Smart Nanomaterials Technology

Azamal Husen *Editor*

Nanobiotechnology for Abiotic Stress Adaptation and Mitigation in Agricultural Crops

Physiological and Molecular Intervention

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Contents

Role of Metal and Metal-Oxide Nanoparticles in Agricultural Crops Under UV Radiation, Stress Adaptation, and Mitigation

Aisha Kamal, Nida Sultan, Sazia Siddiqui, and Ayeesha Khatoon

Abstract Plants, as primary producers, are vulnerable to ultraviolet (UV) radiation, particularly UV-B (280–315 nm), which disrupts cellular processes, impairs photosynthesis, and reduces crop productivity. The ozone layer's breakdown has exacerbated UV-B exposure, intensifying oxidative stress in plants. To counter these challenges, nanotechnology has emerged as a transformative solution. Metal and metal-oxide nanoparticles, such as Si, Ag, TiO_2, and CeO_2, exhibit unique properties, including UV absorption, antioxidant mimicry, and the ability to enhance photosynthesis. These nanoparticles mitigate UV-B-induced damage by acting as UV shields, scavenging reactive oxygen species, and promoting the synthesis of protective metabolites like flavonoids. This chapter explores recent advancements in nanoparticle applications to alleviate UV stress, emphasizing their mechanisms of action and agricultural implications. By bridging nanotechnology and plant science, these innovations hold potential to enhance crop resilience, support sustainable agriculture, and address the challenges posed by climate change.

Keywords UV radiation stress · Nanoparticles · Antioxidant defense · Metal and metal oxide · ROS

1 Introduction

Plants, as primary producers in the ecosystem, are frequently exposed to various abiotic stresses that can significantly impact their growth, development, and productivity. One such stress is ultraviolet (UV) radiation, particularly UV-B (280–315 nm), which has intensified due to the depletion of the ozone layer. Increased UV radiation

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causes a cascade of detrimental effects, including DNA damage, protein oxidation, disruption of photosynthetic machinery, and the generation of reactive oxygen species (ROS). These oxidative stresses impair cellular functions and compromise the overall health and yield of plants, posing a serious threat to agricultural sustainability and food security [7, 8, 14, 15].

The advancement of nanotechnology in recent years has opened new avenues for mitigating the harmful effects of UV stress on plants. Nanoparticles (NPs), with their unique physicochemical properties such as a high surface area-to-volume ratio, catalytic activity, and adjustable size, have shown promising potential in enhancing plant resilience to UV-induced damage [46]. Engineered nanoparticles, including metal-based (e.g., ZnO, TiO_2, and CeO_2) and carbon-based nanomaterials, can serve as UV filters, ROS scavengers, and protective agents for cellular components.

The interaction of nanoparticles with plant systems is a complex phenomenon influenced by their physicochemical characteristics and the plant's metabolic responses. While certain nanoparticles can act as shields by absorbing or scattering UV radiation, others can boost the plant's antioxidant defense mechanisms, facilitating the maintenance of UV-induced cellular damage [30, 40]. Additionally, some nanoparticles enhance the biosynthesis of secondary metabolites, such as flavonoids and phenolic compounds, they are essential for protecting plants from several abiotic stresses including UV radiation [23].

This chapter explores the multifaceted role of nanoparticles in mitigating UV stress in plants, with a focus on their mechanisms of action, applications in agriculture, and potential challenges. It delves into recent advancements in nanoparticle-based strategies for UV stress management, highlighting their implications for crop protection, yield improvement, and sustainable agricultural practices. By bridging nanotechnology with plant science, this emerging field holds promise for addressing the adverse impacts of environmental stresses in a rapidly changing climate.

2 Types of Ultraviolet (UV) Radiation

Ultraviolet (UV) radiation constitutes approximately 7–9% of the solar spectrum and is separated into UV-A (315–400 nm), UV-B (280–315 nm), and UV-C (100–280 nm) subtypes according to wavelength. The majority of UV-B and almost all UV-C radiation are absorbed by the ozone layer, protecting terrestrial organisms from their damaging effects. However, human activities, particularly the production of chlorofluorocarbons (CFCs) and other ozone-depleting compounds, have weakened the outermost layer of ozone, forcing more harmful ultraviolet (UV) rays to reach Earth's surface [4, 44].

UV radiation impacts plants differently based on wavelength and exposure. UV-A, constituting 95% of UV radiation reaching Earth's surface, promotes plant growth and stress resistance by stimulating defense compounds like flavonoids. However, excessive UV-A can damage DNA, affecting plant development [9]. Despite its prevalence, the effects of UV-A on plants remain underexplored, even though it penetrates deeper into leaf tissues.

UV-B, making up 5% of surface UV radiation, is highly biologically active and can harm cellular components, causing growth retardation, oxidative stress, and reduced photosynthetic efficiency. While long-term exposure is damaging, controlled short-term UV-B exposure can induce defense-related compounds like flavonoids, enhancing plant resilience against pests and diseases [10].

UV-C, the most harmful type, hardly makes it to the surface after being mostly consumed by the ozone layer. It can cause severe cellular damage, including DNA destruction, leading to rapid cell death and tissue necrosis. UV-C is occasionally used in controlled environments for sterilization purposes but is not a natural concern due to ozone protection [5].

3 Impact of UV Radiation on Crops

Ultraviolet (UV) radiation, a component of solar radiation, plays a significant role in influencing plant growth, development, and productivity. Increased UV radiation due to stratospheric ozone depletion poses a potential threat to agricultural systems by affecting photosynthesis, nutrient uptake, and overall crop yield. Although plants have evolved adaptive mechanisms to cope with UV exposure, excessive UV radiation can induce physiological, biochemical, and morphological changes (Fig. 1). Its impact on crops varies depending on factors such as plant species, UV intensity, duration of exposure, and environmental conditions.

UV radiation, particularly UV-A and UV-B, alters shoot and leaf morphology, which affects light absorption and photosynthesis [29]. UV-A can induce elongation of leaves and alter petiole length, though some plant accessions (e.g., *A. thaliana* Di-1) exhibit reduced leaf elongation under UV-A exposure [45]. UV-B radiation has profound impacts on the growth of crops, development, and yield. Important physiological functions including photosynthesis, pigment synthesis, and nutrient cycling are disrupted under increased UV-B levels [17]. In crops like maize and rice, UV-B decreases chloroplast density, rubisco activity, and stomatal function, leading to reduced photosynthetic efficiency and growth [23, 35]. Similarly, rice, a staple food crop, exhibits reduced biomass, altered coleoptile growth, and increased oxidative stress from exposure to UV-B [16]. UV-B stress is more severe, damaging chloroplast structures like grana, thylakoids, and chlorophyll components [22, 39]. UV-B exposure impacts photosynthesis through reduced Rubisco or PEP carboxylase activity and increased reactive oxygen species (ROS). Stomatal conductance also significantly decreased under UV-B exposure [17, 49]. It is also reported that UV-B radiation directly impacts biomolecules, including proteins, lipids, and nucleic acids, resulting in metabolic, biochemical, and morphological changes. It induces the formation of pyrimidine dimers in DNA, causing mutations and impairing replication processes [3].

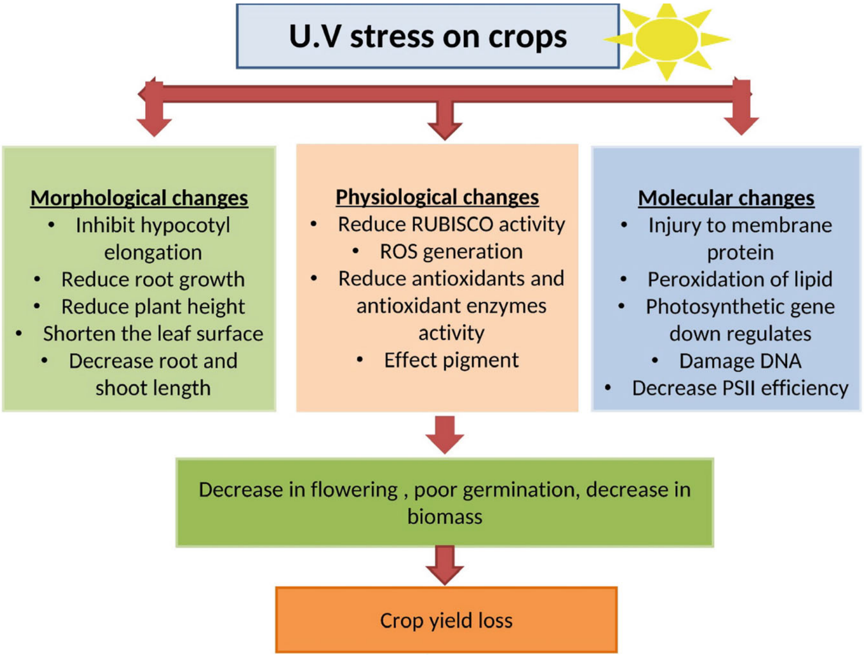

Fig. 1 Impact of UV radiation on morphological, physiological, and molecular traits of plants

4 Plant Defense Strategies Against UV-B Damage

Plants have evolved sophisticated mechanisms to protect against UV-B stress, including DNA repair pathways, antioxidant defenses, and specialized metabolites like flavonoids. UVR8 photoreceptor-mediated signaling activates protective responses, while ROS serve as both stress indicators and signaling molecules. Melatonin further enhances UV-B tolerance by mitigating oxidative damage and regulating protective gene expression (Fig. 2).

4.1 *DNA Damage Repair and Antioxidant Defense*

UV-B can cause DNA damage, including pyrimidine dimer formation, and ROS production [11]. Plants mitigate this through DNA repair pathways and ROS-scavenging systems. Enzymatic antioxidants such as glutathione reductase (GR), catalase (CAT), and superoxide dismutase (SOD), as well as non-enzymatic antioxidants including ascorbic acid, glutathione, and flavonoids, play a crucial role in DNA repair [6]. UV-B-specific photoreceptors, like UVR8, also reported to regulate

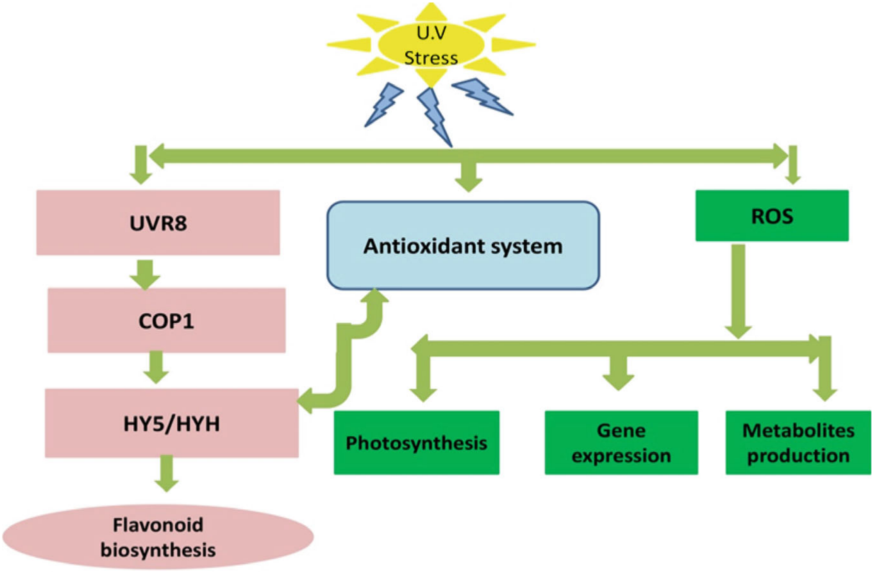

Fig. 2 Adaptive strategies of plants to UV-B radiation

these defenses by activating downstream signaling pathways to promote protective measures [12].

4.2 *Flavonoid Biosynthesis as a Sunscreen*

Flavonoids, synthesized in exposure to UV-B stress, absorb harmful radiation and reduce cellular damage. Key regulators like UVR8, HY5, and MYB transcription factors enhance flavonoid accumulation. The UVR8-COP1-HY5 signaling axis stabilizes HY5, promoting transcription of flavonoid biosynthesis genes [6].

4.3 *Gene Regulation and Signal Integration*

Under UV-B stress, plants use both UVR8-dependent and independent pathways to activate protective genes. UVR8 interacts with transcription factors like MYB13 to induce flavonoid biosynthesis [20, 28]. Other pathways, such as MAPK cascades and ATR-dependent responses, also contribute to stress tolerance, highlighting the complexity of UV signaling networks [18].

4.4 Role of Melatonin

Melatonin acts as an antioxidant and a regulator of UV-B stress responses. UV-B increases melatonin biosynthesis, enhancing ROS scavenging and protecting photosystems from damage. Transgenic plants with elevated melatonin levels exhibit improved UV-B tolerance. For instance, transgenic *Nicotiana sylvestris* protoplasts exhibited lower DNA damage than nontransformed protoplasts under UV-B exposure (0–30 s), as shown by reduced Tail DNA percentage in single-cell gel electrophoresis. This indicates enhanced UV-B resistance in transgenic plants. Similarly, a study demonstrated that Melatonin synthesis enhanced UV-B stress tolerance in apples by reducing reactive oxygen species, boosting photosynthetic efficiency, and elevating total phenolic content [21, 54].

5 Role of Metal and Metal-Oxide Nanoparticles in Mitigating UV-Induced Damage

The detrimental effects of UV radiation threaten agricultural productivity and necessitate innovative strategies to mitigate UV-B-induced stress in plants. To reduce the harmful effects of UV-B radiation on agriculture, several strategies have been proposed. Breeding and genetic engineering efforts aim to develop UV-B-tolerant crop varieties with enhanced antioxidant and DNA repair capabilities [13]. Additionally, protective agricultural practices, such as shading and mulching, can minimize UV-B exposure in sensitive crops.

In recent years, metal and metal-oxide nanoparticles (NPs) have gained a lot of attention because of their special qualities and numerous scientific and technological uses. Because of their special optical, catalytic, and photoprotective qualities, metal and metal-oxide nanoparticles (NPs) have become powerful tools for reducing UV stress [1]. However, certain metal and metal-oxide nanoparticles, including titanium dioxide (TiO_2) and silver oxide (AgNPs), have shown potential in alleviating UV-B-induced damage.

5.1 Titanium Dioxide Nanoparticles (TiO_2-NPs)

TiO_2-NPs, or titanium dioxide nanoparticles, are essential for reducing UV-B induced stress in plants by acting as an effective “sunscreen.” These nanoparticles can absorb and scatter UV-B radiation, reducing its penetration into plant tissues and minimizing cellular damage. They reduce UV-B-induced mortality in *Daphnia magna* and influence photosynthesis in *Chlorella pyrenoidosa*, highlighting their potential in protecting aquatic organisms and mitigating UV-B stress [19, 25]. For instance, a study on *Arabidopsis thaliana* demonstrated that pretreatment with 10 mg/L TiO_2-NPs significantly alleviated UV-B toxicity by enhancing antioxidant enzyme activity, for instance superoxide dismutase (SOD), and promoting the synthesis of flavonoids, which serve as natural UV shields [47]. TiO_2-NPs also preserved the structural integrity of microtubules and reduced DNA damage caused by UV-B in saffron, as evidenced by decreased cyclobutane pyrimidine dimer (CPD) content and fewer mitotic abnormalities. It was also found that 50 mg/L foliar spray of TiO_2-NPs improved plant biomass under UV-B exposure, increasing shoot and root weights significantly [26]. While TiO_2-NPs improve plant adaptability to UV-B stress, careful evaluation of their biological safety is essential. Research has confirmed that concentrations of 10 mg/L are both safe and effective, showing no significant phytotoxic effects on plants like *Arabidopsis*, making TiO_2-NPs a promising nanotool for agricultural applications under enhanced UV-B radiation stress [47].

5.2 *Silicon Nanoparticles (SiNP)*

Silicon (Si) and silicon nanoparticles (SiNPs) perform an important part in reducing UV radiation-induced stress in plants by enhancing physiological and biochemical processes. When exposed to UV-B light, plants experience increased impact of oxidative stress, lipid peroxidation, and disruption to cellular structures like chloroplasts. Si supplementation has been shown to alleviate these effects by boosting antioxidant defenses, including increased activity of enzymes like ascorbate peroxidase and reduced malondialdehyde levels and superoxide radical (O_2^-), which indicate lower lipid peroxidation. Si improves chlorophyll content, photosynthetic efficiency, and the accumulation of flavonoids, anthocyanins, and UV-absorbing compounds, which act as natural sunscreens to shield plant tissues from UV-B damage [24, 37, 51].

When wheat seedlings exposed to UV-B radiation were supplemented with silicon, either as potassium silicate or silicon nanoparticles (SiNPs), plant biomass, chlorophyll content, and soluble sugar levels increased, while oxidative damage and electrolyte leakage decreased [51]. SiNPs further amplify these protective effects due to their higher surface area and bioactivity, offering improved stress resistance and nutrient uptake [43]. These findings highlight the potential of Si and SiNPs as eco-friendly strategies to improve plant resilience under increasing UV-B radiation caused by climate change.

5.3 *Silver Nanoparticles (AgNPs)*

Silver nanoparticles (AgNPs) have emerged as an effective tool for alleviating UV-B-induced stress in plants by improving their morphological, physiological, and biochemical traits. AgNPs mitigate UV stress-induced effects through multiple mechanisms, including their ability to enhance antioxidant enzyme activity, such as the scavengers of reactive oxygen species (ROS), peroxidase (POD), catalase (CAT), and superoxide dismutase (SOD) generated during UV-B exposure. Studies have shown that AgNPs increase the uptake of essential nutrients like nitrogen, magnesium, and iron, crucial for chlorophyll biosynthesis, thereby improving photosynthetic efficiency and chlorophyll content in garden thyme (*Thymus vulgaris* L.) [2]. Furthermore, biosynthesized AgNPs have been reported to increase root length, dissolved carbohydrate content, and secondary metabolites, such as flavonoids and essential oils, which act as natural UV protectants in many crops like like corn (*Zea mays* L.), common beans (*Phaseolus vulgaris* L.), and Indian mustard (*Brassica juncea* L.) [34, 36]. AgNPs also reduce the detrimental impact of UV-B on photosynthetic pigments highlighting their potential to improve plant resilience under UV stress [2].

5.4 Cerium Oxide Nanoparticles (CeNPs)

Cerium oxide nanoparticles (CeNPs) play a pivotal role in safeguarding plants against UV radiation-induced toxicity. These nanoparticles function as potent reactive oxygen species (ROS) scavengers due to their unique ability to switch between Ce^{3+} and Ce^{4+} oxidation states, simulating antioxidant enzyme activity [33]. By mitigating oxidative stress, CeNPs protect cellular components, including lipids, proteins, and DNA, from UV-B radiation-induced damage. Research on mung bean seedlings (*Vigna radiata*) revealed that CeNPs alleviate membrane damage and oxidative stress caused by enhanced UV-B exposure. They achieve this by modulating antioxidant enzyme activities, such as superoxide dismutase (SOD) and catalase (CAT), while also reducing malondialdehyde (MDA) levels, a marker of oxidative damage [41]. Furthermore, CeNPs improve root and shoot growth under UV stress by regulating hormonal balance, particularly auxin and cytokinin levels, and restoring starch deposition in root tips, which is critical for gravity sensing. These actions collectively enhance plant resilience by minimizing structural damage, improving physiological responses, and restoring normal growth patterns [50]. Consequently, CeNPs offer a promising nanotechnology-driven approach for agricultural sustainability under increasing UV radiation stress, fostering plant growth and productivity even in challenging environmental conditions.

6 Mechanisms of UV Stress Mitigation Using Metal Nanoparticles and Metal Oxides

Metal and metal-oxide nanoparticles (NPs) offer innovative strategies to mitigate UV-induced stress in plants by combining their unique physicochemical properties with biological interactions (Fig. 3).

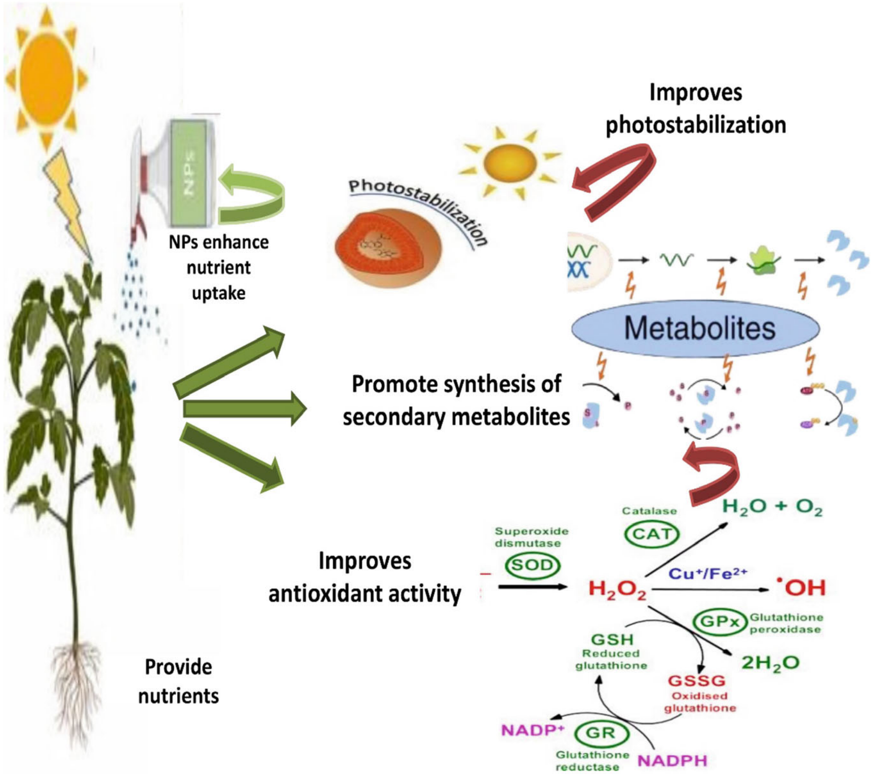

Fig. 3 Adopted strategies by the nanoparticles (NPs) in mitigating UV-induced stress in plants

6.1 UV Absorption and Scattering

Nanoparticles like titanium dioxide (TiO_2), cerium oxide (CeO_2), and zinc oxide (ZnO) effectively absorb and scatter ultraviolet (UV) radiation, reducing its penetration into plant tissues [38]. Their nanoscale size ensures efficient interaction with UV light, minimizing cellular harm brought on by reactive oxygen species (ROS) produced by UV and photo-degradation of plant biomolecules [2, 7]. For example, TiO_2 and CeO_2 NPs act as UV shields due to their wide band gaps, which provide high UV-blocking efficiency. These properties make NPs vital in preventing UV-induced photo-damage and maintaining plant health [27, 53].

6.2 Enhancing Antioxidant Defense Systems

CeO_2 nanoparticles mimic natural antioxidants like superoxide dismutase (SOD) by redox cycling between Ce^{3+} and Ce^{4+} states, scavenging free radicals generated by UV-induced oxidative stress. This antioxidant activity protects plant cells from lipid peroxidation, protein damage, and DNA fragmentation [42, 52]. Similarly, AgNPs, SiNPs and TiO_2-NPs improve the antioxidant enzyme activities in plants, boosting their resilience to oxidative stress [48].

6.3 Improving Photosynthetic Efficiency

Metal-oxide NPs enhance photosynthetic efficiency by stabilizing chloroplast structures under UV stress. TiO_2 NPs, for instance, improve chlorophyll content, stomatal conductance, and water-use efficiency in plants exposed to water and UV stress. These AgNPs, SiNPs and TiO_2-NPs maintain mitochondrial ultrastructure, ensuring energy production and efficient photosynthesis under stressful circumstances [2, 24, 32].

6.4 Promoting Synthesis of Protective Metabolites

Nanoparticles stimulate the production of secondary metabolites such as flavonoids and phenolics, which act as natural sunscreens, absorbing UV light and protecting plant tissues. Additionally, nano fertilizers deliver essential nutrients like nitrogen, phosphorus, and potassium in a controlled manner, promoting plant growth even under adverse UV conditions [2, 31].

6.5 Photo-Stabilization and Material Longevity

The photostability of nanoparticles like TiO_2 and Si ensures energy dissipation from absorbed UV radiation, preventing damage to cellular components. These properties not only protect plants but also enhance material longevity in industrial and agricultural applications [40].

7 Conclusion

Nanoparticles offer a promising avenue for mitigating the harmful impact of UV-B radiation on plants. By enhancing antioxidant defenses, promoting photosynthetic efficiency, and improving nutrient delivery, NPs can help plants adapt to UV-B-induced stress and maintain productivity. However, it is necessary to conduct more research to elucidate the precise mechanisms of NP-plant interactions and to develop guidelines for their safe and effective use in agriculture. As nanotechnology continues to evolve, it holds immense potential to address the challenges of environmentally friendly farming and ensure food security in the face of climate change and environmental stressors.

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