Indian Journal of Agricultural Sciences **95** (11): 1291–1302, November 2025/Review Article
https://doi.org/10.56093/ijas.v95i11.141995

Nano-fertiliser and its role in sustainable crop production–A review

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Received: 05 September 2023; Accepted: 26 September 2025

ABSTRACT

Globally, the agricultural system faces an escalating challenge in providing food to the ever-growing population. Farmers are intensively using commercial synthetic fertilisers to increase agricultural production. Consequently, a larger quantity of applied fertilisers gets lost through leaching, runoff, gaseous emissions, and soil fixation, causing environmental pollution (soil, water, and air) and health issues. In this context, applying nano-fertilisers provides an efficient substitute for traditional fertilisers, which is environmentally sustainable. Nano-formulation of nano-fertiliser with less than 100 nm particle size supplies nutrients more precisely, and exploits plant unavailable nutrients in the rhizospheric zone. Stomatal pores at leaves allow deep penetration of nano-fertiliser due to its smaller size, resulting in higher efficiency in nutrient use. However, applying nano-fertiliser shows a beneficial effect on crops up to a certain level. It also adversely impacts crops, environment, and human health unless used appropriately. In the present investigation, we conducted a comprehensive review to study the application of nano-fertiliser in agriculture production as the best substitute for commercial fertiliser. We can reduce our dependence on commercial synthetic fertilisers, mitigate environmental pollution, and encourage sustainable agriculture practices by connecting the potential of nano-fertilisers. The outcomes propose that nano-fertilisers are a popular substitute nutrient source, suggesting a sustainable and efficient solution for agricultural production.

Keywords: Conventional fertiliser, Environmental pollution, Nano-fertiliser, Sustainable crop production

Food security is one of the most challenging tasks to meet the demand of rapidly growing population worldwide. World's population is estimated to reach 11.0 billion by 2100 (Babu *et al*. 2022) and to fulfill the food demand of the ever-increasing population, at least it needs to produce 50% more food by 2050 (Duary 2021). This increasing food demand was forced farmers to use more fertiliser (Fatima *et al*. 2021) as a result global fertiliser consumption was projected to experience a 2% growth in the fiscal year 2024, reaching a total of 195.4 million metric tonnes (FAO 2023). The use of traditional fertilisers for a prolonged period caused terrible damage to soil structure and reduced the soil microorganisms (Tarafder *et al*. 2020, Kumar *et al*. 2023).

On the other hand, use efficiency of applied nutrients through fertilisers remains very low (nitrogen 30–40%, phosphorus 15–20%, potassium 50–55%, and micronutrients 2–5%) (Duary 2020). Thus, increasing production with minimum inputs, is now a key challenge to improve the livelihoods of small-scale and marginal farming families (Duary *et al*. 2021, Biswas *et al*. 2023). Under these circumstances, it is important to adopt innovative technologies to secure global food security in terms of food production and productivity (Mandal and Lalrinchhani 2021, Abou El-Enin *et al*. 2023).The application of nano-fertiliser thus, provides an innovative, efficient, and eco-friendly substitute of traditional fertilisers (Kalwani *et al*. 2021, Upadhay *et al*. 2023). Nano-fertiliser plays an important role by enhancing crop growth, yield and quality parameters of different crops (Tarafder *et al*. 2020, Toksha *et al*. 2021). Additionally, it strengthens the tolerance capacity of plants against some biotic and abiotic stresses (Seleiman *et al*. 2021). It is a slow-release nutrient supplier and improves nutrient use efficiency (Yadav *et al*. 2023). It also reduces the wastage of fertilisers and adverse environmental affects results in low cost of cultivation (Ajithkumar *et al*. 2021, Mahaletchum 2021).

Nano-fertilisers are one of highly engineered inputs in which plant nutrients are encapsulated with nano-materials (Iqbal 2019, Raimondi *et al*. 2021) and can be directly apply through soil application as well as foliar spray (Mejias *et al*. 2021). Three classes of nano-fertilisers are, Nano-scale fertiliser containing nutrients, conventional fertilisers with nano-scale extracts and nano-scale coating

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(coated with nanoparticles) (Mikkelsen 2018). Having a high surface area-to-volume ratio in the structure of nano-fertiliser, it takes up nutrients (plant) slowly and smoothly (Dhlamini *et al*. 2020, Tarafder *et al*. 2020). Jain *et al*. (2021) presented this as "smart delivery systems" for its control-release kinetics and absorption capacity. In agriculture, mostly NPs are used in nutrient management, plant growth, pest control and also in food processing to improve food quality (Mir *et al*. 2023). In nano-fertilisers, nano-particles are used as carriers of micronutrients (zinc, copper, manganese, iron) and macronutrients (nitrogen, phosphorous, potassium, sulphur and calcium) (Divekar *et al*. 2021). However, the economic and marketing elements of the nano-fertiliser have yet to be extensively studied (Azmi and Elgharbawy 2024).

Recent investigations have dedicated significant attention to the impact of nano fertilisers (Ayenew *et al.* 2024, Reddy *et al*. 2024, Saurabh *et al*. 2024). However, these studies did not comprehensively scrutinize crucial aspects of nano-fertilisers, such as their application across various crops (including vegetables, field crops, fruits, and spices) with the mechanisms of uptake and interactions (with plant life). It was also observed that a comparison between nano-fertilisers and their conventional counterparts with the effects of nano-fertilisers, the emission of greenhouse gas with climate change effect was skipped. Our research unswervingly addresses these critical gaps, providing a thorough database designed for the benefit of various stakeholders. Fig. 1 shows the market share of nano-fertiliser worldwide.

In light of increasing global concerns about food security, environmental degradation, and the need for sustainable agricultural practices, this study thus, aims to review the potential of nano-fertilisers as a viable alternative to traditional fertilisers. It will explore how nano-fertilisers can enhance agricultural production, enhance nutrient use efficiency, and minimize the negative environmental impacts of conventional fertilisers.

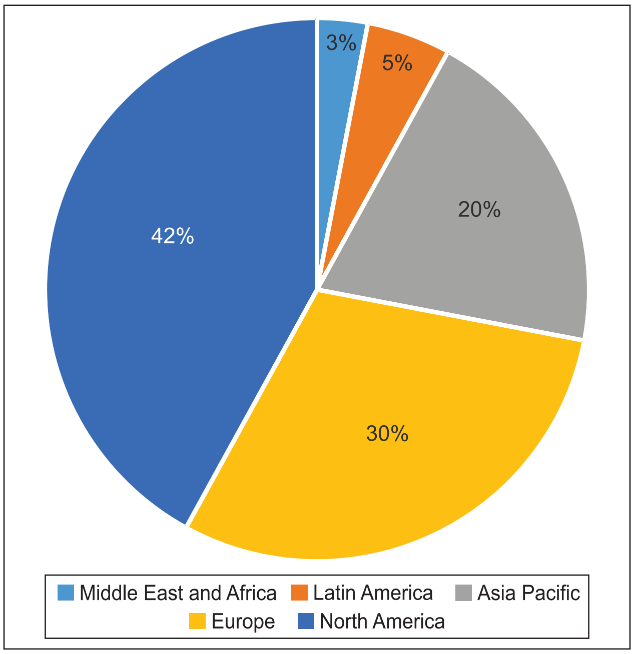

Fig. 1 Worldwide market share of nano-fertiliser. (https://www.precedenceresearch.com/nano-fertilisers-market)

Nano-fertiliser and its interaction with plants: For better understanding the positive impact of nano-fertiliser on plants, it is important to understand the physiological and biochemical responses of plants (Padhan *et al*. 2023). Many morphological and physiological changes occur in plants when it interacts with nano-particles which depend on the properties of the nano-particles (Yadav *et al*. 2023). Nano-pores and stomata presents in plant leaves helps to uptake and deep penetration of nano-fertiliser inside leaves lead to higher nutrient use efficiency in plant (Iqbal 2019, Desai *et al*. 2022). Cell wall diameter (generally varies from 5–20 nm) is more than the diameter of nano-fertiliser, so it can enter through the cell wall very easily and spread up to the plasma membrane (Sultana *et al*. 2021). Absorption of nutrient, translocation, and accumulation are influenced by the shape, size, molecular structure, constancy, and functionalization of nano-fertiliser (Mushtaq *et al*. 2020).

Encapsulation of nutrients with nano-carrier helps to reduce infiltration loss by keeping the nutrients in soil around the root zone and it can enter the soil through hydrogen bonds, molecular force, surface tension, or viscous force (Bernela *et al*. 2021). The process of nano-particle uptake and translocation inside the plants was studied by transmission electron microscopy (Abdel-Aziz *et al.* 2016). Small size of nano-fertilisers facilitates efficient absorption by the plant roots followed by transportation through apoplast and symplast up to the xylem and vascular bundles by which it move to the different parts of the plant (Mahanta *et al*. 2019). Fig. 2 shows the uptake mechanism of nano-fertiliser through foliar and soil application.

Advantages of nano-fertiliser over conventional fertiliser: The application of conventional fertiliser significantly impacts soil nutrient retention, leading to substantial nutrient loss through various processes such as leaching, evaporation, and surface runoff which decrease the efficiency of fertilisers (Shang *et al*. 2019, Maity *et al.* 2024). Generally, nano-fertilisers are prepared in such a way that it plays an important role as a new effective alternative to conventional fertilisers. Nano-fertiliser shows different physical and chemical properties than bulk conventional fertiliser (AL-Tameemi *et al*. 2019). Less amounts of nano-fertilisers are more sustainable than conventional fertilisers (Salcido-Martinez *et al*. 2020, Mahapatra *et al*. 2022). Higher surface area increases reactive sites of nano-particles, which enhance absorption of fertilisers in plants (Sadak and Bakry 2020). Higher surface tension of nano-materials helps in holding the nutrient material more strongly than the conventional surfaces (Easwaran *et al.* 2024). However, smaller size of nano-fertiliser improves the dissolution rate as well as the nutrient use efficiency compared to conventional fertilisers (Kanjana 2020, Sahar

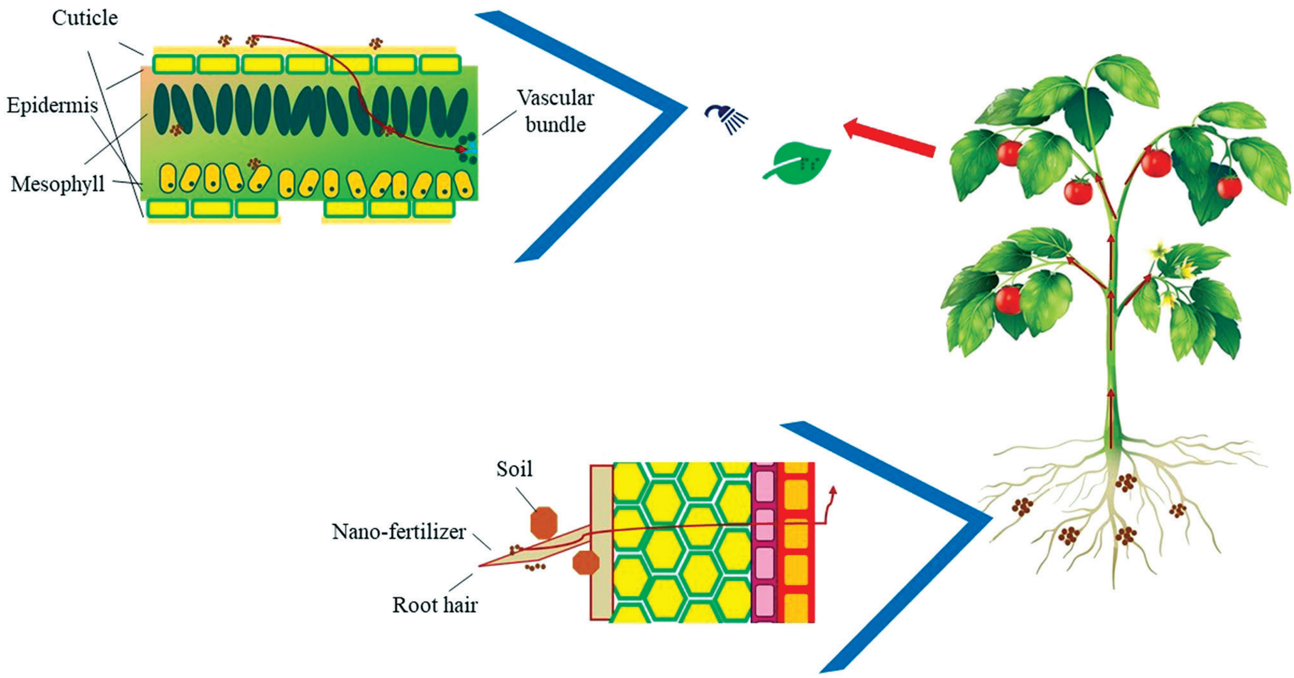

Fig. 2 Foliar and soil application of nano-fertiliser and its uptake mechanism by plant.

et al. 2020). Chemical fertiliser releases its nutrients in 4–10 days while nano-fertiliser takes 40–50 days (Seleiman *et al*. 2021). Since the loss of nano-fertilisers are very less, so nano-fertiliser can apply in small quantity but synthetic fertilisers are applied in huge quantities due to heavy loss through leaching and emission (Iqbal 2019). Since the nano-fertilisers deliver nutrients slowly over a longer period, it is safe for environment (Wangdi 2019) and also reduce negative environmental effects (Okey-Onyesolu *et al*. 2021). Nano formulated micronutrient reduces soil absorption and fixation which improves the bioavailability of nutrients (Ojeda-barrios *et al*. 2020) but in conventional fertiliser nutrients are less soluble due to their big size of particle and high adsorption and fixation to soil particles (Mushtaq *et al*. 2020). Nano-fertilisers showed better performance and efficiency than the most innovative polymer-coated conventional fertilisers in the last 10 years (DeRosa *et al*. 2010).Without changing any chemical formulation, nano-fertilisers increase their stability by aggregation, redox potential, and accessibility of ligands in the soil (Bratovcic *et al*. 2021). Nano-fertilisers are recognised as effective substitute for conventional fertilisers because of its longer shelf life with lesser transportation and application costs (Al-Hchami and Alrawi 2020). Nano-fertilisers are less toxic and harmful for environment and humans than the conventional fertilisers (Nongbet *et al*. 2022).

The adoption of nano-fertilisers in small-scale farming, particularly in developing countries, presents a promising avenue for enhancing agricultural productivity while addressing cost constraints and environmental concerns. However, higher nutrient absorption and reduced wastage of nano-fertiliser lead to cost savings for small and marginal farmers. Nano-fertilisers are expensive due to production cost but due to more efficient, application rate is low. For examples, up to 200 kg conventional fertiliser is required for 1 ha area where as for the same yield only 40 kg nano-fertiliser is required (Su *et al.* 2022). This reduction related with lower input costs of the farmers. One bottle of nano-urea (500 mL) has the similar effect on one bag of urea fertiliser (20 kg). Detailed classification of nano-fertiliser is depicted in Table 1 and Fig. 3. Table 2 and Table 3 lists beneficial effect of different nano-fertiliser on cereal, pulse, oilseed and other crop cultivation.

Effect of nano-fertilisers on the environment: The injudicious use of chemical fertilisers has become a significant concern in modern agriculture, primarily due to its adverse effects on environmental quality and soil ecosystems (Duary *et al*. 2021, Duary 2020). The

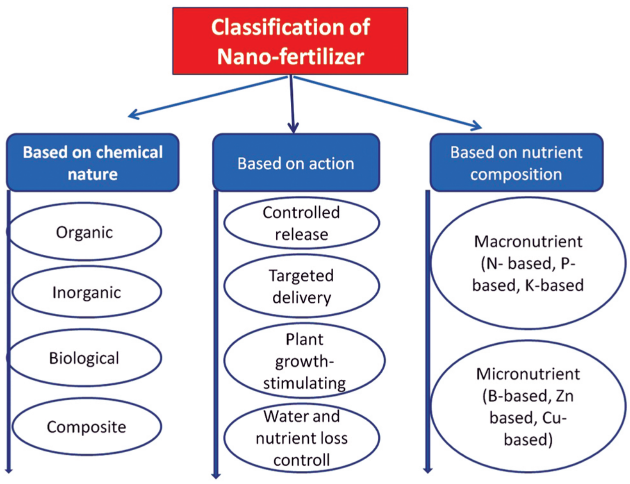

Fig. 3 Classification of nano-fertiliser.

Table 1 Detailed classification of nano-fertiliser

Basis of classification	Types of nano-fertiliser	Description
Based on chemical nature	Organic	Organic nano-fertilisers are made from organic materials or organic sources to supply nutrient gradually into the soil. This fertilisers are eco-friendly and also improve soil health (Alekhya *et al*. 2024).
	Inorganic	Inorganic nano-fertilisers provide a significant advantage in agricultural production by delivering nutrient while minimizing environmental impact. This type of fertiliser includes metalloids and non-metallic nano-particles (Alkhader 2023).
	Biological	Biological nano-fertilisers, also known as nano-biofertilisers. Nano-biofertiliser developed by combining organic fertiliser (biofertiliser) of nano-size (1–100 nm), prepares with the help of certain nano-material coating and living microorganism or basically a combination of nano-material with biofertiliser (Sood 2021). Nano-biofertiliser (developed by nano-biotechnology) is a novel, low-cost, environment friendly fertiliser with both properties of nano-material and biofertiliser (Kumari and Singh 2020).
	Composite	Composite types of nano-fertilisers are specially designed by combining two or more different nano-materials or nano-structures to create a new nano-fertiliser with improved properties and performance. With continuous advancement of nano-composite fertiliser technology, challenges such as nutrient loss, low crop yield can be addressed (Easwaran *et al.* 2024).
Based on action	Controlled-Release	These types of fertilisers are designed to control the release of nutrients providing a continuous supply of essential nutrient up to an extended period. Controlled-release nano-fertilisers are composed of lipids, polymers and inorganic substances (Saurabh *et al*. 2024).
	Targeted Delivery	Targeted delivery type nano-fertilisers are designed to deliver nutrients and other beneficial substances directly to specific plant site, such as the roots, leaves, or seeds of plants. Nano-aptamers are tiny molecule that can bind with plant hormones and enzyme and deliver it into target plant site and they also increase nutrient uptake from soil (Yadav *et al*. 2023).
	Plant Growth-Stimulating	Plant Growth Stimulating (PGS) type nano-fertilisers are designed to enhance growth and development of plants by providing essential nutrients and stimulating plant physiological processes. Nano-fertilisers like carbon nanotubes (CNTs) interact with plant root and improve hormonal activity which stimulates plant growth. Being used as a fertiliser, CNTs mixed with soil and increase the carbon and other nutrient availability in soil (Saurabh *et al*. 2024).
	Water and Nutrient Loss Control	This type of nano-fertilisers are designed to reduce nutrient and water loss promoting sustainable and efficient fertiliser use allowing farmers to use less fertiliser with same crop output (Yadav *et al*. 2023). Polymer, clay based and liposome based nano-fertilisers are the examples of this type nano-fertiliser.
Based on nutrient composition	Macronutrient	Macronutrient nano-fertilisers are specially designed fertilisers which supply essential macronutrients (nitrogen, phosphorus and potassium), to the plants in nano-sized form to assure controlled release and improved absorption by plants (Nongbet *et al*. 2022). Some common macronutrient nano-fertilisers are N nano-fertiliser, P nano-fertiliser, K nano-fertiliser and NPK nano-fertiliser.
	Micronutrient	Micronutrient nano-fertilisers are specialized fertilisers that provide essential micronutrients to plants in a nano-sized form. This fertiliser improves uptake and availability of micronutrient and minimizes the deficiencies (Raiesi Ardali *et al*. 2024). Some common micronutrient nano-fertilisers are Zn Nano-fertiliser Cu Nano-fertiliser, Mn Nano-fertiliser etc.

Table 2 Effect of different types of nano-fertiliser on cereal, pulse and oilseed crop cultivation

Crop	Nano-fertiliser	Effects on crops	References
Rice	Silicone nano-fertilisers	Foliar application of nano-fertiliser along with DAP recoded higher leaf chlorophyll content, grain yield and fertiliser use efficiency.	Al-Khuzai and Al-Juthery (2020)
	Zinc oxide nano-particles (ZnONPs)	Plant growth parameters and reverted the Zn-deficiency symptoms.	Haydar *et al*. (2024)

Contd.

Table 2 (*Concluded*)

Crop	Nano-fertiliser	Effects on crops	References
	Nano-clinoptilolite based nitrogen fertiliser	This nano-fertiliser 14.75%, increased in farmers income, decreased environmental damage 8.77%.	Sun *et al*. (2024)
	Nano-Zn	Improved the yield attributes like number of panicles/m^2, number of filled grains/panicles.	Das *et al*. (2022)
Wheat	Nano-composite NPK fertiliser	As compare to control, plants treated with nano-chitosan-NPK fertiliser resulted significant increase in root length, shoot length and harvest index on sandy soil.	Abdel-Aziz *et al*. (2016)
	ZnO nano-particles	Use of ZnO nano-particle increased grain yield 56% and biomass production 63% than control.	Du *et al*. (2019)
Maize	TiO_2 Nano-particles	Number of cobs in plant, dry weight and corn yield.	Jyothi and Hebsur (2017)
	Nano-zinc and nano-boron	The productivity of the most traits.	Nouraein (2019)
	Nano-Phosphorous	Soil and foliar application of nono-phosphorous along with 75% recommended dose of phosphorous recoded higher dry matter accumulation, chlorophyll content, test weight and yield.	Rashmi and Prakash (2023)
Pearl millet	ZnO nano-particle	Priming of seed with ZnO nano-particles improved seed germination and various agronomic traits like days to flowering, days to maturity and growth.	Kumar *et al*. (2024)
Finger millet	Zinc nano-fertiliser	Germination %, root length and shoot length, plant height, total chlorophyll content, number of tillers.	Morovat *et al*. (2019)
Chickpea	Nano-fertiliser	Number of primary branches, seed weight, seed yield and harvest index.	Drostkar *et al*. (2016)
	Nano Zn, Nano-Fe, Nano-Mn	Application of three micronutrient nano-fertilisers nano-chelated forms improved number of seed/pod, pods/plants, days to maturity, test weight and yield.	Sabaghnia and Janmohammadi (2023)
Green bean	Nano micronutrient	Pod length, pod diameter, pod weight and fresh pod yield.	Marzouk *et al*. (2019)
	Mg nano-fertiliser	Biomass production and photosynthetic pigments.	Salcido-Martinez *et al*. (2020)
Blackgram	Nano-urea	Foliar spray of nano-urea (2-4 mL) at active growth stage recorded highest yield (1587.33 kg/ha).	Islam *et al*. 2023
Greengram	Iron oxide NP solution	Pre-soaking of seed with Fe_2O_3 nano-particle increase 366% root length compared to control.	Palchoudhury *et al*. (2018)
Lentil	ZnO nano-particles	Foliar application of ZnO nano-particle @ 1mg·L^{-1} showed positive response on seed quality and production.	Kolencik *et al*. (2022)
	Nano Zn	Nano Zn spray @20 ppm at 30 and 50 DAS (days after sowing) recorded significant higher leaf area index, dry matter accumulation, test weight, nodule number and nodule dry weight and Zn uptake.	Saha *et al*. (2024)
Soybean	Phosphatic nano-fertilisers	Compare to conventional fertiliser, application of nano-fertiliser increased 32 % crop growth rate and 20% Seed yield.	Bratovcic *et al*. (2021)
	NPK nano-fertilisers	Plant growth characters and seed yield.	Sahar *et al*. (2020)
	Nano-crystalline powder of iron, cobalt and copper	Germination percentage, chlorophyll content, nodule number and crop yield.	Sadique *et al*. (2017)
	ZnONP	ZnO nano fertiliser increased yield, lipid peroxidation, and various antioxidant activity of the crop.	Yusefi-Tanha *et al*. (2020)
Clusterbean	Urea hydroxyapatite nanofertiliser	Application of urea hydroxyapatite nano-fertiliser improves growth and yield of the crop. It also improves the bio-availability of plant nutrients.	Shylaja *et al*. (2020)
Cowpea	Cu nano fertiliser	Antioxidant concentration and Chlorophyll content.	Mustafa *et al*. (2024)

Contd.

Table 2 (*Concluded*)

Crop	Nano-fertiliser	Effects on crops	References
Common bean	Nano-micronutrient	Flower number/plant, photosynthetic pigments, and yield.	Salama *et al*. (2022)
Sesame	Nano-fertiliser	Amount of oil, increased availability of nutrients.	Baekhrad *et al*. (2017)
	Mg-nano fertiliser	Increase total chlorophyll, carotenoid, protein, proline, and soluble sugar.	Varamin *et al*. (2018)
Sunflower	Nano ZnS	Yield and yield attributes, seed oil content.	Dhage and Biradar (2020)
	Zeolite based nano-fertiliser	Germination percentage and growth.	Lateef *et al*. (2016)
Flax	Nano ZnO	1000 seeds wt. (g), oil %,no of capsules/plant, seed yield (kg/fed).	Sadak and Bakry (2020)
Rapeseed	Khazra iron nano chelate	Yield, biological yield and total dry biomass.	Mahdi *et al*. (2019)
Safflower	ZnO nano-particle	Application of ZnO nano-particle @10 g/L increased growth and yield of the crop under water stress condition.	Ghiyasi *et al*. (2023)
Groundnut	ZnONP Potassium nano-fertiliser	Plant growth, seed germination, and stem/ root elongation.	Surendranath and Mohanan (2021)
	Potassium Nano-fertiliser	Application of potassium nano-fertiliser @150 ppm at 30 DAS and 150 at 60 DAS significantly increased nutrient content in seed as well as in shoots.	Afify *et al*. (2019)
	Phosphorus Ensembled Nano-materials (hydroxyapatite)	Foliar application and soil application of this fertiliser improved nutrient concentration (Ca and P) in root and shoot cultivate under gren house condition.	Li *et al*. (2021)
Canola	N, Fe and Mn nano-fertiliser	Foliar application of nano-Fe and Zn along with nano-nitrogen showed positive results on yield and oil content.	Alwakel *et al*. (2021)

Table 3 Effect of different types of nano-fertiliser on performance of other different crops

Crop	Nano-fertiliser	Effect on crops	References
Cotton	Nano-fertilisers	Sympodial branches and opened bolls/plant.	Kanjana (2020)
	Nano-fertiliser (Lithovit)	Application of nano-fertiliser at squaring, initiation of flowering and two weeks after had significant effect on flowering growth and seed cotton yield.	Emara *et al*. (2018)
	Nano NPK fertiliser	Soil and foliar application of nano-fertiliser three times Significantly improved bolls per plant, weight of boll and cotton yield.	Sohair *et al*. (2018)
Potato	Nano-N, Nano-Zn, Nano-Cu	Improved the crop yield, economic return.	Kumar *et al*. (2020)
	NPK nano-fertilisers	Starch rates, NPK nutrient use efficiency, harvest index.	Abd El-Azeim *et al*. (2020)
	Nano Chitosan-NPK	Growth attributing character; yield parameters and photosynthetic pigments.	Elshamy *et al*. (2019)
Tobacco	ZnO nano-particles	Nano-ZnO showed positive result on length of root and shoot, leaf area leaf enzymatic activities.	Tirani *et al*. (2019)
Coffee	ZnO	Growth parameter, dry matter accumulation and net photosynthesis.	Rossi *et al*. (2019)
Spinach	Commercial nano-fertiliser	Increase the leave nutrient content and add new elements	Gil-Diaz *et al*. (2022)
Cucumber	Liquid nano NPK fertlizer	Application of liquid nano-fertiliser in different concentration as 3, 4.5,6 and 9 mL increase leaves number, chlorophyll content and yield than control under greenhouse condition.	Merghany *et al*. (2019)
Tomato	Mixed nano-fertiliser	Root length, root diameter, root biomass.	Rahman *et al*. (2021)
Broccoli	ZnO nano-particle	Seed germination, root length, shoot length, number of leaves.	Awan *et al*. (2021)
Fig	nano-NPK fertiliser	Application of nano-NPK improves soil microbial activity and also crop growth.	Mustafa *et al*. (2022)

substantial loss of nutrients from chemical fertilisers (about 40–70% of nitrogen, 80–90% of phosphorous, 50–70% of potassium and more than 95% micro) not only represents a waste of agricultural inputs but also poses serious threats to environmental health (Karthik and Maheswari 2021). Conventional fertilisers are expensive and harmful for the humans as well as environment causing severe consequences e.g. eutrophication, ground water pollution and diseases (Astaneh *et al*. 2021).Thus, it has to be optimized the dose of chemical fertiliser to minimize the risk of environmental hazards by adopting suitable method of fertilization like nano-fertiliser (Sohair *et al*. 2018). Nanotechnology applied in plant nutrition purposes to increase the nutrient use efficiency, tolerance of plants for different abiotic stress and delivery of elements which are hardly available such as phosphorus, zinc and limiting losses of mobile nutrients like nitrate to the environment (Astaneh *et al*. 2021, Bratovcic *et al*. 2021). Further, nano-fertilisers improve selectivity, slow-release dynamics and resistance to degradation, therefore it reduces the adverse effects on the agro-ecosystem by less accumulation (Sarkar *et al*. 2021). Application of nano-fertilisers could be an effective step towards the sustainable and eco-friendly agriculture to control the release of nutritional elements (Varamin *et al*. 2018). Thus, nano-fertiliser can be considered as an economic alternative to chemical fertilisers (Abd El-Azeim *et al*. 2020). Effect of nano-fertiliser and conventional fertiliser on environment graphically presented on Supplementary Fig. 1.

Drawbacks of nano-fertilisers: Although nano-fertilisers are boon to agriculture and increase crop growth up to a certain limit. However, improper use can cause adverse effects like reduction in growth of crop due to toxic effect of nutrient (AL-Tameemi *et al*. 2019, Mustafa *et al*. 2024, Musheer *et al*. 2024, Noor and Elgharbawy 2024) (Supplementary Table 1). A significant amount of nano-fertiliser accumulates within plants with continuous application, over time which does not affect the plant themselves, but its presence affect the food chain (Ninama *et al*. 2023). Large leaf area is required for foliar application of nano-fertilisers and the leaf may burn due to high concentration of fertiliser (Yadav *et al*. 2023). Nano-fertilisers are necessary to improve crop production without any negative effects on soil health and environment, but negatively affect beyond threshold level (Chhipa and Hajji-Hedfi 2024). Nano-fertilisers basically release nutrients within 6–7 weeks, while traditional fertilisers release within a week (Verma *et al*. 2022). Farm workers inhale the nano-particles during manufacturing and spraying in the field which can reach the blood or other target sites such as brain, liver or heart results in chronic lung effects and may also cause skin irritation, rashes, headaches etc. (Mahil and Kumar 2019, Meghana *et al*. 2021). Again, the reactivity and variability of nano-materials have raised several safety concerns for workers (Bernela *et al*. 2021). Nano-fertilisers have several detrimental effects on soil microflora, fauna, animals, and humans (Sadhukhan *et al*. 2021). Some of the foremost limitations are gaps in research, continuous monitoring and lack of legislation which are restricting the rapid development and implementation of nano-fertilisers as a new source of plant nutrients in agricultural field (Iqbal 2019). Therefore, it is very important to find out the accurate dose and method of nano-fertiliser application in agricultural production.

Effect of nano-fertiliser on GHGs emission: Agro-ecosystem has a major role in global warming as it emits greenhouse gases (GHGs). Conventional method and traditional fertilisers like urea helps to release significant amount of GHS like methane and nitrous oxide. In this context, use of nano-fertiliser getting popularity in crop field as it reduces the GHGs emission along with increasing productivity (Sun *et al*. 2024). Due to small size, this fertiliser control the release and availability of nutrient especially for nitrogen which is essential for reducing emission of GHS specially methane (CH_4) and nitrous oxide (N_2O) (Babu *et al*. 2024). Application of specific nano-fertiliser formulation reduces N_2O emission (0.88 mg m²/day) in rice field than control treatment (1.67 mg m²/day) which has much higher global warming potential than some other GHGs (Mohanraj *et al*. 2019). From his experiment in okra, Mandal *et al*. (2023) reported emission of 0.79–1.71 mg/m^2/day N_2O with application of nano-urea and for convention prilled urea rate of release of N_2O was 2.85 mg/m^2/day. Foliar application of nano-urea in different crops, applied twice, reduces GHGs emission from 164.2 kg CO_2-eq/ha to 416.5 kg CO_2-eq/ha without hampering the yield (Upadhyay *et al*. 2023). Application of FeONP reduces CH_4 and N_2O emission by 50% along with carbon sequestration compare to Urea fertilization in the 4th year of experiment (Yu *et al*. 2024).

The review article established a comprehensive idea of nano-fertilisers and their technicality with various implications. Nano-fertiliser enhances growth and yields for several crops, for example, with ZnONPs addressing Zn deficiency in rice, nano-phosphorous boosting maize yield with reduced doses, Zn-Fe-Mn nano-fertilisers improving chickpea productivity, phosphatic nano-fertilisers increasing soybean growth and seed yield, and potassium nano-fertiliser promoting germination and growth in groundnut. This creates an economical and eco-friendly option for conventional fertilisers by enhancing efficiency of nutrient use, reducing environmental losses, and minimizing harmful effects like eutrophication and pollution. Further, applying nano-fertilisers improves plant stress tolerance, lowers agro-ecosystem degradation, enables slow nutrient release, and makes them a sustainable solution. It saves nutrient loss of around 40–70% nitrogen, 80–90% phosphorus, 50–70% potassium, and over 95% micronutrients. Chemical fertiliser application degrades soil fertility, productivity, and environmental and water quality. Thus, the use of various nano-fertilisers offer a positive impact on sustainable crop production. In this context, the present article highlighted several key points of nano-fertilisers such as an increase in nutrient uptake and utilization, reduction in wastage of fertiliser, and mitigating environmental impact. Nanotechnology tools and techniques in the form of nano-fertilisers could, therefore, be an alternative option for the coming era of agriculture. Small nano-fertilisers allow them to penetrate through leaf cuticles and target delivery. However, special attention must be paid while selecting and applying nano-fertiliser since its effects vary with the type of plant materials influenced by shape, size, and application.

A collaborative study among researchers, agricultural stakeholders, and policymakers is necessary to fully utilize the potential of nano-fertilisers. Even though progress has been made in nano-fertilisers, several issues/gaps need to be addressed in future studies. Specifically, further research is required to elaborate on the following aspects, synthesis of nano-fertiliser; application methods; laws and government regulations; scalability and commercialization. Further investigation could provide insights into the potential of nano-fertilisers to revolutionize the fertiliser industry and contribute to agriculture sustainability. In this review, we have identified these gaps and opted to focus on the following issue: application systems nano-fertilisers across various crops (including vegetables, field crops, fruits, and spices) their uptake mechanisms and interactions with plant comparisons between nano-fertilisers and their traditional counterparts, and effects of nano-fertilisers on GHGs emissions and climate change. Hence, our research contributes to the existing body of knowledge on nano-fertilisers and forms a foundation for future research. The highlighted information could be significant for policymakers, research scholars, scientists, and industrial stakeholders.

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