Fruit Research

REVIEW

Open Access

https://doi.org/10.48130/frures-0024-0037

Fruit Research **2025**, 5: e004

Applications of nanomaterials in agricultural production

Yali Zhang, Sang Lv, Haoyu Wang, Mingxing Tu, Zhumei Xi* and Xianhang Wang*

College of Enology, College of Food Science and Engineering, Viti-viniculture Engineering Technology Center of State Forestry and Grassland Administration, Shaanxi Engineering Research Center for Viti-Viniculture, Heyang Viti-Viniculture Station, Northwest A&F University, Yangling, Shaanxi 712100, China

* Corresponding authors, E-mail: xizhumei@nwafu.edu.cn; wangxianhang@nwafu.edu.cn

Abstract

Nanotechnology has been widely applied in the field of agriculture to meet the requirements of green agricultural development. In agricultural production applications, nanomaterials have been applied as nano-fertilizers, nano-pesticides, and nano-sensors. This article provides a detailed review of recent agricultural applications of nanomaterials. It will also focus on specific agricultural applications, such as transgenics, product preservation, stress resistance, and growth and development. Finally, the challenges of applying nanomaterials for agricultural research are summarized, and solutions are proposed to promote the safe and efficient utilization of nanomaterials in agricultural production to achieve sustainable agricultural development.

Citation: Zhang Y, Lv S, Wang H, Tu M, Xi Z, et al. 2025. Applications of nanomaterials in agricultural production. *Fruit Research* 5: e004 https://doi.org/10.48130/frures-0024-0037

Introduction

As the global population is projected to surge to 9 billion by 2050, the demand for food will escalate alongside rising living standards[1]. This impending milestone necessitates a significant boost in the productivity of staple crops. However, the quest for enhanced crop yield and quality is beset by challenges such as biotic and abiotic stresses. These include the intensification of insect activity due to climate change, water scarcity, diminishing arable land, and soil contamination, all of which impede agricultural productivity. While conventional fertilizers and pesticides have addressed certain agricultural issues, their efficacy is often hindered by limited penetration, solubility, and utilization rates. Moreover, their use can lead to detrimental effects on human health, environmental integrity, and the balance of agricultural ecosystems[2]. Hence, the innovation of efficient, stable, and eco-friendly agrochemicals is imperative to enhance the efficacy and safety of active ingredients in pesticides. The cultivation of superior crop varieties is increasingly vital to fundamentally enhance agricultural output and quality. Traditional breeding methods such as hybridization, mutation breeding, and transgenic breeding are time-consuming and often fall short of desired outcomes[3]. There is an urgent need for innovative technologies that can expedite the breeding process and improve the efficiency of genetic modifications. These advancements are essential for bolstering plant growth, fortifying resistance to environmental stresses, and safeguarding global food security. Citrus fruits, peaches, strawberries, bananas, and other cash crops tend to spoil quickly during the distribution process from farms to households. This is a major cause of global food waste and results in significant economic losses. Therefore, there is an urgent need to develop more sustainable and eco-friendly packaging materials and methods to extend the shelf life of perishable food products.

Nanotechnology, with its ability to transcend the limitations of conventional materials, offers a novel paradigm in materials science. Nano-agriculture represents a cutting-edge research area within modern agriculture. Despite being in its nascent stages, it has already shown remarkable potential. Nanomaterials can stimulate plant growth, enhance nutrient uptake, invigorate metabolic processes, and bolster plants' resilience to various stresses, all while preserving their inherent agronomic characteristics[4]. Nanomaterials can adsorb harmful substances and microorganisms on the surface of fruits, thereby extending their shelf life. In addition, nanomaterials can also act as carriers to effectively deliver preservatives into the interior of fruits, maintaining their nutritional content and quality. Moreover, they can mitigate the adverse environmental and health impacts of traditional agrochemicals[5], serving as eco-friendly soil amendments, agricultural product packaging, and biosensors. Their potential to increase crop yield and quality is substantial. Nanomaterials also support plant transgenic technologies, tackling issues related to stress resistance, growth, and development, and playing a pivotal role in food security and sustainable agricultural practices. They contribute significantly to alleviating the global energy crisis (Fig. 1). Consequently, nanotechnology holds the key to fostering green agricultural development, driving technological advancements in agricultural inputs, enhancing the quality and efficiency of agricultural product processing, optimizing the utilization of biomass resources, and achieving sustainable agricultural growth.

Synthesis of nanomaterials

The synthesis of nanomaterials can be achieved through a variety of approaches, broadly categorized into physical, chemical, and green synthesis methods. Among these, green synthesis methods have garnered significant attention due to their simplicity, efficiency, and the absence of toxic by-products, making them particularly appealing in sectors such as medicine, environmental remediation, and agriculture[6]. These innovative methods surpass the constraints of traditional synthesis techniques, facilitating the production of a diverse array of complex nanomaterials that are more readily accessible. Nanomaterials can be engineered to form a spectrum of functional structures through chemical and physical interactions, primarily leveraging microbial and plant systems.

The use of plant extracts for nanomaterial synthesis is particularly eco-friendly and cost-effective, making it a favored method for agricultural applications. Silver nanoparticles (AgNPs), for instance, are typically synthesized through laser ablation, chemical reduction, photochemistry, and sonochemistry, yet many conventional

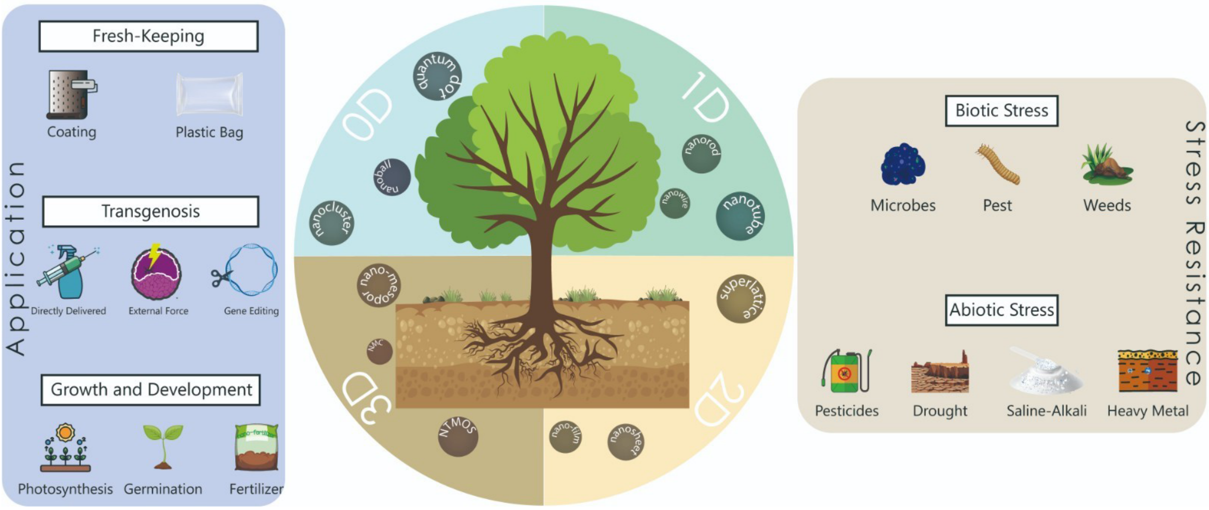

Fig. 1 Applications of nanomaterials in agricultural production.

methods are not only costly but also ecologically harmful. Plant extracts offer a green and economical alternative, serving as reducing and stabilizing agents in the preparation of AgNPs. A case in point is the work by Cheng et al.[7] , who utilized mango peel extract to synthesize AgNPs and subsequently developed a multifunctional nanosilver polylactic acid membrane. The incorporation of AgNPs enhanced the membrane's mechanical properties and its barrier capabilities against water vapor and oxygen. This innovative preservation film demonstrated exceptional antibacterial activity, with inhibition rates surpassing 95% against *Escherichia coli* and *Staphylococcus aureus*. Moreover, in terms of safety, the silver migration and cytotoxicity levels comply with established standards, effectively extending the shelf life of strawberries. The scientific and high-value applications of agricultural waste are further exemplified by the use of *Melaleuca alternifolia* leaves[8], *Carya illinoinensis* leaf[9], castor[10], and banana peel[11], showcasing the potential of these materials in advancing sustainable and eco-friendly agricultural practices.

Agricultural applications of nanomaterials

There are many applications of nanomaterials in plants, such as nano-fertilizers, nano-pesticides, and biosensors, which have addressed many issues related to transgenics, fruit preservation, stress resistance, and growth and development, as shown in Table 1.

Agricultural product preservation applications

Traditional preservation techniques for agricultural produce, such as waxing, refrigeration, and modified atmosphere packaging, often come with drawbacks like high costs, time-consuming processes, and the potential to alter the appearance and taste of the fruits. In stark contrast, nanotechnology offers a suite of preservation methods that are non-toxic, environmentally friendly, biodegradable, antimicrobial, antioxidant, and widely accessible. As a result, these innovative approaches are gaining traction in research and application, gradually supplanting conventional packaging methods. This technology primarily manifests in two forms: nanocoating liquids and nanopackaging materials. Nanocoating liquids involve directly applying a mixture of nanomaterials and other substances onto the surface of agricultural products, while nano packaging materials disperse nanomaterials within other agricultural packaging materials to enhance their performance. By leveraging the unique properties of nanomaterials, these advanced preservation methods not only safeguard the integrity of agricultural products but also contribute to a more sustainable and efficient agricultural industry.

Nanocoating liquids

Nanocomposite coatings are gaining prominence in the realm of food preservation, with chitosan-based nanomaterial composite films emerging as a particularly promising option. Chitosan known for its biocompatibility, biodegradability, and antimicrobial and antioxidant properties often fall short in terms of thermal stability and mechanical strength. To address these limitations, the development of composite nanomaterials has become essential to bolster chitosan's performance. For example, when combined with nano-SiO_2, chitosan forms a chitosan/nano silicon composite nanocoating that has been applied to preserve longan fruit, it significantly extended the shelf life, reduced browning index, delayed weight loss, and prevented an increase in the MDA content and PPO activity[16]. Additionally, chitosan was combined with nano-TiO_2 to form a chitosan/nano-TiO_2 composite nano-coating used to preserve mangoes[26]. Studies comparing the preservation effects of chitosan, chitosan/nano-silicon, and chitosan/nano-TiO_2 on ginkgo seeds[27], and cantaloupes[28] have shown that the preservation and antimicrobial effects of composite materials are superior to those of chitosan alone. Furthermore, composite coatings such as chitosan/nano-SiO_x[29], chitosan/$CaCO_3$[30], chitosan/zein-cinnamaldehyde nanocellulose[31], and cellulose nanofibrils[32] are also widely used to preserve agricultural products.

Nano packaging materials

Incorporating nanomaterials like nano silver, nano-SiO_2, and nano-TiO_2 into preservation films is a game-changer for enhancing packaging performance. These nano-enhancements fine-tune the moisture and oxygen permeability of films, bolster their antimicrobial properties, and extend the shelf life of food products. Hu et al.[17] blended polyethylene (PE) with nano-Ag, nano-TiO_2, and montmorillonite to prepare a novel nanocomposite packaging that delayed the ripening process of kiwifruit. The innovation lies in the inclusion of ethylene inhibitors that facilitate the local oxidation of ethylene, a ripening hormone, thus preventing spoilage without adding to environmental pollution. Looking ahead, the future of fruit packaging preservation is poised to integrate ethylene scavengers and *in-situ* ethylene oxidants directly into food packaging materials or films. These advancements promise to revolutionize the way we preserve and extend the freshness of fruits, offering a more sustainable and effective approach to food preservation.

Table 1. Applications of different nanoproducts in agricultural production.

Nanoproduct	Nanoparticles	Synthesis method	Target	Function	Ref.
Nano-fertilizer	Siliceous natural nanomaterials (SNNMs)	Traditional method	Peach and apricot	Improve nutrient utilization efficiency, enhance light and efficiency, protect plants from high temperatures, drought, and biological stress, and improve fruit quality.	[12]
Nano-fertilizer	Ca-encapsulated carbon dots (Ca-CDs)	Traditional method	Apple	Supplement calcium and mitigate calcium-deficiency stress, boost calcium levels in apple fruits and improve quality attributes such as weight, firmness, and pectin content.	[13]
Nano-fertilizer	Phosphorous-Containing Hydroxyapatite Nanoparticles (nHAP)	Green synthesis (pomegranate peel and coffee ground extracts)	Pomegranate	Provide phosphorus nutrient elements, increase total carbohydrate content, and enhance plant resistance to stress.	[14]
Nano-fertilizer	Se NPs, ZnO NPs	Purchased	Apple	Increase the antioxidant activity of fruits, supplement N, P, and K content, and improve apple fruit yield and nutritional quality.	[15]
Nano-coating/ packaging	Chitosan/nano-silica	Purchased	longan	The coating enhances fruit cold resistance, inhibits the decrease of total soluble solids, titratable acidity, and ascorbic acid, increases defense enzyme activity, and provides a longer storage period.	[16]
Nano-coating/ packaging	Polyethylene with nano-Ag, nano-TiO_2, and montmorillonite blend	Traditional method	Kiwifruit	Delay kiwifruit ripening, reduce kiwifruit fruit decay, and maintain post-harvest storage quality of kiwifruit.	[17]
Nano-pesticide	SeNPs, CeONPs	Green synthesis (Melia azedarach leaves and Acorus calamusas rhizomes extract)	Wheat	Reduce the incidence of wheat stripe rust or yellow rust, SeNPs and CeONPs at a concentration of 30 mg/L significantly improved wheat morphology and physiological parameters.	[18]
Nano-pesticide	MgONFs	Green synthesis (rosemary extract)	Rice	Inhibited bacterial diseases in rice.	[19]
Nanopriming	TiO_2 nanoparticles	Purchased	Corn	Promote the germination and growth of corn seedlings under salt stress.	[20]
Nanopriming	Carbon nanoparticles (CNPs)	Purchased	Lettuce	Alleviate the harmful effects of salt stress on germination.	[21]
Nanopriming	AgNPs	Green synthesis (lime leaf extract)	Rice	Enhance germination and starch metabolism of aged rice seeds.	[22]
Nano-sensor	Single-Walled Carbon Nanotubes (SWNTs)	Traditional method	Ethylene	Detect ethylene gas and determine fruit ripeness.	[23]
Nano-sensor	DNA-SWNT	Purchased + traditional method	Arsenic	Real-time detection of arsenite in underground environments.	[24]
Nano-sensor	Bio-AgNPs-based electrochemical nanosensors	Green synthesis (green tea leaves, mangosteen peel, grapefruit peel)	4-nitrophenol	Sensitive monitoring of 4-nitrophenol (4-NP) in tomato samples.	[25]

Essential oils are secondary metabolites of plants that have many health-promoting benefits and are widely used in nano-preservation. However, due to their instability, essential oils are difficult to use on a large scale. To address this, Oprea et al. developed a nanoencapsulation method for citrus essential oils, including lipid-based methods (including liposomes, solid lipid nanoparticles, nanostructured lipid carriers, and nanoemulsions) and polymer nanostructures[33]. This nanoencapsulation technology overcame the instability of essential oils to provide protection, enhance their bioavailability, and improve their biocompatibility[34]. By encapsulating these potent plant extracts, the nano-preservation field can unlock the full potential of essential oils, ensuring their efficacy and safety in food preservation and other applications.

Excessive pesticide use

The extensive use of pesticides, while helpful in increasing crop yields has negative impacts on crop growth, soil ecosystems, biodiversity, farmer health, and planting costs due to overuse. Technological innovation through the combination of pesticides with nanomaterials can enhance the efficiency of pesticide utilization, which is an important way to achieve sustainable agricultural development.

To reduce excessive pesticide use, nanomaterials can be used for pesticide detection and degradation or as plant-based nano-pesticides. Widely used pesticide residue analysis methods include chromatography and enzyme inhibition methods. Chromatography has a high accuracy but is costly and requires a high level of technical expertise. Enzyme inhibition methods offer the allure of simplicity, cost-effectiveness, and suitability for rapid on-site testing, yet they sometimes fall short in terms of high detection precision. Meanwhile, conventional approaches to the degradation of pesticide residues are often hindered by low efficiency, the risk of secondary pollution, and substantial economic costs. The development of sophisticated pesticide residue analysis methods is essential not only for the protection of human health but also for fostering a more sustainable and eco-friendly society. These methods are crucial for ensuring the safety of our food supply and the preservation of our natural environment. Nanomaterials show strong fluorescence and large surface areas potentially allowing them to be combined with chromatography and enzyme inhibition methods. Zhai et al.[35] combined enzyme inhibition methods with gold nanomaterials to establish an enzyme inhibition method for the rapid detection of organophosphorus pesticides in agricultural products. Gold/silver nanomaterials[36], carbon nanomaterials[37], quantum dots[38], polymer nanoparticles[39], and nanoscale metal-organic frameworks (nMOFs)[40] have also been used to construct various nano-sensors by integrating their various optical, electrochemical, and biological technologies. These materials have enabled the trace detection and degradation of pesticides and have shown a high sensitivity, good stability, low false negative rates, and ease of operation.

Plant-based pesticides, which are naturally derived and primarily composed of carbon, hydrogen, and oxygen, are known for their eco-friendly nature. The integration of nanomaterials with these botanical formulations can enhance the penetration of active ingredients into target organisms, bolster the stability of pesticides, and introduce innovative controlled-release mechanisms. This synergy has been a focal point for agricultural research. For example, Danish et al.[41] synthesized Ag@CfL-NPs using *Cassia fistula* (L.) leaf extract and demonstrated its inhibitory effect on tomato pathogens and controlled insects. Moreover, this nanomaterial application was found to promote tomato growth, increase biomass, enhance photosynthetic efficiency, boost lycopene levels, and improve overall antioxidant properties. *Azadirachta indica* tree extract is widely used as a botanical insecticide and can be combined with nanomaterials to reduce its toxicity[42]. Rotenone is a natural insecticide, but it is limited by its poor stability, susceptibility to degradation, and limited solubility. Chitosan-based nanocomposite particles such as chitosan-graphene oxide[43], and N-deoxycholic acid-O-glycol chitosan (DAGC)[44]. These nanocomposites have been effective in enhancing the water solubility, stability, and safety profile of rotenone.

Nanotechnology can address the low stability, high volatility, and thermal decomposition of plant-based pesticides. The development and promotion of new technologies will further limit the adverse effects of chemical pesticides on the environment and human health. Combining nanomaterials with plant-based pesticides can enhance agricultural production efficiency and sustainability.

Growth and development applications

Treating seeds with nanomaterials can enhance their vitality, increase the activity of various enzymes in plants, promote root growth, enhance photosynthesis, improve plant water and nutrient absorption, enhance nutrient uptake, promote metabolism, and ultimately increase yields and improve plant quality.

Seed germination

The germination stage of seeds is crucial for the growth and development of plants because it directly impacts the subsequent growth of the plants. When provided with adequate moisture and a suitable temperature, seeds will germinate, and the respiratory activity of embryo cells is enhanced. In traditional germination processes, the unique properties of nano-bubbles can promote seed germination and growth rate. The externally generated hydroxyl radicals (·OH) from nanobubble-containing water enhanced the permeability of the seed coat, loosened the cell walls and increased the expression of water channel protein genes in seeds[45]. However, an excess of these radicals, surpassing a toxic threshold, could potentially hinder the hypocotyl elongation and chlorophyll synthesis in plants. The impact of nanomaterials on crop seed germination may promote, inhibit, or have no significant effect. For example, Au NPs have inhibitory effects on arugula seed germination (*Eruca sativa*)[46] and promote soybean[47] seed germination, but they have no significant effect on radish or *Mimusops laurifolia* seed germination[48]. The main factors influencing the effect of nanoparticles on plants include the characteristics of the nanoparticles themselves (concentration, size, type, stability), seed characteristics (size, species), plant growth medium, plant growth stage, and coating materials of the nanoparticles. Given this complexity, further research into the toxicity and efficacy of various nanomaterials on different plant seeds is essential. Such studies will provide invaluable insights to optimize the germination process, ensuring the safe and effective application of nanotechnology in agriculture.

Photosynthesis

Photosynthesis is a crucial process in plant activities and a key pathway for maintaining metabolic balance, and its disruption can disturb the accumulation of energy and metabolism in crops. Nanotechnology can potentially improve plant light utilization efficiency, as nanoparticles can broaden the spectral range and potentially enhance a plant's ability to remove oxygen-free radicals that disrupt photosynthesis. Previous studies have mainly used down-conversion nanomaterials to absorb ultraviolet light to promote electron transfer or convert ultraviolet light into visible light to enhance chloroplast light absorption efficiency. Xu et al.[49] found that spraying up-conversion nanoparticles (UCNPs) on the surface of lettuce to collect near-infrared light from sunlight-promoted electron transfer during photosynthesis and extend the spectral range to near-infrared light. Further analysis showed that over 90% of photosynthesis-related genes were upregulated. However, metal nanoparticles can both promote and inhibit plant photosynthesis. Under stress from Cd and Pb, ZnO NPs loaded onto cotton leaves significantly increased the content of chlorophyll and carotenoids[50]. Conversely, the application of ZnO NPs to *Pisum sativum* L.[51] led to a decrease in chlorophyll levels and impeded photosynthetic efficiency. Nitrogen-doped carbon dots, as a new type of carbon-based nanomaterial, have been proven to improve the photosynthetic efficiency of apple trees[52]. While research on their application in woody plants is limited, it sheds new light on the mechanisms by which nanomaterials can enhance photosynthesis. This knowledge provides a theoretical foundation for the strategic development of efficient nanomaterials for broad agricultural use, potentially revolutionizing the industry.

Nutrient absorption and nutrient transport applications

Nanomaterials have demonstrated the capacity to significantly enhance nutrient absorption and transportation within plants, which in turn can stimulate growth, development, and yield. Traditional fertilizers are often poorly assimilated by plants, leading to nutrient excess, while nano-fertilizers can achieve controlled release, display a higher water absorption capacity, and longer soil residence times. For example, Jiménez-Rosado et al.[53] developed a controlled micronutrient release system using soy protein as the raw material. Trace elements (zinc, copper, iron, and manganese) were incorporated in the form of micro and nanoparticles into the soy protein system. This method combined trace elements and nanotechnology to help crops better absorb micronutrients. Studies have shown that using ZnO nanoparticles in *Brassica napus* L. enhanced the absorption of micronutrients and promoted the biosynthesis of soluble sugars and soluble proteins, thereby promoting seedling development in saline-alkali soil[54]. Moreover, the foliar application of nano-fertilizers has been found to reduce the incidence of fruit cracking in pomegranates, increase the concentration of mineral elements in leaves, and improve both the quantity and quality of fruit production[55].

Research has shown that nanomaterials can exert both positive and negative effects on plant growth and development, but there are still many issues that require further research. To better apply them in agricultural production, it is necessary to determine the nanoparticle size and concentration that are most suitable for specific plant growth stages. It is also necessary to study the mechanisms and connections between photosynthetic and other metabolic pathways after nanomaterial treatment.

Nanomaterial applications for mitigating plant stress

Plants are often subjected to abiotic stresses (physical stress, chemical stress) and biotic stresses. The disruption of the redox balance in plant cells can lead to the accumulation of free radicals, cause changes in cell signaling mechanisms, and produce oxidative damage to biomolecules. Nanomaterials can regulate plant metabolic pathways to reduce the effects of stress and increase crop yield.

Nanotechnology to mitigate biotic stress

Biotic stresses include damage to plants caused by organisms such as fungi, bacteria, insects, and weeds. Although traditional pesticides such as insecticides, herbicides, and fungicides can increase crop yields, they have many drawbacks. The combination of nanomaterials with pesticides can enhance the adhesion, retention, and coverage of pesticides, reduce losses, improve efficiency, and increase biological utilization. Depending on the preparation method of nanopesticides, they can be divided into two categories. One involves directly processing the active ingredients of pesticides into nanoparticles, such as microemulsions, nanoemulsions, and nanodispersions. The field of nanoemulsions is currently experiencing a surge in research and practical applications, offering innovative solutions in agricultural chemistry. Chen et al.[56] used HNTs as an adjuvant to produce an HNTs-CAP emulsion system that showed good stability, leaf adhesion, rain resistance, and an insecticidal effect. In another significant advancement, Yang et al.[57] developed and optimized an oil-in-water (O/W) nanoemulsion to combat the citrus Huanglongbing pathogen *Liberibacter asiaticus*. This delivery system enhanced the therapeutic effect of antimicrobial drugs against *Liberibacter asiaticus* while reducing or eliminating the potential negative effects of chemicals on humans and non-target bacteria. Another method is to construct a nano-drug delivery system, which can be divided into organic polymer formulations, liposome nano-formulations, clay material nano-formulations, and silica nano-formulations, depending on the carrier. Nano-formulations such as nano-capsules, nano-microspheres, nano-micelles, and nano-gels can be constructed to reduce pesticide application and increase efficiency. Mesoporous silica nanoparticles (MSNPs) have an adjustable particle/pore structure and surface functionalization and make valuable drug carriers that are widely used in pesticides[58], such as loading pesticides like acetamiprid, imidacloprid, fipronil, and pyrimethanil. Nano-drug delivery systems show enhanced adhesion to rough surfaces, increased absorption of loaded pesticides by fungi and plants, controlled release of active molecules, and the prevention of off-target effects.

According to research by the United States Environmental Protection Agency (US EPA)[59], compared with traditional pesticides, nanopesticides have shown improved overall efficacy against target organisms, especially in terms of field efficacy. They can also reduce toxicity to non-target organisms, thereby minimizing environmental collateral damage. Nano-pesticides reduce the loss of active ingredients before reaching target organisms, thus reducing their soil-leaching potential. Despite these advantages, there is a legitimate concern that certain nanoparticles could enter the environment or the food chain, potentially endangering human health and disrupting ecological systems. Current assessment methods are inadequate for the application of nano-pesticides, so safety and risk assessments of nano-pesticides should be conducted based on nanotoxicology and nanomedicine to avoid potential risks.

Nanotechnology for abiotic stress applications

Abiotic stresses are major threats to plant growth and development and are caused by various factors including drought, temperature, salinity, heavy metal contamination, and excessive pesticide use. These abiotic stresses can reduce crop yields, hinder plant growth, and even kill plants. Due to their unique physical and chemical properties, nanomaterials have become potential tools for alleviating the negative effects of abiotic stress on plants.

Drought stress

Drought stress is a common abiotic stress that plants face. Nanomaterials can help alleviate plant drought stress by improving their water absorption or regulating symbiotic interactions with beneficial microbes. Studies have shown that ZnO NPs, in conjunction with rhizobacteria PGPR, can alleviate drought and heat stress in wheat[60]. Additionally, the foliar application of metal oxide nanoparticles (MoNPs) such as titanium dioxide (TiO_2), zinc oxide (ZnO), and iron oxide (Fe_3O_4) can enhance a plant's physiological and metabolic activities, thereby helping them resist drought stress[61]. Furthermore, nanomaterials such as carbon nanotubes (CNTs) and graphene oxide (GO) can enhance plant drought tolerance by influencing the expression of relevant response genes[62]. These nano-enabled strategies not only bolster a plant's inherent drought tolerance but also pave the way for innovative agricultural solutions that can support crop productivity in arid environments.

Temperature stress

Spraying low concentrations of ZnO NPs on the leaves of mung beans in the field can change their stomatal conductance, affect plant transpiration, and subsequently influence plant temperature changes[63]. Additionally, nano-ZnO-based low-density polyethylene (NZLDPE) packaging exhibits excellent cold resistance during the cold storage of peaches[64]. Cold stress can damage a plant's photosystem, reduce its chlorophyll content, CO_2 absorption, and transpiration rate, and degrade the enzyme RuBisCO. Studies have found that under cold stress, some proteins in rapeseed show differential expression, with nearly half related to chloroplast physiology. This indicates that rapeseed's cold stress response is partially achieved by regulating its chloroplast function[65]. The application of nano-selenium can mitigate the detrimental effects of cold stress on a plant's photosynthetic parameters, invigorate its antioxidant enzyme activity, and elevate antioxidant compound levels. It stimulates the metabolism of proteins associated with photosynthesis, thereby markedly bolstering the plant's cold stress tolerance[66]. Treatment of chickpeas with TiO_2 NPs in sensitive and tolerant genotypes reduced membrane damage indicators, suggesting that TiO_2 NPs increased the crop's cold resistance[67]. Further transcriptome analysis revealed that under cold stress, chickpeas treated with TiO_2 NPs exhibited varying degrees of differential gene expression compared with a control group in terms of metabolic pathways, cell defense, cell connection and signaling, transcriptional regulation, and chromatin structure. TiO_2 NPs may inhibit low-temperature oxidative stress. These research results demonstrate the potential applications of nanomaterials for alleviating plant cold stress, providing new possibilities for improving crop cold resistance and their adaptability to various growth environments.

Salt-alkaline stress

Excessive salt and alkali contents in the soil can harm plant growth and development, but nanomaterials can interact with plant cells to enhance their plant resistance under salt and alkali stress. For instance, graphene has been shown to mitigate the damage inflicted by salt and alkali stress, thereby promoting the growth and stress tolerance of plants like alfalfa[68]. In addition to acting on leaves and roots, nanomaterials can also act on seeds to enhance their crop salt tolerance. When applied to cotton seeds, they can regulate ROS homeostasis and Ca^{2+} signal transduction, thereby improving salt tolerance in cotton seedlings[69]. In a study on improving cucumber salt tolerance, nano-cerium dioxide validated CsAKT1 as a key gene using the CRISPR/Cas9 system, marking the first use of CRISPR/Cas9 technology to validate key genes for nano-enhanced plant salt tolerance. These findings suggest that genome editing technologies like CRISPR/Cas9 could serve as a powerful adjunct to traditional mutagenesis for identifying genes that are critical for enhancing plant stress resistance through nanotechnology. The research underscores the potential of nanomaterials to not only improve plant salt tolerance but also to innovate approaches for enhancing crops' adaptability to adverse environmental conditions, offering novel strategies for agricultural sustainability in harsh ecosystems.

Metal pollution

Metal pollution is a serious environmental issue, as metal pollutants can accumulate in soil, sediments, and water bodies. They can enter the food chain through plants and animals, thereby causing harmful effects on human health and the ecosystem. Nanomaterials can effectively address this problem. For example, The application of nano-hydroxyapatite (NHAP) has been shown to decrease the mobility and bioavailability of lead (Pb) in soil, thus ameliorating conditions for plant growth[70]. Carbon-based materials have received significant attention as carriers for metal pollution treatment due to their large surface area, high functional group contents, low costs, and environmental friendliness. Biochar (ZBC) possesses strong electronegativity and abundant oxygen-containing functional groups and can regulate soil's physicochemical properties and alter soil's microbial structure. Thus, it provides an inexpensive method to facilitate the immobilization of heavy metals in the environment. Studies have shown that the addition of zero-valent iron to maize straw biochar composite material (MSB-nZVI) significantly reduced the chromium content in soil[71]. Furthermore, a rice straw-derived biochar-loaded nano zero-valent iron composite (nZVI@BC) exhibited superior remediation performance in copper, zinc, arsenic, cadmium, and lead-contaminated soil compared with biochar[72]. Graphene (G), carbon nanotubes (CNTs), and their derivatives are commonly used for soil remediation and facilitate the transfer and enrichment of pollutants or their adsorption sites to the surface of nanomaterials. Combining these materials with biochar can achieve a higher adsorption efficiency. Adding a small amount (≤ 0.5%) of graphene oxide (GO) to poultry litter biochar enhanced the adsorption of copper and zinc while retaining trace nutrient elements, thereby improving the fertilizer utilization efficiency in highly weathered soils[73]. These methods offer new possibilities for mitigating the harm caused by metal pollution to the environment and human health.

When subjected to abiotic stress, plants produce excessive ROS, which can inflict damage on cellular components and potentially culminate in cell death. Many studies have shown that introducing nanomaterials that can scavenge ROS alleviates the impact of abiotic stress. Among these, nano enzymes stand out due to their heightened enzymatic activity and their dual nature, harnessing the distinctive attributes of nanomaterials along with the catalytic capabilities of enzymes. Nanoenzymes are characterized by their high activity, stability, cost-effectiveness, adjustable catalytic activity, and multifunctionality, which position them to surpass the limitations of natural enzymes, such as their limited stability, singular catalytic functions, and high production costs. Since 2007, when Gao et al.[74] first discovered that iron oxide nanoparticles (Fe_3O_4 NPs) showed peroxidase-like activity, a series of nanomaterials have been found to possess antioxidant enzyme-like activity and have been applied to resist non-biological stress in plants, as shown in Table 2. Overall, the application of nanoenzymes for abiotic stress management in plants shows great potential for improving a plant's resilience to environmental challenges. Further research and development efforts in this area are needed to optimize the use of nanoenzymes and explore their full range of benefits for enhancing a plant's stress tolerance.

Table 2. Applications of nanoenzymes for plant abiotic stress.

Crop	Nanomaterial	Application method	Stress type	Mechanism	Ref.
Cotton	Polyacrylic acid-modified Mn_3O_4 nanoparticles (PAA@Mn_3O_4-NPs, PMO)	Foliar application	Salt stress	Adjustment of endogenous antioxidant system expression, maintenance of cytoplasmic Na/K balance.	[75]
Rapeseed	Polyacrylic acid-coated nanoceria (PNC)	Seed soaking	Salt stress	Regulation of ROS homeostasis and α-amylase activity, maintenance of cytoplasmic Na/K balance.	[76]
Pisum sativum Linn and *Eucommia*	carbon dot nanozymes (CDzymes)	Foliar application	Salt stress	Actively clearing ROS as an exogenous enzyme.	[77]
Rice (*Oryza sativa* L.)	AgNPs	Seed soaking	Salt stress and rice blast fungus (*Magnaporthe oryzae*)	Actively remove ROS as an exogenous enzyme, induce immune response rather than the antibacterial activity of AgNPs themselves.	[78]
Maize	Poly (acrylic) acid-coated Mn_3O_4 nanoparticles (PAA@Mn_3O_4 nanoparticles)	Root application	Drought stress	Enhances the mitotic ability of root tip cells by maintaining ROS homeostasis, thus improving maize drought resistance.	[79]
Paeonia ostii	Graphene oxide (GO)	Root application	Drought stress	Rich pore structure strongly binds water molecules, acts as a water-holding agent, and adjusts endogenous antioxidant system expression.	[80]
Brassica napus	γ-Fe_2O_3 NPs	Root application	Drought stress	Actively remove ROS as an exogenous enzyme.	[81]
Boehmeria nivea	Multiwall carbon nanotubes (MWCNTs)	Root application	Cadmium (Cd) pollution	MWCNTs enhance Cd uptake and transport in ramie seedlings, mitigate Cd-induced toxicity, promote plant growth, reduce oxidative stress, activate antioxidant enzymes, and elevate specific antioxidant levels.	[82]
Maize seeds (*Zea mays* L. Zhengdan 958)	Quaternary ammonium iminofullerenes (IFQA)	Seed soaking treatment	Oxygen (H_2O_2) stress	Actively remove ROS as an exogenous enzyme and promote maize root hair growth.	[83]
Breviolum minutum	Engineered poly(acrylic acid)-coated cerium dioxide nanoparticles (CeO_2, nanoceria)	Symbiotic cultivation	High-temperature stress	Alleviate heat-induced oxidative stress and enhance the heat resistance of algae.	[84]

Transgenic technology applications

Nanomaterials are widely used as gene delivery vectors in animal transgenic technologies, but they cannot yet overcome the cell wall barrier to integrate exogenous genes into the cell genome. Therefore, their applications in plant gene transformation are in their infancy. Nevertheless, compared with traditional transgenic methods, nanomaterial-mediated plant transgenic technologies have shown unique advantages. Traditional gene transformation methods include vector-mediated methods and direct injection methods. Vector-mediated methods are widely used and have shown a high transformation efficiency, but they have limitations and safety issues regarding the host. Direct injection methods, while less invasive and simpler in execution, are often hampered by limitations such as low transformation rates, the need for costly equipment, and the potential for cellular damage. When used as plant transgenic vectors, nanomaterials can overcome some of the drawbacks of traditional methods, providing new possibilities for plant gene transformation s shown in Table 3.

The transfection of plant cells with nanocarrier-gene complexes is governed by two main strategies. The first involves the application of external forces, such as ultrasound, electroporation, and magnetic fields, to facilitate the penetration of the cell wall and the seamless integration of foreign genes into the plant cell genome. This method bypasses the complex intermediate steps associated with traditional Agrobacterium-mediated transformation, offering a more direct and efficient route. Nanomaterials provide a protective shield for exogenous genes, safeguarding them from environmental stress and enzymatic degradation. For example, Liu et al.[85] and others combined starch nanoparticles with fluorescent materials on the surface and then bound them with plasmid DNA to form complexes. After ultrasound and DNase I treatment, they co-cultured plasmid DNA-nanoparticle complexes with plant suspension cells, which efficiently entered the cell wall, cell membrane, and nuclear membrane of plant suspension cells. Zhao and colleagues[86] found that in the presence of a magnetic field, exogenous DNA loaded onto Fe_3O_4 magnetic nanoparticles was transported to pollen. This approach produced transgenic cotton through hybrid pollination, indicating that the magnetic effect may open up new pathways for transgenic species. Mesoporous silica nanoparticles (MSNPs), with their adjustable particle size, high pore volume, and expansive surface area, have become valuable tools in the development of

Table 3. Applications of nanomaterials in gene editing.

Need external force	Nanoparticles	Nanoparticle characteristics	Functional modification	Transgenic plants (tissues or cells)	Transgenic plant expression characteristics	Ref.
No	GONs	Layered structure with excellent stability, high biocompatibility, and effective protection of siRNA.	PEI and PEG	*Nicotiana benthamiana* (*N. benthamiana*)	Efficient gene silencing at the mRNA level of around 97% was achieved within 24 h, with mRNA and protein expression of the target gene fully restored to normal levels by 120 h.	[91]
No	AuNCs	High biocompatibility and protection of siRNA from RNase degradation.	PEI	*N. benthamiana*	PEI-AuNCs delivered siRNA into mature mGFP5-expressing Nb leaves, resulting in efficient gene knockdown at both mRNA and protein levels.	[89]
No	SWNT	A high aspect ratio, exceptional tensile strength, and high biocompatibility ensure the optimal activity of biomolecules.	PEI	*N. benthamiana*, *E. sativa*, wheat, cotton	13.6 μg of GFP was obtained per gram of fresh leaf.	[88]
No	DNA nanostructures	Specific and transient gene targeting through sequence design, controllable attachment, and protection of siRNA cargo without toxicity or damage.	No	*N. benthamiana*, arugula, and watercress	DNA nanostructures can be efficiently internalized into plant cells, with the relative internalization efficiency ranked from high to low as DHT, tetrahedron, and nanowires. All show protein-level silencing.	[92]
No	MSNs	Larger surface area, larger pore volume, adjustable mesoporous pore size.	TMAPS, APTMS	*Nicotiana tabacum* BY-2, *Arabidopsis*	Gene delivery to *Nicotiana tabacum* protoplasts and *Arabidopsis* root for transient expression.	[93]
Gene gun method	carbon-supported gold nanoparticles	Good dispersibility, minimal damage to plants, capable of piercing tough plant cell walls and nuclear membranes, and inserting genes into chromosomal loci.	No	*Nicotiana tabacum*, *Oryza sativa*, *Leucaena leucocephala*.	Carbon-supported gold nanoparticles produced by the heat treatment of biogenic nanoparticles were a more effective plant-transformation carrier than commercially available gold microparticles.	[94]
Gene gun method	MSNs	Larger surface area, larger pore volume, and adjustable mesoporous pore size.	TEG modification, gold nanoparticles coverage	*N. benthamiana*	GFP-expressing callus sectors were observed ten days after the bombardment of a proliferating callus culture grown on a non-selective medium. This transfer system produced both transient and stable transgenic plant materials.	[95]
Magnetic field	Magnetic gold nanoparticles (mGNPs)	Superparamagnetic with strong targeting under an applied magnetic field condition.	Fluorescein isothiocyanate (FITC), PEG	Canola	Stable expression and the delivery efficiency of nanoparticles to canola protoplasts was approximately 95%.	[96]
Magnetic field	Fe_3O_4	Superparamagnetic with strong targeting under an applied magnetic field condition.	PEI	Maize	Transient expression of exogenous genes in maize pollen, followed by normal expression in its offspring, demonstrating genetic stability.	[97]

plant transgenic systems. Many studies have used functionalized MSNPs to develop MSNP-mediated plant transgenic systems, where gold-coated MSNP carriers increased the density and performance of biologically mediated delivery. Past research on the nanoparticle-mediated delivery of biomolecules to plant cells has mainly focused on nucleic acids, including double-stranded/single-stranded DNA and siRNA, with fewer methods for protein delivery. However, in recent years, microinjection and cell-penetrating peptide methods have also been applied to introduce model proteins into plant cells. Martin-Ortigosa and colleagues[87] used plasmid DNA coated with protein-loaded Au-MSNPs. Through particle bombardment, they transformed it into plant tissues that subsequently released proteins and plasmid DNA. This study represented a breakthrough in the biological delivery of proteins and plasmid DNA to plant cells through Au-MSNPs. The co-delivery of protein-nanomaterial complexes has improved plant transformation efficiency, with nanomaterials playing a protective role in this process and providing powerful tools for basic and applied research in plant science. These studies offer new insights and methods to develop more efficient plant transgenic systems and improve plant transformation efficiency.

Direct transformation methods such as spraying and injection use zero-dimensional and one-dimensional nanomaterials, which are small enough to cross plant cell walls. Carbon-based materials such as single-walled carbon nanotubes, multi-walled carbon nanotubes and carbon nanodots have become popular nanocarriers for achieving complete plant genetic transformation. Demirer and colleagues[88] prepared polyethyleneimine-functionalized single-walled carbon nanotubes (SWNT-PEI), which instantly transformed complete *Nicotiana tabacum* through direct leaf infiltration. The SWNT-based delivery platform achieved DNA plasmid transformation in model and crop plants without transgenic integration. It showed a high efficiency, non-toxicity, and no tissue damage. The process from functionalized single-walled carbon nanotubes to transgenic expression only required 5 d, which was significantly shorter than *Agrobacterium*-mediated transformation. Zhang and colleagues[89] synthesized polyethyleneimine-functionalized gold nanoclusters (PEI-AuNCs) as carriers for siRNA and delivered siRNA into complete plants *via* injection into leaf tissues. PEI-AuNCs protected siRNA from RNase degradation and achieved effective gene knockout without toxicity. Liu et al.[90] synthesized amine-functionalized carbon dots (A-CDs), a pH-responsive nanomaterial with the unique ability to switch surface charge and facilitate gene import into the nucleus. These versatile vectors enable transient transfection in mature, whole plants, thereby contributing to the advancement of efficient gene delivery systems.

Prospects

To meet the rapidly growing global food demand in the mid-century as well as the requirements for the freshness of fruits, interdisciplinary integration of plant science, agricultural science, and other fields is essential. Nano-agriculture offers an innovative solution that helps to ensure food supply and security. With the development of nanotechnology, it is expected that more innovative nano-agricultural products and technologies will emerge in the future. For instance, nanotechnology may be integrated with the Internet of Things, artificial intelligence, and other technologies to develop smarter agricultural equipment and systems, achieving automated and intelligent agricultural production. The application of nanotechnology will promote the development of precision agriculture by precisely controlling the nutrients and water required for crop growth, thereby improving agricultural production efficiency. This helps to reduce the use of chemical fertilizers and pesticides, decrease chemical pesticide residues, enhance the natural defense mechanisms of crops, improve food safety and nutritional value, reduce environmental pollution, and promote the development of ecological and sustainable agriculture. Nanotechnology can serve as a vector for gene-editing technology, facilitating the genetic improvement of crops and the cultivation of varieties more adaptable to climate change and pests and diseases. However, it also faces challenges in terms of technological maturity, cost-effectiveness, environmental impact, and regulatory aspects. We should also pay attention to the migration issue, where nanomaterials may migrate from the coating into the interior of the fruit, and then enter the human body through consumption, the potential impact on human health needs further research. It also requires policy support and public education to realize its potential in sustainable agriculture.

Author contributions

The authors confirm contribution to the paper as follows: writing - original draft: Zhang Y, Wang X, Lv S; writing - review & editing: Tu M, Xi Z, Wang X; format organization: Wang H. All authors reviewed the results and approved the final version of the manuscript.

Data availability

The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Acknowledgments

This work was supported by the Development Program of Shaanxi (Program No. 2023-YBNY-075) and the National Natural Science Foundation of China (32002000, 32202423). Thank you to EditorBar (www.editorbar.com) for language polishing the article.

Conflict of interest

The authors declare that they have no conflict of interest.

Dates

Received 5 April 2024; Revised 3 September 2024; Accepted 26 September 2024; Published online 9 January 2025

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