoprotection. Treatment of NPs showed enhancement of the content of light-harvesting pigments, increased content of chlorophyll, carotenoid, nonphotochemical quenching (NPQ), etc. Chitosan NPs play a crucial role in mitigating drought conditions. Encapsulation of chitosan NPs with S-nitroso glutathione (GSNO) increased the photosynthetic rates, the ratio of shoot and root under water deficit conditions i.e. drought as compared to the application of free i.e. alone GSNO that indicates the slow release of NO and generates tolerance to drought in sugarcane [105]. According to [106], SiNPs have been reported to alleviate drought stress in such a way that reduced the conductance of stomata and modification of properties of the cell wall, and also helps to slow the release of nutrients, and stores more amount of water which ultimately results into the management of salinity and developed tolerance towards saline and drought conditions with eco-friendly. Biosynthesized magnetite (Fe_3O_4) nanoparticles (NPs) have shown effectiveness in alleviating drought stress by enhancing the quantum yield efficiency of Photosystem II (PSII) represented by ΔF/Fm' and the electron transport rate (ETR). These enhancements ultimately lead to the strengthening of the LH complex. When applied at lower concentrations, these magnetite NPs have demonstrated positive effects in mitigating the adverse effects of drought on plants [107].

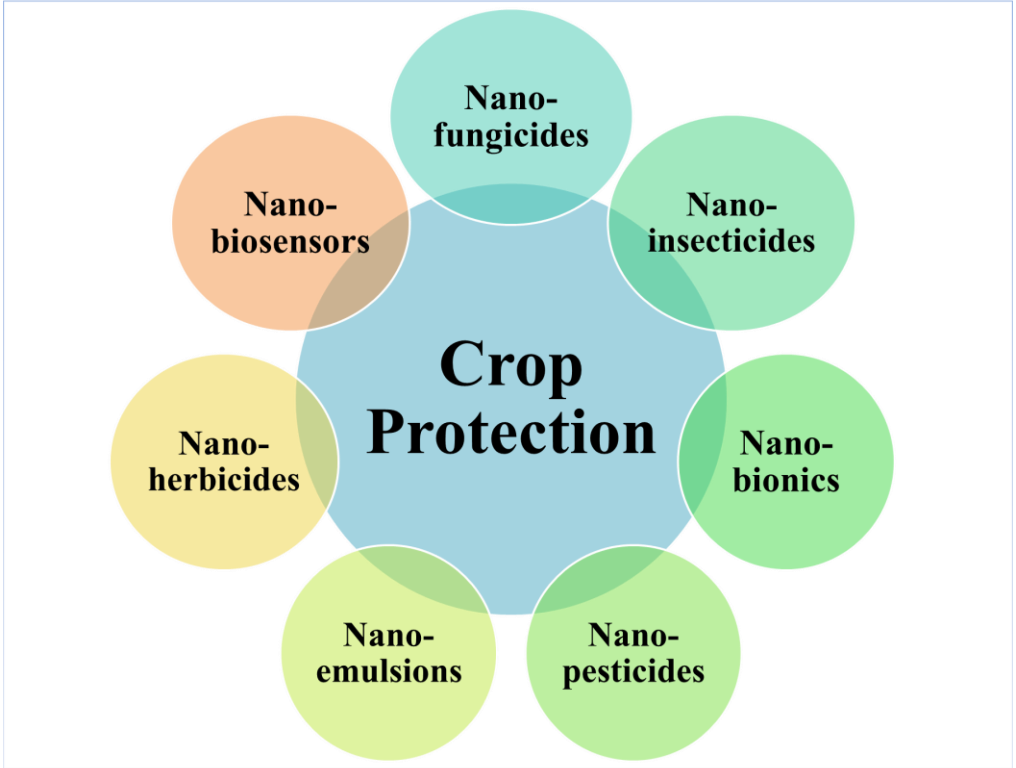

Fig. 3. Different ways of crop protection

Table 3: NPs for crop protection against abiotic stress

Sr. no.	Name of NPs	Dose of Application (mg/L)	crop	Tolerance to abiotic stress	References
1	ZnO	-	*B. napus*	Salinity	[76]
2	ZnO	25-200	Cotton	Oxidative	[77]
3	TiO_2	2-5	*A. thaliana*	Salinity, Water, oxidative	[108]
4	ZnO	15-60	*A. italiana*	Salinity, water, oxidative	[108]
5	AgNp	1	Wheat	Salinity	[109]
6	AgNP	25-100	Wheat	Heat	[110]
7	AgNP	10, 20, 30	*T. vulgaris* & *T. daenensis*	Salinity	[111]
8	AgNP	50 & 100	*T. vulgaris*	UV-B	[112]
9	Au	300	Wheat	Salinity	[113]
10	Mn_3O_4	1 &5	*Cucumis sativus*	Salt	[48]
11	Al_2O_3	30-60	Soybean	Flooding	[114]
12	Si	200	*Cucumis sativus*	Salinity, drought	[115]
13	Fe_3O_4	5-120	*Setaria italic*	Drought	[116]
14	Fe_3O_4	60	*Dracocephalum moldavica*	Salinity	[117]
15	Cu	52-86	Maize	Drought	[118]
16	ZnO	30	*Vigna radiata*	Heat	[100]

17	ZnO	1000	*Trigonella foenum-graeam*	Salt	[119]
18	Se	10, 50	*Capsicum annum*	Salinity	[120]
	Si	200, 1000			
	Cu	100, 500			
19	TiO_2	10-30	*Vicia faba*	Salinity	[121]
20	Se	10, 50, 100	Sorghum	Heat	[122]
21	AgNp & IAA	-	*Daucus carota*	Metal (Cd)	[123]

C. Alleviation of biotic stress by nanoparticles

The major problem in the production of garlic and onion is found due to soil-borne fungus *Stromatinia cepivora* which causes white rot disease. The alleviation of such disease was possible with the help of biologically synthesized AgNPs by using *Fusarium oxysporum*. The treatment of spraying and dipping effectively reduced the incidence of disease in field conditions. Hence, AgNPs can be used as nano fertilizers for garlic and onion production and as nano-fungicides against white rot disease. In-vitro efficacy of these NPs showed maximum antifungal activity at 200 mg/L against *S. cepivora* [124].

In tomato plants significant economic loss due to damage by *Clavibacter michiganensis* throughout the world. The copper (Cu) and potassium silicate NPs play a crucial role in the severe reduction of *C. michiganensis*. The combined application of potassium silicate and copper NPs results in a significant reduction of bacteria and also reduces the loss of yield due to bacteria by 16.1% especially because of a low dose of CuNPs. The joint application of both these NPs stimulated the activities of several enzymes such as APX, SOD, GPX, and PAL and also reduced the phenols and glutathione content in leaves which ultimately favored tolerance towards oxidative stress caused by such bacteria [125].

The production of strawberries is affected due to foodborne disease and harms their nutraceutical and nutritional qualities. [126] reported that ZnO NPs effectively control pathogens such as *Botrytis cinerea*. The antifungal activity of ZnO NPs and photoactivated ZnO NPs showed a reduction in radial mycelial growth of *B. cinerea* by 12% and 80% respectively. In-field spraying of ZnO NPs in the presence of light i.e. sunny day reduced the severity or incidences of *B. cinerea* by 43% and also increased crop production by 28.5% and enhances the ability of storage and avoid spoilage of harvested fruits by 8 days. ZnO NPs resulted in the enhancement of inflorescence growth by 37.5% and inhibited runners growth by 32.8% and had no harmful effects on the leaves and crowns of the strawberry plant.

Silicon nanoparticles (SiNPs) have been found to interact with plant cell walls and contribute to the formation of a second layer of cuticle, which serves as a physical barrier against pathogen penetration. This interaction between SiNPs and plant cell walls can enhance plant defense mechanisms and reduce the frequency of diseases caused by various pathogens such as *Pyricularia oryzae Cavara*, *Bipolaris sorokiniana Shoemaker*, *Pyricularia grisea Sacc*., and *Rhizoctonia solani Kühn*. The application of SiNPs to plants has been shown to help in mitigating the impact of these pathogens by reinforcing the plant's defense system [127].

Application of ZnO NPs in Zn deficient plants showed significant antibacterial and antifungal activities and also generates ROS and Zn ions released that help to inactivation of the bacterial cell wall and also showed higher antimicrobial activity [128]; [129]. As per the available reports, SiNPs interplay with the cell wall and generates an extra cuticle layer that is helpful in the prevention of entry of pathogen inside a plant cell and develops resistance to diseases in different crops [130]. The *Pyricularia grisea* caused blast disease in the finger millet. The blast disease in finger millet was suppressed by 75% with the help of copper chitosan nanoparticles and also enhanced yield by about 89%. The application of these NPs also effectively increased defense enzymes both qualitatively and quantitatively [131]. The study conducted by [132], investigated the larval mortality of *Helicoverpa armigera* (a species of moth) when exposed to titanium dioxide nanoparticles. [133], focused on the enterotoxin efficacy against *Sitophilus oryzae* (rice weevil) in the presence of different nanoparticles, including Al_2O_3, TiO_2, and ZnO. The researchers examined the effectiveness of these nanoparticles in controlling *Sitophilus oryzae* populations. Nanoforms of silver, carbon, silica, and alumino-silicates have shown the potential in restricting plant diseases and can be considered as alternatives to commercially available fungicides. These nanoforms can be engineered to encapsulate or bind active components such as fungicidal agents. The controlled release of these active components from the nanoforms allows for sustained and targeted delivery, thereby maximizing their efficacy while minimizing potential negative effects [109].

[134], reported that application of TiO_2 and Si NPs increased the concentration of chlorophyll and the ability of gas exchange of rice leaf with a decrease in malondialdehyde content, leakage of electrolyte, and improve activities of catalase, peroxidase, ascorbate peroxidase, superoxide dismutase in shoots of rice. The NPs found effective at 20-30 mg/L concentration to alleviate the Cd (Cadmium) toxicity. The foliar use of NPs is effective in improving biomass, photosynthesis, and reducing Cd accumulation in rice plants. This positive outcome can be primarily attributed to two factors such as the reduction of oxidative bursts and the enhancement of the antioxidant defense system due to the

application of NPs. CuNPs were found more fungi toxic to control mycelial growth as compared to protective fungicides containing $Cu(OH)_2$ and effectively suppressed symptoms of grey mold on plum fruit, especially Ag NPs that completely inhibited the development of disease. Cu NPs found effective between 162-310 μg/ml whereas ZnO NPs found significantly effective between 235-848 μg/ml to inhibit the growth of fungi. Cu, ZnO, and Ag NPs found more toxic at the germination of spore level as compared to the growth of mycelia. Most fungal species were found to be insensitive to CuO-NPs and Ag-NPs, except for *B. cinerea*. *B. cinerea*, on the other hand, exhibited sensitivity to both Ag-NPs and Cu-NPs, with an EC50 (half-maximal effective concentration) value of 307 μg/mL [135].

Table 4: NPs for crop protection against biotic stress

Sr. No.	**Name of NPs**	**Dose of Application**	**Crop**	**Resistance to biotic stress**	**References**
1	Si		Tomato	Early blight & black root rot	[136]
2	Ag	50-100 μg/ml	*Vigna unguiculata*	*Xanthomonas campestris & X. axonopodis*	[137]
3	MgO	7-10 μg/ml	*Solanum lycopersicum*	Wilt disease (*Ralstonia solanacearum)*	[138]
4	Al_2O_3	400 mg/L	*Solanum lycopersicum*	Fusarium root rot	[139]
5	Ag	100 μg/ml	*Prumus domestica*	Grey mold (*Botrytis cinerea*)	[140]
6	Cu	450 mg/L	In-vitro study	*Fusarium spp.*	[141]
7	MgO	200-250 μg/ml	Tobacco	Tobacco bacterial wilt (*Ralstonia solanacearum*)	[142]
8	Chitosan copper	30-100 mg/L	In-vitro study	*Sclerotium rolfsii & Rhizoctonia solani*	[143]
9	Coumarin chitosan	0.1-1.0 mg/ml	In-vitro study	*A. solani, F. oxysporium, F. moniliforme*	[144]
10	Ag	50 mg/L	Tomato	TMV & PVY	[145]
11	Ag	200 ppm	*S. tuberosum*	Tomato spotted wilt virus (TSWV)	[146]
12	Ag	0.1μg/μL	*S. tuberosum*	Potato virus Y (PVY) & TMV	[147]
13	ZnO	100 μg/ml	*N. benthamiana*	TMV	[148]
14	SiO_2	100 μg/ml	*N. benthamiana*	TMV	[148]
15	CNT	100-500 mg/L	*N. benthamiana*	TMV	[149]
16	TiO_2	200 ml	*Vicia faba*	Broad bean stain virus (BBSV)	[150]
17	NiO	150 μg/L	*Cucumis sativus*	Cucumber mosaic virus (CMV)	[151]
18	Ag	50-100 μg/mL	In-vitro	*X. axonopodis pv. malvacearum* & *X. campestris pv. campestri*	[137]
19	CuO	100 mg/L	Citrus	*Phytophthora parasitica*	[152]
20	Ag	5 μg/mL	*Arabidopsis thaliana*	Black spot (*Alternaria brassicicola)*	[153]
21	TiO_2	40 mg/L	Wheat	Yellow stripe rust (*Pst*)	[154]

V. NANOPARTICLES MEDIATED GENE TRANSFER AND CROP PROTECTION

In plant breeding nanotechnology is used for the transfer of plant DNA for insect pest resistance [155]. The DNA is protected from various enzymatic reactions during its transfer into and within plant cells with the help of nanoparticles [156]. Nanomaterial-assisted biomolecule transfer refers to the use of nanomaterials, such as nanoparticles or nanotubes, to facilitate the delivery of biomolecules, particularly DNA and RNA, into cells [157]. This field of research holds promise in various applications, including transgene expression, genome editing, and gene silencing [158]; [159]; [160]. The plant cell wall is a complex structure composed of various polysaccharides, proteins, and other components. It provides rigidity and protection to the plant cell, but it also poses a challenge to the transformation of biomolecules into plant cells. However, certain plant tissues, such as pollen, have a chemically inert cell wall that is more amenable to genetic transformation [159]. The use of chitosan-coated single-walled carbon nanotubes (SWCNTs) to deliver a DNA plasmid into chloroplasts resulted in high transient expression levels in various plant species, namely *Eruca sativa* (commonly known as arugula), *Nasturtium officinale* (watercress), *Nicotiana tabacum* (tobacco), and *Spinacia oleracea* (spinach) [161]. In recent years, there has been a lot of increase in research fascinated by nanomaterial-based gene silencing and genome editing techniques in addition to transgene expression. These approaches offer novel and efficient methods for modifying the genomes of plants [158]. The successful transfer of conjugates of DNA (deoxyribonucleic acid) and CNTs (carbon nanotubes) into various plant species, namely tobacco, arugula, cotton, and wheat. This research highlights the potential application of DNA-CNT conjugates for genetic engineering and plant modification [162]. The siRNA delivery platform mediated by CNTs demonstrated high silencing efficiency in plant cells. This suggests that CNTs can effectively deliver small interfering RNA (siRNA) molecules, which can lead to the downregulation of specific target genes in plants [163]. On the other hand, the NP-based delivery platform, specifically polyethyleneimine-coated gold nanoparticles (PEI-AuNPs), successfully delivered siRNA into intact plant cells, resulting in a significant decrease (76%) in the expression of the target gene [160]. While nanobiotechnology holds great promise for plant transformation, there are still areas that require further investigation. One crucial aspect is the stability of nanobiotechnology-assisted genome modification. Researchers need to study the long-term effects and stability of these modifications to ensure that the desired traits are maintained over successive generations of plants. The process of delivering genetic cargo to plant cells offers numerous advantages over conventional methods. One of the key benefits of NP-based delivery is its ability to efficiently transfer NP-bound GE nucleases to plant cells without causing damage to the target tissue. This is crucial because previous delivery methods often posed challenges and limitations in terms of tissue damage and efficiency. By utilizing NP-based methods, these issues have been overcome, leading to improved success rates and robustness in GE [164]. Silica nanoparticles (SiNPs) can be utilized for the transportation of proteins in tomato plants through the vascular system. SiNPs might be used as a plant transport medium in the future, according to research [165]. According to [166], mesoporous silica nanoparticles (MSN)/DNA complexes have been shown to have improved transport efficiency. Transfection refers to the process of introducing foreign genetic material, such as DNA, into cells. MSNs can act as carriers or delivery vehicles for DNA, facilitating its uptake by cells. [155], discuss the use of nano barcodes as identification tags in the multiplexed analysis of gene expression for environmental stress resistance. Nanobarcodes are particles developed using semi-automated electroplating of inert metals like gold and silver. These particles are used to label genetic material and enable the simultaneous analysis of multiple gene expressions in a single experiment.

NPs play a crucial role in the transfer of genetic materials in plants to facilitate genetic engineering, genetic material stabilization, and improve their dsRNA efficacy for the improvement of plants [167]. Chitosan NPs found effective in protecting pearl millet from Downey mildew and also changed gene expression profile and resulting in the upgradation of genes for phenylalanine ammonia-lyase, catalase, peroxidase, superoxide dismutase, and polyphenol oxidase [168]. Nanomaterials also improve the germination of seeds. Seed can be treated with nanomaterials before sowing i.e. at the starting growth stages and helpful in the growth of plant and productivity that results in enhancement of emergence of seedling, radicle/plumule length, enzyme activities, respiration, photosynthesis, and crop productivity [169]. Natural germination of crops is a little bit time-consuming and productivity loss as compared to nano-teated seeds results in higher seed germination and productivity [170].

VI. MOLECULAR RESPONSES TRIGGERED BY NANOPARTICLES DURING THE STRESS RESPONSE

The biological processes that take place in plants are the outcome of molecular activities. Mechanisms of defense against several biotic and abiotic stresses are influenced by the interaction of various biomolecules and the expression of genes. Stresses, including those caused by various environmental factors, can have significant impacts on the molecular mechanisms of plants at both cellular and genetic levels. These stresses can disrupt normal plant functions and hinder their growth and development. Therefore, it becomes crucial to assess and understand the effects of nanoparticles on plants, as they may interact with plants' molecular responses in ways that could either exacerbate or mitigate the stress-induced effects. Photosynthesis, the most important physiological activity in plants, are susceptible to abiotic stressors such as heat or high NaCl levels [171]. High temperatures affect the chlorophyll content and ultimately result in a decrease in photosynthesis [172]. Peroxisomes are cell membranes in eukaryotic cells. They play a crucial role in various metabolic pathways, including the metabolism of reactive oxygen species (ROS) and nitrogen species. Peroxisomes are involved in processes such as fatty acid oxidation, detoxification of harmful substances, and the synthesis of specific lipids. Exposure to MoS_2 NPs (Molybdenum disulfide nanoparticles) has led to the upregulation of certain genes related to peroxisome biogenesis. These genes include peroxin-1 (gene-18618), peroxin-2 (gene-976), peroxin-5 (gene-6672), peroxin-16 (gene-7385), and protein Mpv17 (gene-5958). The application of MoS_2 NPs upregulated mostly DNA replication-related genes and plays a crucial role in cell division to mitigate environmental stress. Underexposure to MoS_2 NPs significantly upregulated genes related to gluconeogenesis/glycolysis, porphyrin synthesis, and TCA cycles [173]. ZnO-NPs treatment resulted in a significant alteration in stress-induced gene expression in rapeseed plants. Specifically, certain genes were downregulated, while others were upregulated. The downregulated genes included *SKRD2, MYC,* and *MPK4*, whereas the upregulated genes were *MYC, ARP,* and *MPK* [174]. [175], reported that ZnO NPs upregulated the *miR156a* and *miR159a* in barley, whereas, in the case of maize, these genes or miRNAs were downregulated [176]. One area of interest is the potential regulation of plant metabolism by TiO_2-based nanomaterials through the expression of specific miRNAs [177]. Application of ZnO-NPs to rice revealed effective antioxidant system modulation as well as NP-induced gene expression of transcription factors involved in the chilling response, including *OsbZIP52*, *OsMYB4*, and *OsMYB30* [178]. Generation of ROS and various stress markers like *TBARS*, *dnaK* type molecular chaperone hsc70.1, and proline were decreased through disease-resistant protein, serine hydroxymethyl transferase, and thiazole biosynthetic enzyme and is revealed by biochemical and proteomics study. Treatment of bioengineered silver nanoparticles results in significant improvement in the immunity of plants with a decrease in ROS and stress enzymes by 0.6-19.8 fold [153]. In response to the biotic stress caused by *Puccinia striiformis f. sp. tritici (Pst*), biogenic TiO_2 NPs cause the up- and downregulation of proteins that improve defense and disease resistance in wheat plants [154]. According to transcriptome analysis, (50 nm) Cu-based NPs altered the expression of genes involved in oxidative stress response, brassinosteroid production, and root development [179].

Table 5. Plant transcriptomic and proteomic response to NPs under biotic and abiotic stresses

Sr. No.	NPs	Crop	Stress	Most regulated genes	Expression	References
1	TiO_2, Ag, MWCNTs	*Arabidopsis thaliana*	Wounding, drought, salinity, biotic stress	Genes related to drought response	Upregulation	[180]
				Salt-responsive genes, *P. syringae* pv., SAR, root hair, and *Alternaria brassicicola*	Downregulation	
				Genes related to phosphate starvation	Downregulation	
2	Al_2O_3	Soybean	Flooding	Protein synthesis/degradation, lipid metabolism, glycolysis-related proteins	Upregulation/ Downregulation	[181]
				FQRI	Downregulation	
				PABP2, *NmrA-Like*	Upregulation	
3	Ag	Soybean	Flooding	Cell metabolism and stress signaling root proteins	Upregulation/ Downregulation	[182]
				Proteins related to fermentation, Glyoxalase II3, *PDC, ADHI*	Downregulation	
4	TiO_2	Chickpea	Cold	*PEPC*, chlorophyll a/b binding protein, *LRubisco*, *SRubisco*	Upregulation	[183]
5	Ag	*Arabdopsis thaliana*	*Alternaria brassicicola*	Cell signaling, metabolism, bioenergy, miscellaneous functions, biogenesis, storage responsive proteins	Downregulation/ Upregulation	[184]
6	Ag	Soybean	Flooding	*BKRI*, Protein metabolism, protein synthesis, cell division/organization, metabolism of AA-related	Upregulation	[185]

				proteins		
7	Si	Tomato	Salinity	*AREB, CRK1, TASI4, NCED3*	Upregulation	[186]
				MAPK3, APX2, RBOHI, ERF5, DDF2, MAPK2	Downregulation	
8	Ag	Tomato	Salinity	*MAPK2, CRK1, AREB, PSCSI*	Upregulation	[187]
				DDF2, ZFHDI, TASI4	Downregulation	
9	TiO_2	Chickpea	Cold	Cell signaling, cell defense, chromatin modification, transcriptional regulation responsive genes	Downregulation/ Upregulation	[188]
10	Si	Rice	Cd	*LSIL, HMA3*	Upregulation	[189]
				NRAMP5, LCT1	Downregulation	
11	TiO_2	*Arabidopsis thaliana*	TC	*ECS, APT, GS, APR, SiR*	Upregulation	[190]
12	Ag	*Cajanus cajan*	Fluoride	*PSCSI, NADPH oxidase*	Downregulation	[191]
13	Ag	*Arabidopsis thaliana*	Drought	Oxidative stress and metal response-related genes	Upregulation	[192]
				Auxin and ethylene-related genes	Downregulation	
14	ZnO	Rice	Cold	*OsCu/ZnSOD1, OsCu/ZnSOD2, OsCu/ZnSOD3, OsPRX11, OsPRX65, OsPRX89, OsCATA, OsCATB, OsbZIP52, OsMYB4, OsMYB30, OsNAC5, OsWRKY76, OsWRKY94*	Upregulation	[178]
15	ZnO	Soybean	Temperature	*WRKY1, MAPK1, HDA3, CAT, EREB, R2R3MYB, HSF-34*	Upregulation	[193]
16	Si	Wheat	Heat	*TaP1P1, TaNIP2*	Overexpression	[194]
17	ZnO	*Arabidopsis thaliana*	Heat	*TGS-GUS*	Downregulation	[195]
18	Zn	*Brassica napus* L.	Salinity	*SKRD2, MYC, MPK4*	Downregulation	[174]
				ARP, MPK, MYC, SKRD2	Upregulation	
19	Si	Rice	Cd	*LCT1, NRAMP5*	Downregulation	[196]
				HMA3, LSI1	Upregulation	
20	FeO & Hydrogel	Rice	Cd	*OsHMA2, OsHMA3, OsLCT1*	Downregulation	[197]

	NPs					
21	TiO_2	*Cicer arientinum* L.	Cold	*RUBISCO, PEPC*	Upregulation	[188]

VII. NANOTOXICOLOGY AND REGULATORY PERSPECTIVES

Nanomaterials have shown tremendous potential for various applications due to their unique properties at the nanoscale. However, it is crucial to ensure that the use of these materials does not pose any risks to human health or the environment. The safety of nanomaterials is a topic of ongoing research and regulation to address any potential concerns. The potential risks associated with nanomaterials arise from their small size and increased surface area, which can lead to altered chemical reactivity and potential toxicity. It is important to conduct thorough toxicity studies and risk assessments to understand the potential hazards and exposure pathways of these materials. To address these concerns, regulatory bodies, and research organizations are actively working on developing guidelines and standards for the safe handling and use of nanomaterials. These efforts aim to ensure that any potential risks are identified and mitigated early in the development and commercialization process. Moreover, ongoing research is focused on understanding the interactions of nanomaterials with biological systems and the environment. This includes studying their behavior in the human body, assessing their potential to accumulate in ecosystems, and investigating any long-term effects they may have. Overall, the field of nanotoxicology and the regulatory landscape are evolving to better understand and manage the potential risks of nanomaterials. Ongoing research, collaboration between scientists and regulatory agencies, and the development of standardized testing methods will contribute to a comprehensive understanding of nanomaterials' safety and help establish appropriate regulations to protect human health and the environment. Many nanotoxicological studies and projects are being carried out all over the globe (OECD, EU, USA, Canada) to find the nanotoxicological standardized methods needed to overcome this issue [198]. Nanotechnology holds great promise for revolutionizing agriculture and addressing various challenges. However, the potential antagonistic effects of nanoparticles in ecosystems highlight the need for cautious and responsible use, as well as ongoing research to ensure the safe and sustainable implementation of nanotechnology in agriculture [199].

VIII. CONCLUSION AND FUTURE PERSPECTIVES

The application of NPs improved the biochemical, morpho-physiological, and molecular features of plants [101]. In the area of plant sciences, nanotechnology has made significant development. From nanomaterial creation through their use in the growth, development, enhancement, protection, and improvement of many plant-related characteristics. The rapid increase in the global population necessitates improved agricultural output. Utilizing contemporary technologies that can increase agricultural productivity is essential. It is recognized that nanoparticles have good impacts on plant growth and development, crop enhancement, their use as fertilizers, insect control, and post-harvest technology. Genome editing technologies, such as transcription activator-like effector nucleases (TALENs), zinc finger nucleases (ZFN), and the clustered regularly interspaced short palindromic repeat/CRISPR-associated protein (CRISPR/Cas) system, have revolutionized biological research. These tools have provided researchers with powerful methods to precisely modify the genetic material of organisms, including plants. However, one of the challenges in genome editing is the delivery of foreign DNA or editing components into plant cells. Efficient delivery methods are crucial for successful genome editing and the introduction of desired traits in plants. Traditional methods, such as Agrobacterium-mediated transformation and biolistic particle bombardment, have been used for many years, but they have limitations in terms of efficiency and precision. To overcome these challenges, scientists are exploring new approaches, and one promising strategy is the use of nanoparticle-mediated CRISPR technology. Nanoparticles can serve as carriers for delivering CRISPR components into plant cells, enhancing the efficiency and precision of genome editing. Nanoparticles can protect the CRISPR components from degradation, facilitate their entry into cells, and promote their release at the desired target sites within the plant genome. Indeed, the use of nanoparticles (NPs) in agriculture holds great promise for improving crop productivity and sustainability. NPs can be engineered to possess unique properties that make them useful in various agricultural applications, such as nutrient delivery, crop protection, and soil remediation. The correct dosage and activity of NPs on the surface of plant targets present a significant challenge, particularly reducing chemical compounds collected from plant bulk materials, such as mineral fertilizers, which have developed into a useful characteristic that makes NPs use in the future easier. However, there are still several challenges that need to be addressed before the full potential of NPs in agriculture can be realized. One of the key challenges is understanding the physiological, molecular, and biochemical impacts of NPs on plants. While it is known that NPs can be taken up by plants and interact with their cellular components, the specific mechanisms and pathways involved are not yet fully understood.

Extensive studies are needed to unravel the complex interactions between NPs and plants, including their uptake, translocation, and effects on plant growth, development, and metabolism.

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