D-6228
[1-8]

REVIEW ARTICLE
Agricultural Science Digest

Nanofertilizers: A Comprehensive Guide to its Impact on Crop Productivity: A Review

Subrata Das[1], Manvir Kaur[1], Vandna Chhabra[1], Jaismeen Purba[1]

10.18805/ag.D-6228

ABSTRACT

A considerable amount of resources are lost when conventional fertilizers are added to the soil. Thus, nanofertilizers are gaining popularity day by day due to their ability to increase crop yield, nutrient use efficiency and eco-friendly nature. Because of reduced particle size and high surface-to-volume area, it shows several benefits over traditional fertilizers. Nanofertilizers are one of the most appealing and affordable alternatives to conventional fertilizers that can increase food production worldwide in a sustainable manner. The application of nanofertilizers technology has greatly expanded in the precision agriculture sector, where nutrients are precisely administered to lower input costs. One of the prominent methods for attaining higher productivity is foliar application. Foliar spray is more common due to controlled, reduced dosage and is still possible in adverse soil and weather conditions which ultimately gets absorbed quickly and reduces environmental pollution. A new perspective on sustainable agriculture is opened by the several advantages of the nanofertilizers. However, a slight change in the concentration may adversely affect crops, soil health and the ecosystem. Based on this context, this review presents a description of the overall aspects of nanofertilizers in agriculture.

Key words: Eco-friendly, Nanofertilizer, Nanoparticle, Stress, Sustainable agriculture.

Agriculture and human evolution have been going on simultaneously. The surging population of developing countries is in dire need of high demand for food grain which is set to increase up to 59-98% between 2005 to 2050, which is more than the FAO estimation of 54% (Glotra and Singh, 2023). By 2100, the global population is expected to reach 11 billion (Adam, 2021). In addition to using traditional agricultural practices and fertilizers on an orderly basis, conventional agriculture can significantly increase crop growth, yield and dietary value. Therefore, chemical fertilizers have been essential for technological developments have significantly increased productivity, they also have adverse effects on the ecosystem. A stagnant phase occurred in nutrient use efficiency (NUE) of conventional fertilizers which is going below 30-35, 18-20 and 35-40% for N, P and K respectively over time (Thimiri and Khan, 2016). Over 50% of the chemical fertilizers and insecticides end up in the soil and water bodies (Baweja *et al*., 2020). Eutrophication occurs due to nitrate-nitrogen and phosphorus that are leached out in the environment, major human illnesses are caused by these leached NO3-N (Shamsuddin *et al*., 2023). Thus, it is imperative to implement alternatives to lessen reliance on ineffective conventional fertilizers.

Nanotechnology significantly changed the science world and is expanding exponentially (Fig 1), it gained vast importance in the modern era, along with its applications. Nanoparticles (NPs) are minute molecules ranging from 1 - 100 nm in size (El-Saadony *et al*., 2019). Unique characteristics of nanomaterials paired with native or traditional practices might lead to a breakthrough in science. The nanotechnology concept is not new, studies previously conducted on NPs have shown substantial improvement due to increased surface area-to-volume ratio (An *et al*., 2022).

[1]Lovely Professional University, Jalandhar-144 001, Punjab, India.

Corresponding Author: Manvir Kaur, Lovely Professional University, Jalandhar-144 001, Punjab, India.
Email: manvir.agr.pau@gmail.com; manvir.26499@lpu.co.in
ORCIDs: 0009-0008-6309-9673, 0000 0001 9843 2271, 0009 0004 2676 2561,0009-0006-6536-9863

How to cite this article: Das, S., Kaur, M., Chhabra, V. and Purba, J. (2025). Nanofertilizers: A Comprehensive Guide to its Impact on Crop Productivity: A Review. Agricultural Science Digest. 1-8. doi: 10.18805/ag.D-6228.

Submitted: 16-10-2024 **Accepted:** 12-03-2025 **Online:** 10-05-2025

In general, NFs have a lot of potential for plant nutrition since they can reduce costs and environmental contamination while raising crop yield. Based on usage and how it's absorbed by the crop it can be used for seed priming, foliar treatment, or soil application. The NPs absorbed in plants are impacted by a sequence of processes that occur in the soil, such as surplus phosphate creates bonds with other nutrients in the soil and gets fixed (Prasad *et al*., 2016). Root exudates change the NPs' surface structure and prevent their uptake through the roots (Cervantes-Avilés *et al*., 2021), these problems can be resolved through foliar application and seed priming. Seed priming with NPs enhances seed germination and resistance. NFs as a priming agent lowers losses due to environmental repercussions (Esper *et al*., 2020). Foliar application directly delivers nutrients to the target area which minimizes the negative consequences of stress. Furthermore, studies have demonstrated foliar sprays of NFs are safe as they can be delivered to the plant in a regulated manner which reduces toxicity (Kah *et al*., 2018).

Benefits of nanofertilizers

Minimal bulkiness

NFs have a vast surface area-to-volume ratio (An *et al*., 2022; El-Saadony *et al*., 2019), which implies that nanotechnology may reduce the size of bulky conventional alternates. NFs are advantageous than conventional ones since the amount of bulk may be greatly reduced (Pohshna *et al*., 2020). The result of 600 on-farm trials conducted in Rajasthan revealed that the amount of urea applied by farmers can be effectively reduced by half. The result suggested that nano alternatives may significantly enhance NUE, as seen by a 50% reduction in prilled urea usage (Kumar *et al*., 2020).

Controlled release

The constraints associated with traditional agrochemicals have resulted in intense study in controlled release. Controlled release systems (CRSs) (Fincheira *et al*., 2023) use modern technology to precisely target parts. A CRS enables the effective and delayed release of nutrients in the ecosystem, reducing human exposure (Kumar *et al*., 2019). Additionally, the advantages of CRS are such as low toxicity, higher efficiency, durability, sustainability and technical advancement (An *et al*., 2022). Stability and solubility were promoted by nanoencapsulation of organic matrixes which ultimately decreased the dosage and created the scope of encapsulating hydrophobic materials (Shao *et al*., 2022). This approach allows regulated dissolving, decreasing environmental degradation while also enhancing hydrophilic molecules' solubility. CRS can help reduce phytotoxicity, soil degradation, volatilization and leaching losses (Nuruzzaman *et al*., 2016). Thus, NFs are projected to be more potent than conventional ones, increasing crop yield by 20 to 30% (Rajput *et al*., 2021).

Lesser use

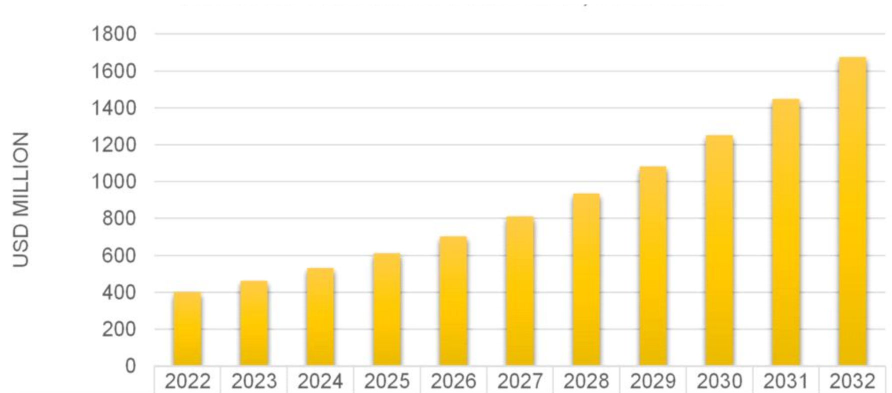
Advances in technology have made it possible to produce physiologically relevant metal NPs on a massive scale. These NPs are being utilized as a "Smart delivery system" (Jain *et al*., 2021) which ultimately enhances the efficacy thus reducing nutrient loss and boosting absorption in plant cells. To reduce the usage to an optimum level, NFs effectively target and evade biological barriers by controlled, gradual release and other multifunctional characteristics. 600 trials in Rajasthan resulted in significantly reduced prilled urea usage when supplied with nano alternative (Kumar *et al*., 2020). A 50% reduction in conventional fertilizer occurred in wheat due to the application of NFs which significantly increased the yield to 4.82 t/ha in 1st location (Kumar *et al*., 2021).

Types of nano fertilizers

Macronutrient based

Nitrogen nanofertilizers

Nitrogen is a primary element that is for crucial metabolic activities of plants. It's involved in regulating amino acids, nucleic acid and chlorophyll formation. Nano urea particles are 30 nanometres in diameter and have 10,000 times higher surface area to volume size than conventional urea (Rawate *et al*., 2022). Nano urea comprises 4% nitrogen by weight. One bottle of nano urea (500 ml) corresponds to 45 kg of urea (Kumar *et al*., 2020), so the quantity is required less than prilled urea and it can be easily handled. As the efficiency of nano urea is 85-90% in comparison to conventional urea which is only up to 25%, Foliar spray in the critical period of plants results in higher crop yield (Rawate *et al*., 2022). Studies indicated an increase in the yield of rice as 100% nano N was applied (Rathnayaka *et al*., 2018). A zeolite-based nitrogenous nanomaterial



	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Market Size	401.8	461.67	530.92	611.09	703.97	811.68	936.68	1081.9	1250.6	1447	1675.6

Source: www.precedenceresearch.com.

Fig 1: Nanofertilizers market size, 2022-2032.

increased N content in plants and also had a positive impact on soil pH and nitrogen availability (Rajonee *et al*., 2016).

Phosphorus nanofertilizers

Phosphorus is essential for several biochemical processes and energy transfer. Adenosine di- and triphosphates play a crucial role in energy transmission. Studies have shown that only 10-20% of P from conventional fertilizers is taken by plants. 32.6% increment in growth and 20.4% in yield have been reported in the soybean by applying nanohydroxyapatite-based fertilizer (Liu and Lal, 2014). Surface-modified zeolites showed higher phosphorus use efficiency which is mostly lower than 20% in traditional fertilizers (Preetha and Balakrishnan, 2017). Danish scientists discovered that there is no requirement to attach P to the soil, as the element present in NPs is directly absorbed through leaves (Husted, 2018). Polysaccharides and lignin were combined with phosphatic materials in various mass ratios which resulted in prolonged release (Fertahi *et al*., 2020).

Potassium nanofertilizers

Potassium has significant regulatory responsibilities in plants. It helps in photosynthesis, osmoregulation, ion balance, translocation of photosynthates and stomatal regulation. A minimum of 60 enzymes activate with the help of potassium. Deficiency can make plants more prone to drought, flooding and extreme heat. Despite the lack of a clear rationale for their creation, potassium NFs outperform traditional fertilizers. Nano K @ 6/1000 concentration applied in *Ocimum* has shown improved vegetative parameters, biological yield and potassium content (Ghahremani *et al*., 2014). K NFs applied in sesame reduced water stress by regulating the stomatal conductance (Mahdavi Khorami *et al*., 2020). A foliar spray of nano K fertilizer on *Cucurbita pepo* resulted in increased leave and drought tolerance due to greater nutrient absorption (Gerdini, 2016). Methacrylic acid and chitosan NPs applied in garden peas resulted in a reduced root elongation rate, though several key proteins were upregulated at lower quantities, all levels exhibited genotoxic effects (Khalifa and Hasaneen, 2018).

Secondary nutrient-based nanofertilizers

Calcium helps stabilize cell walls, retain minerals in soil, neutralize toxins and in seed formation. Ca concentration is increased by foliar spray but its efficiency is limited due to restrictions in uptake, epidermal features and low translocation in phloem (Bernela *et al*., 2021). Research on pomegranate at different calcium NF doses resulted in decreased fruit cracking and boosted productivity (Davarpanah *et al*., 2018a). Nano calcium considerably increased fruit quality and quantity, with the highest at 2% concentration (Ranjbar *et al*., 2020). By spraying nano-CaCO3 in lisianthus, flowering occurred 15 days prior and a 56.3% increment in the count was recorded (Seydmohammadi *et al*., 2020).

Magnesium is essential for plant development as it's a component of chlorophyll, facilitating photosynthesis.. The need for magnesium fertilization has been overlooked, terming it as "the forgotten element" (Cakmak and Yazici, 2010). Leaching and improper fertilization are the major causes of Mg loss. K, Ca and, NH4 cations regulate the Mg uptake in plants. Mg and Fe NP in black-eyed peas resulted in a significant improvement in all evaluated attributes (Delfani *et al*., 2014). Nano-Mg and $MgSO_4$ applied in *Phaseolus vulgaris* (200 ppm) resulted in an almost 300% increment in yield (Salcido-Martínez *et al*., 2023). Magnesium hydroxide NPs at 500 ppm concentration prompted 100% seed germination both *in vivo* and *in vitro* conditions. Leaves of in vitro plants had magnesium levels of 103.52 mg/kg, whereas in vivo plants had 114.58 mg/kg (Shinde *et al*., 2020).

Sulfur is a key constituent of chlorophyll, strengthens crop resilience and enhances nitrogen efficiency. Plants easily absorb sulfate salts, but it doesn't fulfill the sulfur requirement. However, plants only absorb it ensuing biological oxidation is done (Valle *et al*., 2019). Thus, reducing particle size may dramatically affect the oxidation rate. Research on *Ocimum basillicum* in salt stress conditions indicated no significant influence of sulfur NF (Alipour, 2016). Nano sulfur applied in *Helianthus annuus* has shown an increase of dry matter, yield and oil content 11-12%, 15% and 14.7% respectively in contrast to sulfur through gypsum (Subramanian *et al*., 2022).

Micronutrient based

Iron nanofertilizers

Enzymatic biological processes in plants are regulated by iron. Plants can't absorb high amounts of iron as it's in insoluble form. Iron chelate nanocarriers are resilient and gradually release throughout a wide pH range. Iron-based NFs are beneficial since they do not include ethylene-based chemicals, which cause senescence. Iron NPs increased seed weight and iron level by 7% and 34% in black-eyed peas (Delfani *et al*., 2014). Lipids and protein content were high in the lower level of ferrous oxide NPs applied in soybean (Sheykhbaglou *et al*., 2018). Fe_2O_3 NPs significantly increased the root and shoot weight of the crop, this NP was formulated by an extract of cornelian cherry (Chaudhuri and Malodia, 2017). In pinto beans, nano iron fertilizer applied helped mitigate drought and salt stress (Fatollahpour *et al*., 2020).

Zinc nanofertilizers

Zinc nanocarriers can be applied directly in soil, as a foliar spray and also as a priming agent to increase seed germination. Seed priming approach is straightforward, effective and economically viable. Zinc is often provided as zinc oxide or zinc sulfate to alleviate zinc deficiencies. ZnO in less dosage as soil applicant improved absorption in cucumber (Moghaddasi *et al*., 2017). Anthocyanin in petal and chlorophyll content was boosted by applying ZnO NPs (Seydmohammadi *et al*., 2020). Antibacterial properties of

ZnO nanomaterials were reported to be gradual (Sirelkhatim *et al*., 2015). Peanut plants supplied with ZnO NPs and chelated $ZnSO_4$ reported enhanced seed germination, chlorophyll and root and shoot development (Prasad *et al*., 2012). Zn NPs showed a Positive influence on growth and higher biomass in *Cyamopsis tetragonoloba* (Raliya and Tarafdar, 2013).

Silver nanofertilizers

Silver NPs have higher efficiency as an antibacterial material rather than bulk silver, due to larger surface area (Qing *et al*., 2018). Because of these properties, the antibacterial effectiveness of AgNPs is becoming increasingly important in plant protection. More root nodulation was observed in *Vigna sinensis* as AgNP was applied (50 ppm) (Pallavi *et al.,* 2016*)*. Nanosilver particles of 50 nm were beneficial for managing wilt in chickpeas *(Kaur et al.,* 2018). At higher concentrations, the results demonstrated that AgNPs have excellent antibacterial properties against microorganisms such as *Bacillus cereus*, *Trichoderma sp.* and *Staphylococcus aureus*. Different concentrations of silver NPs were tested on corn, watermelon and zucchini, resulting in increased germination at concentrations higher than 1.5 mg/ml (Almutairi and Alharbi, 2015). AgNPs at various dosages affected the vegetative parameters in beans also stimulated plant development and affected the rhizosphere's microbial diversity (Salama, 2012).

Titanium nanofertilizers

In broad beans, 0.01% nano TiO_2 greatly enhances the leaf area, root length and dry matter. Applying nanoscale TiO_2 to canola increases seedling vigor and germination also higher doses resulted in larger plumules and radicals (Mahmoodzadeh *et al*., 2013). TiO_2 increased oil content and promoted early maturity in sunflower (Kolenèík *et al*., 2020). TiO_2 nanomaterial applied in rice significantly enhanced the biomass while also decreasing the toxic metal Cd in plant tissues (Rizwan *et al*., 2019). Roots exposed to both TiO_2 and Cd in maize plants showed increased Cd uptake and greater phytotoxicity than foliar spray (Lian *et al*., 2020). Various concentrations of TiO_2 resulted in promoting germination in wheat while, also showing inhibitory effects at high dosages (Feizi *et al*., 2012).

Nano biofertilizers

Biofertilizers are compounds that improve crop productivity by combining strains of various microorganisms. Therefore, nano biofertilizers are biofertilizers combined with nanostructures (Thirugnanasambandan, 2018). The three most significant characteristics of nano biofertilizers are the interaction of nanocarriers with microbes, long shelf life and transportation of desired substances. Although plant growth promotes rhizobacteria, VAM and nitrogen-fixing rhizobacteria can be employed as nano biofertilizers, mostly PGPR is used (Thirugnanasambandan, 2018). Prior research found a beneficial impact from the combination of PGPR and gold NPs. However, biofertilizers combined with silver nanocarriers showed a negative impact on microbial biological processes (Duhan *et al*., 2017).

Effects on nanofertilizers

Significant enhancement of yield and produce quality is evident and quantified with application of NFs (Table 1).

Influence on seed germination and growth

In ideal concentration nanomaterials permeate the seed coat thus, increasing holes which ultimately have a positive effect on water uptake and gaseous exchanges (Guha *et al*., 2018)**.** Silver NP application in corn, watermelon and zucchini has a germination percentage of 100% (Almutairi and Alharbi, 2015). In chickpea seed priming with thiamine-containing chitosan NPs was done (Muthukrishnan *et al*., 2019), which resulted in 10 times more auxin in seedlings and increased secondary root count. Nanocarrier materials

Table 1: Nanofertilizers in enhancing agricultural production and quality Improved Crop Yield and Quality.

Nanofertilizers	Crops	Effect
Nano N	*Oryza sativa* L.	Highest plant height, tillers, dry matter and yield in 100% Nano N (Rathnayaka *et al*., 2018)
ZnO and TiO_2 NPs	*Helianthus annuus*	Enhanced oil production with higher nutritional value (Kolenčík *et al*., 2020)
TiO2 and SiO_2	*Oryza sativa* L.	Enhanced growth, inhibits Cd translocation *(Rizwan et al*., 2019)
Nano NPK	*Solanum tuberosum* L.	Higher NUE (Al-Juthery and Al-Shami, 2019)
Ag NPs	*Vigna sinensis*	More root nodulation thus increasing nutrient content (Pallavi *et al*., 2016)
MgO NPs	*Gossypium spp*.	Increased chlorophyll, higher production (Kanjana, 2020)
Fe NPs	*Zea mays* L.	Enhanced morphological features and in half dosage higher leaf area and proline content (Elanchezhian *et al*., 2017)
Nano-calcium fertilizer	*Punica granatum*	Reduced fruit cracking (Davarpanah *et al*., 2018b)
Nanoscale zero-valent iron	*Oryza sativa* cv. Gobindabhog L.	Higher biomass and accumulation of antioxidants (Guha *et al*., 2018)

Table 2: Limitations of nanofertilizer utilization.

Properties	Effects
Transformation of NPs	Nanomaterials' reactivity allows them to interact with environmental factors which causes physicochemical changes
	NPs can potentially cause toxicity in soil due to interaction
Accumulation of NPs	Nanomaterials can aggregate in plants, inhibiting growth and generating ROS
	Accumulation in food materials can pose serious health issues
Safety concern	The reactive nature and unpredictability of NPs pose safety issues to workers

boost the biological effectiveness of active substances by enhancing their physio-chemical properties. Numerous have demonstrated that priming seeds with nanomaterials can significantly increase the efficiency over conventional alternatives (Rizwan *et al*., 2019).

Stress mitigation

Plants get affected physiologically and morphologically due to drought conditions which leads to poor yield (Fatollahpour *et al*., 2020). Photosynthesis is restricted in drought conditions resulting in the termination of plant growth (Almaroai and Eissa, 2020). When the water scarcity worsens, soil salinity rises, resulting in a considerable drop in production. In semi-arid tropics, foliar spray is most suitable as a substantial amount of water is needed in the root zone. Foliar spray of K nano chelates helps in avoiding the detrimental effect of drought stress as well as increases the pheno-morphological and biochemical features (Mahdavi Khorami *et al*., 2020). Studies have indicated that Fe and Zn NFs sprayed under water scarcity conditions have increased the yield of beans (Fatollahpour *et al*., 2020). The membrane stability index significantly improved with the application of nano-chelate fertilizer (Moitazedi *et al*., 2023). A foliar spray of SiO2 NPs improves growth indices even with water scarcity (Sharf-Eldin *et al*., 2023).

The exact mechanism of NPs in salt-stressed plants is still not clear, but it has been revealed that few NPs are responsible for the regulation of particular genes that interfere with salt-stress physiology (Cervantes-Avilés *et al*., 2021). Salinity induces chlorophyll breakdown, lowers biomass, inhibits growth and affects water level. Silica NFs applied through foliar spray boosted the salt tolerance of crops by increasing antioxidants (Hajihashemi and Kazemi, 2022). Zn and ZnO NPs reduce the influence of salinity while increasing antioxidants and protein (Ahmed *et al*., 2021). Silicon NFs have beneficial effects in reducing salt stress (Rajput *et al*., 2021). Nevertheless, silica-based nano products are yet to be studied as its relatively new. Research on ZnO and ZnO-Si NPs under salt stress conditions has shown different results while the former had some phytotoxicity, the latter didn't have any toxic effect (Elshoky *et al*., 2021).

Limitation of nanofertilizers

Although nanofertilizers are beneficial for agriculture, researchers are concerned about potential negative impacts occurring due to the mishandling. Furthermore, inadequacies in research and adequate monitoring impede the widespread use of nanomaterials. These minute particles can infiltrate biological systems and represent significant potential risks, hence consequences of nanofertilizers on environments are still unclear (Mishra and Khare, 2021). Overuse of NFs can lead to undesirable and lasting effects on the ecosystem. CeO_2 NPs applied in cucumber resulted in the reduction of Ce_4+ to Ce_3+, these transported materials may be hazardous to human health (Ma *et al*., 2017). As a result, it's critical to assess and pinpoint these detrimental effects (Kumaraswamy *et al.,* 2021). And the same is briefly decsibed as under (Table 2).

CONCLUSION

The discovery of engineered NPs represents a technical leap in science. Nanotechnology's usage in modern-day farming is yet in its early stages. However, it can alter and revolutionize the agricultural sector, especially in terms of nutrient supply. According to the information gained, the influence of NFs varies from plant to plant and is determined by their delivery, particle size, concentration and other crucial factors. Biologically created NPs can enhance soil dispersion and reduce the need for harmful pesticides. Crop yield may be significantly boosted once the correct dose is identified for specific plant needs. As a sustainable input green NPs have the potential to be deployed as a nutrient source to plants, greatly contributing to more eco-friendly nano-fertilization practices.

Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

REFERENCES

Adam, D. (2021). How far will global population rise? Researchers can't agree. Nature. 597(7877): 462-465.

Ahmed, R., Yusoff Abd Samad, M., Uddin, M.K., Quddus, M.A., Hossain, M.A.M. (2021). Recent trends in the foliar spraying of zinc nutrient and zinc oxide nanoparticles in tomato production. Agronomy. 11(10): 2074.

Alipour, Z.T. (2016). The effect of phosphorus and sulfur nanofertilizers on the growth and nutrition of Ocimum basilicum in response to salt stress. Journal of Chemical Health Risks. 6(2).

Al-Juthery, H.W.A. and Al-Shami, Q.M.N. (2019). The effect of fertigation with nano NPK fertilizers on some parameters of growth and yield of potato (*Solanum tuberosum* L.). Al-Qadisiyah Journal for Agriculture Sciences. 9(2): 225-232.

Almaroai, Y.A. and Eissa, M.A. (2020). Role of marine algae extracts in water stress resistance of onion under semiarid conditions. Journal of Soil Science and Plant Nutrition. 20(3): 1092-1101.

Almutairi, Z.M. and Alharbi, A. (2015). Effect of silver nanoparticles on seed germination of crop plants. International Journal of Nuclear and Quantum Engineering. 9(6): 689-693.

An, C., Sun, C., Li, N., Huang, B., Jiang, J., Shen, Y., Wang, C., Zhao, X., Cui, B., Wang, C. (2022). Nanomaterials and nanotechnology for the delivery of agrochemicals: Strategies towards sustainable agriculture. Journal of Nanobiotechnology. 20(1): 11.

Baweja, P., Kumar, S., Kumar, G. (2020). Fertilizers and pesticides: Their impact on soil health and environment. Soil Health. pp. 265-285.

Bernela, M., Rani, R., Malik, P., Mukherjee, T.K. (2021). Nanofertilizers: Applications and future prospects. In Nanotechnology. Jenny Stanford Publishing. pp. 289-332.

Cakmak, I. and Yazici, A.M. (2010). Magnesium: A forgotten element in crop production. Better Crops. 94(2): 23-25.

Cervantes-Avilés, P., Huang, X., Keller, A.A. (2021). Dissolution and aggregation of metal oxide nanoparticles in root exudates and soil leachate: Implications for nanoagrochemical application. Environmental Science and Technology. 55(20): 13443-13451.

Chaudhuri, S. K. and Malodia, L. (2017). Biosynthesis of zinc oxide nanoparticles using leaf extract of *Calotropis gigantea*: Characterization and its evaluation on tree seedling growth in nursery stage. Applied Nanoscience. 7(8): 501-512.

Davarpanah, S., Tehranifar, A., Abadía, J., Val, J., Davarynejad, G., Aran, M., Khorassani, R. (2018). Foliar calcium fertilization reduces fruit cracking in pomegranate (*Punica granatum* cv. Ardestani). Scientia Horticulturae. 230: 86-91.

Delfani, M., Baradarn Firouzabadi, M., Farrokhi, N., Makarian, H. (2014). Some physiological responses of black-eyed pea to iron and magnesium nanofertilizers. Communications in Soil Science and Plant Analysis. 45(4): 530-540.

Duhan, J. S., Kumar, R., Kumar, N., Kaur, P., Nehra, K., Duhan, S. (2017). Nanotechnology: The new perspective in precision agriculture. Biotechnology Reports. 15: 11-23.

Elanchezhian, R., Kumar, D., Ramesh, K., Biswas, A.K., Guhey, A., Patra, A.K. (2017). Morpho-physiological and biochemical response of maize (*Zea mays* L.) plants fertilized with nano-iron (Fe_3O_4) micronutrient. Journal of Plant Nutrition. 40(14): 1969-1977.

El-Saadony, M.T., El-Wafai, N.A., El-Fattah, H.I.A., Mahgoub, S.A. (2019). Biosynthesis, optimization and characterization of silver nanoparticles using a soil isolate of Bacillus pseudomycoides MT32 and their antifungal activity against some pathogenic fungi. Adv. Anim. Vet. Sci. 7(4): 238-249.

Esper Neto, M., Britt, D.W., Jackson, K.A., Braccini, A.L., Inoue, T.T., Batista, M.A. (2020). Early development of corn seedlings primed with synthetic tenorite nanofertilizer. Journal of Seed Science. 42.

Elshoky, H.A., Yotsova, E., Farghali, M.A., Farroh, K.Y., El-Sayed, K., Elzorkany, H.E., Rashkov, G., Dobrikova, A., Borisova, P., Stefanov, M. (2021). Impact of foliar spray of zinc oxide nanoparticles on the photosynthesis of *Pisum sativum* L. under salt stress. Plant Physiology and Biochemistry. 167: 607-618.

Fatollahpour Grangah, M., Rashidi, V., Mirshekari, B., Khalilvand Behrouzyar, E., Farahvash, F. (2020). Effects of nano-fertilizers on physiological and yield characteristics of pinto bean cultivars under water deficit stress. Journal of Plant Nutrition. 43(19): 2898-2910.

Feizi, H., Rezvani Moghaddam, P., Shahtahmassebi, N., Fotovat, A. (2012). Impact of bulk and nanosized titanium dioxide (TiO_2) on wheat seed germination and seedling growth. Biological Trace Element Research. 146: 101-106.

Fertahi, S., Bertrand, I., Ilsouk, M., Oukarroum, A., Zeroual, Y., Barakat, A. (2020). New generation of controlled release phosphorus fertilizers based on biological macromolecules: Effect of formulation properties on phosphorus release. International Journal of Biological Macromolecules. 143: 153-162.

Fincheira, P., Hoffmann, N., Tortella, G., Ruiz, A., Cornejo, P., Diez, M.C., Seabra, A.B., Benavides-Mendoza, A., Rubilar, O. (2023). Eco-efficient systems based on nanocarriers for the controlled release of fertilizers and pesticides: Toward smart agriculture. Nanomaterials. 13(13): 1978.

Gerdini, F.S. (2016). Effect of nano potassium fertilizer on some parchment pumpkin (*Cucurbita pepo*) morphological and physiological characteristics under drought conditions. International Journal of Farming and Allied Sciences. 5(5): 367–371.

Ghahremani, A., Akbari, K., Yousefpour, M., Ardalani, H. (2014). Effects of nano-potassium and nano-calcium chelated fertilizers on qualitative and quantitative characteristics of *Ocimum basilicum*. International Journal for Pharmaceutical Research Scholars. 3(12): 241-325.

Glotra, A. and Singh, M. (2023). Nanofertilizers: A review on the futuristic technology of nutrient management in agriculture. Agricultural Reviews. 44(2): 238-244.

Guha, T., Ravikumar, K.V.G., Mukherjee, A., Mukherjee, A., Kundu, R. (2018). Nanopriming with zero valent iron (nZVI) enhances germination and growth in aromatic rice cultivar (*Oryza sativa* cv. Gobindabhog L.). Plant Physiology and Biochemistry. 127: 403-413.

Hajihashemi, S. and Kazemi, S. (2022). The potential of foliar application of nano-chitosan-encapsulated nano-silicon donor in amelioration the adverse effect of salinity in the wheat plant. BMC Plant Biology. 22(1): 148.

Husted, S. (2018). Innovative approach taken to phosphorus nanofertilizer research. AG Chemi Group. www.agchemigroup.eu.

Jain, D., Sanadhya, S., Saheewala, H., Joshi, A., Bhojiya, A.A., Mohanty, S.R. (2021). The role of nanofertilizers in smart agriculture: An effective approach to increase nutrient use efficiency. Agricultural Biotechnology: Latest Research and Trends. pp. 493-510.

Kah, M., Kookana, R.S., Gogos, A., Bucheli, T.D. (2018). A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. Nature Nanotechnology. 13(8): 677-684.

Kanjana, D. (2020). Foliar application of magnesium oxide nanoparticles on nutrient element concentrations, growth, physiological and yield parameters of cotton. Journal of Plant Nutrition. 43(20): 3035–3049.

Kaur, P., Thakur, R., Duhan, J.S., Chaudhury, A. (2018). Management of wilt disease of chickpea *in vivo* by silver nanoparticles biosynthesized by rhizospheric microflora of chickpea (*Cicer arietinum*). Journal of Chemical Technology and Biotechnology. 93(11): 3233-3243.

Khalifa, N.S. and Hasaneen, M.N. (2018). The effect of chitosan-PMAA-NPK nanofertilizer on *Pisum sativum* plants. 3 Biotech. 8(4): 193.

Kolenèík, M., Ernst, D., Urík, M., Ďurišová, Ľ., Bujdoš, M., Šebesta, M., Dobroèka, E., Kšiòan, S., Illa, R., Qian, Y. (2020). Foliar application of low concentrations of titanium dioxide and zinc oxide nanoparticles to the common sunflower under field conditions. Nanomaterials. 10(8): 1619.

Kumar, S., Nehra, M., Dilbaghi, N., Marrazza, G., Hassan, A.A., Kim, K.H. (2019). Nano-based smart pesticide formulations: Emerging opportunities for agriculture. Journal of Controlled Release. 294:131-153.

Kumar, Y., Singh, T., Raliya, R., Tiwari, K.N. (2021). Nano fertilizers for sustainable crop production, higher nutrient use efficiency and enhanced profitability. Indian Journal of Fertilisers. 17(11): 1206-1214.

Kumar, Y., Tiwari, K.N., Singh, T., Sain, N.K., Laxmi, S., Verma, R., Sharma, G.C., Raliya, R. (2020). Nanofertilizers for enhancing nutrient use efficiency, crop productivity and economic returns in winter season crops of Rajasthan. Annals of Plant and Soil Research. 22(4): 324-335.

Kumaraswamy, R. V, Saharan, V., Kumari, S., Choudhary, R.C., Pal, A., Sharma, S. S., Rakshit, S., Raliya, R., Biswas, P. (2021). Chitosan-silicon nanofertilizer to enhance plant growth and yield in maize (*Zea mays* L.). Plant Physiology and Biochemistry. 159: 53-66.

Lian, J., Zhao, L., Wu, J., Xiong, H., Bao, Y., Zeb, A., Tang, J., Liu, W. (2020). Foliar spray of TiO_2 nanoparticles prevails over root application in reducing Cd accumulation and mitigating Cd-induced phytotoxicity in maize (*Zea mays* L.). Chemosphere. 239: 124794.

Liu, R. and Lal, R. (2014). Synthetic apatite nanoparticles as a phosphorus fertilizer for soybean (Glycine max). Scientific Reports. 4(1): 5686.

Ma, Y., He, X., Zhang, P., Zhang, Z., Ding, Y., Zhang, J., Wang, G., Xie, C., Luo, W., Zhang, J. (2017). Xylem and phloem based transport of CeO2 nanoparticles in hydroponic cucumber plants. Environmental Science and Technology. 51(9): 5215-5221.

Mahdavi, K.A., Masoud, S.J., Amini, D.M., Rezvan, S., Damavandi, A. (2020). Sesame (*Sesame indicum* L.) biochemical and physiological responses as affected by applying chemical, biological and nano-fertilizers in field water stress conditions. Journal of Plant Nutrition. 43(3): 456-475.

Mahmoodzadeh, H., Nabavi, M., Kashefi, H. (2013). Effect of nanoscale titanium dioxide particles on the germination and growth of canola (*Brassica napus*). pp. 25-32.

Mishra, D. and Khare, P. (2021). Emerging nano-agrochemicals for sustainable agriculture: benefits, challenges and risk mitigation. Sustainable Agriculture Reviews 50: Emerging Contaminants in Agriculture. pp. 235-257.

Moghaddasi, S., Fotovat, A., Khoshgoftarmanesh, A.H., Karimzadeh, F., Khazaei, H.R., Khorassani, R. (2017). Bioavailability of coated and uncoated ZnO nanoparticles to cucumber in soil with or without organic matter. Ecotoxicology and Environmental Safety. 144: 543-551.

Moitazedi, S., Sayfzadeh, S., Haghparast, R., Zakerin, H.R., Jabari, H. (2023). Mitigation of drought stress effects on wheat yield *via* the foliar application of boron, zinc and manganese nano-chelates and supplementary irrigation. Journal of Plant Nutrition. 46(9): 1988-2002.

Muthukrishnan, S., Murugan, I., Selvaraj, M. (2019). Chitosan nanoparticles loaded with thiamine stimulate growth and enhances protection against wilt disease in Chickpea. Carbohydrate Polymers. 212: 169-177.

Nuruzzaman, M.D., Rahman, M.M., Liu, Y., Naidu, R. (2016). Nanoencapsulation, nano-guard for pesticides: A new window for safe application. Journal of Agricultural and Food Chemistry. 64(7): 1447-1483.

Pallavi, Mehta, C.M., Srivastava, R., Arora, S., Sharma, A.K. (2016). Impact assessment of silver nanoparticles on plant growth and soil bacterial diversity. 3 Biotech. 6: 1-10.

Pohshna, C., Mailapalli, D.R., Laha, T. (2020). Synthesis of nanofertilizers by planetary ball milling. Sustainable Agriculture Reviews. pp. 75-112.

Prasad, R., Prasad, S., Lal, R. (2016). Phosphorus in soil and plants in relation to human nutrition and health. In Soil Phosphorus. CRC Press. pp. 65-80.

Prasad, T., Sudhakar, P., Sreenivasulu, Y., Latha, P., Munaswamy, V., Reddy, K.R., Sreeprasad, T.S., Sajanlal, P.R., Pradeep, T. (2012). Effect of nanoscale zinc oxide particles on the germination, growth and yield of peanut. Journal of Plant Nutrition. 35(6): 905-927.

Preetha, P.S. and Balakrishnan, N. (2017). A review of nano fertilizers and their use and functions in soil. Int. J. Curr. Microbiol. Appl. Sci. 6(12): 3117-3133.

Qing, Y., Cheng, L., Li, R., Liu, G., Zhang, Y., Tang, X., Wang, J., Liu, H., Qin, Y. (2018). Potential antibacterial mechanism of silver nanoparticles and the optimization of orthopedic implants by advanced modification technologies. International Journal of Nanomedicine. pp. 3311–3327.

Rajonee, A.A., Nigar, F., Ahmed, S., Huq, S.I. (2016). Synthesis of nitrogen nano fertilizer and its efficacy. Canadian Journal of Pure and Applied Sciences. 10: 3913-3919.

Rajput, V.D., Minkina, T., Feizi, M., Kumari, A., Khan, M., Mandzhieva, S., Sushkova, S., El-Ramady, H., Verma, K.K., Singh, A. (2021). Effects of silicon and silicon-based nanoparticles on rhizosphere microbiome, plant stress and growth. Biology. 10(8): 791.

Raliya, R. and Tarafdar, J.C. (2013). ZnO nanoparticle biosynthesis and its effect on phosphorous-mobilizing enzyme secretion and gum contents in Clusterbean (*Cyamopsis tetragonoloba* L.). Agricultural Research. 2: 48-57.

Ranjbar, S., Ramezanian, A., Rahemi, M. (2020). Nano-calcium and its potential to improve 'Red Delicious' apple fruit characteristics. Horticulture, Environment and Biotechnology. 61: 23.30.

Rathnayaka, R., Mahendran, S., Iqbal, Y.B., Rifnas, L.M. (2018). Influence of urea and nano-nitrogen fertilizers on the growth and yield of rice (*Oryza sativa* L.) cultivar Bg 250. International Journal of Research Publications. 5(2): 1-7.

Rawate, D., Patel, J.R., Agrawal, A.P., Agrawal, H.P., Pandey, D., Patel, C.R., Verma, P., Chandravanshi, M. (2022). Effect of nano urea on productivity of wheat (*Triticum aestivum* L.) under irrigated condition. Pharma Innov. 11: 1279-1282.

Rizwan, M., Ali, S., ur Rehman, M.Z., Malik, S., Adrees, M., Qayyum, M.F., Alamri, S.A., Alyemeni, M.N., Ahmad, P. (2019). Effect of foliar applications of silicon and titanium dioxide nanoparticles on growth, oxidative stress and cadmium accumulation by rice (*Oryza sativa*). Acta Physiologiae Plantarum. 41: 1-12.

Salama, H.M.H. (2012). Effects of silver nanoparticles in some crop plants, common bean (*Phaseolus vulgaris* L.) and corn (*Zea mays* L.). Int Res J Biotechnol. 3(10): 190-197.

Salcido-Martínez, A., Sánchez, E., Pérez-Álvarez, S., Ramírez-Estrada, C.A. (2023). Agronomic biofortification with magnesium nanofertilizer and its effect on the nutritional quality of beans. Notulae Botanicae Horti Agrobotanici Cluj-Napoca. 51(4): 13246.

Seydmohammadi, Z., Roein, Z., Rezvanipour, S. (2020). Accelerating the growth and flowering of Eustoma grandiflorum by foliar application of nano-ZnO and nano-$CaCO_3$. Plant Physiology Reports. 25: 140-148.

Shamsuddin, A.S., Syed Ismail, S.N., Othman, N.M.I., Zakaria, N.H., Abd Manan, T.S., Ibrahim, M.A., Abdul Mutalib, M. (2023). Human health risk assessment of nitrate in private well waters of shallow quaternary alluvial aquifer. Environmental Geochemistry and Health. 45(11): 7741-7757.

Shao, C., Zhao, H., Wang, P. (2022). Recent development in functional nanomaterials for sustainable and smart agricultural chemical technologies. Nano Convergence. 9(1): 11.

Sharf-Eldin, A.A., Alwutayd, K.M., El-Yazied, A.A., El-Beltagi, H.S., Alharbi, B.M., Eisa, M.A.M., Alqurashi, M., Sharaf, M., Al-Harbi, N.A., Al-Qahtani, S.M. (2023). Response of maize seedlings to silicon dioxide nanoparticles (SiO_2NPs) under drought stress. Plants. 12(14): 2592.

Sheykhbaglou, R., Sedghi, M., Fathi-Achachlouie, B. (2018). The effect of ferrous nano-oxide particles on physiological traits and nutritional compounds of soybean (*Glycine max* L.) seed. Anais Da Academia Brasileira de Ciências. 90: 485-494.

Shinde, S., Paralikar, P., Ingle, A.P., Rai, M. (2020). Promotion of seed germination and seedling growth of *Zea mays* by magnesium hydroxide nanoparticles synthesized by the filtrate from Aspergillus niger. Arabian Journal of Chemistry. 13(1): 3172-3182.

Sirelkhatim, A., Mahmud, S., Seeni, A., Kaus, N.H.M., Ann, L.C., Bakhori, S.K.M., Hasan, H., Mohamad, D. (2015). Review on zinc oxide nanoparticles: Antibacterial activity and toxicity mechanism. Nano-Micro Letters. 7: 219-242.

Subramanian, K.S., Rajeswari, R., Yuvaraj, M., Pradeep, D., Guna, M., Yoganathan, G. (2022). Synthesis and characterization of nano-sulfur and its impact on growth, yield and quality of sunflower (*Helianthus annuus* L.). Communications in Soil Science and Plant Analysis. 53(20): 2700-2709.

Thimiri Govinda Raj, D.B., Khan, N.A. (2016). Designer nanoparticle: nanobiotechnology tool for cell biology. Nano Convergence. 3(1): 22.

Thirugnanasambandan, T. (2018). Advances and trends in nano-biofertilizers. Available at SSRN 3306998.

Valle, S.F., Giroto, A.S., Klaic, R., Guimarães, G.G.F., Ribeiro, C. (2019). Sulfur fertilizer based on inverse vulcanization process with soybean oil. Polymer Degradation and Stability. 162: 102-105.