Journal of Education for Pure Science- University of Thi-Qar
Vol.15, No. 3 (2025)
DOI:https://doi.org/10.32792/jeps.v15i3.605
Website:jceps.utq.edu.iq Email:jceps@eps.utq.edu.iq

Efficiency of Nanofertilizers in plant (Review)

Bihar M. Al-Ani[1], Thamer M. Badawi [2*]

[1] Department of biotechnology, College of science, University of Anbar, Ramadi, Iraq
[2]The Ministry of Education in Iraq, Directorate of Education in Anbar, Ramadi, Iraq

[*] Corresponding email: Thamer_ma1980@yahoo.com

Received 6 /12/2024, Accepted 27 /2/2025, Published 1 /9/2025

Abstract:

Nanofertilizers represent a modern technology that improves agricultural production quality, biologically supports it, and promotes environmental safety and financial stability. To overcome the obstacles of traditional agriculture, nanotechnology provides practical solutions. Nanofertilizers play a vital role in reducing the environmental damage caused by Chemical fertilizers. They can penetrate plant epidermis more effectively and have greater reactivity, allowing for a controlled release of nutrients. This reduces nutrient excess, enhances nutrient utilization efficiency, and ensures targeted distribution. These fertilizers increase soil fertility and improve plants' capacity to absorb nutrients, thereby enhancing the efficiency of nutrients. As an excellent alternative to traditional chemical fertilizers, nanofertilizers (NFs) have effectively promoted environmental sustainability, while boosting crop productivity through intelligent nutrients delivery. Depending on the properties of NFs and their application methods, NFs may be absorbed by plants through their roots or leaves. They also reduce production costs and harmful environmental impacts, and enhance the plant's ability to withstand biotic and abiotic stress. However, the overuse of NFs in various plants, as excessive doses can lead to Phytotoxicity as it may harm plant growth and environment. The main difficulties facing NFs manufacturers are non-toxicity, cost, recycling, and the ability to recover them after use and biological decomposition. The Physical and Chemical Properties of the soil have an impact on NPs. as they widely affect the aggregation, dispersion, fixation, stability, NPs transfer, and bioavailability.

Keywords: Nanofertilizers, Chemical fertilizers, Nanotechnology, Nanonutrients

1-IntroductionSection

The lack of food production and environmental crises are among worldwide influential matters that require direct political and scientific solutions [1,2], Also manufacturing development and the increase in population numbers, which leads to an increase in toxic substances and thus environmental pollution [3]. To meet the rising calorie needs associated with population growth, food production must increase by 60-70% [4, 5] provide the global need for food, it is pivotal to enhance the efficiency of resources used in production. Modern technology and the scientific advancement have made chemical fertilizers used in recent decades essential in maintaining adequate food production and boosting crop yields [6, 7]. To increase crop production in developing countries, chemical fertilizers accounted for 50%. However, chemical fertilizers and the efficiency of the nutrients used, including nitrogen, phosphorus, potassium, and micronutrients, are still low due to the loss of nutrients from soils or the transfer of nutrients into slowly cycling / intractable accumulations within the soils [8], leading to decreased soil fertility because of the negative balance of soil nutrients, and increased mining of soil nutrients [9].Also, to achieve the desired yield, the excessive utilization of chemical fertilizers has become prevalent, causing a decline in soil quality due to soil, environmental, and water pollution[10]. [11] reported that the long term application of chemical fertilizers hurts the ecosystem by stiffening the soil, reducing soil fertility, contaminating water and soil, as well as depleting essential nutrients of soil and minerals. Furthermore, it caused world warming and climate alteration, the poor use of non-renewable resources such as rock phosphate, oil, and gas, etc., and environmental issues such as air and groundwater pollution, eutrophication and surface runoff [12]. In addition to the contamination of groundwater, the concentration of nitrates rises due to widely used fertilizers reaching a toxic level [13]. It also raises the material cost of production and reduces profits for farmers [14].To restore natural resources, harmful environmental impacts must be reduced to make intensive agriculture productive, using new methods that protect the environment and increase agricultural production [15].An example of this is Nano fertilizers (NFs), which intelligently deliver agricultural chemicals and have gained great interest in terms of reducing harmful environmental impacts and achieving high crop productivity [16, 17].NFs contains micro and macro nutrients and is delivered to plants in a smart and controlled way [18] by their large surface area to volume ratio , very small size and potential to be coated with different substances to control the release rate promote the nutrient delevary efficiency and reduced fertilizer application rates [19]. When NFs are used as a foliar fertilizer or added to the soil, they can enter plant systems because of its chemical and physical characteristics and the tiny dimensions of their particles (<100 nm), which makes them benefit more than regular chemical fertilizers [20]. This review aims to study the effects of nanotechnology on plant nutrition, growth and productivity, and how nanomaterials can be used to deliver nutrients more efficiently to plants, which may lead to increased agricultural production and reduced waste of resources. In addition, the environmental impacts of these technologies will be addressed, including potential risks from toxic accumulations in the ecosystem.

1- Nanotechnology

Nanotechnology is described as a promising technology that contributes to increasing sustainable competitiveness and significantly solving environmental problems and societal challenges [21]. The increasing demand for agricultural production to meet bioenergy from limited or low arable land, and because of poverty, economic development activities, dependence on basic commodities, and malnutrition, all of this can be overcome through development in the fields of technology and science increase production [18].Through current nanotechnology, production can be increased significantly by using effective nutrient systems, precision agriculture, improved plant protection methods, etc. [22]. Nanotechnology has contributed to developing an effective system for plant nutrients and water management systems, Nano pesticides, increasing the exploitation of solar energy by plants, and minimizing environmental damage [23]. The low efficiency (20-50%) and high material cost of traditional fertilizers have prompted scientists to enhance the use and development of NFs [24].To increase physiological factors and thus increase germination, growth, and productivity rates [6].This is achieved by increasing the plant's ability to get more light [25].

Therefore, nanofertilizers are used as an alternative to chemical fertilizers because they are environmentally friendly [26,27]. Nanofertilizers are defined as nanoparticles or nanomaterials used to improve plant growth and production by delivering beneficial and necessary nutrients in a nanoform [28, 10]. [19] categorised nanofertilizers into four groups depending on their composition: nutrient-loaded nanofertilizers, micronutrient nanofertilizers, macronutrient nanofertilizers, and plant growth-enhancing nanomaterials.

Plant productivity is affected by the type of fertilizer added, and the artificial fertilizers added at high rates have led to a decrease in soil fertility and depletion of agricultural soil, thus reducing plant productivity [29].According to recent studies, the fertilizers used represent about 30% of the achieved plant production, and the remaining 70%

depends on agricultural inputs and other factors used [30].Large quantities of fertilizers added to the soil are stabilized or lost to the environment through the leaching process, runoff, and volatilization [31].Consequently, a decrease in the efficiency of the synthetic fertilizers used [25]. Thus, it affects the availability of nutrients in the plant, as small amounts of fertilizer reach the target sites in the plant [32]. High doses of synthetic fertilizers used by farmers to obtain high production to achieve balance with the growing population affected the balance of nutrients in the soil and increased the concentration of salts thus affecting the productivity of plants [18].

Nano-selective materials typically, less than 100 nm in size are added to the soils to provide nutrients, offering several advantages such as: (1) Providing plant nutrient requirements through foliar application or soil addition (2) An environmentally friendly and low-cost source (3) The efficiency of the fertilization process is high (4) Complementing the role of chemical fertilizers, (5) protecting the environment from pollution risks [33].Nanotechnology is an application that deals with plant nano-nutrition and nano-nutrients in many ways, including absorption and transport of nano-elements, metabolism, and the provision of nanonutrients necessary for plant growth in the rhizosphere to increase production [23].Compared to larger scales of the same material, reducing the size of a substance at the nanoscale changes its physical and chemical features [34]. Nano technology is used in agriculture by 1-Using Nano-agricultural chemicals, 2- Increasing and improving food production, 3- Increasing the soil's capacity to keep water and improving its quality 4- Enhancing the absorption of elements and the use of nutrients that stimulate plant growth, 5 - Using nano-sensors and smart monitoring using wireless communication devices to maintain the farm and help farmers by accurately reporting plant needs [35].

Nanofertilizers, through various mechanisms, enhance plant growth. For example, increasing the solubility of nutrients like phosphate [36], reducing the harmful effects of abiotic and biotic stresses, (e.g. drought, flooding, salinity). increasing the production of plant hormones in the soil which improves plant nutrition [37, 38] through different mechanisms like phytohormons biosynthesis regulating, modulating the available phytohormones and regulating the process of signaling [39]. Improving nitrogen fixation and thus enhances plant growth [37] Sustainable environment [40], and Increase soil fertility [34]. The nutrients in nanofertilizersare encapsulated in a thin protective layer, in the form of nanoparticles, or in the form of an emulsion [10]. Nutrients can be released according to environmental conditions such as moisture, temperature, and soil acidity. The release of elements can be controlled slowly or quickly, which improves plant growth compared to traditional fertilizers, thus improving the efficiency of nutrients used in smart nanofertilizers and reducing nutrient losses in traditional fertilizers [41].Nanofertilizers supply nutrients to the plant in nanoforms, which enhances plant growth and productivity [42].They are classified according to the needs of plants into three categories: nano-particulate fertilizers, micro nanofertilizers, and macro nanofertilizers [43]. Nanoparticles with a diameter of less than 100 nanometers are distributed in liquid or powder form [44].Fertilizers added to fields lose more than half of them and do not reach their intended locations for many reasons, including hydrolysis, photolysis, leaching, microbial immobilization, and degradation [45].Nanotechnology has the capacity to develop the current artificial framework into modern systems in agriculture [46].Increasing the efficiency of modern agricultural chemical nutrients [47]and solving agricultural and environmental problems [48]. NFs can be developed using nanotechnology using synthetic or that are manufactured from plants (green fertilizers) by mechanical, biological, or chemical methods [49]. To synthesize nanoparticles, there are two methods: 1- The bottom-up approach and 2- The top-down approach. Nanoparticles are prepared in the first method by manufacturing nanoparticles from atoms, molecules, and smaller monomers. In the second method, nanoparticles are prepared by breaking a bulk into small nano-sized particles.

2- Nanofertilizer

Nanofertilizers refers to macro- or micro-plant nutrients or carriers of plant nutrients, and they are also called elements coated with nanomaterials NFs [50]. Mineral nutrients in the form of NFs can paticipate in plant nutrition in two mechanisms: the first way includes using nanostructured elements integrated in a carrier complex which may or may not be a nanosubstance, as is the case of NPs of primary elements inserted by absorption or adsorptionin a matrix such as chitosan, polyacrylic acid, clay or zeolite [51]. The second is to employ the element itself in a nanostructured form (in suspension or encapsulated), such as for theNPs of Fe or Zn for applying to soil, substrate or by foliarspray [52]. Both types of NF have high solubility and rapid absorption without discharged as compared with traditional fertilizers [53].

To increase the nutrient use efficiency (NUE) values for plants, according to the plant's needs, nutrients are released by encapsulating or encapsulating the NFs with a nanomaterial [54]. Synthetic fertilizers can release nutrients within 4-10 days, while NFS can release them within 40-50 days [55]. Slow release of nutrients in the environments could be carried out by using zeolites. Zeolites include a group of naturally forming minerals having crystal structure layered honeycomb-like and their web of interconnected tunnels and cages can be loaded with nitrogen and potassium along with others slowly dissolving component containing phosphorous, calcium and a complete suite of minor and trace nutrients [56].

Nanoparticles affect some metabolic processes in plants [57]. NFS is more beneficial than synthetic fertilizers because it has unique properties, as Figure 1 shows [48, 58]. Because of the small volume of NFS particles (<100 nm), they have the ability to enter plants when added to the soil or foliar [59], in addition to NFS having a high surface area, which increases the nutrients available to the plant and plant NUE [59, 20]. NFs can increase the dispersion of nutrients in the soil and are soluble in water, increasing their availability to plants. While NPs are stabilized in the soil and because of their big particle size and high absorption, their solubility is low, so it is encapsulated to make them available to plants and increase their absorption [10].

Figure 1. The most important advantages of NFs or/and NPs [60].

Methods of the nanofertilizer application

There are three ways to add nanofertilizers: 1- Foliar spraying [61]. 2- Soaking, where cotton seeds were soaked in nano fertilizers, and the result was positive by reducing the number of chemical fertilizers used by a half [4]. 3- Added to the soil, as in wheat [62]. Nanofertilizers enter by organic chemicals present in the environment or ion passage, or endocytosis, through developing required pores, or through links to carrier proteins, and/or entering through aquaporins (Fig. 2) [63].

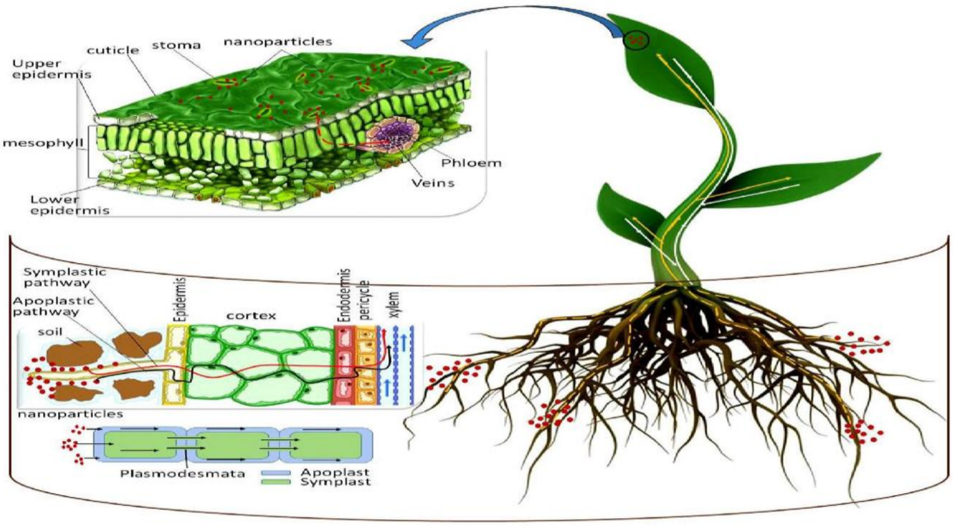

Figure 2. Mode of entry of NPs into plants [64]

Absorption and translocation of NFs in plants

To give an idea about the appropriate applications of NPs in plants, it is necessary to study the absorption and movement of NPs from soil to plants. For example, if NFs or NPs best to be transported by the xylem tissue, it is recommended to apply an irrigation system, and if they prefer to be transported from the phloem tissue, external application is suitable for it, NPs size, NFs composition, and pore diameter (5-20nm) for the cell wall and plant physiology [58]. Nanoparticles with smaller sizes can pass through the cell wall pores and enter the cell membrane, but, nanoparticles that are larger than the size of the cell wall pores have been found to accumulate outside the cell preprints [65]

It affects NFs in plants through its effect on the transport and accumulation of nutrients released from them [66]. NPs in foliar applications, before entering the plant tissues, they encounter the cuticular barrier [67]. The leaf epidermis has two entry paths: the first is the hydrophilic or stomatal path, which is dedicated to polar solutes, and the second is the lipophilic or stomatal path, which is designated for non-polar solutes that enter through diffusion into the leaves [68]. Factors that affect the absorption of NPs through leaves must be taken into account, including the size and number of stomata and the difference in leaf morphology [38]. Nutrients do not return to their original locations because nutrients move unidirectionally and non-cyclically in the vascular systems through the xylem or phloem [40]. There is another way for NPs to be transmitted through the symplastic passage through plasmodesmata from one cell to another [69]. When the nanoparticles reach the central cylinder, they will be transferred to other parts through the xylem (apoplast) [70]. The transporation in the apoplast pathway is controlled by osmosis, while the transporatrion in symplastic pathway is controlled by diffusion **[71].**

3- Mechanisms and mode of entry of NPs in plantscells

NPs entry into plant cells was propounded by three mechanisms [72]. The first is that NPs cross the cell membrane by diffusion easily because it is small in size. The transit is associated with a lot of characteristics in plants such as volume, hydrophobicity, constitution, charge, and shape of molecules [73]. The second, NPs are conveyed into the cell actively through engulfing the Plasma membrane a behavior known as endocytosis [74]. The third is through trans-membrane proteins that regulate the transit of NPs into cells [75]. limited by some factors namely the size of micro pores. The mode of transport from plant cells to tissues is by foliar /shoots or roots. This is mediated either through an apoplastic or symplastic mode of transport [76].

Physical and Chemical Properties of soil and their effects on NPs

The Physical and Chemical Properties of the soil have an impact on NPs. These properties include soil pH, texture, clay minerals, structure, Organic matter in the soil, the ability to ion exchange (CEC), and the microbial community, as they widely affect the aggregation, dispersion, fixation, stability, NPs transfer, and bioavailability [77].

Developing smart agriculture using NFs

To increase NUE values, it is suggested to use smart NFs fertilizers by releasing nutrients in a slower, more controlled, and better manner that suits the plant's nutritional needs over time [78]. To achieve a slow and steady release of nutrients over long periods, semi-permeable layers are used (Control the dissolution of fertilizers in soil or water) inside the fertilizers or on their surfaces [79]. different mechanisms suggested for controlled fertilizer release. Liu and Shaviv inserted the multi-staged diffusion pattern to elucidate this process: water weeps into the covering of fertilizer when it is used and irrigated, leading to the absorption of moisture by the rigid fertilizer pith and dissolved partially. consequence, osmotic pressure increases in the granule leading to awful release (faile mechanism) or diffusion release. the awful release takes place when the osmotic pressure overruns the membrane's resistance sill, resulting in a burst of the coating and the pith being quickly released. This occurs with a crisp coating such as sulfur. Otherwise, polymeric covering like Polyolefin is employed in the diffusion mechanism. the pith is gradually released through the right membrane by diffusion because the membrane can tolerate pressure increase [80]. Therefore, this will provide an amount of nutrients in a timely manner and significantly reduce the losses of nutrients in the environment. Nanosensors have great with great capabilities in agriculture and production and are considered a promising tool. They are very small nano-devices that connect to the object to be discovered. These small sensors have the ability to detect chemical, biological, and physical processes, respond to them, and transmit these responses to humans in the form of signals for processing [81]. Nanosensors provide information about real-time field conditions, plant growth, plant diseases, and pesticides, and also help predict environmental stressors [82].

Nanocarriers in based fertilizers

They are fertilizers that, when formulated with plant nutrients that contain NMs, reduce the harmful effects of conventional fertilizers used in large quantities and/or increase the efficiency of the plant nutrients. Nanocarriers such as Silica, Fe oxide, C- coated Fe and polymers do not contain any nutrients at all [83].

4- Beneficial effects of nanofertilizers

Nanomaterials have benefits in agriculture, including:

1- Improved absorption by plants 2- Protecting plants from agricultural chemical wastes [84] 3- Availability of fertilizers controlling their release during the growth period and preventing the loss of fertilizers through filtration and complete absorption by the plant, increasing and maintaining soil fertility 4- Reducing water and soil pollution by decreasing the use of chemical fertilizers and thus increasing food products and reducing fertilizer filtration [85] 5- Manipulating the genetic structure of plants using nano-devices 6- Post-harvest management 7- Diagnosing plant diseases 8- Increasing the quality and efficiency of rapid absorption rates of nanomaterials 9- Reducing negative effects by adding excessive doses , reducing soil toxicity, and increasing the efficiency of nutrient use [10, 86] 10- Reducing the demand for fertilization of plants and the number of irrigations 11- Increasing crop production in quantity and quality [34].12- Their cost-efficiency and eco friendliness as a provenance of plant nutrients [87].

5- Accumulation and phytotoxicity by plants

Several studies have noted that nanoparticles can interact with DNA immediately and produce reactive oxygen variety and cause oxidative stress in the plant, causin different compose of DNA damage,like single-strand (SSBs) and double-strand breaks (DSBs), mutations, chromosomal abnormality, and eventually, cell death [89] and lipid peroxidation, thus causing phytotoxicity [90]. After the accumulation of nanoparticles in plants, some negative effects and characteristics can be observed, including 1- The different parts of the plant are damaged in general 2- The rate of seed germination decreases 3- The quality of crops deteriorates 4- The photosynthesis process changes 5- The weight of biomass, shoots, and root length decreases 6- Fat peroxide increases, 7- The rate of transpiration decreases, 8- Poisoning of plants occurs at the genetic level, 9- DNA damage increases [90]. Plants inherently have some defenses to overcome nanotoxicity by activating enzymatic and nonenzymatic protection systems [90,91]. Nanoparticles are transported by symplast or apoplasts through plasmodesmata and can accumulate in plant cells and may cause toxicity [92]. Their toxic and useful influences are based on concentration, size, surface properties, and plant species. NPs can promote plant growth when applied at low concentrations and under controlled conditions, but, at higher concentrations or with prolonged exposure, they may damage cellular structures like membranes, proteins, and DNA. NPs can also overlap with water and nutrient uptake, obstruct enzyme activities, and release toxic metal ions, as a result, decline plant growth [93].

Conclusion

The effect of nanomaterials varies based on the type of plant, the method of application, as well as the shape, size, and concentration of nanomaterials. Their small size provides a large surface area, facilitating movement in the soil and plant. Nanomaterials can improve food production and reduce environmental negative impacts particularly via nanofertilzer, which are highly soluble, enabling them to penetrate the cuticle and reach the target site, promote plant resistance to biotic and abiotic stresses, eventually increasing production. The intelligent delivery of nanomaterials can reduce fertilizers usage, improved NUE, minimize nutrient loss by leaching, and surface runoff. Moreover, nano-sensors and seed coating can decrease production costs and environmental impacts. Foliar application of NFs generally is more effective than soil application, enhancing physiological, biological, and chemical characteristics, growth, crop quality, and production. However, a major bother with Nano fertilizers, is their toxicity. Therefore, it is critical to determine the appropriate dosage for each plant to prevent any negative or toxic effects.

References

[1] K. M. Aguilar-Pérez, J. I. Avilés-Castrillo, and G. Ruiz-Pulido, "Nano-sorbent materials for pharmaceutical-based wastewater effluents—An overview," *Case Studies in Chemical and Environmental Engineering*, vol. 2, p. 100028, 2020. doi: 10.1016/j.cscee.2020.100028.

[2] M. Bilal, D. Barceló, and H. M. Iqbal, "Occurrence, environmental fate, ecological issues, and redefining of endocrine disruptive estrogens in water resources," *Science of the Total Environment*, vol. 800, p. 149635, 2021. doi: 10.1016/j.scitotenv.2021.149635.

[3] M. A. Qamar, S. Shahid, M. Javed, M. Sher, S. Iqbal, A. Bahadur, and D. Li, "Fabricated novel g-C3N4/Mn doped ZnO nanocomposite as highly active photocatalyst for the disinfection of pathogens and degradation of the organic pollutants from wastewater under sunlight radiations," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 611, p. 125863, 2021. doi.org/10.1016/j.colsurfa.2020.125863

[4] A. V. Vakhrouchev and V. B. Golubchikov, "Numerical investigation of the dynamics of nanoparticle systems in biological processes of plant nutrition," *in Journal of Physics: Conference Series*, vol. 61, no. 1, p. 31, IOP Publishing, 2007. doi. 10.1088/1742-6596/61/1/007

[5] M. Van Dijk, Morley T, Rau ML, Saghai Y. A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. Nature Food. 2021 Jul;2(7):494-501. doi.org/10.5281/zenodo.4911252

[6] M. D. Meena, P. K. Joshi, H. S. Jat, A. R. Chinchmalatpure, B. Narjary, P. Sheoran, D. K. Sharma, "Changes in biological and chemical properties of saline soil amended with municipal solid waste compost and chemical fertilizers in a mustard–pearl millet cropping system," *CATENA*, vol. 140, pp. 1-8, 2016. doi.org/10.1016/j.catena.2016.01.009

[7] S. Chaudhary, G. S. Dheri, and B. S. Brar, "Long-term effects of NPK fertilizers and organic manures on carbon stabilization and management index under rice-wheat cropping system," *Soil and Tillage Research*, vol. 166, pp. 59-66, 2017. doi.org/10.1016/j.still.2016.10.005

[8] T. A. P. A. N. Adhikari and S. I. V. A. K. O. T. I. Ramana, "Nano Fertilizer: Its impact on crop growth and soil health," *J. Res. Pjtsau*, vol. 47, pp. 1-70, 2019. https://epubs.icar.org.in/index.php/TJRP/article/view/97462

[9] D. Chugh, V. S. Viswamalya, and B. Das, "Green synthesis of silver nanoparticles with algae and the importance of capping agents in the process," *Journal of Genetic Engineering and Biotechnology*, vol. 19, no. 1, pp. 1-21, 2021. doi.org/10.1186/s43141-021-00228-w

[10] H. Chhipa, "Nanofertilizers and nanopesticides for agriculture," *Environmental Chemistry Letters*, vol. 15, pp. 15-22, 2017. doi.org/10.1016/B978-0-323-90619-7.00015-1

[11] H.N. Pahalvi, L. Rafiya, S. Rashid, B. Nisar, A.N. Kamili. Chemical fertilizers and their impact on soil health. Microbiota and Biofertilizers, Vol 2: Ecofriendly tools for reclamation of degraded soil environs. 2021:1-20. https://doi.org/10.1007/978-3-030-610104_1

[12] S.K. Singh, A. Patra, Y. Verma, A. Chattopadhyay, A. Rakshit, S. Kumar. Potential and risk of nanotechnology application in agriculture vis-à-vis nanomicronutrient fertilizers. Soil Science: Fundamentals to Recent Advances. 2021:513-552. doi.org/10.1007/978-981-16-0917-6_26.

[13] A. Aftab, R. Aziz, A. Ghaffar, M. T. Rafiq, Y. Feng, Z. Saqib, M. K. Rafiq, M. A. Awan [f], "Occurrence, source identification and ecological risk assessment of heavy metals in water and sediments of Uchalli lake–Ramsar site, Pakistan," *Environmental Pollution,* vol. 334, p. 122117, 2023. doi: 10.1016/j.envpol.2023.122117.

[14] B. P. Singh, V. Kumar, M. Chander, M. B. Reddy, M. Singh, R. S. Suman, & V. Yadav, "Impact of Soil Health Card Scheme on Soil Fertility and Crop Production Among the Adopted Farmers," *Indian Journal of Extension Education*, vol. 59, no. 1, pp. 122-126, 2023.doi.org/10.48165/IJEE.2023.59125

[15] S. Babu, R. Singh, D. Yadav, S. S. Rathore, R. Raj, R. Avasthe, & V. K. Singh, "Nanofertilizers for agricultural and environmental sustainability," *Chemosphere*, vol. 292, p. 133451, 2022. doi: 10.1016/j.chemosphere.2021.133451.

[16] R. Raliya, V. Saharan, C. Dimkpa, & P. Biswas, "Nanofertilizer for precision and sustainable agriculture: current state and future perspectives," *Journal of Agricultural and Food Chemistry*, vol. 66, no. 26, pp. 6487-6503, 2017. doi.org/10.1021/acs.jafc.7b02178

[17] C. F. Okey-Onyesolu, M. Hassanisaadi, M. Bilal, M. Barani, A. Rahdar, J. Iqbal, & G. Z. Kyzas, "Nanomaterials as nanofertilizers and nanopesticides: An overview," *ChemistrySelect*, vol. 6, no. 33, pp. 8645-8663, 2021. doi.org/10.1002/slct.202102379

[18] Y. Shang, M. K. Hasan, G. J. Ahammed, M. Li, H. Yin, & J. Zhou, "Applications of nanotechnology in plant growth and crop protection: a review," *Molecules*, vol. 24, no. 14, p. 2558, 2019. doi: 10.3390/molecules24142558.

[19] Liu, R., & Lal, R. (2015). Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. *Science of the total environment*, *514*, 131-139. https://doi.org/10.1016/j.scitotenv.2015.01.104

[20] M. F. Seleiman, N. Al-Suhaibani, N. Ali, M. Akmal, M. Alotaibi, Y. Refay, & M. L. Battaglia, "Drought stress impacts on plants and different approaches to alleviate its adverse effects," *Plants*, vol. 10, no. 2, p. 259, 2021. doi: 10.3390/plants10020259.

[21] A. Union, "Corruption perceptions index 2018," 2019. https://www.sipotra.it/wp-content/uploads/2019/02/2018_CPI_AfricanUnion_Map_EN.pdf

[22] S. V. Anstalt, "Food and agriculture organization of the United Nations," 2013. https://www.fao.org/4/i3300e/i3300e.

[23] A. Ditta, M. Arshad, and M. Ibrahim, "Nanoparticles in sustainable agricultural crop production: applications and perspectives," *in Nanotechnology and Plant Sciences*, pp. 55-75, 2015. doi: 10.1007/978-3-319-14502- 0_4 [2].

[24] T. Aziz, M. A. Rahmatullah, M. A. Maqsood, I. A. Tahir, and M. A. Cheema, "Phosphorus utilization by six Brassica cultivars (*Brassica juncea* L.) from tri-calcium phosphate; a relatively insoluble P compound," *Pakistan Journal of Botany*, vol. 38, no. 5, pp. 1529-1538, 2006. https://www.researchgate.net/ publication/236649476

[25] K. S. Subramanian, A. Manikandan, M. Thirunavukkarasu, and C. S. Rahale, "Nano-fertilizers for balanced crop nutrition," in *Nanotechnologies in Food and Agriculture*, pp. 69-80, 2015. doi.org/10.1007/978-3-319-14024-7_3

[26] S. Davarpanah, A. Tehranifar, G. Davarynejad, J. Abadía, and R. Khorasani, "Effects of foliar applications of zinc and boron nano-fertilizers on pomegranate (*Punica granatum* cv. *Ardestani*) fruit yield and quality," *Scientia Horticulturae*, vol. 210, pp. 57–64, Oct. 2016. doi.org/10.1016/j.scienta.2016.07.003

[27] A. Mikhak, A. Sohrabi, M. Z. Kassaee, and M. Feizian, "Synthetic nanozeolite/nanohydroxyapatite as a phosphorus fertilizer for German chamomile (*Matricariachamomilla* L.)," *Industrial Crops and Products*, vol. 95, pp. 444–452, Jan. 2017. doi: 10.1016/j.indcrop.2016.10.045.

[28] P. K. Mani and S. Mondal, "Agri-nanotechniques for plant availability of nutrients," in *Plant Nanotechnology: Principles and Practices*, pp. 263–303, 2016. doi.org/10.1007/978-3-319-42154- 4_11
[29] O. Adeyemi, R. K. Afshar, E. Jahanzad, M. L. Battaglia, Y. Luo and A. Sadeghpour, "Effect of wheat cover crop and split nitrogen application on corn yield and nitrogen use efficiency," *Agronomy*, vol. 10, no. 8, p. 1081, Jul. 2020. doi.org/10.3390/agronomy10081081
[30] S. x. LI, Z.h. WANG, Y.f. MIAO, S. q. LI, "Soil organic nitrogen and its contribution to crop production," *J. Integr. Agric*., vol. 13, no. 10, pp. 2061–2080, Oct. 2014. doi.org/10.1016/S2095-3119(14)60847-9.
[31] M. A. M. Eid, A.A. Abdel-Salam, H.M. Salem, S. E. Mahrous, M. F. Seleiman, A.A. Alsadon, T.H. I. Solieman and A. A. Ibrahim, "Interaction effects of nitrogen source and irrigation regime on tuber quality, yield, and water use efficiency of Solanum tuberosum L.," *Plants*, vol. 9, no. 1, p. 110, Jan. 2020. doi.org/10.3390/plants9010110.
[32] R. M. Tariq, F. Khan, A.H. Shah, S. Fahad, F. Wahid, J. Ali, M. Adnan, M. Ahmad, M. Irfan, M. Zafar-ul-Hye, M.L. Battaglia, T. Zarei, R. Datta, I.A. Saleem, H. Rehman, S. Danish,"Effect of micronutrients foliar supplementation on the production and eminence of plum (*Prunus domestica* L.)," *Quality Assurance and Safety of Crops & Foods*, vol. 12, no. SP1, pp. 32–40, Oct. 2020. doi: 10.15586/qas.v12iSP1.793
[33] T. Guru, N. Veronica, R. Thatikunta, and S. N. Reddy, "Crop nutrition management with nano fertilizers," *Int. J. Environ. Sci. Technol*., vol. 1, no. 1, pp. 4–6, 2015. 10.21608/jenvbs.2018.3880.1029.
[34] A. El-Ghamry, A. A. Mosa, T. Alshaal, and H. El-Ramady, "Nanofertilizers vs. biofertilizers: new insights," *Environment, Biodiversity and Soil Security*, vol. 2, pp. 51–72, Feb. 2018. doi. 10.21608/JENVBS.2018.3880.1029
[35] L. F. Fraceto, R. Grillo, G.A.de Medeiros, V. Scognamiglio, G. Rea and C. Bartolucci "Nanotechnology in agriculture: which innovation potential does it have?" *Frontiers in Environmental Science*, vol. 4, p. 186737, Mar. 2016. doi.org/10.3389/fenvs.2016.00020
[36] M. F. Seleiman, K.F. Almutairi, M. Alotaibi, A. Shami, B. A. Alhammad and M. L. Battaglia, "Nano-fertilization as an emerging fertilization technique: *Why can modern agriculture benefit from its use?" Plants*, vol. 10, no. 1, p. 2, Dec. 2020. doi.org/10.3390/plants10010002.
[37] S. Mehnaz, "Azospirillum: a biofertilizer for every crop," in *Plant Microbes Symbiosis: Applied Facets*, pp. 297–314, New Delhi: Springer India, 2014. doi.org/10.1007/978-81-322-2068-8_15
[38] M. R. Wiesner, G. V. Lowry, K. L. Jones, M. F. Hochella, Jr., R.T. Di Giulio, E. Casman and E. S. Bernhardt, "Decreasing uncertainties in assessing environmental exposure, risk, and ecological implications of nanomaterials," *Environ. Sci. Technol*., vol. 45, no. 4, pp. 1310–1316, Feb. 2011. DOI: doi.org/10.1021/es803621k
[39] N. Rasool. Plant hormones: role in alleviating biotic stress. Plant Hormones Recent Adv New Perspect Appl. 2022 Apr 16;2022: 17.doi: 10.5772/intechopen.102689
[40] T. J. Lough and W. J. Lucas, "Integrative plant biology: role of phloem long-distance macromolecular trafficking," *Annu. Rev. Plant Biol*., vol. 57, no. 1, pp. 203–232, Jun. 2006. doi.org/10.1146/annurev.arplant.56.032604.144145
[41] M. H. Siddiqui, M. H. Al-Whaibi, M. Firoz, and M. Y. Al-Khaishany, "Role of nanoparticles in plants," *in* *Nanotechnology and Plant Sciences*: *Nanoparticles and Their Impact on Plants**, pp. 19–35, 2015. doi.org/10.1007/978-3-319-14502-0_2.
[42] C. O. Dimkpa and P. S. Bindraban, "Fortification of micronutrients for efficient agronomic production: a review," *Agronomy for Sustainable Development*, vol. 36, no. 1, p. 7, Mar. 2016. doi.org/10.1007/s13593-015-0346-6
[43] H. Chhipa and P. Joshi, "Nanofertilisers, nanopesticides and nanosensors in agriculture," in *Nanoscience in Food and Agriculture 1*, pp. 247–282, 2016. doi.org/10.1007/978-3-319-39303-2_9.
[44] J. Jampílek and K. Kráľová, "Application of nanotechnology in agriculture and food industry, its prospects and risks," *Ecological Chemistry and Engineering S.*, vol. 22, no. 3, pp. 321–361, Sep. 2015, doi.org/10.1515/eces-2015-0018
[45] A. M. Rather, S. Narayan, K. Hussain, F. A. Khan, S. A. Mir, A. A. Malik and J. I A. Bhat, "Influence of nitrogen, copper and zinc nanofertilizers on growth characteristics of chilli (*Capsicum annuum* var. *annuum*

L.)," *The Pharma Innovation Journal*, vol. 11, no. 12, pp. 946–949, 2022. doi.org/10.22271/tpi

[46] R. Prasad, A. Bhattacharyya, and Q. D. Nguyen, "Nanotechnology in sustainable agriculture: recent developments, challenges, and perspectives," *Front. Microbiol*., vol. 8, p. 1014, Jun. 2017. doi: 10.3389/fmicb.2017.01014.

[47] R. G. Kerry et al., "Agricultural nanotechnologies: Current applications and future prospects," *in Microbial Biotechnology*: Volume 1. Applications in Agriculture and Environment, 2017, pp. 3–28. doi:10.1007/978-981-10-6847-8_1.

[48] M. Usman et al., "Nanotechnology in agriculture: Current status, challenges and future opportunities," *Sci. Total Environ.*, vol. 721, p. 137778, Jun. 2020. DOI: 10.1016/j.scitotenv.2020.137778.

[49] M. D. Singh and B. Kumar, "Bio efficacy of nano zinc sulphide (ZnS) on growth and yield of sunflower (*Helianthus annuus* L.) and nutrient status in the soil," *Int. J. Agric. Sci*., vol. 9, pp. 0975-3710, 2017. https://www.researchgate.net/publication/320009311

[50] M. C. DeRosa, C. Monreal, M. Schnitzer, R. Walsh and Y. Sultan, "Nanotechnology in fertilizers," *Nature Nanotechnology*, vol. 5, no. 2, pp. 91–97, Feb. 2010. doi.org/10.1038/nnano.2010.2

[51] M. Golbashy M, Sabahi H, Allahdadi I, Nazokdast H, Hosseini M. Synthesis of highly intercalated urea-clay nanocomposite via domestic montmorillonite as eco-friendly slow-release fertilizer. Archives of Agronomy and Soil Science. 2017 Jan 2;63(1):84-95. doi. org/10.1080/03650340.2016.1177175

[52] V.F. Fedorenko, Buklagin DS, Golubev IG, Nemenushchaya LA. Review of Russian nanoagents for crops treatment. Nanotechnologies in Russia. 2015 Mar;10(3):318-324. doi.org/10.1134/S199507801502010X

[53] A.B. Morales-Díaz, Ortega-Ortíz H, Juárez-Maldonado A, Cadenas-Pliego G, González-Morales S, Benavides-Mendoza A. Application of nanoelements in plant nutrition and its impact in ecosystems. Advances in Natural Sciences: Nanoscience and Nanotechnology. 2017 Feb 2;8(1):013001. https://doi.org/10.1088/2043-6254/8/1/013001

[54] A. Qureshi, D. K. Singh, and S. Dwivedi, "Nano-fertilizers: a novel way for enhancing nutrient use efficiency and crop productivity," *Int. J. Curr. Microbiol*. Appl. Sci., vol. 7, no. 2, pp. 3325–3335, Feb. 2018. doi.org/10.20546/ijcmas.2018.702.398

[55] F. Kahrl, Y. Li, Y. Su, T. Tennigkeit, A. Wilkes, and J. Xu, "Greenhouse gas emissions from nitrogen fertilizer use in China," *Environ. Sci. Policy*, vol. 13, no. 8, pp. 688–694, Dec. 2010. doi.org/10.1016/j.envsci.2010.07.006

[56] J.C. Tarafdar, I.R. Indira Rathore. Nanonutrient from fungal protein: future prospects on crop production. InEmerging trends in agri-nanotechnology: fundamental and applied aspects 2018 (pp. 37-55). Wallingford UK: CAB International. doi:10.1079/9781786391445.0037

[57] Z. Zahra, M. Arshad, R. Rafique, A. Mahmood, A. Habib, I. A. Qazi, and S. A. Khan, "Metallic nanoparticle (TiO2 and Fe3O4) application modifies rhizosphere phosphorus availability and uptake by Lactuca sativa," *J. Agric. Food Chem*., vol. 63, no. 31, pp. 6876–6882, Aug. 2015. doi: 10.1021/acs.jafc.5b01611.

[58] A. Pitambara and Y. M. Shukla, "Nanofertilizers: A recent approach in crop production," in Nanotechnology for Agriculture: *Crop Production & Protection*, 2019, pp. 25–58. doi:10.1007/978-981-32-9374-8_2

[59] J. F. Liscano, C. E. Wilson, R. J. Norman-Jr, and N. A. Slaton, "Zinc availability to rice from seven granular fertilizers," *Arkansas Agricultural Experiment Station*, Fayetteville, CA, USA, Dec. 2000. doi:10.5555/20001916712

[60] M. F. Seleiman, K. F. Almutairi, M. Alotaibi, A. Shami, B. A. Alhammad, and M. L. Battaglia, "Nano-fertilization as an emerging fertilization technique: Why can modern agriculture benefit from its use?", *Plants*, vol. 10, no. 1, p. 2, Dec. 2020. doi.org/10.3390/plants10010002

[61] J. S. Duhan, R. Kumar, N. Kumar, P. Kaur, K. Nehra, and S. Duhan, "Nanotechnology: The new perspective in precision agriculture", *Biotechnology Reports*, vol. 15, pp. 11–23, Sep. 2017. doi.org/10.1016/j.btre.2017.03.002

[62] A. Hafeez, A. Razzaq, T. Mahmood, and H. M. Jhanzab, "Potential of copper nanoparticles to increase growth and yield of wheat", *J. Nanosci. Adv. Technol*., vol. 1, no. 1, pp. 6–11, 2015. doi.org/10.24218/jnat.2015.02.

[63] B. Toksha, V. A. Sonawale, A. Vanarase, D. Bornare, S. Tonde, C. Hazra, D. Kundu, A. Satdive, S. Tayde, and A. Chatterjee, "Nanofertilizers: A review on synthesis and impact of their use on crop yield and environment", *Environmental Technology & Innovation*, vol. 24, p. 101986, Nov. 2021. doi.org/10.1016/j.eti.2021.101986

[64] O. R. Devi, N. Ojha, B. Laishram, S. Dutta, and P. Kalita, "Roles of nano-fertilizers in sustainable agriculture and biosafety", *Environment and Ecology*, vol. 41, no. 1B, pp. 457–463, 2023. https://www.researchgate.net/publication/369901590

[65] Wu H, Li Z. Nano-enabled agriculture: How do nanoparticles cross barriers in plants?. Plant Communications. 2022 Nov 14;3(6). https://doi.org/10.1016/j.xplc.2022.100346

[66] E. Corredor, P. S. Testillano, M. J. Coronado, P. González-Melendi, R. Fernández-Pacheco, C. Marquina, M. R. Ibarra, J. M. de la Fuente, D. Rubiales, A. Pérez-de-Luque, and M. C. Risueño, "Nanoparticle penetration and transport in living pumpkin plants: in situ subcellular identification," *BMC Plant Biol*., vol. 9, p. 1, Dec. 2009. doi.org/10.1186/1471-2229-9-45

[67] M. Pollard, F. Beisson, Y. Li, and J. B. Ohlrogge, "Building lipid barriers: biosynthesis of cutin and suberin," *Trends Plant Sci*., vol. 13, no. 5, pp. 236–246, May 2008. doi.org/10.1016/j.tplants.2008.03.003

[68] T. Eichert, A. Kurtz, U. Steiner, and H. E. Goldbach, "Size exclusion limits and lateral heterogeneity of the stomatal foliar uptake pathway for aqueous solutes and water-suspended nanoparticles," *Physiol. Plant*., vol. 134, no. 1, pp. 151–160, Sep. 2008. doi.org/10.1111/j.1399-3054.2008.01135.x

[69] J. Lv, P. Christie, and S. Zhang, "Uptake, translocation, and transformation of metal-based nanoparticles in plants: recent advances and methodological challenges," *Environ. Sci. Nano*, vol. 6, no. 1, pp. 41–59, 2019. doi: 10.1039/C8EN00645H

[70] C. Larue, J. Laurette, N. Herlin-Boime, H. Khodja, B. Fayard, A. M. Flank, F. Brisset, and M. Carriere, "Accumulation, translocation and impact of TiO2 nanoparticles in wheat (*Triticum aestivum* spp.): influence of diameter and crystal phase," *Sci. Total Environ*., vol. 431, pp. 197–208, Aug. 2012. doi.org/10.1016/j.scitotenv.2012.04.073

[71] A.A. Sembada, I.W. Lenggoro. Transport of nanoparticles into plants and their detection methods. Nanomaterials. 2024 Jan 5;14(2):131. https://doi.org/10.3390/nano14020131

[72] S. Behzadi et al., "Cellular uptake of nanoparticles: journey inside the cell," *Chem. Soc. Rev*., vol. 46, no. 14, pp. 4218–4244, 2017. doi.org/10.1039/C6CS00636A

[73] C. Auría-Soro, T. Nesma, P. Juanes-Velasco,A. Landeira-Viñuela, H. Fidalgo-Gomez, V.Acebes-Fernandez, R. Gongora, M.J. Almendral Parra, R. Manzano-Roman, M. Fuentes. Interactions of nanoparticles and biosystems: microenvironment of nanoparticles and biomolecules in nanomedicine. Nanomaterials. 2019 Sep 24;9(10):1365 doi.org/10.3390/nano9101365

[74] P. Foroozandeh and A. A. Aziz, "Insight into cellular uptake and intracellular trafficking of nanoparticles," *Nanoscale Res. Lett.*, vol. 13, no. 1, p. 339, Dec. 2018. doi.org/10.1186/s11671-018-2728-6

[75] J. H. Li, B. Au, J. Rentsch, S. Block, and H. Ewers, "Directed manipulation of membrane proteins by fluorescent magnetic nanoparticles," *Biophys. J.,* vol. 118, no. 3, p. 313a, Feb. 2020. doi: 10.1016/j.bpj.2019.11.1764

[76] A. Pérez-de-Luque, "Interaction of nanomaterials with plants: what do we need for real applications in agriculture?" *Front. Environ. Sci*., vol. 5, p. 12, Apr. 10, 2017.doi.org/10.3389/fenvs.2017.00012

[77] K. Khalkhal, B. AsgariLajayer, and M. Ghorbanpour, "An overview on the effect of soil physicochemical properties on the immobilization of biogenic nanoparticles," *in Biogenic Nanoparticles and Their Use in Agro-Ecosystems*, 2020, pp. 133–160. doi.org/10.1007/978-981-15-2985-6_8.

[78] H. Bley, C. Gianello, L. D. Santos, and L. P. Selau, "Nutrient release, plant nutrition, and potassium leaching from polymer-coated fertilizer," *Rev. Bras. Ciência do Solo*, vol. 41, Mar. 27, 2017. doi.org/10.1590/18069657rbcs20160142

[79] M. Y. Naz and S. A. Sulaiman, "Slow release coating remedy for nitrogen loss from conventional urea: a review," *J. Control. Release*, vol. 225, pp. 109–120, Mar. 10, 2016. doi.org/10.1016/j.jconrel.2016.01.037

[80] Choudhury R. K., D. Mukhopadhyay, K. Bhattacharyya and S. Balo. Smart Nutrient Delivery System: A precise way of synchronized release and better utilization of Nitrogen and inducing lodging resistance in Rice

(*Oryza sativa* L.) agronomically.
Poster · September 2024 DOI: 10.13140/RG.2.2.34863.75686
[81] E. Omanović-Mikličanina and M. Maksimović, "Nanosensors applications in agriculture and food industry," *Bull. Chem. Technol. Bosnia Herzegovina*, vol. 47, pp. 59–70, Jan. 2, 2016.
[82] H. Chen and R. Yada, "Nanotechnologies in agriculture: new tools for sustainable development," *Trends Food Sci. Technol*., vol. 22, no. 11, pp. 585–594, Nov. 1, 2011. doi.org/10.1016/j.tifs.2011.09.004
[83] A. Ditta and M. Arshad, "Applications and perspectives of using nanomaterials for sustainable plant nutrition," *Nanotechnology Rev*., vol. 5, no. 2, pp. 209–229, Apr. 1, 2016. doi: 10.1515/ntrev-2015-0060
[84] A. Yadav, K. Yadav, K.A. Abd-Elsalam. Exploring the potential of nanofertilizers for a sustainable agriculture. Plant Nano Biology. 2023a Aug 18:100044. https://doi.org/10.1016/j.plana.2023.100044
[85] A. Yadav, K. Yadav, K.A. Abd-Elsalam. Nanofertilizers: types, delivery and advantages in agricultural sustainability. Agrochemicals. 2023b Jun 9;2(2):296-336. https://doi.org/10.3390/agrochemicals2020019
[86] M. R. Khan and T. F. Rizvi, "Application of nanofertilizer and nanopesticides for improvements in crop production and protection," *in Nanoscience and Plant–Soil Systems*, 2017, pp. 405–427.doi.org/10.1007/978-3-319-46835-8_15
[87] K. Ghazaryan, D. Pandey, S. Singh, V. Varagyan, A. Alexiou, D. Petropoulos, A. Kriemadis, V.D. Rajput, T. Minkina, R.K. Singh, J.R. Sousa. Enhancing Crop Production: Unveiling the Role of Nanofertilizers in Sustainable Agriculture and Precision Nutrient Management. Egyptian Journal of Soil Science. 2024 Sep 1;64(3):981-1007. DOI. 10.21608/EJSS.2024.282778.1748
[88] E. Tassi, L. Giorgetti, E. Morelli, J. R. Peralta-Videa, J. L. Gardea-Torresdey, and M. Barbafieri, "Physiological and biochemical responses of sunflower (*Helianthus annuus* L.) exposed to nano-CeO2 and excess boron: modulation of boron phytotoxicity," *Plant Physiol. Biochem*., vol. 110, pp. 50–58, Jan. 1, 2017. doi.org/10.1016/j.plaphy.2016.09.013
[89] J.C. Chow. Biophysical insights into nanomaterial-induced DNA damage: Mechanisms, challenges, and future directions. AIMS Biophysics. 2024;11(3):340-69. doi: 10.3934/biophy.2024019
[90] D. K. Tripathi, S. Singh, S. Singh, R. Pandey, V. P. Singh, N. C. Sharma, S. M. Prasad, N. K. Dubey, and D. K. Chauhan, "An overview on manufactured nanoparticles in plants: uptake, translocation, accumulation and phytotoxicity," *Plant Physiol. Biochem*., vol. 110, pp. 2–12, Jan. 1, 2017. doi.org/10.1016/j.plaphy.2016.07.030
[91] P. K. Shukla, P. Misra, and C. Kole, "Uptake, translocation, accumulation, transformation, and generational transmission of nanoparticles in plants," *in Plant Nanotechnology: Principles and Practices*, 2016, pp. 183–218. doi.org/10.1007/978-3-319-42154-4_8
[92] P. V. Reddy, J. A. Hernandez-Viezcas, J. R. Peralta-Videa, and J. L. Gardea-Torresdey, "Lessons learned: are engineered nanomaterials toxic to terrestrial plants?" *Sci. Total Environ*., vol. 568, pp. 470–479, Oct. 15, 2016. doi.org/10.1016/j.scitotenv.2016.06.042
[93] K. Hashmi, S. Gupta, P. Mishra, T. Khan, S. Joshi. The Vital Role of Nanoparticles in Enhancing Plant Growth and Development. Engineering Proceedings. 2024 Sep 23;67(1):48. doi.org/10.3390/engproc2024067048