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REVIEW ARTICLE

Application of nanotechnology and proteomic tools in crop development towards sustainable agriculture

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Abstract

The increase in global population which translates to increased demand for food called for urgent attention from key players and policy makers in agricultural sector. Also, the effects of climate change and its consequent biotic and abiotic stresses in plants has greatly affect the sustainability of agriculture and production of food. These challenges require novel and sustainable approaches to improve the quality and yield of crops. The vast application of nanoparticles in different fields of study is attributed to their distinct chemical and physical characteristics. However, in agriculture, their application is limited because of their safety concern. Currently, research is tailored to study the response of plants to various nanoparticle treatments; however, these studies are inconclusive due to limited knowledge on the mechanisms of plant–nanoparticle interactions. Recently, studies on nanobiotechnology have taken a new dimension from preliminary bioassay experiments to more complex, research-oriented studies using various omics tools. Changes in protein expression caused by plant–nanoparticle interaction at any developmental stages, or tissue types may be investigated using suitable proteomics techniques. This review discussed the various applications of nanotechnology and proteomic tools in plant growth and development. Plant–nanoparticle interactions and the application of nanoparticles and proteomic tools in genetic engineering of plants to attain agricultural sustainability and food safety are also discussed. Informative and thorough understanding of plant–nanoparticle interaction will serve as a blueprint that will enable plant scientist and genetic engineers to develop plant biomarkers and explore their potential application for crop improvement.

Keywords Biomarkers · Food security · Genetic engineers · Nanoantimicrobials · Nanofertilizers · Nanopesticides

Introduction

The global population is growing at an alarming rate and has been projected by the United Nation to reach about 10 billion in 2050 (Chouhan et al. 2021). To meet the food requirements of this growing population, there is a need to increase food production by over 70% and this must come from the currently available arable land which is limited and under severe threat from biotic and abiotic factors alike (Kumar et al. 2021a, b). Consequently, most of this arable land has been converted into land for residential, industrial, and other purposes such as recreational parks and gardens among others making land even less available (Winding et al. 2020). Additionally, traditional agricultural system that relies on the use of manual labour for food production and the conventional system that depends on the use of chemical fertilizer and pesticides are unreliable and cannot be sustained for optimum food security and safety (Kumar et al.

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2021a, b). This is aggravated by the structural reduction in farm productivity in many regions of the world because of chemical efficacy and plant breeding programs to boost yield. This indicates that increasing chemical inputs is not directly proportional to a rise in farm productivity (Busby et al. 2017; Kumar et al. 2020; Singh and Trivedi 2017). As a result, most governmental and non-governmental interventions are geared towards adopting nature-based solutions to address these problems of agricultural sustainability, food security, and food safety (Kumari et al. 2020). Furthermore, global warming and climate change, which result in a constant increase in atmospheric CO_2 levels, as well as the intensity and frequency of various abiotic stresses like drought, extreme temperatures, and flooding, have a significant impact on plant growth, yield, and survival (Raza et al. 2023b; Rivero et al. 2022). In many cases, this leads to a multifactorial stress combination phenomenon (i.e. biotic and abiotic stresses) (Zandalinas et al. 2022). Therefore, there is need for interventions using modern day technology to manage this biotic and abiotic stresses to enhance food security and safety.

Nanotechnology is at the fore front of current technology and innovations in addressing major agricultural and food industry problems (Majumdar and Keller 2021). The United Nations' 2030 Agenda for Sustainable Development include developing crops that are resilience and adaptable to environmental conditions. This is a major strategy for achieving food security, as it optimizes resources through precision farming, reduced yield lost and implementing effective food storage and recycling techniques to reduce waste (Majumdar and Keller 2021). The exceptional characteristics and properties of engineered nanoparticles are being extensively studied in precision agriculture to improve on the nutritional quality and productivity of crops (Seleiman et al. 2020), regulated and selective plant nutrient release (Fellet et al. 2021; Grillo et al. 2021), crops protection against pest (Abdelaziz et al. 2022; Elmer et al. 2018; Lopez-Lima et al. 2021) and improve plants resistance to harsh climatic conditions (Djanaguiraman et al. 2018; Jacobson et al. 2018; Liu et al. 2022).

Various formulation of nanoparticles such as hydroxyapatite, nano-clay, silicon oxide (SiO_2), manganese (MnO), zinc oxide (ZnO), iron oxide (Fe_3O_4), cerium oxide (CeO_2), Molybdenum (MoO_3), carbon nanotubes, and fullerenes, have been reported to promote plant growth and enhance the delivery of macro- and micro-nutrient to plant tissues (Majumdar and Keller 2021). It was reported that nano-formulations have been found to improve active components of soil nutrients by improving their solubility, release rate, and availability within the soil (Kah et al. 2019; Khan and Duke 2001). However, the use of nanoparticles in agriculture has been constrained by a lack of knowledge regarding their uptake, mobilization, transport, and the accompanying biological responses in plants. Climate change, species variation, age, effective dose, duration of exposure, as well as the composition, size, surface coating, shape, stability, and solubility of nanoparticles are factors that affect plants response to nanoparticles (Majumdar and Keller 2021). Due to recent advancements in analytical equipment such as single particle inductively coupled plasma mass spectrometry (sp-ICP-MS), electron microscopy, and synchrotron-based imaging techniques, it is easier to trace and monitor the transport of nanoparticles in plant tissues after foliar or root application (Avellan et al. 2019; Castillo-Michel et al. 2017; Keller et al. 2018). According to Sanzari et al. 2019, unlike their bulk analogues, nanoparticles can penetrate plants' leaves or roots and transcend beyond biological membranes. The chemical mechanisms behind nanoparticle uptake, absorption, and transport in plants, however, are yet unknown (Sanzari et al. 2019).

A clear and thorough understanding of the various biological networks at different levels is important to fully utilize the benefits of nanotechnology for sustainable food production in agriculture (Yin et al. 2018). Due to the high sensitivity and accuracy of analytical and bioinformatics tools, recent studies on nanoparticles–plant interaction have progressed from ordinary single endpoint assays to discovery oriented, high-throughput system biology approaches, referred as “omics” (Quanbeck et al. 2012). Omics technique involve the screening of targeted or untargeted biomolecules in an organism which maybe gene (genomics), mRNA (transcriptomics), proteins (proteomics) or metabolites (metabolomics). Computational biology approach has been used over the years to unravel the molecular mechanisms in plants and reveal the behaviour of genes, proteins, and metabolites in response to environmental stress (biotic or abiotic) (Majumdar and Keller 2021). Proteomic technique has received more attention in precision agriculture recently due to the urgent need to understand the mechanism of complex agronomic traits and plants’ response to nanoparticle application studies. Proteins are the major players involves in signalling and stress response by plant because they are directly involved in cellular homeostasis. Information about the functions and translation of certain regions of plant genomes can be obtain by characterizing their proteins, therefore, proteomics complements transcriptomic and metabolomic for an in depth understanding of the various cellular mechanism in plants.

Plant genome sequencing will lead to a revolution in how we approach issues of food insecurity, safety, and human health in the twenty-first century (Agrawal et al. 2013). *Arabidopsis thaliana* and *Oryza sativa* are just two examples of the numerous plants whose genomes have previously been sequenced and annotated; many others are still being worked on (Kumar et al. 2021a, b). Crop germplasm collections can be characterized using modern technology to increase and sustainably supply food. For instance, the analysis of more than 20,000 wild and domesticated barley genotypes using genotyping and bioinformatics tools demonstrates the utilization of genetic resources in crop improvement (Langridge and Waugh 2019; Milner et al. 2019). Therefore, in this review, we address the numerous ways that nanotechnology and proteomics techniques might be applied to produce food that is safer to meet the need of the growing global population. This review will also provide a database for crop scientists to use as they produce new and improved crop varieties.

Agricultural applications of nanoparticles

Agricultural practices have not yet fully explored the potentials of nanotechnology. There are multiple benefits of nanotechnology in the agricultural sector which include plant growth promoters (nanofertilizers) (Quang and Chuc 2022), nanopesticides, nanoinsecticides, and nanoantimicrobials (Ingle 2021), and nanomaterials for food storage and packaging (Sharma et al. 2017; Singh et al. 2023) among others. One of nanotechnology's goals in agriculture is to improve yield through nutrient management optimization, control release of nutrient in fertilizer and reduced application of chemicals as herbicides or insecticides (Chen et al. 2013; Zhu et al. 2017). Nanomaterials can alter the traits of plants, such as the physiological and biochemical responses of plants which can directly influence plant yield and the quality of produce from the plant (Gardea-Torresdey et al. 2014; Zuverza-Mena et al. 2017). Plant scientists are increasingly becoming interested in agricultural application of nanotechnology due to its beneficial effects (Feizi et al. 2012; Haghighi and Teixeira da Silva 2014). According to Batsmanova et al. (2013) and Scott and Chen (2013), nanoagrotechnology is currently focused on farming that uses nanoparticles with special qualities to increase livestock and crop productivity (Batsmanova et al. 2013; Scott and Chen 2013). In sustainable agriculture, nanotechnology can aid in waste reduction while enhancing plant protection, disease detection, and plant growth monitoring (Mishra et al. 2017). Scientists have recently been working to demonstrate the viability of using nanobiotechnology as a tool for crop improvement through a variety of research projects in numerous sectors. The effectiveness of carbon-based or metallic nanoparticles in terms of absorption, integration, transport, persistence, and effects on growth and development of plant species with varied commercial applications has been the focus of a substantial amount of research. According to some of this study, exposure to nanoparticles encourages plant growth and development (Mishra et al. 2017).

Nanofertilizers

One of the most recent developments in nanotechnology is nanofertilizers; nano-based products with the ability to supply nutrients to crop plants at a controlled rate (Ingle 2021). Unique characteristics of nanoparticles such as reduced particle size and wide surface area may promote improved interaction and effective nutrient absorption for crop fertilization. It is thought that incorporating nanotechnology into fertilizer formulation could enhance effective nutrient absorption, providing considerable economic and environmental benefits (Kumar et al. 2021a, b; Zulfiqar et al. 2019). According to recent research, nanofertilizers slowly and under controlled conditions release nutrients into the soil, assisting in the site-specific target delivery of agrochemicals and reducing the risk of nanomaterial toxicity. (Heinisch et al. 2019; Solanki et al. 2015). For example, Au, SiO_2, ZnO, SnO_2, and TiO_2 nanoparticles have been reported to enhance the growth and development of plants through increased absorption of elements and nutrients (Singh et al. 2017). Additionally, nanofertilizer has been shown to improve the performance of plants in terms of high absorption, an increase in crop production, a rise in photosynthesis rate, and a notable increase in the surface area of the leaves. Eutrophication and water contamination are avoided by controlling the release of nutrients in nanofertilizers (Ingle 2021).

Nanopesticides and nanoantimicrobial

There is a growing concern about the problem of pest and pathogens attack in agriculture (Mohamed and Abd-Elsalam 2018). Biotic factors such as pest and diseases are responsible for yearly loss of about 20–40% of crops. Most management techniques for plant pests and diseases include the use of toxic pesticides and antimicrobials that have a negative impact on people and the environment (Solanki et al. 2015). Also, another shortcoming is the issue of antimicrobial resistance in food crops since most of the conventional antibiotics are no longer effective against these pathogens causing a lot of spending with little or no result (Abd-Elsalam and Prasad 2018; Mohamed and Abd-Elsalam 2018). Furthermore, antimicrobial and pesticide residue in crops is another shortcoming resulting from the use of conventional pesticides and antibiotics. These residues end up with consumers in the food chain, particularly human, and animals resulting in other health challenges. Additionally, the ecosystems, soil, water, and air are also interrupted because of the large-scale usage of these antibiotics and chemicals (Bansal 2011). Due to these numerous challenges resulting from the use of conventional pesticides and antibiotics, there is a need to source for other alternative measures with better efficacy and safety.

Nanopesticides

Recent research aims at producing pesticides with high degradability, solubility, thermal stability with control release of its active constituents (Nuruzzaman et al. 2016). Nanoparticles are active components of nanopesticides used for crop protection against pathogens (Javed et al. 2023). For example, *Rhyzopertha dominica* and *Sitophilus oryzae* which are pest found in stored grains were inhibited by aluminium nanoparticle (Kah et al. 2018). Chitosan nanoparticles was reported to act against cotton *Spodoptera littoralis* (leafworm), *Aphis nerii* (oleander aphid), *Cacopsylla pyricola* (nymphs of the pear psylla), and *Meloidogyne javanica* (rootknot nematode) (Malerba and Cerana 2016; Solanki et al. 2015). Leafhoppers and Jassids (sucking pests) have been controlled using imidacloprid–sodium alginate nanoformulations (Kumar et al. 2014) and Si nanoparticles to inhibit leaf worm (*S. littoralis*) in tomato plants (El-Bendary and El-Helaly 2013).

Nanoantimicrobial

Different literature reports have shown the use of metallic nanoparticles such as Ag, Zn, Ti, and Cu to control microorganisms particularly bacteria and fungi (Daniel et al. 2023; Ingle 2021; Matysiak et al. 2016; Solanki et al. 2015). Silver nanoparticles have been widely used as antimicrobials against different pathogens, including plant pathogens (Mohamed and Abd-Elsalam 2018). The antifungal activity of different particle sizes of Ag nanoparticles against different soil-borne fungi, including *Magnaporthe grisea* and *Bipolaris sorokiniana* was carried out by Jo et al. (2009). The findings from the research showed that silver nanoparticles with particle sizes between 20 and 30 nm had better efficacy because they could penetrate and colonize the inner structure of plant tissues than those with larger particle sizes (Jo et al. 2009). Furthermore, their results also showed improvement in the potential of the nanoparticle to inhibit spore producing fungal pathogens in plants with reduced toxicity than the synthetic fungicides (Jo et al. 2009). Mishra et al. (2017) also studied the antifungal potential of small-sized Ag nanoparticles against phytopathogenic fungus *Bipolaris sorokiniana,* a causative organism for spot blotch disease in wheat crops. The findings show a high inhibition of the pathogen which was attributed to the particle size of the nanoparticle (Mishra et al. 2014). According to a different study, exposure to Ag nanoparticles in the soil matrix reduced the viability and activity of land snails and fungi present within the soil (Ali et al. 2015).

The antimicrobial activity of TiO_2 and ZnO nanoparticles have also been well documented. There are reports on the potential effect of TiO_2 nanoparticles in enhancing plant growth and their possible usage as an antimicrobial agent (Mohamed and Abd-Elsalam 2018). Cui et al. (2009) reported that TiO_2 nanoparticles significantly inhibit the growth of *Psilocybe cubensis* and *Pseudomonas syringae* in cucumber plant with a resultant increase in 30% photosynthetic activity in the plant (Cui et al. 2009). The antimicrobial activity of TiO_2 nanoparticle is attributed to its smaller particle size, shape, and crystal structure (Mohamed and Abd-Elsalam 2018). Other reports postulated that oxidative stress through the generation of reactive oxygen species (ROS) may be linked to their antimicrobial mechanism resulting in site-specific nucleic acid DNA damage in the organism (Albukhaty et al. 2022; Roy et al. 2010; Younis et al. 2023). Various degree of antimicrobial activity of ZnO nanoparticles against different organisms in plants have been reported. According to El-Sawy et al. (2017), different concentrations of ZnO nanoparticles (50, 100, and 200 mg/L) sprayed on eggplant under greenhouse condition caused a significant inhibition of *Cucumber mosaic virus* when compared to other chemicals such as 2-nitromethyl phenol and seaweeds extract. Additionally, morphological, and physiological traits like leaf area, plant height, number of leaves and branches, fruit weight per plant, flowers, and fruits all significantly improve when exposed to nanoparticles (El-Sawy et al. 2017). A good antibacterial agent against the bacterium *Xanthomonas* sp. that causes tomato and rose bacterial spot disease is TiO_2 nanoparticle, either alone or in combination with zinc or silver. Studies conducted in the field and in a greenhouse revealed that rose plants treated with TiO_2/Zn had significantly less severe bacterial spot disease than untreated control plants (Paret et al. 2013a, b).

Applications of nanotechnology in plant stress management

The continual problem of global warming and it effect on the plant has affected a lot of crops causing severe loss farmers. This problem will affect crop production in the future making it even more complex due to the anticipated rise in biotic and abiotic stresses such as salinity, inorganic nutrient imbalances, and heavy metals (Zandalinas et al. 2022). This has also made it difficult to predict plants response to some of these stresses either individually or when combined (multiple stresses) (Zandalinas and Mittler 2022). Apart from initiating distinct physiological and molecular reactions to stress, plants modify multiple metabolic pathways to alleviate the impact of stress on growth and development. Additionally, they adjust to novel energy requirements imposed by varying climatic and environmental conditions (Rivero et al. 2022). Furthermore, several pathogens and pest outbreaks have been associated with changes in climatic conditions such as increase in the frequency and severity of drought, heat waves, or flooding (Markham and Greenham 2021; Salih et al. 2020). Therefore, the present efforts of crop development through traditional and conventional means will not be sufficient to feed the growing human population by 2050. Hence, there is a need to embrace recent technology, which is more reliable and sustainable for crop production (Raza et al. 2023c).

Currently, nanotechnology is gaining more attention as an emerging solution for crop production under abiotic stresses (Iqbal et al. 2020). Although issues about the toxicity of nanoparticles to plants is still a matter of concern, there are limited literatures available to explain the underlining mechanism of action of nanoparticles in plant growth and development. Therefore, in this section, we provide an overview of the various applications of nanoparticles to ameliorate abiotic stress conditions in plants.

Response of plant to different abiotic stress is affected majorly by the degree of stress, duration of exposure and age or developmental stage of the plant (Ding and Yang 2022; Rivero et al. 2022; Zandalinas et al. 2021). Exogenous use of plant modulators to reduce stress induces undesired effects which can have adverse effects on plant performance at different phenological stages. Current research has shown a development–dependent response of plants to various types of exogenous materials in terms of accelerating or delaying growth indices (Kupke et al. 2022; Ostrowska et al. 2021; Ranjan et al. 2022). Recent studies focuses on the use of appropriate amount of nanoparticles for ameliorating the antagonistic effects of abiotic stress such as drought and salinity (Abdelsalam et al. 2023; Usman et al. 2020; Zahedi et al. 2023; Zulfiqar and Ashraf 2021). Several types of nanoparticles such as Ag and ZnO nanoparticles have been reported to activate the antioxidant defence systems indifferent plant tissues, decreasing the amount of reactive oxygen species (ROS) and improving plants growth (Acharya et al. 2020; Mahakham et al. 2017; Szőllősi et al. 2020; Waqas Mazhar et al. 2022). However, nanoparticles-mediated alleviation of various stresses highly depends on the amount of nanoparticles applied, species and age of plant (Raza et al. 2023b). The mechanisms showing nanoparticles-induced effects on different developmental stages of stressed plants are shown in Fig. 1.

During seed priming with nanoparticles, the nanoparticles can be absorbed through the seed coat, enhancing water uptake, and hence increasing the rate of germination. Exposure of the seeds to nanoparticles can also induce oxidative respiration, leading to the generation of ROS such as H_2O_2, which acts as a signalling molecule to stimulate seed germination-associated metabolic pathways, including increasing the activities of α-amylase and Gibberellin (GA) biosynthesis and decreasing abscisic acid (ABA) biosynthesis. Moreover, the antioxidant defence system is activated via ROS signalling pathway. Foliar and soil application of nanoparticle can also improve plant growth through ROS signalling pathway enhancing seed viability, and seed quality (Raza et al. 2023b).

It has been reported that seed priming with nanoparticles instead of bulk or ionic materials enhances sprouting and seedling development (Abbasi Khalaki et al. 2021; do Espirito Santo Pereira et al. 2021; Kandhol et al. 2022). Sprouting of seed is a very crucial and important stage of seed development as different metabolic adjustments and

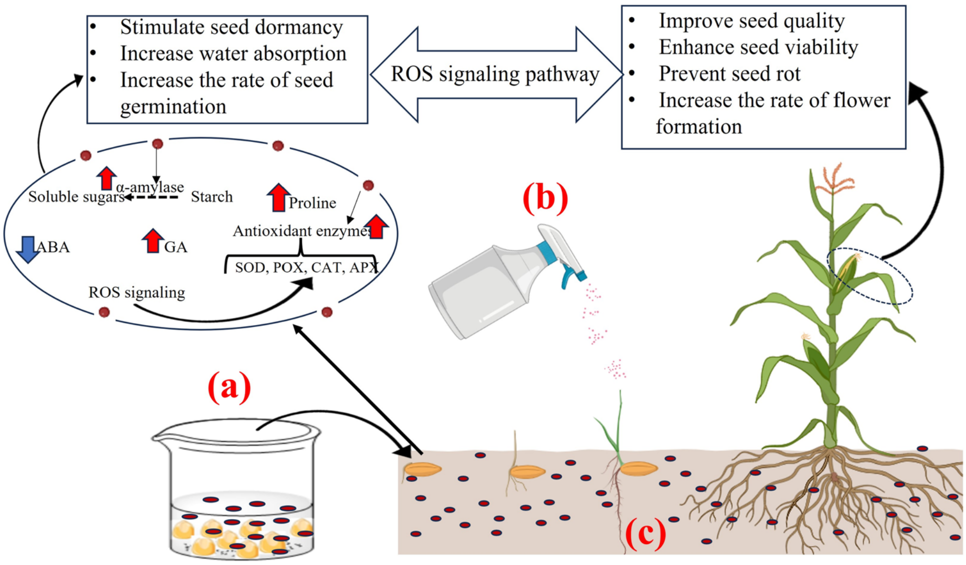

Fig. 1 A schematic diagram of a proposed mechanism of environmental stress mitigation through nanoparticle application at different stages of plant development. Three common route of nanoparticle applications include **a** seed priming with nanoparticles, **b** foliar spray as nanopesticides or nanoantimicrobials, and **c** soil mix with nanoparticles/soil irrigation in the form of nanofertilizers. Red and blue arrows show up and down regulations, respectively (Raza et al. 2023b)

nutrients needed to survive the harsh environmental stresses are accumulated at this stage. Nanoparticles can break seed dormancy by increasing the rate of nutrient and water uptake, activating enzymes such as catalase (CAT), superoxide dismutase (SOD), amylases and proteases, thereby triggering plant defence systems in the presence of environmental stresses (Acharya et al. 2020; Mahakham et al. 2017; Szőllősi et al. 2020). This series of event might improve seed vigour which may be required at seedling development stage. Priming seeds with metallic nanoparticles have been become a common practice; for example, it was reported that there was an up regulation of α-amylase activity which increases soluble carbohydrate content at seedling stage when *Oryza sativa* seeds were primed with Ag nanoparticles (Mahakhamet al. 2017). Furthermore, priming of rapeseed (*Brassica napus* L.) seeds with 25, 50 and 100 ppm of ZnO nanoparticles increased seed germination indices under 150 mM NaCl stress due to enhanced proline and soluble sugar contents (El-Badri et al. 2021). Another study by El-Badri et al. (2021) shows the regulation of abscisic acid (ABA) and gibberellin gene expression in germinating grape seeds primed with Se and ZnO nanoparticles under salt stress increasing the rate of germination of the seeds when compared to the unprimed and water primed seeds. *Oryza sativa* seeds primed with 25 ppm of ZnO nanoparticles shows a significance increase in growth and yield under drought stress compared with the unprimed seeds (Waqas Mazhar et al. 2022). It was also reported that priming of *Zea mays* seed with ZnO nanoparticles under drought stress increased the osmo-protectant levels, including proline and antioxidant enzymes such as SOD, CAT and POD (peroxidase) (Waqas Mazhar et al. 2022). Similarly, priming of *Zea mays* seeds with 60 ppm of TiO_2 nanoparticles influenced the germination rate and seedling vigour under salt stress, because of increase in antioxidant enzyme activities (Shah et al. 2021). Also, seed priming with nanoparticles has been reported to minimize damage to the photosynthetic parameters and ultrastructural changes in plant cells under unfavorable conditions by activating H_2O_2 signaling and the antioxidant defence system (Salam et al. 2022). According to Li et al. (2022), plants are better equipe to withstand stress when nanomaterials such carbon nanotubes are used. For instance, 90 ppm of multi-walled carbon nanotubes (MWCNT) were reported to improve grape (*Vitis vinifera* L.) seeds' ability to withstand salinity stress enhancing germination rate and seedling development. This improvement was majorly attributed to malondialdehyde (MDA) content and a decrease in tolerance capacity caused by the antioxidant enzyme system being activated (Li et al. 2022). Martínez-Ballesta et al. (2016), reported that treatment of broccoli (*Brassica oleracea* L.) seedling under salt stress with MWCNT led to higher aquaporin transduction, which increases the rate water uptake and net CO_2 adjustment. The study concluded that environmentally friendly nanopriming techniques can improve the rate of seed germination by increasing water intake through nanopores, strengthening the antioxidant system, and speeding up starch hydrolysis. Nanoparticles application at the seedling stage can alleviate growth decreases due to stress. The probable mechanism of the nanoparticles' activity at this stage of development is consistent with seeds germination (Raza et al. 2023b). Foliar treatment of *Cucumis sativus* L. seedlings with ZnO nanoparticles under drought stress was reported to increase plant biomass in a pot experiment. This was attributed to increase in enzymatic and nonenzymatic antioxidant activities by the nanoparticles to decrease ROS production and, therefore, MDA content (Ghani et al. 2022). Similarly, application of ZnO nanoparticles to wheat (*Triticum aestivum*) under salinity stress at the vegetative and maturity stages was reported to enhance growth related indices such as fresh and dry weights, yield, and photosynthetic pigments (Adil et al. 2022). The use of functionalized nanoparticles to control biotic and abiotic stresses in plants is gaining more attention recently. Various studies have shown their role in enhancing plants' response to forms of stress (Raza et al. 2023b, b). For instance, application of 50 ppm functionalized graphene oxide with glycine betaine reduces the severe effects of salinity stress in sweet basil (*Ocimum basilicum* L.) with a resultant change in the metabolite's profiles, antioxidant enzymes, and membrane integrity of the plant (Ganjavi et al. 2021).

Nanoparticles can change the metabolic processes of plants beyond the physiological and biochemical state of seed germination (Li et al. 2021). In a study carried out by Kasote et al. (2019), *Citrullus lanatus* L. seedlings treated with Fe nanoparticles show an increase in nonenzymatic antioxidant activities which in turn activated jasmonate-associated defence response in the plant. This shows the potential of Fe nanoparticles to stimulate signaling pathways in plants. Additionally, it was reported that application of ZnO and single-walled carbon nanotubes (SWCNT) to *Sophora alopecuroides* seedlings enhances their salinity stress tolerance by altering their glycolytic and carbon/nitrogen metabolic pathways, and citric acid cycle to generate which is use by the plant for their growth and development (Wan et al. 2020). Different abiotic stresses affect reproductive stage of plant development; a vital stage of flowering plants (Salehi et al. 2022). Reports have shown the vulnerability of major developmental stage of plants such as phase transition, flowering initiation, sporogenesis, and gametogenesis to environmental stresses, which can render the male plant (staminate) sterile and cause abortion of seed (Raza et al. 2023a, b; Salehi et al. 2022). Few reports have reported on the effect of nanoparticles on the reproductive stage of plant development under different stress conditions. Conversely, the timely application of nanoparticles can enhance plant yield, in addition to seed viability and healthy fruit. For instance, Ghorbanian et al. (2017) reported that foliar application of SiO_2 and TiO_2 nanoparticles to barley significantly increases the weight of the seed and yield under drought. Furthermore, Elsheery et al. (2020) reported that foliar treatment of a full bloom *Mangifera indica* L. trees with 50–150 ppm of ZnO and Si nanoparticles after a month of applying NaCl stress shows a significant increase in growth parameters, nutrient absorption, carbon assimilation, proline content, and antioxidant enzyme activities resulting in a consequent decrease in flower deformity and seed abortion of the plant. Application of Fe nanoparticles to soil was reported to upregulate genes associated with photosynthesis and downregulation of oxidative stress associated genes in *Triticum aestivum* L. under combined cadmium and drought stress, hence improving growth and grain productivity (Adrees et al. 2020). In another by Dimkpa et al. (2017), it was reported that foliar and soil application of three micronutrient nanoparticles (ZnO, B_2O_3, and CuO) 3 weeks post germination increased growth and grain yield of wheat by 33–36% under drought stress. According to their report, soil application of nanoparticles was more efficient as compared to foliar application (Dimkpa et al.2017). Nevertheless, there is need for further study on the effect of nanoparticles on the reproductive stage of plants under different kinds of stress conditions. In conclusion, application of nanoparticles either through seed priming or foliar application regulates the molecular mechanisms of seed germination, seed dormancy breakage and plants development by upregulating the expression levels of oxidative stress-associated genes, proteins and metabolites accumulation to strengthen defence system-mediated tolerance (Fig. 1), hence enhancing plants to withstand the different environmental stresses through modulation of key signaling molecules such as H_2O_2 and other transcription factors associated with stress regulation. Though studies about the various mechanism involves in the interactions of nanoparticles and the various stage plant development has received little attention over the years; future work should consider the molecular study of this processes using various omics tools to analyze the various changes involves in the phenotypic and agronomic faces of plant tolerance to various abiotic stresses.

Absorption, translocation, and fate of nanofertilizers in plants

There is a growing interest in research to understand the absorption, translocation, and fate of nanoparticles used as nanofertilizer in plants (Ingle 2021; Solanki et al. 2015). This is because accumulation of nanoparticle in plant is proportional to its phytotoxicity in the ecosystem (Giorgetti 2019; Jogaiah et al. 2021; Remédios et al. 2012). The most stable metallic nanoparticles during absorption are TiO_2 and SiO_2, while ZnO and CuO may undergo transformation (Solanki et al. 2015). No matter the species of a plant, the root system absorbs and transports ZnO^{2+}, Cu^{2+}, Al^{3+}, Ag^{2+}, and Fe_3O_4 nanoparticles to the foliar section of the plant. Rico et al. (2011) demonstrated the species-dependent absorption of nanomaterials in plants, including CeO_2 and $Ni(OH)_2$ nanoparticles in both the stem and the leaves and Al, Ag, Cu, and ZnO nanoparticles in the leaves (Figs. 2, 3). Additionally, magnetic nanoparticles behave differently in plants' systems (Rico et al. 2011). The type of growth medium affects how magnetic nanoparticles are absorbed. In contrast to sand, hydroponic medium showed a greater absorption, which may be due to magnetic nanoparticles' adhesion to the soil (Solanki et al. 2015).

The diameter of the cell wall pore determines whether nanoparticles can enter the cellular components of plants. The effectiveness of translocation is affected by the size of the employed nanoparticles. If a nanoparticle's size is less than the size of the pores in the cell wall, it can readily enter the cell and pass through to the plasma membrane. A particle may aggregate if it is larger than the pore in the cell wall, which would prohibit the plant from absorbing the nanoparticle. In this situation, the nanoparticle can be functionalized, which could help enlarge the existing pores in the cell wall or perhaps create new ones (Ingle 2021; Rico et al. 2011). As a result, the large particle enters the plant system more easily. According to studies conducted by Panpatte et al. (2016) and Mali et al. (2020), plant cells can take up nanoparticles by binding to carrier proteins, aquaporins, ion channels, or endocytosis (Mali et al. 2020; Panpatte et al. 2016). In addition, nanoparticles can enter the plant cell by forming a complex with membrane transporters or by dispersing through the root exudates (Guleria et al. 2022; Kumari et al. 2020). Additionally, research from other studies demonstrates that nanoparticles can enter the plant system through the leaf stomata or trichome (Burkhardt et al. 2012; Eichert et al. 2008; Fernández and Eichert 2009).

Through biotransformation within or outside the cell, nanoparticles are also transported into the plants. Diffusion or aqueous pores are the two ways that the solutes can reach the plant system (Lv et al. 2020). The nanoparticles target many cytoplasmic organelles after entering the plant cell, interfering with the plant metabolic process (Ingle 2021). For instance, TiO_2 nanoparticles were found in the parenchyma and vascular tissues after their absorption by the root in wheat (Larue et al. 2011). The internalization and upward translocation of ZnO nanoparticles within *Lolium perenne* (ryegrass) cells were also reported (Lin and Xing 2008). According to their report, ZnO nanoparticles may move upward from the cells of ryegrass root to the vascular tissues of the plant. Absorption and accumulations of ZnO nanoparticle in *Glycine max* seedlings treated with 500–4000 ppm of

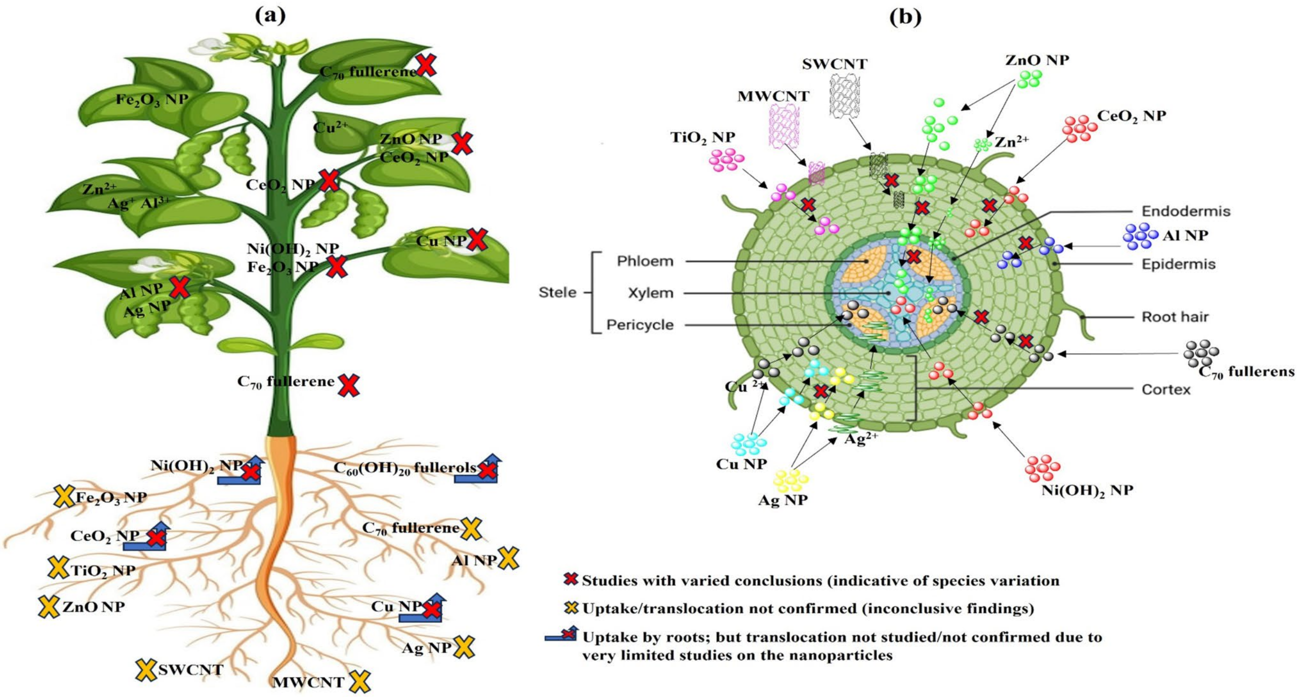

Fig. 2 Absorption, translocation, and biotransformation pathway of nanoparticles in a plant: **a** selective absorption and translocation of nanoparticles via various routes; **b** transverse cross section of root showing differential absorption and interaction of various nanoparticles on exposure

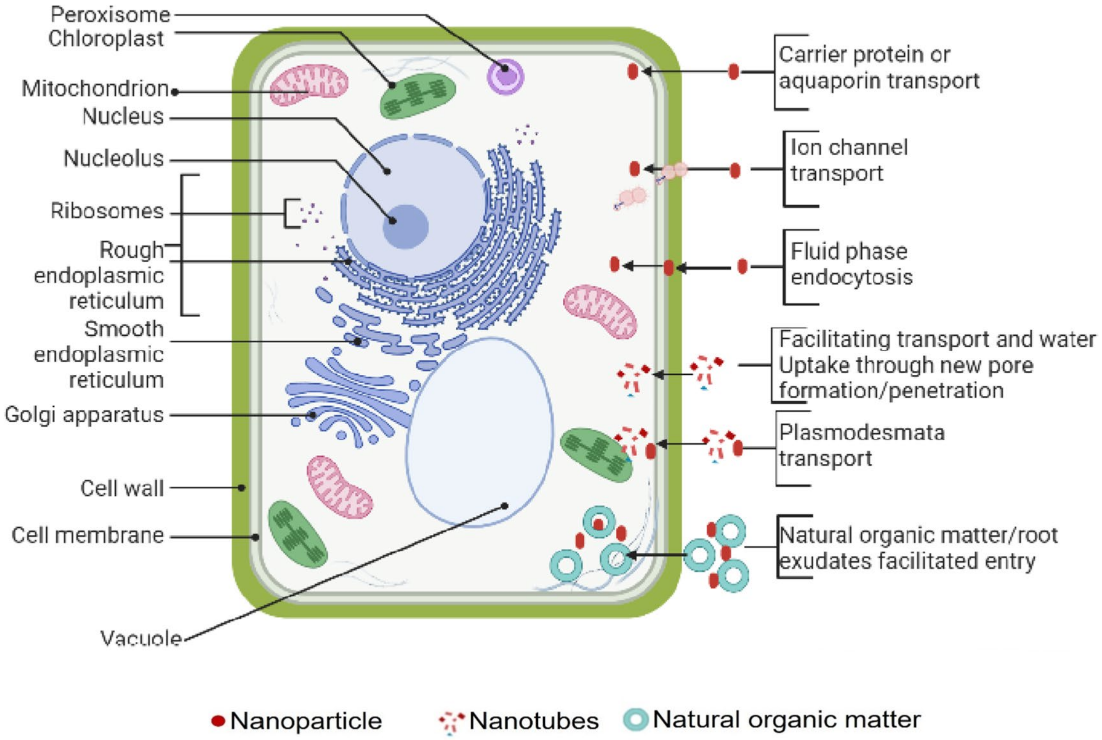

Fig. 3 Possible mode of absorption of nanoparticles at cellular level in plant

the nanoparticle was reported by Lopez-Moreno et al. 2010). The report shows a higher absorption of ZnO nanoparticles at 500 ppm. It was reported that at higher concentration, the nanoparticle agglomerated hence, preventing their absorption by the seed through the cell pore (López-Moreno et al. 2010). Further study using X-ray absorption spectroscopy shows the localization of Zn^{2+} in the plant rather than ZnO nanoparticles suggesting the role of the root system in surface ionization of ZnO. Furthermore, using high-magnification transmission electron microscopy, they found ZnO nanoparticle in the cytoplasm, apoplast, and nuclei of the vascular cylinder and endodermal cells of the plant (López-Moreno et al. 2010).

Magnetic nanoparticles absorption by plants is influenced by the type of growth media. In pumpkin plants, absorption, translocation, and accumulation of Fe_2O_3 nanoparticles was higher in hydroponic growth medium when compared to sand. Plant grown in the soil absorb low amount of the nanoparticle due to the adherence of the magnetic nanoparticle to sand and soil grains (Zhu et al. 2008). In contrast, no nanoparticle absorption was reported in treated lima bean plants, suggesting that plant species may also play a role in nanoparticle absorption (Solanki et al. 2015). Another study demonstrated that due to the magnetic nanoparticles' large particle size, pumpkin plants were unable to absorb them (Wang et al. 2011). Corredor et al. (2009) studied the effect of functionalization on the absorption of nanoparticle in through application of carbon-coated Fe nanoparticles to the leaf of pumpkin plant. It was observed that the epidermal cell of the plant contains the nanoparticles, but no trace of the nanoparticle was found in the xylem (Corredor et al. 2009). Additionally, Lee et al. (2008) reported on the absorption and translocation of Cu nanoparticle in wheat and mung bean cultivated in agar medium. Their research demonstrates how Cu nanoparticles migrate across cell membranes and aggregate inside of cells (Lee et al. 2008). Most studies on other nanoparticles are only conducted up to the germination stage of the plants, in contrast to the studies on TiO_2 and ZnO nanoparticles, which have significant information on their absorption, translocation, and accumulation. Determining the full potential of nanotechnology applications in agriculture requires a complete understanding of the destination of nanoparticles in plants, a topic that is still unexplored (Martin-Ortigosa et al. 2012). The possibility for internalization via cell walls without the use of mechanical force has since been studied in several research report, including those that used biolistic, ultrasound, vortexing, or electroporation (Rico et al. 2011). One of these studies used mesoporous silica nanoparticles to help deliver plasmid DNA to Arabidopsis roots; another used double-layered hydroxide clay nanosheets to help deliver RNAi molecules to *Nicotiana tabacum*; and a third used DNA origami nanostructures to help deliver siRNA to *Nicotiana benthamiana* (Rico et al. 2011). These studies used fluorescence microscopy, phenotypic pest resistance, and mRNA and protein levels quantification to demonstrate the transport of biomolecules. The delivery of plasmid DNA and siRNA into various types of model and non-model plants has been reported in recent studies to use carbon nanotubes (CNTs), particularly single-walled CNTs (SWCNTs) (Demirer et al. 2019a, b; Kwak et al. 2019). The transport of plasmid DNA and GFP transgenic expression targeting the nuclear genome with mRNA and protein-level measurement is made easier by CNTs, as demonstrated by Demirer et al. (2019a, b). Based on fluorescence microscope imaging, Kwak et al. (2019) confirmed the delivery of plasmid DNA using CNTs and the transitory expression of the YFP transgene in the chloroplast. It is interesting to note that CNTs can be found in extracted chloroplasts, protoplasts, and whole leaves (Demirer et al. 2019a, b; Kwak et al. 2019). This remarkable discovery may be attributable to CNTs' size, surface chemistry, and charge all of which can help direct the particle to its many subcellular targets (Giraldo et al. 2014; Wong et al. 2016). It was found that positively charged CNTs localized in the chloroplasts and nuclei of the leaves were functionalized with polyethyleneimine polymers. The surface of CNTs was functionalized using chitosan polymer derivatives for chloroplast gene transport, on the other hand. The physical and chemical characteristics that influence the nuclear and subcellular locations of these nanoparticles must, therefore, be further investigated to better tailor them for varied tissue use. Fascinatingly, both investigations demonstrated the protection of plasmid DNA cargo from endonuclease degradation regardless of the surface chemistry of the CNTs, resulting in temporary gene expression, a characteristic that can be valuable for plant scientists and genetic engineers (Giraldo et al. 2014).

Application nanobiotechnology in agriculture to enhance plant breeding and crop productions

Nanobiotechnology is an emerging multidisciplinary field of scientific research that incorporates nanotechnology with biology. It involves the use of nanotechnological skills to modify living organisms to enable the interactions of biological and nonbiological materials (Priyanka et al. 2020). Different crop management techniques have been improved significantly using nanotechnology-based agrochemicals. Nanotechnology helps in increasing the efficacy of pesticides, herbicides, and fertilizers through controlled release, and under environment friendly manner. In a previous study, chitosan and sodium alginate was used for encapsulation of imidacloprid which resulted in enhancement of its efficacy in soil applications (Lugani et al. 2021). The technology promises to improve plant pathogen detection, targeted genetic engineering, enhances conservation and management of crop productions (Pramanik and Pramanik 2016). This technology can also be used to improve crop yield by developing healthy seeds and improving the effectiveness of fertilizers and pesticides (Lugani et al. 2021). It is also used for soil and water cleaning, remediation, and genetic engineering and molecular-based crop breeding to enhance crop production (Parisi et al. 2015; Wani and Kothari 2018). Nanocarriers are used for controlled release of plant growth regulators, herbicides, and pesticides. In a recent study, treatment of mustard plant (*Brassica juncea*) with atrazine (using polyepsilon caprolactone as carrier) nanocapsules showed improved herbicidal activity, decreased photosynthetic rates and stomatal conductance, increased oxidative stresses, weight loss, and growth reduction (Lugani et al. 2021).

Nanoparticle-mediated DNA or gene transfer in plants has been used for developing insect resistant plant varieties by some researchers (Raza et al. 2023a). Conventional plant breeding is a time-consuming and arduous process that demands substantial labour to expand the genetic diversity and enhance crop quality. Within this framework, agricultural production may be augmented by the utilization of nanoparticle-mediated genetic engineering methods. These approaches involve the incorporation of favourable genetic traits or characteristics into crops, rendering them resilient to climate change (Cunningham et al.2018). Genome editing plays a crucial role in enhancing agricultural productivity, boosting desirable characteristics, and enhancing crop resilience to both biological and environmental stress such as drought and salt (Chennakesavulu et al. 2021; Joshi et al. 2020; Nazir et al. 2022; Tariq et al. 2023; Yaqoob et al. 2023; Zaman et al. 2023). Genome editing techniques such as zinc-finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), and clustered regularly interspaced short palindromic repeats (CRISPR) are highly precise and efficient tools that have revolutionized the field of nanobiotechnology and agriculture. The CRISPR/Cas approach has demonstrated superior outcomes compared to ZFNs and TALENs in terms of ease of use and the ability to target several genes simultaneously (Raza et al. 2023a). TALENs and ZFNs are complex and very expensive, as well as their tendency to produce large number of off-target score. On the other hand, CRISPR/Cas is a simple and cost-effective technique that presents new opportunities for plant breeding (Gao et al. 2020; Yaqoob et al. 2023). The CRISPR/Cas technology facilitates the expedited process of plant breeding and the creation of mutant plant libraries (Chen et al. 2019). Efficient transformation and rejuvenation techniques are crucial for focused alteration of desired traits when utilizing genome editing technologies. Although *Agrobacterium tumefaciens*-mediated transformation is commonly employed, its implementation can be arduous and time-consuming, thereby necessitating the exploration of alternative methodologies (Raza et al. 2023a).

An efficient delivery technique is necessary for introducing chemicals such as DNA and RNA into plant cells when utilizing CRISPR technology for plant genome editing. The usual method for accomplishing this involves the use of plasmids or RNA protein complexes delivered via gene gun Agrobacterium, cationic delivery, or viral infection (Sharma and Lew 2022). Nevertheless, the use of ribonucleoprotein complexes exhibits reduced off-target scores compared to plasmid-based delivery reagents when introduced into plant cells (Raza et al. 2023a). Moreover, recent advances in nanotechnology can enhance the delivery of genetic materials to plants for gene editing purposes (Hofmann et al. 2020). This technology has become a useful tool in genetic engineering of plants to deliver useful genetic material such as RNA and DNA independently or in combination with other nanomaterials (Mujtaba et al. 2021). For example, single guide RNA (sgRNA), a CRISPR reagent, was delivered into a plant genome using carbon nanocarriers for effective gene knockdown (Demirer et al. 2020). The carrier (Cas9 nanosystem) is specifically designed for precise targeting of tissues and cells. Additionally, lipid nanoparticles can carry Cas9/sgRNA complexes and Cas9 ribonucleoprotein to tissues, enhancing genome editing procedures (Cheng et al. 2020). Unique characteristics of the Cas9 delivery method include stability, remarkable editing efficiency and absence of off-target mutations (Qiu et al. 2021). Alternative approaches for delivering genome editing agents into specific tissues involve the use of nanoparticles composed of poly (lactic-co-glycolic acid) that encapsulate CRISPR/Cas9 plasmids (Jo et al. 2020). Nanoparticles have been used in gene knockout using Cas9 and gene knock-in into the genome of an organisms (Chou et al. 2020). Since most of these studies have been conducted in animal or mammalian cells, it is necessary to investigate their potential in plant cells.

Nanobiotechnology methods, particularly the use of nanoparticles, have enhanced the precision of plant breeding by generating novel gene combinations and expediting the removal of undesirable genes from vast populations (Pérez-de-Luque 2017). The process of magnetofection including the usage of transgene–nanoparticle complexes that are bioconjugated has been reported in dicot plants (Zhang et al. 2019). The use of nanocarrier in plants has shown great potential in transporting nanoparticles and other useful genetic materials into plant cells without causing any harm to the tissues (Santana et al. 2020).

Speed breeding has emerged as a promising method for creating more cultivars quickly under normal conditions (Watson et al. 2018). Hence, combining genome editing, speed breeding, and nanoparticles can accelerate the breeding cycle and improve crop production (Ahmar et al. 2021).

Chimerically edited plants can be generated by delivering genome editing reagents and then subjected to speed breeding methods to develop many generations in a short time under controlled conditions for regeneration as transgene-free plants (Ahmar et al. 2021). A recent report demonstrated that CRISPR plasmids coated with carbon dots on the surface could be carried into plant cells through the foliar spray, leading to the successful editing of target genes (Doyle et al. 2019). Future studies should investigate editing stress-inducible genes via nanoparticle-mediated genome editing to boost crop productivity under stress conditions.

Studies have shown that previous research has examined the distribution of a nano-biomolecule bioconjugated complex in a manner that does not cause harm or alteration to cells and does not have negative effects on plants or the environment (Busch et al. 2019; Hu et al. 2020; Sapsford et al. 2013). These nanocarriers can transport payloads to organelles while causing little residual effects on daughter cells (Hu et al. 2020). Hence, the integration of plant nanotechnology, speed breeding, and genome editing presents a highly promising strategy for efficiently generating stress-tolerant plants to sustain the ever-growing human population. Efficiently improving and creating interconnected systems are crucial for benefiting mankind, such as the transportation of genome editing DNA and nanoparticles.

Using proteomic tools to study plant–nanoparticle interaction

A comprehensive study of the proteins in plants in response to nanoparticles can clarify the interactions between various mechanisms involved in the regulation of metabolites in plant cells by efficiently screening candidate proteins and associated pathways. Untargeted proteomics has been used in several studies to determine important proteins of plants that are involved in cellular signalling or stress responses linked to nanoparticles. In this section of the review, we provide an overview of different studies that employed proteomic tools to study the changes in plant proteins because of their interaction with different metallic nanoparticles (Table 1 and Fig. 4).

Different studies have reported on the effect of ZnO nanoparticles on various plant proteomes. In soybean seedlings treated with 10, 50, and 100 ppm of biosynthesized and chemically synthesized ZnO nanoparticles, Mustafa et al. (2023) found that protein folding, hormone and redox metabolism were changed. Furthermore, they reported that the amount of *HSP70* protein and an accumulation of ascorbate peroxidase and peroxiredoxin increases soybeans treated with biosynthesized ZnO nanoparticles than seedlings treated with chemically synthesized ZnO nanoparticles (Mustafa et al. 2023). Sawati et al. (2022) reported that proteins associated with transport, stress response, photosynthesis, and glycolysis were severely altered in *Brassica napus* treated with 5, 10, and 15 mg/L of ZnO nanoparticles and Hossain et al. (2016) reported on the down regulation of mRNA expression level and GDSL motif lipase 5 in soybean treated with 500 ppm of ZnO nanoparticles. In a different investigation, the proteomic analysis of *Nicotiana tabacum* var. Burley exposed to 50 ppm of Ag nanoparticles for 7 days led to the regulation of proteins associated with defense and oxidative stress response in the plant's roots and energy and carbohydrate metabolism, photosynthesis, and electron transport chain in plant's leaves (Peharec Štefanić et al. 2019). The amount of mRNA expression levels and GDSL motif lipase 5 protein in soybean decreased after 3 days of treatment with 50 ppm of Ag nanoparticles (Hossain et al. 2016). Several distinct proteins involved in transcription, protein synthesis/degradation, cell wall destruction, and apoptosis were discovered in rice (Oryza sativa) treated with Ag nanoparticles for 20 days (Mirzajani et al. 2014). Accordingly, a proteomic study of *Lycopersicon esculentum* L treated with 100 ppm of TiO_2 nanoparticles was reported to cause changes in photosynthesis-related proteins and plasma membrane intrinsic protein of the plant (Cevik 2023) while *Solanum lycopersicum* treated with nanoporous quercetin-loaded silicon-stabilized hybrid lipid for 35 days caused an alteration in proteins involved in cytoprotection against oxidative and chromatin remodelling of the plant (Guerriero et al. 2023). According to a proteomic study of soybean roots treated with 200 mg/L of Quantum dots Cd nanoparticles, 99 proteins were over expressed while 44 were under-expressed, respectively, (Majumdar et al. 2019). The affected proteins are involved in urate oxidation, TCA cycle, ATP synthesis-coupled proton transport, and glycolysis in plants. β-oxidation of fatty acids, sphingosine, jasmonic acid, and lignin biosynthesis involved in stress signalling pathways were over expressed (Majumdar et al. 2019).

Although studying plant proteomes can provide a wealth of knowledge, so far, research on nanoparticles focused mainly on toxicity. To understand the biological process involved in the change of KAuCl4 to Au nanoparticles in a young plant such as *A. thaliana* plants, gel-based proteomics and transcriptomics was used (Tiwari et al. 2016). Trypsin was used to break down about 10–15 spots from 2DE samples of roots and shoots into peptides, which were then examined using MALDI–TOF–MS. In plant tissues, Au nanoparticles had an impact on oxidative stress, electron transport chain activity, and glucose metabolism. GSTs may be crucial in regulating oxidative stress during the conversion of Au^+ to Au nanoparticles since they are produced in response to increased Au accumulation in *A. thaliana* shoots. In *Phaseolus vulgaris* plants, 2 week treatment with 250–1000 mg/L of CeO_2 nanoparticle through foliar spray and root absorption had a substantial impact on energy

Table 1 Summary of the effects of nanoparticles on protein expression of plants

Types of nanoparticles	Size (nm)	Plants	Routes of application	Treatment period (days)	Concentration	Parts of plant analysed	Regulated proteins/ pathways implicated	References
ZnO	360	Soybean	Root	2	10, 50, and 100 ppm	Root	Hormone metabolism, protein folding, and redox metabolism. Increase in ascorbate peroxidase and peroxiredoxin, heat shock proteins	Mustafa et al. (2023)
ZnO	300	Soybean	Root	2	10, 50, and 100 ppm	Root	Protein folding, hormone and redox metabolism. Decrease in heat shock protein 70 (HSP70)	Mustafa et al. (2023)
TiO_2	30	*Lycopersicon esculentum* L	Leaf	2	100 ppm	Leaf	Photosynthesis-related proteins and plasma membrane intrinsic proteins	Cevik (2023)
Nanoporous quercetin-loaded silicon-stabilized hybrid lipid	100	*Solanum lycopersicum*	Leaf	35	4 mg/50 mL of formulation	Leaf	Proteins involved in cytoprotection against oxidative and chromatin remodelling	Guerriero et al. (2023)
ZnO	30	*Brassica napus*	Leaf	30	5, 15, and 25 mg/L	Leaf	Photosynthesis-associated proteins, glycolysis and transport proteins, and stress response were severely altered	Sawati et al. (2022)
Ag	50	*Nicotiana tabacum* var. Burley	Root	7	50 ppm	Root and leaf	Defense and oxidative stress response in root and energy and carbohydrate metabolism, electron transport chain, and photosynthesis in leaf	Peharec Štefanić et al. (2019)

Table 1 (continued)

Types of nanoparticles	Size (nm)	Plants	Routes of application	Treatment period (days)	Concentration	Parts of plant analysed	Regulated proteins/ pathways implicated	References
CdS Quantum dots	8	Soybean	Root	14	200	Root	Transmembrane proteins, ATP-dependent ion transporter and other metabolic pathways such as TCA cycle, fatty acid oxidation, and amino acid biosynthesis pathways were regulated	Majumdar et al. (2019)
CeO_2	10–30	*Phaseolus vulgaris* L	Root	14	250–2000 mg/L	Leaf	Photosynthesis, carbon fixation, oxidative stress and protein biosynthesis, and turnover	Salehi et al. (2018)
Au		*Arabidopsis thaliana*	Root	5	10 ppm	Root and shoot	Oxidative stress response in root and oxidative stress response, carbohydrate metabolism, pentose phosphate shunt, electron transport chain in shoot	Tiwari et al. (2016)
Al_2O_3	30–60	Soybean	Root	3	500 ppm	Root and leaf	Oxidation–reduction cascade-related genes, such as GDSL motif lipase 5, SKU5 similar 4, galactose oxidase, and quinone reductase	Hossain et al. (2016)
ZnO	< 50	Soybean	Root	3	500 ppm	Root and leaf	mRNA expression levels and GDSL motif lipase 5 abundance proteins were regulated	Hossain et al. (2016)
Ag	15	Soybean	Root	3	50 ppm	Root and leaf	Decrease in mRNA expression levels and GDSL motif lipase 5 abundance proteins	Hossain et al. (2016)

Table 1 (continued)

Types of nanoparticles	Size (nm)	Plants	Routes of application	Treatment period (days)	Concentration	Parts of plant analysed	Regulated proteins/pathways implicated	References
Al_2O_3	30–60	Soybean	Root	3	50 ppm	Root	Protein synthesis/degradation, glycolysis, and lipid metabolism. NmrA-like negative transcriptional regulator was up-regulated, and flavodoxin-like quinone reductase was downregulated	Mustafa et al. (2015)
CeO_2	67	*Phaseolus vulgaris* L	Root	96–102	`62.5–500 ppm	Seed	Storage, carbohydrate metabolism, protein folding, defense response, Fe binding	Majumdar et al. (2015)
Ag	18	*Oryza sativa*	Root	20	30.60 mg/L	Whole plant	Oxidative stress, Ca^{2+} regulation and signalling, transcription, Protein degradation, cell wall damage, apoptosis	Mirzajani et al. (2014)

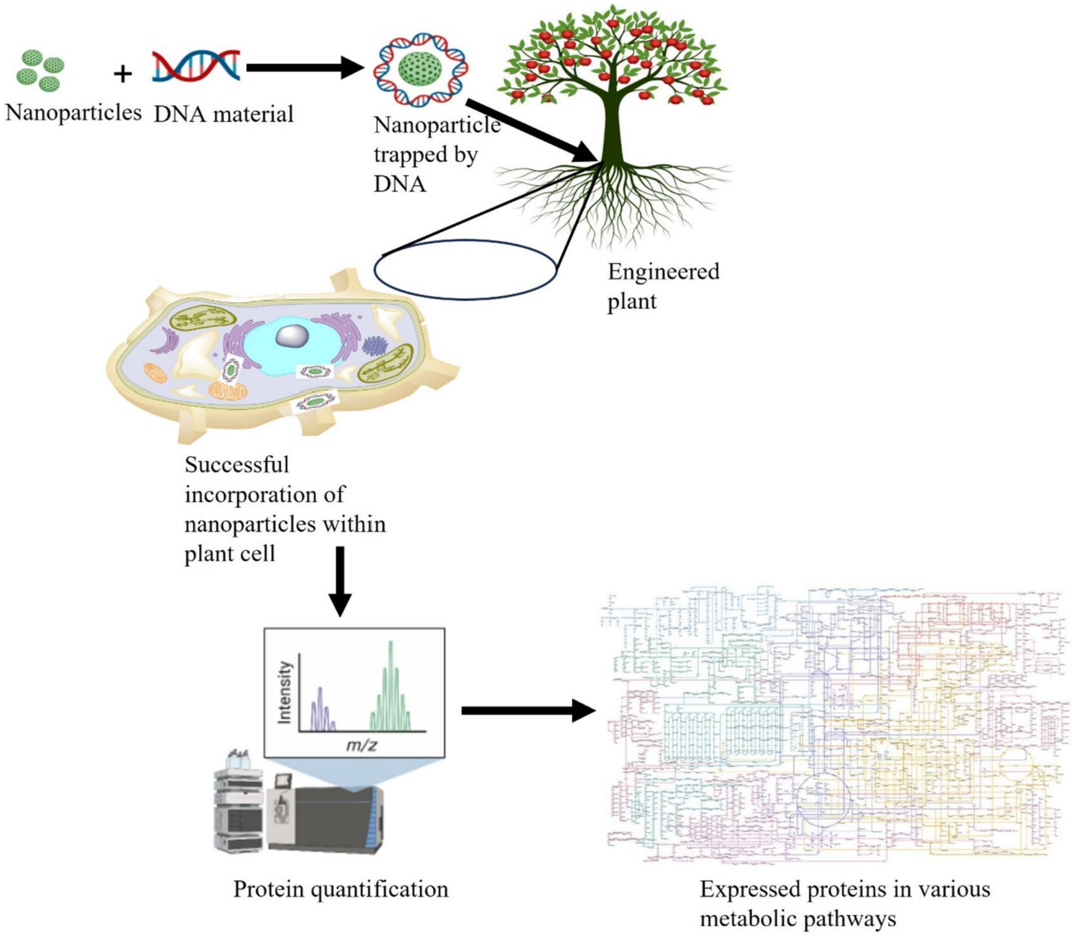

Fig. 4 Application of proteomic tools to study the interaction of nanoparticles with plants proteins in various metabolic pathways

production and carbon fixation (Salehi et al. 2018). According to a study by Nelson et al. (2016) and Wu et al. (2017), CeO_2 nanoparticles elicit stress or a mimic of antioxidant enzyme in plant cells. This involved reduced production of RuBisCo, increased production of light-dependent thylakoid proteins involved in photosynthesis and changes enzyme activity in the mitochondrial electron transport chain. Two crucial oxidative stress-responsive enzymes, ascorbate peroxidase and glutathione peroxidase were downregulated in *Phaseolus vulgaris* (Nelson et al. 2016; Wu et al. 2017). At molecular level in *Solanum lycopersicum* and kidney beans as well as at the transcriptome level in *A. Thaliana*, altered ascorbate peroxidase enzyme responses have also been observed (Tumburu et al. 2015). Surprisingly, transcription factor such as elongation factor 1-α which are important for protein biosynthesis and turnover, were found to be downregulated in the leaves and seeds of bean plants treated with 125–500 mg/kg CeO_2 nanoparticles. In bean leaves and seeds, lipoxygenase, a protein involved in the synthesis of fatty acids, oxido-reductase and iron binding activity were also downregulated (Majumdar et al. 2015; Salehi et al. 2018). When compared to the controlled experiment, the differentially regulated proteins in parent plants treated with CeO_2 nanoparticles were predominantly downregulated (Majumdar et al. 2015).

Conclusions and future perspective

Sustainable agriculture is key to ensuring sufficient supply of safe and quality food to the booming global population. However, global challenges caused by climate change have challenge the agricultural sector to seeking for solution in other to answers question about drought, and salinity stress which has significantly affected global food production and supply. To address these challenges, there is need for interdisciplinary and convergent approaches to solving the current challenge of food insecurity and maximize resource optimization. Nanoparticles have a significant impact on the growth and development of plants enhancing their drought and salinity stress tolerance. Furthermore, the potential of nanotechnology in promoting plant growth and development such as nanofertilizer, nanopesticides, nanoinsecticides, and nanoantimicrobial is key to solving the global food insecurity problem. Furthermore, nanotechnology has been used in the genetic engineering of crops to enhance the expression of certain genes or traits and as a carrier or cargo for target.

Although there has been notable progress in crop genetics and breeding using nanotechnology, the process of transferring foreign DNA for genome editing with the CRISPR/Cas system continues to present difficulties. Polymeric nanostructures and nanogels are potential molecular nanocarriers that can enhance the transport of biomolecules for precise genome editing in agricultural plants. Although nanoparticle-mediated CRISPR/Cas9 complex supply is more sophisticated compared to other delivery methods in plant science fields, further investigation is necessary to validate the efficacy, consistency, and timeliness of the CRISPR system. The integration of the CRISPR/Cas9 system with nanoparticles has the potential to revolutionize agricultural breeding and genetics delivery in plants. In addition, the integration of genome editing using the CRISPR/Cas9 system, nanobiotechnology using nanoparticle, and speed breeding with a short life cycle can be utilized to tackle the challenge of feeding a growing global population while simultaneously managing the escalating risk posed by abiotic stress factors. This technique has the potential to expedite crop breeding methods and result in the development of novel crop varieties that have enhanced stress tolerance and increased yields. This combination might also enable the development of transgene-free crops, which is a crucial element of sustainable agriculture. Nevertheless, further study is necessary to comprehend the underlying mechanisms and tackle the possible hazards linked to the use of NPs and genome editing in agriculture.

Conversely, competent application of nanotechnology in agriculture will require a molecular understanding of plant–nanoparticle interactions provided by omics techniques such as proteomics. This review highlights the various applications of nanoparticles in crop development, the role of nanoparticles in genetic manipulations of crops, the interactions between plants and nanoparticles and the application of proteomic tools to study the effects of these interactions. Advances in analytical techniques like proteomic and bioinformatic tools enable the integration of data obtained at subcellular levels to provide a detailed understanding of mechanisms controlling biological processes or reactions in plants. Data integration from studies on the interactions between plants and nanoparticles is still in its early stages and requires greater attention. This review will act as a knowledge base for the development of biomarkers for nanotoxicity in plants or for prospective use of nanoparticles in crop development and systemic acquired resistance in plants. Additionally, it can support the production of nanoparticle-based stress–signalling molecule detectors, which can subsequently be used to trigger the controlled release of agrochemicals.

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Data availability The data supporting the texts, tables, and figures of this review article are available within the manuscript with sources and references.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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