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Nanotechnology in maize nutrition: mechanisms, agronomic impacts, and ecological implications

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Abstract

One of the most significant staple crops in the world is maize and its demand all over the globe is ever increasing. Nevertheless, achieving higher productivity is challenging due to ineffective nutrient absorption and the constraints of conventional fertilisers. The latest advancements in nanotechnology have proposed new fertilizer formulations that can enhance nutrient transfer, regulate flow rates, and improve plant uptake. These achievements would contribute to the amplification of additional growth, yield, and to an increased adaptability to environmental pressure, favouring the decrease of overall input requirements. The nitrogen, phosphorus, potassium and other trace minerals nano-based compounds have shown to have great potential in enhancing more efficient nutrient use and in enabling farming systems within maize production to be more sustainable. Although these advantages existed, there has been some uncertainty about the long-term environmental impacts, build-up of nanoparticles in the soil and food safety. Cost, accessibility to farmers and restrictions by the regulatory agencies are also barriers that slow down the widespread use. Continuous research is thus required to i) develop biodegradable and environmentally responsible nano-fertilisers, ii) test their performance in the field conditions and iii) make sure that the safety requirements are well-defined. Nanotechnology may also play a very important role in enhancing the production and sustainability of maize farming based on careful innovation.

Abbreviations

% : Percent
Ag: Silver
Ca: Calcium
CMC: Carboxy Methyl Cellulose
CS-Si NF: Chitosan-Silicon Nano Fertilizer
Cu: Copper
Cu-SA: Copper- salicylic acid
DNA: Deoxyribonucleic acid
K: Potassium
MDA: Malondialdehyde
Mg: Magnesium
MoO_3: Molybdenum trioxide
N: Nitrogen
N_2O: Nitrous oxide
Na^+: Sodium ion
$NiFe_2O_4$: Nickel Ferrite
NMs: Nanomaterials
NPs: Nanoparticles
NUE: Nutrient Use Efficiency
P: Phosphorus
POD: peroxidase
Si: Silicon
SiO_2: Silicon dioxide
Zeo: Zeolite
Zn: Zinc
ZnO: Zinc Oxide
$ZnSO_4$: Zinc Sulphate

Introduction

Zea mays L. (maize) is the most common cereal crop with an annual production of over one billion tonnes on almost 200 million hectares in almost every part of the world. It is cultivated in all continents and is an important source of calories, feed, and industrial raw material. The major producers include countries like the United States, China and Brazil, whereas in most parts of sub-Saharan Africa, Latin America and Asia; maize is a subsistence food source to millions of people worldwide. As the leading cereal by production volume, maize contributes significantly to global food security, nutrition, and rural livelihoods, particularly in developing regions. Maize meets at least 30 percent of the daily energy needs of over 4.5 billion people in 94 countries, and is also essential as animal feed and as feedstock in various industries, including bio energies (Shiferaw *et al.* 2011, Erenstein *et al.* 2022). Maize is and will remain a crucial source of energy both as food and as livestock feed, but the importance of bioenergy industries is increasing, as well as the growth in population, urbanization, and shift toward higher meat intake in the diet (Ranum *et al.* 2014, Grote *et al.* 2021). In other areas, like the United States, as much as 40 percent of maize output is channelled to the production of ethanol, further fuelling the food, feed and fuel nexus competition. This scenario brings into perspective the invaluable status of maize in the food systems in the entire world and its pressing need to balance between the contradictory aspects in the circumstances of mounting pressure on natural resources.

Low efficiency of nutrient use that causes agronomic and environmental issues is also characteristic of the traditional use of fertilizers to produce maize. Applied nitrogen (N) usually only crossovers 30-40% into the crop, and the rest is lost through procession, leached, and volatilized or fixed in the soil. Similarly, it can be as low as 20% of the assimilation of micronutrients, in particular, zinc (Zn), which is yet another constraint on crop nutrition and yield potential (De Aguiar *et al.* 2022, De Souza *et al.* 2025). To offset these inefficiencies, farmers will resort to applying more fertilizers, which, however, has the downside of causing diminishing returns where the additional nutrients are not efficiently consumed by the plant. These inefficiencies are not limited to the farm level. Maize does not absorb all its nitrogen, which is typically washed away to the adjacent water masses, where it causes eutrophication and growth in algae (Wei *et al.* 2020). Moreover, conventional nitrogen fertilizers contribute significantly to N_2O emissions, which is a potent greenhouse gas that contributes to changes in the climate. Uninterrupted high use of mineral fertilizers may also interfere with the community of microorganisms in the soil, decrease the quality of soil health, and decrease agricultural productivity over a long-term period (Cheng *et al.* 2024, Imran 2024). Although there are short-term gains in the use of more fertilizers, the long-term effect on sustainability is that more creates environmental destruction and weakens the soil quality.

Nanotechnology has also found application as a cutting-edge in agricultural science with nano fertilizer formulations created at the nanoscale (<100 nm) representing a radical advance to conventional inputs. Their unusual physicochemical characteristics, which encompass ultrafine particle sizes and a high surface area per unit volume in addition to greater reactivity, basically alter their behaviour in the soil-plant system. These characteristics are facilitating the improved solubility, mobility, and bioavailability of nutrients, which results in the uptake and absorption of nutrients by crop plants, such as maize (Santhosh Babu *et al.* 2024). The nano-fertilizers are designed to be slowly released and delivered compared with the traditional fertilizers that can release nutrients fast and in an inefficient manner. This regulated release aligns the availability of the nutrients with the demand of the plant over a period of time, which significantly increases the utilization of the nutrients and reduced losses into the environment (El-Saadony *et al.* 2021). Also, nano-fertilizers can decrease the total amount of inputs, which leads to lower production costs and eliminates some adverse effects on the environment, which is the primary and still unaddressed issue related to nano-fertilizers (Elsabagh *et al.* 2024). However, the environmental and ecological safety of these fertilizers remains a major issue regardless of the good yields in terms of agronomics. Some nanoparticle formulations are antimicrobial and can be used to disrupt soil microbial communities on which nutrient cycling, plant growth promotion and soil health depend (Strekalovskaya *et al.* 2024).

Despite the promise of nano-fertilizer in the increased production, nutrient absorption, and quality of maize, there are still significant challenges, including effects on the environment, which are yet to be felt, especially those related to the persistence of nanoparticles, such as soil ecosystems and effects relating to the dynamics of microorganisms. Moreover, comparative field-scale studies are uncommon that can evaluate both agronomic. Value and ecological risk, and it is hard to make certain conclusions about it due to the scalability and viability.

To this end, this review critically examines the dual uses of nano-fertilizers in maize production as a potential sustainable solution to increase nutrient utilization efficiency and crop productivity, and simultaneously quantifies their ecological footprint and safety.

Nano-Fertilizers: Concepts and Types

Nano-fertilizers are fertilizers, which have nanoparticles or nanostructures that assist in the improved nutrient provision to plants. They are a branch of nanotechnology in agriculture, intended to make it more efficient, with more targeted release, and less harmful to the environment (Saraiva *et al.* 2022). Nano fertilisers take advantage of the characteristics of nanomaterials, including high surface area and controlled release, to enhance nutrient utilisation efficiency, lessen runoff, and decrease environmental effects, hence, resulting in sustainable farming (Iqbal 2019).

Nano-fertilizers can be categorized according to their action, nutrient and the type of material used.

Action-based nano-fertilisers can be controlled-release-based which release nutrients gradually, targeted delivery, which targets nutrients directly to particular parts of the plant, or formulations that enhance plant growth or minimise water and nutrient losses. Nutrient-wise, they can be inorganic, organic, or hybrid, combining different sources for enhanced efficiency. Material-wise, nano-fertilizers may be surface-coated, coated with synthetic polymers or biological substances, or serve as nanocarriers like carbon nanotubes or quantum dots to transport nutrients. (Figures 1 & 2, Table 1). These diverse classifications allow for tailored applications that improve nutrient utilization and reduce the impact on the surrounding ecosystems in sustainable agriculture.

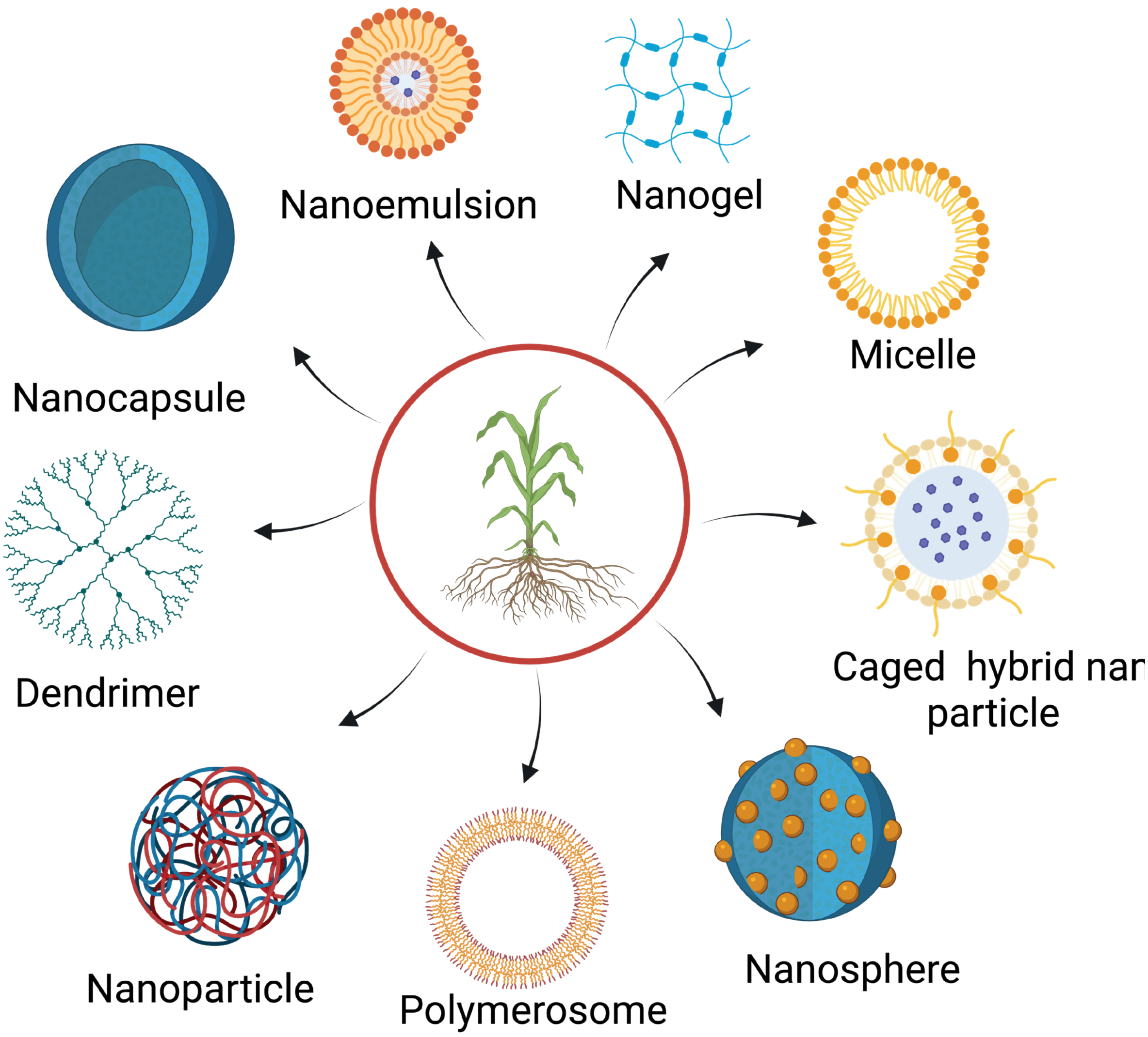

Fig. 1 - Nano fertilizer technologies (Created in https://BioRender.com)

Methods of synthesis and delivery to the maize systems

Table 1 - Synthesis approaches and agronomic impacts of nano-fertilizers in maize

Nano-fertilizer/particles	Method of synthesis	Impact	Reference
Nano micronutrient (MoO_3 -NPs)	Sol-gel method	239.4 g maize grain weight per plant of compared to all conventional treatments	(Sary and Abd El-Aziz 2025)
Ca, P, Cu or Zn	Sol-gel technique	Increased absorption of metal ions by plant roots	(Borak *et al.* 2022)
Nano ZnO	Hydrothermal method	Plant growth, pigments and antioxidant activity increased by 59% compared to conventional methods	(Azam *et al.* 2022)
Nano Zinc	Green synthesis using leaf extract	18% increase was visible on the fresh cob yield when compared to standard fertilizer dose Positive effects were observed on plant growth traits	(Rajesh *et al.* 2021)
Chitosan-silicon nano fertilizer	Ionic gelation method	CS-Si NF boosted yield (43.4%) and test weight (45%) over SiO_2.	(Kumaraswamy *et al.* 2021)
Nano hydroxyapatite fertilizers	Microwave and ultrasound methods	Increased plant height, chlorophyll, water status, phosphorus uptake, and biomass	(Sajadinia *et al.* 2021)
Chitosan nanoparticles (NPK)	Ionic gelation	CS/NPKS gave highest chlorophyll Increase in the height of plants and the number of leaves	(Dhlamini *et al.* 2020)
Zn & Si nano particles	Wet-chemical nanoparticle synthesis	Mitigate salinity effect on maize	(Shoukat *et al.* 2024)
Hydroxyapatite nanoparticles (HN)	HN: chemical precipitation method	Taller plants, more leaves, higher chlorophyll content, greater dry matter, longer cobs, more rows and kernels per cob, higher grain weight, higher stover and kernel yields	(Rashmi and Prakash 2023)
Nano rock phosphate (NP)	NP: Mechanical ball milling		
CMC-coated hydroxyapatite nanoparticles	CMC: Surface modification / coating method		
Chitosan nano fertilizer (copper & salicylic acid)	Co-encapsulation through ionic gelation.	Seed treatment raised vigour and enzyme activity foliar spray boosted antioxidants doubled chlorophyll and lowered MDA. application of nano fertilizer enhanced sucrose translocation through the slow release and Cu-SA synergy.	(Sharma *et al.* 2020)

Nano Rock Phosphate	Ball milling	Improved maize growth and yield, with performance comparable to SSP in terms of the uptake of P, recovery, and nutrient utilization.	(Adhikari *et al.* 2014)
Controlled-release of P fertilizer	Nano composite polymer coating	Increase in growth parameters	(Channab *et al.* 2024)
Urea nano particles	Biological synthesis	improved growth parameters reduce urea use by at least 25%.	(Singh *et al.* 2023)
Nano Silica	Green synthesis-rice husk	Nano-Si effectively enhanced plant P concentration	(Akca *et al.* 2023)
Nano nitrogen loaded chitosan particles	Polymerization-based chemical synthesis	25% reduction in mineral N use without yield loss effective, economical, and eco-friendly alternative to full mineral N application	(Abou El Enin *et al.* 2023)
Nanoparticles (Mg, K, P)	Mechanical milling	Improved soil water retention and provided a slower, more prolonged release of Mg, K and P compared to conventional fertilizers, reducing nutrient losses, enhanced growth and P uptake	(Elsabagh *et al.* 2024)
Polymer coated urea	Polymer coating	20% higher yield, reduced N loss	(Gil-Ortiz *et al.* 2021)
Nano ZnO particles	Wet chemistry technique	Seed priming and coating with ZnONPs, especially at 20 mg L^{-1}, improved maize growth, yield traits, shoot Zn content, and soil nutrient availability compared to bulk $ZnSO_4$ and control. At 40 mg L^{-1}, ZnONPs further enhanced chlorophyll, cellulose, microbial activity, and soil enzyme functions	(Tondey *et al.* 2021)

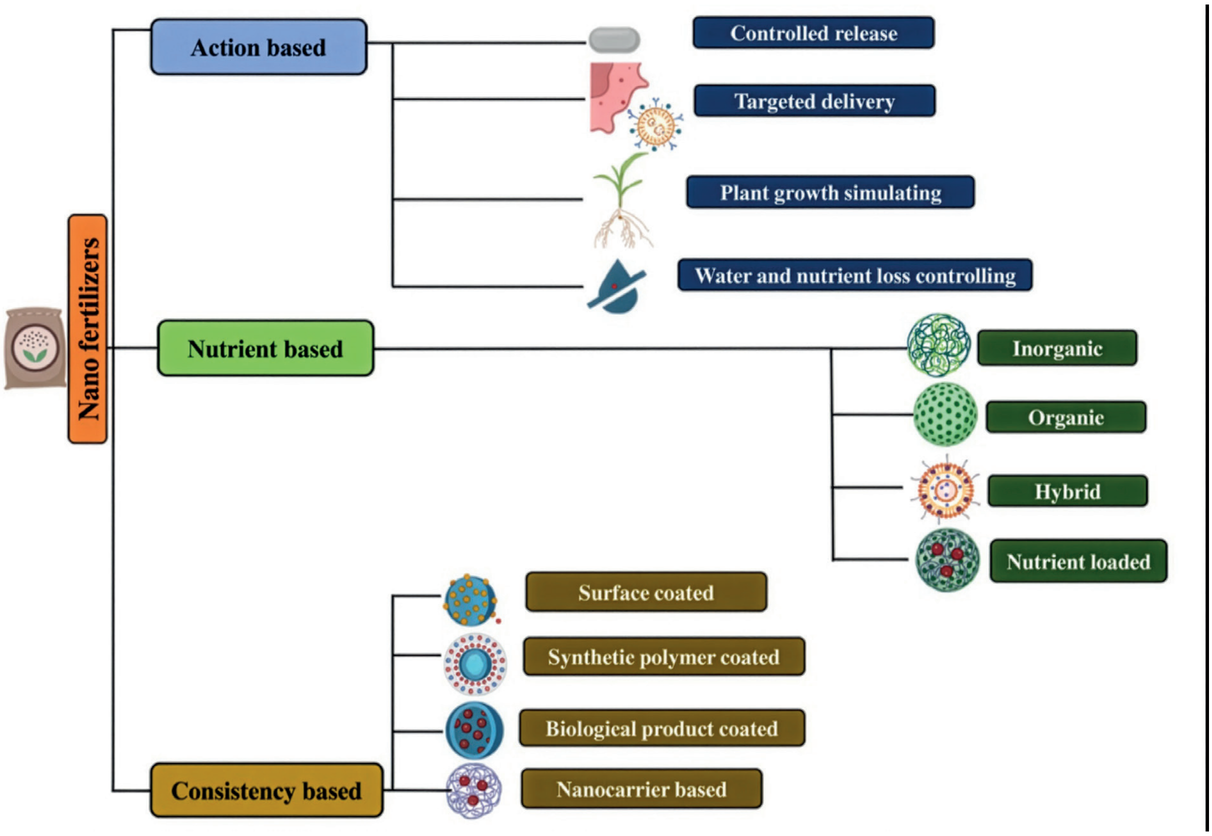

Fig. 2 - Classification of Nano fertilizers (Created in https://BioRender.com)

Role of Nano-Fertilizers in Maize Production

Agronomic Benefits of Nano-Fertilizers in Maize

Nano-fertilizers provide significant advantages over conventional/ traditional fertilizers such as enhanced nutrient utilization, sustainability and quality of agricultural produce (Lazcano *et al.* 2021). The nanoscale size of fertilizers enhances absorption and facilitates penetration in plant tissue, even it interacts with soil microbiome, which plays a crucial element for soil nutrient cycling and plant growth (Lazcano *et al.* 2021). Being characterized by higher efficiency nano fertilizers offers a significant influence on crop production compared to productive and marginal soil (Shoukat *et al.* 2025). Nano Si/Zn application apart from increasing nutrient use efficiency (NUE), led to enhanced biomass production (110%) and grain yield (106%) which shows a strong correlation with harvest index and Si content in the shoot (Shoukat *et al.* 2025). (Figure 3, Table 2). Nanoparticle formulation of plant nutrients significantly minimizes the standard application of convention fertilizers lead to significant enhancement of crop health and yield. Bio-fermentation-based developed urea nanoparticles reduce their dosage by 25 and 50%. Further, it outperformed and significantly reduced dosage in comparative of recommended conventional urea dosage by a minimum of 25% (Singh *et al.* 2023). Designing small nano particles serving as a novel approach for saving nutrients, conserving natural resources and energy, which prevents water contamination and reduces nutrient losses and enhances plants nutritive composition (Kumar *et al.* 2020).

Improved NUE

Nutrient physical state influences the status of crystallinity, morphology and interacts with the soil-plant-microbe interface. This affects nutrient uptake, mobilization/assimilation and distribution inside the crop plant (Kalia *et al.* 2019). Silver nanoparticles at different dosage enhances nitrogen, phosphorus and potassium uptake as well as use efficiency, significantly enhance leaf area and yield (Jhanzab *et al.* 2015).

Micronutrient formulations such as microcapsules and nanocapsules, nanomaterials (NMs), and nanoparticles (NPs) develops intelligent nutrient delivery platform which synchronizes the crop nutrient demand and its release (Monreal *et al.* 2016). Nano-fertilizers related research has gained momentum and developed intri-

Table 2 - Agronomic impacts of nano fertilizers in maize cultivation

Nanoparticles based fertilizer	Application	Reference
Chitosan-silicon nano fertilizer	Higher seedling vigour index	(Kumaraswamy *et al.* 2021)
	Slow Si release for lasting effect	
	Boosted antioxidants and photosynthesis	
Chitosan	Slow and gradual release of copper and salicylic acid	(Sharma *et al.* 2024)
	Increased defence enzyme activity	
	Copper and salicylic acid improved metabolic activity	
	Improved overall yields	
Silicon dioxide nanoparticles	Reducing dependence on harmful pesticides and fertilizers	(Hadri *et al.* 2024)
Zinc oxide nano-particle	With application, plant traits such as height, improved	(Adhikari *et al.* 2015)
Porous silica nanoparticles	Nano silica boosted protein, chlorophyll, and phenol levels in maize	(Suriyaprabha *et al.* 2012)
Ag nanoparticles and Magnetic Field	Maize yield rose by 35%, highest with magnetic field and silver nanoparticles	(Berahmand *et al.* 2012)

guing topic in recent years. Nano-fertilizers possess strong ionizing capability, improved chemical stability, enhanced NUE, improved root absorption dynamics, reduced nutrient losses, increased pH lenience and bountiful crop productivity (Zulfiqar *et al.* 2019). They are structured as such to site-specific delivery of active ingredient as per demand, which avoids toxicity and enhances plant sustainability for surviving in challenging environmental conditions. The basic principle behind it is minimum resource and free from toxicity (Al-Juthery *et al.* 2021). It is most responsive due to its small size it enters plant cells through the epidermis and gradually release which enhance target delivery of nutrients (ul Ain *et al.* 2023).

Reduction in fertilizer application rates

Nano composites and nano fertilizers possess potential for prevention of nutrient fixation and loss through controlling nutrient release from fertilizer granules (Subramanian *et al.* 2015). Nano-zeo urea treatment enhances crop growth yield due to elevated nutrient uptake than conventional urea. Similarly, slow-release fertilizer such as zeolites and nanoporous zeolite in cooperation with chemical fertilizers such as potassium sulphate, urea and calcium hydroxyapatite, increased its availability for 60 days (Ramesh *et al.* 2010, Kottegoda *et al.* 2011).

Compared to conventional chemical fertilizer nanoparticles possess unique chemical features that enable lower dosage of fertilizers, owing to their small size, large surface to volume ratio and optical properties (Raliya *et al.* 2017). A notable advantage of this innovative approach curtails over-dosage fertiliser application, minimizing nutrient leaching, avoiding negative environmental effects and enhancing its utilization efficiency. Due to the precise delivery of nutrients through distinguished eco-friendly nanometre-sized particles, it enhances nutrient absorption and improves crop utilization (Sales *et al.* 2024). Nanotechnology is significant in farming and soil science, leading upcoming major economic force and component of modern agriculture as well as agri-food. Moreover, it minimizes nutrient losses, waste generation and supplies nutrients as per proper plant demand (El-Ghamry *et al.* 2018). Conventional fertilizer application is a major cause of soil acidification; mineral imbalances and groundwater degradation are also harmful to the soil and atmosphere (Stewart *et*

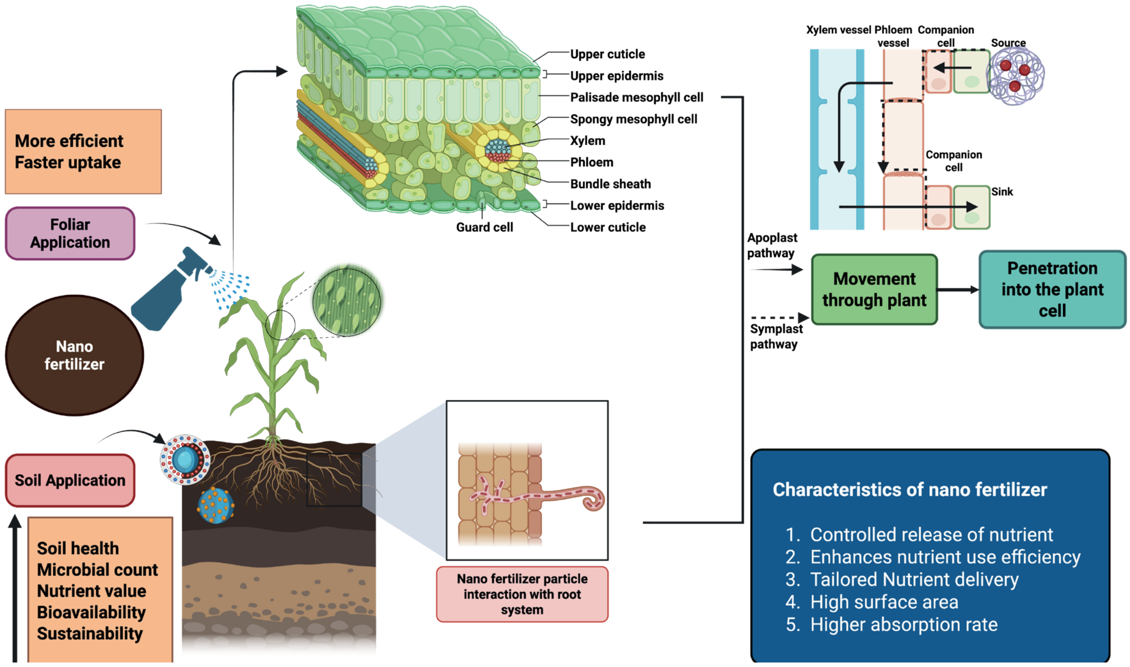

Fig. 3 - Mechanisms of nano fertilizers in maize (Created in https://BioRender.com)

al. 2005), while nano fertilizers applied either by foliar application or soil incorporation provide an alternative, efficient nutrient delivery and increased impact (Naderi and Daneh-Shahraki 2013).

Enhanced yield and growth parameters

In addition to their role in mineral nutrition, nano-fertilizers amplify plant height, leaf area, chlorophyll content, grains per ear, kernel weight, ear size, and yield (Sabharwal *et al.* 2025). Chitosan encapsulated silicon nano-fertilizer application specialized by its slow release, field experiment was done 0.08% CS-Si NF raised yield by 43.4% and test weight by 45% over SiO_2. Fecund and myriad effects of developed nano-fertilizer

Table 3- Comparison of fertilizer types in maize production

Parameter	Nano fertilizer	Conventional fertilizer	Reference
Yield/Productivity	Comparable or higher yields with 25-50% less N; up to 66% yield increase under stress	Requires full recommended dose for similar yields; lower efficiency under stress	(Upadhyay *et al.* 2023a)
Nutrient Use Efficiency	Improved uptake of N, Zn, Si, P, K, Mg	Lower NUE (30-35% for N); higher nutrient losses	(Upadhyay *et al.* 2023b)
Environmental Impact	Reduced nutrient leaching, lower GHG emissions, less pollution	Higher risk of leaching, runoff, and GHG emissions	(Elsabagh *et al.* 2024)
Stress Tolerance (e.g., Salinity)	Improved tolerance via ionic/osmotic balance, reduced Na^+ accumulation, better K/Na ratio	Less effective in mitigating stress; higher Na^+ accumulation	(Shoukat *et al.* 2024)
Application Rate	Effective at 50-75% of recommended N dose with foliar nano sprays	Requires 100% recommended dose for optimal results	(Reddy *et al.* 2022)
Cost & Energy Efficiency	Lower input costs, higher energy use efficiency, better economic returns	Higher input costs, lower energy efficiency	(Singh *et al.* 2023)
Quality parameters	Enhanced protein content and nutrient density in grains/fodder	Standard or lower quality, especially under suboptimal conditions	(Kashyap *et al.* 2023)
Release Profile	Sustained/controlled nutrient release, improved water retention	Rapid release, higher risk of nutrient loss	(Sajadinia *et al.* 2021)

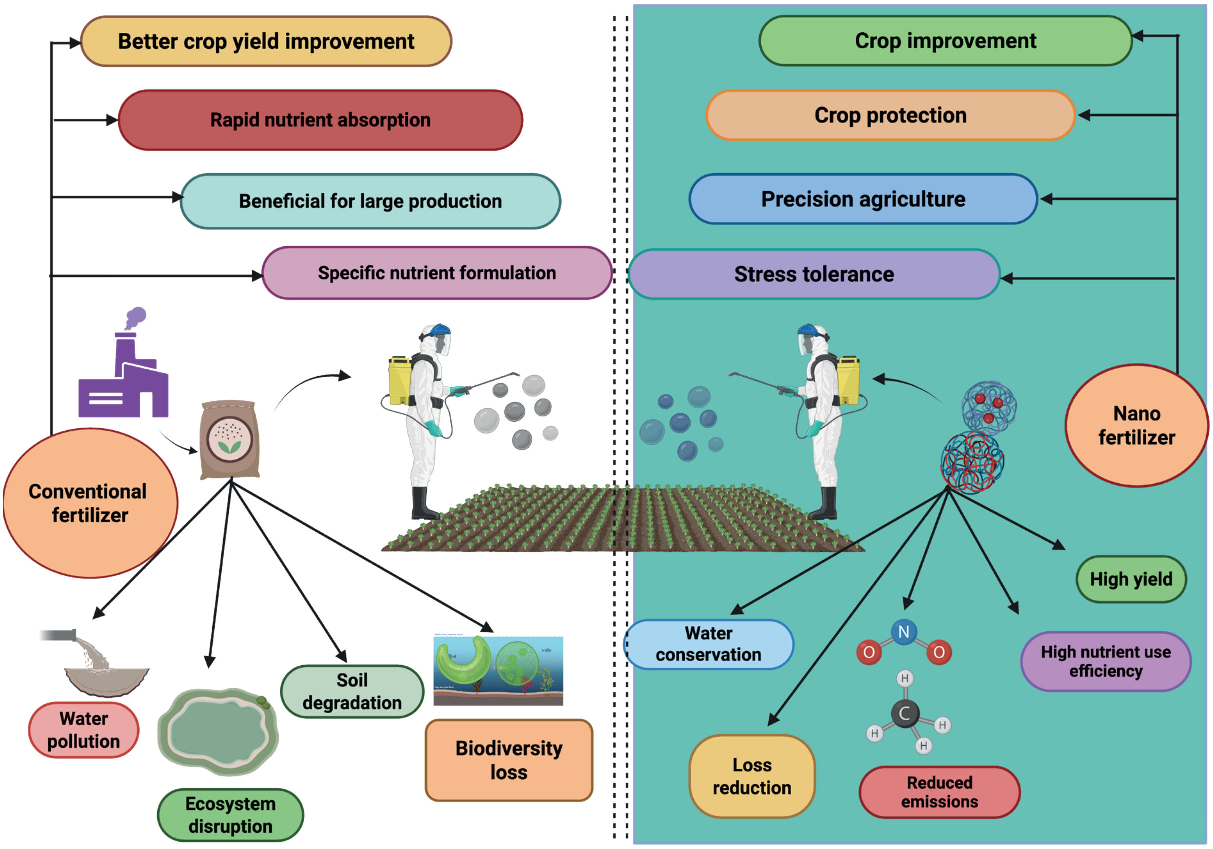

Fig.4 - Comparative study of traditional fertilizer and nano fertilizer (Created in https://BioRender.com)

over SiO_2 could be attributed to slow/protective release of Si from nano-fertilizer (Kumaraswamy *et al.* 2021). Nano-fertilizers provide a larger surface area for different plant metabolic reactions, a high photosynthesis rate and to produce more crop dry matter and yield (Singh 2017). Furthermore, studies on utilization of nano-zeolite-coated nitrogen fertilizer have demonstrated sustained release, enhanced crop growth, yield, quality and nutrient uptake were consistently higher than conventional urea (Manikandan and Subramanian 2016). Zinc and Silicon application combination enhances agronomic traits of maize and higher yield (Sabharwal *et al.* 2025).

Stress tolerance

Biotic and abiotic stress limit the growth of plants and overall production. To overcome stress plants have evolved various systemic signalling pathways, including electricity, calcium, reactive oxygen species (ROS), hydrodynamic waves, and hormones (e.g., jasmonic acid, abscisic acid) (Gilroy *et al.* 2014, Mittler and Blumwald 2015). Nano-fertilizer application led to significant change in the metabolite profile of maize. It significantly enhanced sugar metabolism, limited Na accumulation and optimize potassium-to-sodium ratio thereby developing stress tolerance in maize (Shoukat *et al.* 2024). Application of nano-fertilizer such as nano scale Zn and Si significantly boosts antioxidant properties, proline content, relative water content, chlorophyll content and metabolic homeostasis developing maize resilience against salinity stress (Shoukat *et al.* 2025). Similar findings have been reported with the utilization of nickel ferrite ($NiFe_2O_4$) nanoparticles (NPs) in improving the drought and salt tolerance in maize due to its peroxidase (POD)-like activity which enhances the stress tolerance (Tang *et al.* 2025). Phytoliths reinforce plant tissue and biochemical resistance against pest which is often reduced by excessive use of chemical pesticides and fertilizers (Saranya *et al.* 2024).

Advantages of nano fertilizers in maize

Enhanced nutrient use efficiency

Nano-fertilizers are essential tools in modern agriculture, enhancing crop growth and yield by improving nutrient use efficiency (NUE) while minimizing nutrient losses and reducing cultivation costs (Singh 2017). Nano-fertilizers increase crop growth, yield, and utilization of nutrient through controlled release, higher absorption, and improved bioavailability. When concentrated properly, it enhances productivity, nutrition and stress tolerance whereas its misuse can lead to toxicity. They enhance antioxidant properties, enzyme control, and essential oils, and provide alternative fertilizers in place of traditional ones that are environmentally friendly (Hussain *et al.* 2023).

The efficacy of this fertilizer in improving the efficiency of nutrient use (NUE) is attributed to nanoscale properties. Those characteristics facilitate quicker and better uptake and use by plants (Kumar *et al.* 2021). Because of their nanoscale, nano-fertilizer is able to infiltrate the plant system and reach the target site more succinctly, offering nutrients to the target location with minimal losses and waste. They ensure steady and regulated release of nutrients, which minimizes the leaching, volatilization, and denitrification. The coordinated supply matches the nutrient supply with the stage of plant growth, increasing the total efficiency of utilization (Al-Juthery *et al.* 2021). Their large surface area also enhances interactions with the plant roots and leaves, activating nutrient pathways and enzyme activity, which enhances absorption and assimilation. Therefore, crops become more productive with less fertilizer application and nutrient management becomes more effective and environmentally friendly. In general, nano-fertilizers increase NUE, as they allow specific delivery, reduce waste, and synchronize the supply of nutrients and plant needs (Figure 4 and Table 3).

Less impact on the environment

Nano-fertilizers limit the environmental footprint mainly in various ways that increase their effectiveness and reduce wastage. These, as the review indicates, involve controlled-release mechanisms, which regulate the nutrient supply to the needs of plants, thereby minimizing nutrient runoff, leaching and volatilization, which are well-known contributors to environmental pollution. It is their nanoscale size and their special physicochemical properties that lead to their specific delivery and use in plants, thereby reducing the amount of nutrients entering the soil and water cycle. In addition, more eco-friendly synthesis methods are also used to produce nano-fertilizers, which further lowers the ecological impact of nano-fertilizers. There is also the opportunity to reduce the dosage of fertilizers and make them more efficient with the help of nano-fertilizers and, therefore, to reduce such issues as water and air pollution, soil erosion, and greenhouse emissions caused by using traditional fertilizers (Saurabh *et al.* 2024).

Improved crop resilience

Nano-fertilizers contribute to crop resilience by improving the efficiency of nutrient absorption, facilitating the supply of nutrients gradually and through a targeted approach, minimizing the depletion of nutrients in the soil in the form of drainage loss and volatility losses. This accurate nutrient regulation assists plants in being less susceptible to abiotic stresses, as they usually have a well-functioning and reliable supply of nutrients. Moreover, they enhance healthier root length and growth, and plant growth, further improving the resistance of the plant to biotic and abiotic stress, which benefits crop tolerance (Ur Rahim *et al.* 2021).

Possible Risk and Environmental Issues

Important possible risks and environmental issues related to the use of nano fertilizers:

Nanoparticle Accumulation and Persistence

Extensive release of nanomaterials into the environment and the food chain can be a threat to human health (Beezhold *et al.* 2017). Research shows that there is a build-up of nanoparticles (Borah *et al.* 2025) in soil and water systems due to the increased use of nano fertilizers, which poses a question of the permanence of the environmental concerns in the long run.

Soil and Water Contamination

Metal oxides such as Zn oxide and titanium dioxide can be toxic to plants in high concentrations, which may interfere with the process of plant metabolism and growth (Goyal *et al.* 2025). Since nanoparticles are tiny, they can move freely through soil and water systems more than conventional fertilizers, which may affect unintended organisms.

Impacts on Soil Organisms

Nanoparticles may be absorbed by soil organisms and may also disrupt soil microbial communities, which contributes to the normal functioning of healthy ecosystems. This may affect the fertility of the soil and nutrient balance in the long run.

Potential Toxicity

Effects Areas of primary health effects of nanoparticles in this review include reduced cell viability, cell death, generation of reactive oxygen species, generation of oxidative stress (depending on dose), DNA damage, apoptosis, and induction of inflammatory response (Kumah *et al.* 2023).

Food Chain Contamination

There are concerns about nanoparticles entering the food chain through plant uptake and bioaccumulation. These substances can also result in environmental contamination and have a detrimental influence on both human health and biodiversity through several pathways, including bioaccumulation (Oyewole *et al.* 2024).

Challenges in Adoption and Field Application

The integration of nanotechnology into agriculture, particularly through the use of nano-fertilizers, holds significant promise for improving crop productivity, soil fertility and nutrient management, yet it also raises critical challenges that must be carefully addressed before large-scale adoption can occur. Despite the acknowledged intelligent delivery mechanisms, protective functions, and the ability to produce minimal losses in nutrients relative to traditional inputs, the application of these innovative agrochemicals is limited by scientific, environmental, financial and regulatory uncertainties. An environmental safety issue is one of the most critical issues. The nanoparticles are not large and can thus move readily within the soil and water systems, and consequently they hang around and may accumulate at the ecosystems. This form of property, though, has the potential to aid in reducing the nutrient leaching, is also a hazard in the shape of destabilization of the aquatic ecosystems or the relocation of the essential soil microbial communities, which are the central to the nutrient cycles, organic matter decays and the long-term soil fertility. This unwanted environmental noise can undermine the sustainability advantages that these technologies are expected to deliver. Another area of high concern is human health. Directly exposed employees (farm workers) may be exposed to the formulation via inhalation or skin contact due to the ability of nanoparticles to permeate biological membranes and gain access to the systemic circulation, which can lead to respiratory or inflammatory effects and other health-related issues. Similarly, consumers can also be exposed to risk since the plants can take in these particles that can, in turn be absorbed by the gut microbes or bloodstream and cause unknown effects, such as inflammation, allergy, and long-lasting consequences (Mahesha *et al.* 2023). The second issue which has also gained attention is the possibility of developing resistance, which is already being witnessed with conventional agrochemicals. The repeated and constant dependence on particular nano-formulations can potentially provoke the evolution of pests, pathogens, and weeds, which, in the end, will result in decreased efficacy of these products, which will trigger new rounds of resistance that agriculture has been unsuccessful in addressing. Moreover, the regulatory environment of nanotechnology in agriculture is still immature due to the newness and intricacy of the sector. Standardization of testing procedures, assessment of eco-toxicological impacts and development of flexible policies, which can change as new information emerges, are overwhelming. Along with scientific and environmental uncertainty, economic and practical obstacles also become barriers to the widespread use of nano-agrochemicals. Research, development and production of such advanced formulations are very expensive compared to conventional fertilizers, making them less accessible to farmers, especially in developing countries. Lack of a clear legislative backing of their use also makes their commercial implementation more complicated due to marketing issues (Avila *et al.* 2022). Besides this, their lasting impacts, including eco-toxicity and effects on the environment, in general, are very uncertain, which leaves a major gap in knowledge that contributes to a lack of confidence in their safety and sustainability. All these factors, whether these are environmental and health risks or resistance potential, high costs and ambiguity in policies makes it clear that though nano-fertilizers have an attractive future of sustainable agriculture, it is only through close scientific scrutiny, open policymaking and coordinated actions by the scientists, industry stakeholders and regulators that the full potential of nano-fertilizers can be fully realised. Such a trade-off between the innovation promotion and human and environmental health protection will be needed in order to make nanotechnology a viable and acceptable instrument of modern agriculture.

Future prospects and sustainable pathways

Nanotechnology and agriculture have enormous potential in increasing crop production, minimizing environmental effects and allowing sustainable agriculture, but they require careful application and utmost caution. These applications include nano-fertilizer, which is already evolving exceptionally fast thanks to the creation of nanoparticle properties and nanoparticle production methods, which have resulted in multipurpose formulations that can be used not only to supply nutrients, but also to respond to environmental factors like rainfall or crop life cycle. Such smart fertilizer would save a lot of nutrients and increase the output. Nevertheless, their long-term ecological impacts are still surrounded by a lot of mystery despite this commitment. The impact of nanoparticles on the health of the ground, the community of living things and the stability of the overall ecosystem is not well known, particularly over the decades of continuous use. At the same breath, they also put much doubt on the sustainability of their engagement with organisms in the agricultural landscape and the direct benefit of crops. To deal with these issues, there is a need of conducting interdisciplinary research, which would bring together the knowledge of nanotechnology, agronomy, ecology and soil science. Meanwhile, the education and training of farmers is essential to make their use safe and effective with a focus on the adequate application of the technology, awareness of the possible risks, and correspondence of the farming activity with the new scientific discoveries. Policymakers should be able to put in place flexible regulations that are backed up by the standardised safety measures, which could evolve with the emerging discoveries, with the research institutions being more focused on the long-term and ecosystem-wide research to determine the environmental and health consequences. Nano-formulations, including controlled-release devices fitted with nano-biosensors, multifunctional nano-carriers delivering several nutrients at a time, and biodegradable nano-materials are being developed as innovative strategies to enhance the efficacy in nutrient utilization, reduce fertilizer needs and pollution, and aid food security in a cost-efficient and environmentally friendly fashion. Historically, the world population growth and the intensification of agriculture have been dependent on the use of heavy agrochemicals; effective but with several limitations including low solubilities, loss of nutrient and poor absorption by plants, with the fact that these conventional fertilizers and pesticides pollute the soil, water and air. To ensure the protection of ecosystems and, at the same time, address the need, the experts cite the smarter application of agrochemicals, whereby nano-based formulations are highly beneficial. It has been observed that nano-fertilizers are more soluble, less toxic and effective in application compared to the traditional inputs, better instruments of precise nutrient regulation and reduced environmental pollution. Nano-fertilizer and nano-pesticides made with elements such as phosphorus, potassium, iron, manganese, zinc, copper and molybdenum, among others, provide superior performances compared to their traditional counterparts, resulting in greater efficiency and improved crop responses. Collectively, they have the potential to enhance agriculture into a more sustainable, productive, and environmentally sound one with the aid of favourable regulatory oversight, international collaboration and engagement of farmers (Rehmanullah *et al.* 2020).

Conclusion

Nano-fertilizers are a new technology aimed at enhancing the efficiency of nutrient usage, crop development and yield in maize and at reducing losses and environmental degradation caused by traditional fertilizers. Their nano-scale properties, which enable a gradual release and accurate delivery of nutrients, can be employed in the form of stress resistance and the general requirement of fertilizer. These are the advantages but there is concern of persistence of nanoparticles, the potential of soil and microbial impacts and penetration into the food chain. Field-based studies are also not extensive in the long term, and safe use regulatory frameworks are not yet developed. Advancements in the nano-formulations of biodegradable and environmentally friendly components along with awareness of the farmers and the policies guided by science, will be necessary. These efforts might make nano-fertilizers critical in promoting sustainable maize production and world food security.

Authorship Contribution Statement

Manuscript content: MA, ES, GG and KD ; Tables, pictures and in drafting the sections and editing : MA,GS, SG, SV ; MA, SV and GS involved in final editing and finalized the manuscript. All the authors involved and approved the final version of the manuscript.

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