engineering proceedings

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Proceeding Paper

The Vital Role of Nanoparticles in Enhancing Plant Growth and Development †

Satya [1,*], Kulsum Hashmi [1], Sakshi Gupta [1], Priya Mishra [1], Tahmeena Khan [2] and Seema Joshi [1]

[1] Department of Chemistry, Isabella Thoburn College Lucknow, University of Lucknow (U.P.), Lucknow 226007, India; hashmikulsum786@gmail.com (K.H.); sakshi2696gupta@gmail.com (S.G.); chemophilic2122@gmail.com (P.M.); sjoshiitc@gmail.com (S.J.)

[2] Department of Chemistry, Integral University Lucknow (U.P.), Dashauli 226026, India; tahminakhan30@yahoo.com

* Correspondence: sasatya7745@gmail.com

† Presented at the 3rd International Electronic Conference on Processes—Green and Sustainable Process Engineering and Process Systems Engineering (ECP 2024), 29–31 May 2024; Available online: https://sciforum.net/event/ECP2024.

Abstract: Nanotechnology has facilitated various applications in food and agricultural industries due to the unique characteristics of nanoparticles (NPs), such as their large surface area, reactivity, tendency to agglomerate, ability to penetrate, and specific size and structure. The exploration of nanoparticles in agriculture is gaining interest because of their ability to minimize the use of chemical fertilizers and significantly enhance plant growth. Several studies have demonstrated NPs' effects on plants, depending on their size, shape, concentration, coatings, self-aggregate tendency, and stability. Here, we provide an overview of the applications of recently developed nanoparticles, including metallic and non-metallic nanoparticles and carbon-based nanomaterials.

Keywords: nanoparticles; plant growth; plant development; seed germination; applications

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Citation: S.; Hashmi, K.; Gupta, S.; Mishra, P.; Khan, T.; Joshi, S. The Vital Role of Nanoparticles in Enhancing Plant Growth and Development. *Eng. Proc.* **2024**, *67*, 48. https://doi.org/10.3390/engproc2024067048

Academic Editor: Juan Francisco García Martín

Published: 23 September 2024

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1. Introduction

Nanotechnology plays a vital role in improving methods for monitoring ecological conditions, managing pathogenicity, managing crop capacity (for photosynthetic respiration), increasing nutrient or pesticide absorption, and accelerating flowering and seed germination. NPs have proven to be highly beneficial for plant development [1]. The initial stages of plant growth and development begin with seed germination, followed by root elongation and shoot emergence [2]. Seed germination forms the foundation for the productivity, growth, and overall development of plants. Significant improvements in both germination rates and overall yield have been achieved with NPs-treated seeds [3]. Various studies have revealed that controlled concentrations and moderate doses of NPs greatly promote seed germination [4] and facilitate robust plant growth. Additionally, they have been shown to enhance photosynthetic efficiency and increase chlorophyll content [5–7], as well as improve water and fertilizer utilization (Figure 1). In this study, we present a summary of the applications of recently developed NPs, including metallic, non-metallic, and carbon-based nanomaterials, which significantly enhance plant development by improving growth, stress resistance, and nutrient uptake. AgNPs boost growth and protect mustard plants from pathogens [8], while copper NPs enhance stress tolerance in Arabidopsis [9]. Fe_2O_3NPs improve iron uptake and photosynthesis in soybeans [10], while AuNPs promote seed germination and growth in wheat [11]. Silicon NPs increase drought tolerance in tomatoes [12], while ZnONPs enhance growth and nutrient uptake in maize [13]. Despite their benefits, NPs can also exhibit toxic effects under certain conditions. Their beneficial or harmful impacts significantly depend on dosage, exposure duration, and the specific type of NPs used.

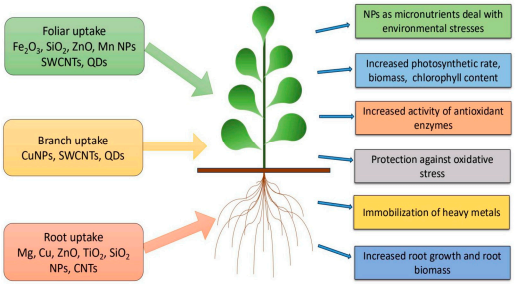


Figure 1. Various NPs used as fertilizers for improvements of plant growth.

2. Nanoparticles for Enhancing Plant Growth and Development

2.1. Silver Nanoparticles (AgNPs)

AgNPs are currently the most extensively manufactured nanomaterial, and they are incorporated into a wide range of agricultural applications. Moderate doses of AgNPs have been shown to increase the level of chlorophyll and carbohydrate contents, improve photosynthetic efficiency in different plant species, and improve water and fertilizer utilization [14,15]. Shaikhaldein et al. (2020) studied the morphophysiological effects of AgNPs on *Maerua oblongifolia* (*M. oblongifolia*) in vitro. Different concentrations of AgNPs exhibited distinct effects on the morphological characteristics like shoot number, shoot length, fresh weight, dry weight, and leaf number of *M. oblongifolia* compared to the control group. Notably, 20 mg/L concentration of AgNPs increased the shoot length, fresh weight, and dry weight, along with the highest levels of chlorophyll a and chlorophyll b (Figure 2). Moreover, concentrations of 20, 30, and 40 mg/L of AgNPs resulted in the highest number of shoots (Figure 3). This demonstrates the concentration-dependent impact of AgNPs on the growth and development of *M. oblongifolia* [16].

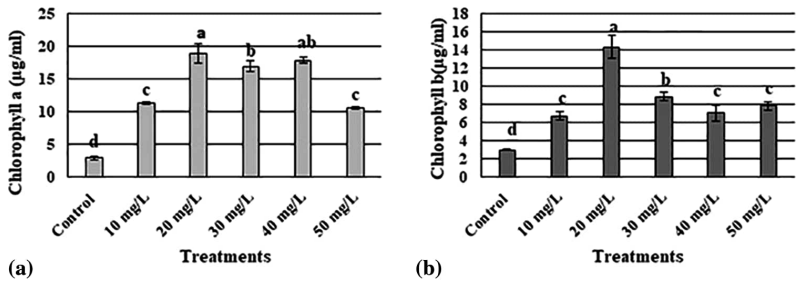


Figure 2. Variation in (**a**) chlorophyll a and (**b**) chlorophyll b content of *M. oblongifolia* at different concentrations of AgNPs. The letters 'a'–'d' represent significant differences between the treatments at $p \leq 0.05$, based on Duncan's test.

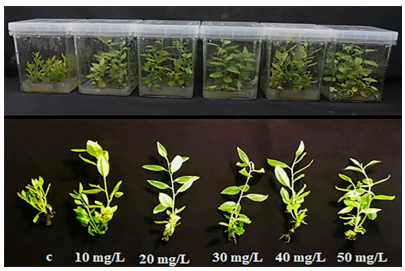
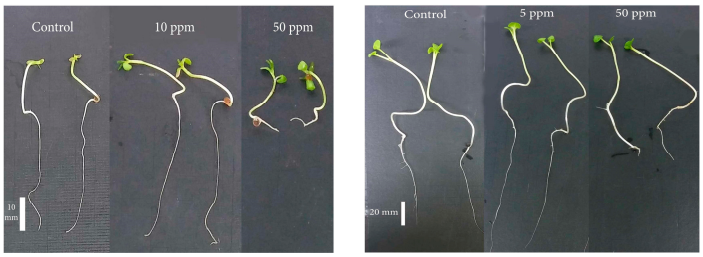


Figure 3. Variation in number of shoots of *M. oblongifolia* at different concentrations of AgNPs.

Furthermore, in cowpea, *Brassica* sp. [17], fenugreek [18], and *Lupinus termis* [19], the germination percentage was notably higher in AgNP-treated plants compared to the control. AgNPs are also utilized as fungicides for preventing fungal diseases and are employed as agents to facilitate the ripening of fruits [20,21].

2.2. Zinc Oxide Nanoparticles (ZnONPs)

In agricultural practices, ZnONPs serve multiple functions, acting as fertilizers, pesticides, herbicides, and growth regulators [22,23]. Sarkhosh et al. (2022) investigated the effect of various concentrations of ZnONPs on the growth of *Camelina sativa* and *Brassica napus* L. (*B. napus*) crops. In the case of *Camelina*, the highest germination percentage was observed in seeds treated with 10 ppm ZnONPs compared to the control condition (Figure 4a), and for *B. napus*, the maximum germination percentage was recorded at a concentration of 5 ppm ZnONPs (Figure 4b) [24].



(**a**) (**b**)

Figure 4. The impact of ZnONPs on the growth of (**a**) *Camelina* seedlings and (**b**) *B. napus* seedlings.

The application of ZnONPs demonstrated a significant enhancement in various physiological and growth factors of wheat [25]. Jankovskis et al. (2022) tested the effects of ZnONPs on wheat (*Triticum aestivum* L.), which significantly increased the chlorophyll b content at 1 mg/L and increased the leaf length at 4 mg/L; meanwhile, although root length increased at 1 mg/L, it decreased at 2 and 4 mg/L concentrations of ZnONPs (Figure 5) [26].

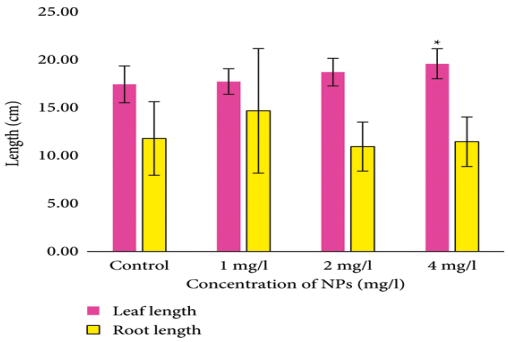


Figure 5. Leaf and root lengths of wheat (*Triticum aestivum* L.) treated with ZnONPs. An asterisk (*) denotes a statistically significant difference compared to the control ($p < 0.05$).

2.3. Copper Nanoparticles (CuNPs) and Copper Oxide Nanoparticles (CuONPs)

Various research studies have presented evidence demonstrating the antimicrobial application of CuNPs against a range of phytopathogens [27–29]. Ntasiou et al. (2021) synthesized and modified four CuNPs (CuNPs Type 1 to 4) by means of the wet chemistry approach. Among these, CuNPs Type 3 and CuNPs Type 4 demonstrated potent protective activity against both *Fusicladium oleagineum* and *Colletotrichum acutatum*. Their control efficacy values were notably higher as compared to the reference commercial compounds, copper oxide and copper hydroxide (Figure 6) [29].

Badawy et al. (2021) discovered that CuONPs improve the growth metrics of wheat plants [30]. The impact of CuONPs on Indian mustard (*Brassica juncea* L.) differed based on the application method. Faraz et al. (2022) applied CuONPs as a foliar spray on *Brassica juncea* plants, leading to augmented growth, improved antioxidant capacity, and an elevated photosynthetic rate. However, at higher concentrations, the effect on growth was found to be minimal [31]. In another work, irrigation with CuONPs raised the levels of macro- and micronutrients in the roots of *L. sativa* plants [32].

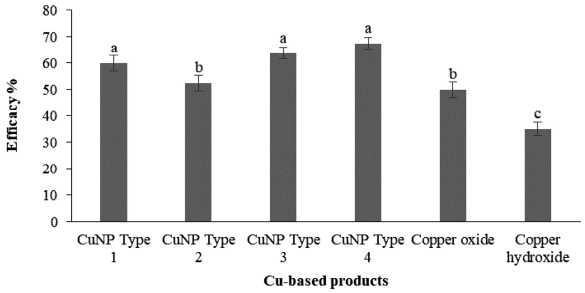


Figure 6. Efficacy percentages of treatments using CuNPs and conventional copper-based products against *Fusicladium oleagineum*. The letters 'a'–'c' represent significant differences between the treatments at $p = 0.05$, based on Fisher's LSD test.

2.4. Iron-Based Nanoparticles

Iron-based NPs possess an intriguing characteristic in that they have the capacity to influence stomatal opening, germination, and seedling growth through various complex effects [33,34]. They also demonstrate the potential to shield plants from drought, potentially by mitigating the oxidative stress induced by water deficiency [35]. Additionally, treated plants exhibit heightened chlorophyll biosynthesis [36]. FeNPs have proven to be effective in the remediation of heavy metals in both soil and water [37,38]. Plaksenkova et al. (2019) studied the impact of Fe_3O_4NPs on rocket (*Eruca sativa Mill.*). They investigated the changes in morphology, chlorophyll contents, germination rate, genotoxicity, and level of miRNA expression at 1, 2, and 4 mg/L concentrations of Fe_3O_4NPs, which positively affected the growth and development of rocket plants. Fe_3O_4NPs significantly increased the germination percentage and shoot and root length. At a 4 mg/L concentration of Fe_3O_4NPs, the maximum germination rate (Figure 7a) and shoot length (Figure 7b) were observed. However, a decreased root length was observed at this concentration as compared to control. The chlorophyll a content and miRNA expression level increased at a 1 mg/L concentration (Figure 7c,d) [39].

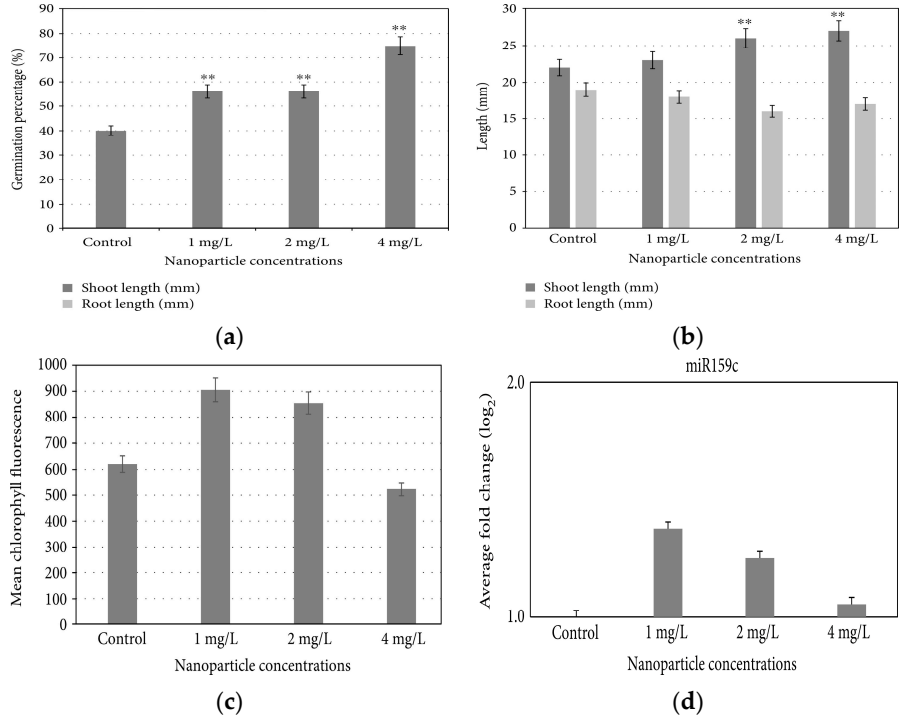


Figure 7. Effect of exposure to Fe_3O_4NPs on (**a**) germination percentage, (**b**) shoot and root length, (**c**) chlorophyll content, and (**d**) miRNA expression of rocket plants. Double asterisk (**) indicates significant difference from the control at $p < 0.01$.

When rice seeds (*cv. Gobindabhog*) were exposed to FeNPs during germination, they displayed heightened seedling growth, cell viability, and cell membrane integrity, higher chlorophyll contents, and increased metabolic activity [40]. Furthermore, in a study conducted by Khan et al. (2020), the impact of Fe_3O_4NPs on rice plants subjected to arsenic stress was examined. They observed that a lower concentration of Fe_3O_4NPs significantly lowered the arsenic levels and facilitated plant growth. Conversely, a higher concentration failed to produce the same effects. These studies indicated that the effects of Fe_3O_4NPs varied depending on their dosage [41].

2.5. Titanium Dioxide Nanoparticles (TiO_2NPs)

TiO_2NPs have been shown to have an impact on various aspects of plants, including growth cell division, callus induction, cell size, and hormone levels (specifically Gibberellins and cytokinins), resulting in a significant increase in treated *Rosmarinus officinalis* plants [42]. TiO_2NPs increased the levels of photosynthetic pigments in the wheat plants under drought stress [43]. The favourable effects of TiO_2NPs on seed germination have also been observed in chickpea (*Cicer arietinum*) and in fodder crops like berseem and oat [44,45]. Recently, Shah et al. (2021) reported a significant impact of TiO_2NP priming on seeds of maize (*Zea mays* L.) plants under salinity stress (Figure 8) [46].

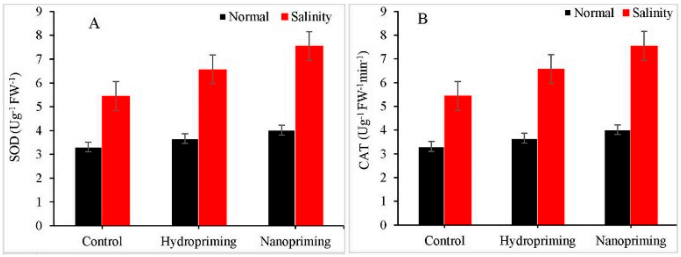


Figure 8. Impact of TiO_2NP nanopriming on the application of (**A**) SOD and (**B**) CAT enzymes in maize plants under saline and normal conditions.

2.6. Carbon-Based Nanomaterials

Carbon nanotubes (CNTs) have demonstrated a positive impact on tomato germination and seedling growth [47]. Additionally, research on six plant species including maize, soybean, rice, barley, tobacco, tomato and switchgrass demonstrated that single-walled carbon nanohorns (SWCNHs) enhanced the seed germination of these plant species [48]. Recently, Ren et al. (2020) discovered that the addition of single-walled carbon nanotubes (SWCNTs) to the plant vitrification solution significantly improved the relative survival rate in the cryopreservation of Agapanthus praecox embryogenic callus. The callus treated with SWCNTs exhibited elevated levels of antioxidants, including SOD, and POD, in comparison to the control group (Figure 9) [49].

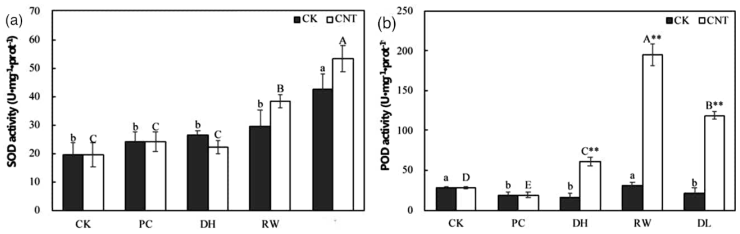


Figure 9. Effect of SWCNTs on the (**a**) SOD and (**b**) POD of the cryopreservation system. (CK= cryopreservation without adding SWCNTs; CNT= cryopreservation with SWCNTs –added; PC = after pre-culture; DH= after dehydration; RW= after rapid cooling–warming; DL= after dilution). Values with different lowercase letters show significant differences among samples in the control group at the $p = 0.05$ level, while values with different uppercase letters indicate significant differences among samples in the SWCNTs group at the $p = 0.05$ level. Double asterisks (**) indicate highly significant differences between groups at the same stage, at the $p = 0.01$ level.

2.7. Other NPs

Various studies have demonstrated the positive effect of NPs on seed germination, plant growth, and plant development. Studies have shown that silica nanoparticles (SiO_2NPs) enhanced the rate of germination of rice, thyme, broad bean, sunflower and lettuce [50–54]. Lemongrass (*Cymbopogon flexuosus*), known for its medicinal properties and essential oil production, experiences improved growth and yield with the application of silicon nanoparticles (SiNPs) [55]. Jayarambabu et al. (2016) demonstrated that magnesium nanoparticles (MgNPs) positively affect seed germination in maize plants [56]. Even though cerium is not considered an essential element for plants, it has been shown to have positive effects on various aspects including seed germination, plant growth, yield, as well as chlorophyll and saccharide content [57]. It inhibited the accumulation of cadmium [58]. Chitosan, a naturally occurring compound found in the exoskeleton of crustaceans, has been extensively studied for its effects on cell signalling molecules [59], film-forming ability, and antibacterial properties [60].

3. Toxic Effects of NPs

The above examples illustrate how NPs can positively influence plant growth and development, but NPs also show toxic effects. Both their toxic and beneficial impacts depend on factors like concentration, size, surface properties, and plant species. At low concentrations and under controlled conditions, NPs can enhance plant growth by improving nutrient uptake, increasing photosynthesis, and strengthening stress tolerance. However, at higher concentrations or with prolonged exposure, they may generate excessive reactive oxygen species (ROS), causing oxidative stress that damages cellular structures like membranes, proteins, and DNA. NPs can also interfere with water and nutrient absorption, disrupt enzyme activities, and release toxic metal ions, all of which impair plant growth [61–63].

To mitigate the toxic effects of NPs on plant growth and development, several strategies can be employed. Using NPs in controlled, low concentrations is essential to prevent overexposure. Surface modifications with biocompatible materials or the use of controlled-release systems can limit toxicity by reducing metal ion release and oxidative stress [64]. Soil amendments and phytoremediation plants can help to reduce NPs' bioavailability in the soil. Additionally, antioxidant supplements can protect plants from ROS damage, while controlling NPs' size and using biodegradable or eco-friendly NPs can further minimize long-term environmental effects [65]. These approaches can help to balance the positive uses of NPs in agriculture while reducing their negative effects on plant health and growth.

4. Conclusions

NPs offer several advantages over traditional fertilizers, making them a superior option for promoting plant growth through their targeted delivery, enhancing absorption and minimizing losses due to leaching. They also offer multifunctional capabilities by combining growth promotion, disease resistance, and stress tolerance, while improving soil quality by enhancing soil structure and microbial activity. This literature survey shows that controlled concentrations and moderate doses of NPs greatly promote plant growth. It is conceivable that the long-term use of NPs may impact the environment due to their accumulation in the soil [66–68]. Further exploration of NPs is required to enhance the growth of agricultural products and to minimize environmental challenges.

Author Contributions: Conceptualization, S.J., S. and T.K.; resources, S.J.; data curation, S., T.K. and S.J.; writing—original draft preparation, S., K.H., S.G., P.M., T.K. and S.J.; writing—review and editing, S., T.K. and S.J.; visualization, S., T.K. and S.J.; supervision, S.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data was generated during the study.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Farooqui, A.R.; Tabassum, H.; Ahmad, A.; Mabood, A.; Ahmad, A.; Ahmad, I.Z. Role of nanoparticles in growth and development of plants: A review. *Int. J. Pharm. Bio Sci.* **2016**, *7*, 22–37. [CrossRef]
2. Rico, C.M.; Peralta-Videa, J.R.; Gardea-Torresdey, J.L. Chemistry, biochemistry of nanoparticles, and their role in antioxidant defense system in plants. *Nanotechnol. Plant Sci.* **2015**, *1*, 1–17.
3. Ali, S.; Mehmood, A.; Khan, N. Uptake, translocation, and consequences of nanomaterials on plant growth and stress adaptation. *J. Nanomater.* **2021**, *2021*, 6677616. [CrossRef]
4. Shelar, G.B.; Chavan, A.M. Myco-synthesis of silver nanoparticles from *Trichoderma harzianum* and its impact on germination status of oil seed. *Biolife* **2015**, *3*, 109–113.
5. Sharma, P.; Bhatt, D.; Zaidi, M.G.H.; Saradhi, P.P.; Khanna, P.K.; Arora, S. Silver nanoparticle-mediated enhancement in growth and antioxidant status of *Brassica juncea*. *Appl. Biochem. Biotechnol.* **2012**, *167*, 2225–2233. [CrossRef]
6. Vannini, C.; Domingo, G.; Onelli, E.; Prinsi, B.; Marsoni, M.; Espen, L.; Bracale, M. Morphological and proteomic responses of *Eruca sativa* exposed to silver nanoparticles or silver nitrate. *PLoS ONE* **2013**, *8*, e68752. [CrossRef]
7. Hatami, M.; Ghorbanpour, M. Effect of nanosilver on physiological performance of pelargonium plants exposed to dark storage. *J. Hortic. Res.* **2013**, *21*, 15–20. [CrossRef]
8. Giri, V.P.; Shukla, P.; Tripathi, A.; Verma, P.; Kumar, N.; Pandey, S.; Dimkpa, C.O.; Mishra, A. A review of sustainable use of biogenic nanoscale agro-materials to enhance stress tolerance and nutritional value of plants. *Plants* **2023**, *12*, 815. [CrossRef] [PubMed]
9. Hernández-Hernández, H.; Juárez-Maldonado, A.; Benavides-Mendoza, A.; Ortega-Ortiz, H.; Cadenas-Pliego, G.; Sánchez-Aspeytia, D.; González-Morales, S. Chitosan-PVA and copper nanoparticles improve growth and overexpress the SOD and JA genes in tomato plants under salt stress. *Agronomy* **2018**, *8*, 175. [CrossRef]
10. Feng, Y.; Kreslavski, V.D.; Shmarev, A.N.; Ivanov, A.A.; Zharmukhamedov, S.K.; Kosobryukhov, A.; Yu, M.; Allakhverdiev, S.I.; Shabala, S. Effects of iron oxide nanoparticles (Fe_3O_4) on growth, photosynthesis, antioxidant activity and distribution of mineral elements in wheat (*Triticum aestivum*) Plants. *Plants* **2022**, *11*, 1894. [CrossRef]
11. Manaf, A.; Wang, X.; Tariq, F.; Jhanzab, H.M.; Bibi, Y.; Sher, A.; Razzaq, A.; Fiaz, S.; Tanveer, S.K.; Qayyum, A. Antioxidant enzyme activities correlated with growth parameters of wheat sprayed with silver and gold nanoparticle suspensions. *Agronomy* **2021**, *11*, 1494. [CrossRef]
12. Rea, R.S.; Islam, M.R.; Rahman, M.M.; Nath, B.; Mix, K. Growth, nutrient accumulation, and drought tolerance in crop plants with silicon application: A review. *Sustainability* **2022**, *14*, 4525. [CrossRef]
13. Seleiman, M.F.; Ahmad, A.; Alhammad, B.A.; Tola, E. Exogenous application of zinc oxide nanoparticles improved antioxidants, photosynthetic, and yield traits in salt-stressed maize. *Agronomy* **2023**, *13*, 2645. [CrossRef]
14. Rani, P.U.; Yasur, J.; Loke, K.S.; Dutta, D. Effect of synthetic and biosynthesized silver nanoparticles on growth, physiology and oxidative stress of water hyacinth: *Eichhornia crassipes* (Mart) Solms. *Acta Physiol. Plant.* **2016**, *38*, 58. [CrossRef]
15. Mohamed, A.K.S.; Qayyum, M.F.; Abdel-Hadi, A.M.; Rehman, R.A.; Ali, S.; Rizwan, M. Interactive effect of salinity and silver nanoparticles on photosynthetic and biochemical parameters of wheat. *Arch. Agron. Soil Sci.* **2017**, *63*, 1736–1747. [CrossRef]
16. Shaikhaldein, H.O.; Al-Qurainy, F.; Nadeem, M.; Khan, S.; Tarroum, M.; Salih, A.M. Biosynthesis and characterization of silver nanoparticles using *Ochradenus arabicus* and their physiological effect on *Maerua oblongifolia* raised in vitro. *Sci. Rep.* **2020**, *10*, 17569. [CrossRef]
17. Pallavi; Mehta, C.M.; Srivastava, R.; Arora, S.; Sharma, A.K. Impact assessment of silver nanoparticles on plant growth and soil bacterial diversity. *3 Biotech* **2016**, *6*, 254. [CrossRef]
18. Jasim, B.; Thomas, R.; Mathew, J.; Radhakrishnan, E.K. Plant growth and diosgenin enhancement effect of silver nanoparticles in Fenugreek (*Trigonella foenum-graecum* L.). *Saudi Pharm. J.* **2017**, *25*, 443–447. [CrossRef]
19. Al-Huqail, A.A.; Hatata, M.M.; Al-Huqail, A.A.; Ibrahim, M.M. Preparation, characterization of silver phyto nanoparticles and their impact on growth potential of *Lupinus termis* L. seedlings. *Saudi J. Biol. Sci.* **2018**, *25*, 313–319. [CrossRef]
20. Vinković, T.; Novák, O.; Strnad, M.; Goessler, W.; Jurašin, D.D.; Parađiković, N.; Vrček, I.V. Cytokinin response in pepper plants (*Capsicum annuum* L.) exposed to silver nanoparticles. *Environ. Res.* **2017**, *156*, 10–18. [CrossRef]
21. Ibrahim, E.; Zhang, M.; Zhang, Y.; Hossain, A.; Qiu, W.; Chen, Y.; Wang, Y.; Wu, W.; Sun, G.; Li, B. Green-synthesization of silver nanoparticles using endophytic bacteria isolated from garlic and its antifungal activity against wheat *Fusarium* head blight pathogen *Fusarium graminearum*. *Nanomaterials* **2020**, *10*, 219. [CrossRef]
22. Khot, L.R.; Sankaran, S.; Maja, J.M.; Ehsani, R.; Schuster, E.W. Applications of nanomaterials in agricultural production and crop protection: A review. *Crop Prot.* **2012**, *35*, 64–70. [CrossRef]
23. Ditta, A.; Arshad, M. Applications and perspectives of using nanomaterials for sustainable plant nutrition. *Nanotechnol. Rev.* **2016**, *5*, 209–229. [CrossRef]

24. Sarkhosh, S.; Kahrizi, D.; Darvishi, E.; Tourang, M.; Haghighi-Mood, S.; Vahedi, P.; Ercisli, S. Effect of Zinc Oxide Nanoparticles (ZnO-NPs) on Seed Germination Characteristics in Two Brassicaceae Family Species: *Camelina sativa* and *Brassica napus* L. *J. Nanomater.* **2022**, *2022*, 1892759. [CrossRef]
25. Hussain, A.; Ali, S.; Rizwan, M.; ur Rehman, M.Z.; Javed, M.R.; Imran, M.; Chatha, S.A.; Nazir, R. Zinc oxide nanoparticles alter the wheat physiological response and reduce the cadmium uptake by plants. *Environ. Pollut.* **2018**, *242*, 1518–1526. [CrossRef]
26. Jankovskis, L.; Kokina, I.; Plaksenkova, I.; Jermaļonoka, M. Impact of different nanoparticles on common wheat (*Triticum aestivum* L.) plants, course, and intensity of photosynthesis. *Sci. World J.* **2022**, *2022*, 3693869. [CrossRef] [PubMed]
27. Pariona, N.; Mtz-Enriquez, A.I.; Sánchez-Rangel, D.; Carrión, G.; Paraguay-Delgado, F.; Rosas-Saito, G. Green-synthesized copper nanoparticles as a potential antifungal against plant pathogens. *RSC Adv.* **2019**, *9*, 18835–18843. [CrossRef]
28. Malandrakis, A.A.; Kavroulakis, N.; Chrysikopoulos, C.V. Synergy between Cu-NPs and fungicides against *Botrytis cinerea*. Sci. *Total Environ.* **2020**, *703*, 135557. [CrossRef]
29. Ntasiou, P.; Kaldeli Kerou, A.; Karamanidou, T.; Vlachou, A.; Tziros, G.T.; Tsouknidas, A.; Karaoglanidis, G.S. Synthesis and characterization of novel copper nanoparticles for the control of leaf spot and anthracnose diseases of olive. *Nanomaterials* **2021**, *11*, 1667. [CrossRef]
30. Badawy, A.A.; Abdelfattah, N.A.; Salem, S.S.; Awad, M.F.; Fouda, A. Efficacy assessment of biosynthesized copper oxide nanoparticles (CuO-NPs) on stored grain insects and their impacts on morphological and physiological traits of wheat (*Triticum aestivum* L.) plant. *Biology* **2021**, *10*, 233. [CrossRef]
31. Faraz, A.; Faizan, M.; Hayat, S.; Alam, P. Foliar application of copper oxide nanoparticles increases the photosynthetic efficiency and antioxidant activity in *Brassica juncea*. *J. Food Qual.* **2022**, *2022*, 5535100. [CrossRef]
32. Kohatsu, M.Y.; Pelegrino, M.T.; Monteiro, L.R.; Freire, B.M.; Pereira, R.M.; Fincheira, P.; Lange, C.N. Comparison of foliar spray and soil irrigation of biogenic CuO nanoparticles (NPs) on elemental uptake and accumulation in lettuce. *Environ. Sci. Pollut. Res.* **2021**, *28*, 16350–16367. [CrossRef] [PubMed]
33. Kasote, D.M.; Lee, J.H.; Jayaprakasha, G.K.; Patil, B.S. Seed priming with iron oxide nanoparticles modulate antioxidant potential and defense-linked hormones in watermelon seedlings. *ACS Sustain. Chem. Eng.* **2019**, *7*, 5142–5151. [CrossRef]
34. Asadi-Kavan, Z.; Khavari-Nejad, R.A.; Iranbakhsh, A.; Najafi, F. Cooperative effects of iron oxide nanoparticle (α-Fe_2O_3) and citrate on germination and oxidative system of evening primrose (*Oenthera biennis* L.). *J. Plant Interact.* **2020**, *15*, 166–179. [CrossRef]
35. Mohasseli, V.; Farbood, F.; Moradi, A. Antioxidant defense and metabolic responses of lemon balm (*Melissa officinalis* L.) to Fe-nano-particles under reduced irrigation regimes. *Ind. Crop. Prod.* **2020**, *149*, 112338. [CrossRef]
36. Wang, Y.; Wang, S.; Xu, M.; Xiao, L.; Dai, Z.; Li, J. The impacts of γ-Fe_2O_3 and Fe_3O_4 nanoparticles on the physiology and fruit quality of muskmelon (*Cucumis melo*) plants. *Environ. Pollut.* **2019**, *249*, 1011–1018. [CrossRef]
37. Fajardo, C.; Costa, G.; Nande, M.; Martín, C.; Martín, M.; Sánchez-Fortún, S. Heavy metals immobilization capability of two iron-based nanoparticles (nZVI and Fe_3O_4): Soil and freshwater bioassays to assess ecotoxicological impact. *Sci. Total Environ.* **2019**, *656*, 421–432. [CrossRef]
38. Litter, M.I. A short review on the preparation and use of iron nanomaterials for the treatment of pollutants in water and soil. *Emerg. Mater.* **2022**, *5*, 391–400. [CrossRef]
39. Plaksenkova, I.; Jermaļonoka, M.; Bankovska, L.; Gavarāne, I.; Gerbreders, V.; Sledevskis, E.; Snikeris, J.; Kokina, I. Effects of Fe_3O_4 nanoparticle stress on the growth and development of rocket *Eruca sativa*. *J. Nanomater.* **2019**, *2019*, 2678247. [CrossRef]
40. Guha, T.; Ravikumar, K.V.G.; Mukherjee, A.; Mukherjee, A.; Kundu, R. Nanopriming with zero valent iron (nZVI) enhances germination and growth in aromatic rice cultivar (*Oryza sativa* cv. *Gobindabhog* L.). *Plant Physiol. Biochem.* **2018**, *127*, 403–413. [CrossRef]
41. Khan, S.; Akhtar, N.; Rehman, S.U.; Shujah, S.; Rha, E.S.; Jamil, M. Biosynthesized iron oxide nanoparticles (Fe_3O_4 NPs) mitigate arsenic toxicity in rice seedlings. *Toxics* **2020**, *9*, 2. [CrossRef] [PubMed]
42. Golami, A.; Abbaspour, H.; Hashemi-Moghaddam, H.; Gerami, M. Photocatalytic Effect of TiO_2 Nanoparticles on Essential Oil of *Rosmarinus officinalis*. *J. Biochem. Technol.* **2018**, *9*, 50.
43. Faraji, J.; Sepehri, A. Ameliorative effects of TiO_2 nanoparticles and sodium nitroprusside on seed germination and seedling growth of wheat under PEG-stimulated drought stress. *J. Seed Sci.* **2019**, *41*, 309–317. [CrossRef]
44. Hajra, A.; Mondal, N.K. Effects of ZnO and TiO_4 nanoparticles on germination, biochemical and morphoanatomical attributes of *Cicer arietinum* L. *Energy Ecol. Environ.* **2017**, *2*, 277–288. [CrossRef]
45. Maity, A.; Natarajan, N.; Vijay, D.; Srinivasan, R.; Pastor, M.; Malaviya, D.R. Influence of metal nanoparticles (NPs) on germination and yield of oat (*Avena sativa*) and berseem (*Trifolium alexandrinum*). *Proc. Natl. Acad. Sci. India Sect. B Biol. Sci.* **2018**, *88*, 595–607. [CrossRef]
46. Shah, T.; Latif, S.; Saeed, F.; Ali, I.; Ullah, S.; Alsahli, A.A.; Jan, S.; Ahmad, P. Seed priming with titanium dioxide nanoparticles enhances seed vigor, leaf water status, and antioxidant enzyme activities in maize (*Zea mays* L.) under salinity stress. *J. King Saud Univ. Sci.* **2021**, *33*, 101207. [CrossRef]
47. Khodakovskaya, M.; Dervishi, E.; Mahmood, M.; Xu, Y.; Li, Z.; Watanabe, F.; Biris, A.S. Carbon nanotubes are able to penetrate plant seed coat and dramatically affect seed germination and plant growth. *ACS Nano* **2009**, *3*, 3221–3227. [CrossRef] [PubMed]
48. Lahiani, M.H.; Chen, J.; Irin, F.; Puretzky, A.A.; Green, M.J.; Khodakovskaya, M.V. Interaction of carbon nanohorns with plants: Uptake and biological effects. *Carbon* **2015**, *81*, 607–619. [CrossRef]

49. Ren, L.; Deng, S.; Chu, Y.; Zhang, Y.; Zhao, H.; Chen, H.; Zhang, D. Single-wall carbon nanotubes improve cell survival rate and reduce oxidative injury in cryopreservation of Agapanthus praecox embryogenic callus. *Plant Methods* **2020**, *16*, 130. [CrossRef]
50. Shah, V.; Belozerova, I. Influence of metal nanoparticles on the soil microbial community and germination of lettuce seeds. *Water Air Soil Pollut.* **2009**, *197*, 143–148. [CrossRef]
51. Adhikari, T.; Kundu, S.; Rao, A.S. Impact of SiO_2 and Mo nano particles on seed germination of rice (*Oryza sativa* L.). *Int. J. Agric. Food Sci. Technol.* **2013**, *4*, 809–816.
52. Roohizadeh, G.; Majd, A.; Arbabian, S. The effect of sodium silicate and silica nanoparticles on seed germination and growth in the *Vicia faba* L. *Trop. Plant Res.* **2015**, *2*, 85–89.
53. Abbasi Khalaki, M.; Ghorbani, A.; Moameri, M. Effects of silica and silver nanoparticles on seed germination traits of *Thymus kotschyanus* in laboratory conditions. *J. Rangeland Sci.* **2016**, *6*, 221–231.
54. Janmohammadi, M.; Sabaghnia, N. Effect of pre-sowing seed treatments with silicon nanoparticles on germinability of sunflower (*Helianthus annuus*). *Bot. Lith.* **2015**, *21*, 13–21. [CrossRef]
55. Mukarram, M.; Khan, M.M.A.; Corpas, F.J. Silicon nanoparticles elicit an increase in lemongrass (*Cymbopogon flexuosus* (Steud.) Wats) agronomic parameters with a higher essential oil yield. *J. Hazard. Mater.* **2021**, *412*, 125254. [CrossRef]
56. Jayarambabu, N.; Kumari, S.B.; Rao, V.K.; Prabhu, Y.T. Enhancement of growth in maize by biogenic-synthesized MgO nanoparticles. *Int. J. Pure Appl. Zool.* **2016**, *4*, 262–270.
57. Ramírez-Olvera, S.M.; Trejo-Téllez, L.I.; García-Morales, S.; Pérez-Sato, J.A.; Gómez-Merino, F.C. Cerium enhances germination and shoot growth, and alters mineral nutrient concentration in rice. *PLoS ONE* **2018**, *13*, e0194691. [CrossRef] [PubMed]
58. Wang, Y.; Wang, L.; Ma, C.; Wang, K.; Hao, Y.; Chen, Q.; Mo, Y.; Rui, Y. Effects of cerium oxide on rice seedlings as affected by co-exposure of cadmium and salt. *Environ. Pollut.* **2019**, *252*, 1087–1096. [CrossRef]
59. Farhadihosseinabadi, B.; Zarebkohan, A.; Eftekhary, M.; Heiat, M.; Moosazadeh Moghaddam, M.; Gholipourmalekabadi, M. Crosstalk between chitosan and cell signaling pathways. *Cell. Mol. Life Sci.* **2019**, *76*, 2697–2718. [CrossRef]
60. Ma, Y.; Fu, L.; Hussain, Z.; Huang, D.; Zhu, S. Enhancement of storability and antioxidant systems of sweet cherry fruit by nitric oxide-releasing chitosan nanoparticles (GSNO-CS NPs). *Food Chem.* **2019**, *285*, 10–21. [CrossRef]
61. Szőllősi, R.; Molnár, Á.; Kondak, S.; Kolbert, Z. Dual effect of nanomaterials on germination and seedling growth: Stimulation vs. phytotoxicity. *Plants* **2020**, *9*, 1745. [CrossRef] [PubMed]
62. Zhou, P.; Adeel, M.; Shakoor, N.; Guo, M.; Hao, Y.; Azeem, I.; Li, M.; Liu, M.; Rui, Y. Application of nanoparticles alleviates heavy metals stress and promotes plant growth: An overview. *Nanomaterials* **2020**, *11*, 26. [CrossRef] [PubMed]
63. Kolesnikov, S.; Timoshenko, A.; Minnikova, T.; Tsepina, N.; Kazeev, K.; Akimenko, Y.; Zhadobin, A.; Shuvaeva, V.; Rajput, V.D.; Mandzhieva, S.; et al. Impact of metal-based nanoparticles on cambisol microbial functionality, enzyme activity, and plant growth. *Plants* **2021**, *10*, 2080. [CrossRef] [PubMed]
64. Paramo, L.A.; Feregrino-Pérez, A.A.; Guevara, R.; Mendoza, S.; Esquivel, K. Nanoparticles in agroindustry: Applications, toxicity, challenges, and trends. *Nanomaterials* **2020**, *10*, 1654. [CrossRef]
65. Maurer-Jones, M.A.; Gunsolus, I.L.; Murphy, C.J.; Haynes, C.L. Toxicity of engineered nanoparticles in the environment. *Anal. Chem.* **2013**, *85*, 3036–3049. [CrossRef]
66. Satya; Hashmi, K.; Gupta, S.; Singh, N.; Khan, T.; Joshi, S. Nanofabrication of Metals and Their Compounds for Effective Medicinal and Environmental Applications (A Review). *Russ. J. Gen. Chem.* **2023**, *93*, 635–665. [CrossRef]
67. Khan, T.; Rahman, Q.I.; Raza, S.; Zehra, S.; Ahmad, N.; Husen, A. Nanodimensional materials:an approach toward the biogenic synthesis. In *Advances in Smart Nanomaterials and their Applications*; Husen, A., Siddiqi, K.S., Eds.; Elsevier: Amsterdam, The Netherlands, 2023; pp. 523–568. ISBN 978-0-323-99546-7.
68. Veg, E.; Joshi, S.; Khan, T. Design and Fabrication of Heterojunctions of Thiosemicarbazones and Metal Oxide Nanoparticles in Search of Their Medicinal Activity. *Eng. Proc.* **2024**, *67*, 46. [CrossRef]

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