



Review Paper

Nano Fertilisers in Maize (*Zea mays* L.) Production: Pathways to Efficiency, Sustainability, and Climate-Smart Agriculture

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Key Words	Abstract
Nano fertilisers, maize (<i>Zea mays</i> L.), nutrient use efficiency, climate-smart agriculture, sustainability, economic viability.	Maize (<i>Zea mays</i> L.) is a critical cereal crop underpinning food security, livestock nutrition, and industrial applications worldwide. Conventional fertilisers have historically driven yield gains, but their low nutrient-use efficiency and environmental consequences—such as soil degradation, eutrophication, and greenhouse gas emissions—pose major sustainability challenges. Nano fertilisers, particularly nano urea and nano diammonium phosphate (DAP), represent a promising innovation designed to enhance nutrient delivery, reduce losses, and improve crop uptake efficiency. This review synthesises current evidence on the agronomic, physiological, environmental, and economic impacts of nano fertilisers in maize systems. Field trials demonstrate that nano formulations can reduce nitrogen and phosphorus inputs by up to 25% without compromising yield, while improving chlorophyll content, photosynthetic activity, stress tolerance, and nutrient recovery efficiency. Integration with organic amendments such as farmyard manure further strengthens soil fertility and microbial activity, enhancing long-term sustainability. Environmental benefits include reduced nitrous oxide emissions, lower nutrient runoff, and decreased energy intensity in fertiliser use. Economically, nano fertilisers lower input costs, improve benefit–cost ratios, and offer value to smallholder farmers in resource-constrained settings. Despite these advantages, challenges remain, including the need for long-term multi-location trials, robust regulatory frameworks, and farmer awareness programs. Future research should explore ecosystem impacts, integration with precision agriculture, and synergistic use with biofertilisers. Collectively, nano fertilisers offer a climate-smart, resource-efficient pathway to sustainable maize production and contribute to global food security goals.

Introduction

Maize (*Zea mays* L.) is one of the world's most important cereal crops, serving as a staple food, primary livestock feed, and essential industrial raw material. Its contribution to food security is substantial, particularly in developing countries where it provides a significant share of daily caloric intake and supports rural livelihoods.¹ The global demand for maize is increasing due to population growth, greater dietary diversification, and its importance in the production of biofuels. Consequently, sustainable intensification of

maize cultivation has become a priority for agricultural systems worldwide.²

Traditional fertilisers, particularly those containing nitrogen and phosphorus, have been crucial in increasing maize productivity. However, their efficiency remains low, with nutrient use efficiency often below 40% for nitrogen and 20% for phosphorus. This inefficiency leads to nutrient losses through leaching, volatilisation, and runoff, contributing to soil degradation, eutrophication of water bodies, and greenhouse gas emissions.^{3,4} Additionally, over time, excessive reliance on chemical

fertilisers raises significant concerns about long-term soil quality and environmental harm.

In response, nano fertilisers have emerged as promising alternatives. Nano urea and nano diammonium phosphate (DAP) are engineered at the nanoscale to enhance nutrient delivery, reduce losses, and improve crop uptake efficiency. Their unique properties—such as high surface area, controlled release, and better leaf penetration—enable precise

nutrient management, thereby improving productivity while minimising environmental impacts.^{5,6} Recent studies suggest that integrating nano fertilisers into maize nutrient regimes can reduce conventional fertiliser requirements without compromising yield, offering a pathway toward climate-smart and resource-efficient agriculture (Table 1).⁷

Table 1: Comparison of Conventional Fertilisers and Nano Fertilisers in Maize Production

Parameter	Conventional Fertilisers	Nano Fertilisers (Nano Urea & Nano DAP)
Nutrient Use Efficiency	Nitrogen < 40%; Phosphorus < 20% (low efficiency)	Nitrogen assimilation ↑; Phosphorus recovery up to 48.4%
Nutrient Losses	High losses via leaching, volatilisation, runoff	Controlled release reduces nutrient losses significantly
Soil Health Impact	Long-term degradation, reduced microbial activity	Improved nutrient cycling; better integration with FYM
Environmental Effects	Contributes to eutrophication & GHG emissions	Lower nitrous oxide emissions; reduced ecological footprint
Agronomic Performance	Requires higher doses to maintain yield	Yield maintained with 25% lower N & P inputs
Economic Viability	Higher input costs; lower benefit–cost ratio	Reduced fertiliser costs (up to 30%); higher profitability
Stress Tolerance	Limited support under drought/heat stress	Enhanced antioxidant activity; improved resilience
Sustainability Outlook	Unsustainable with prolonged use	Climate-smart, resource-efficient, supports UN SDGs

2. Nano Fertiliser Technology

Nano fertilisers are a new generation of nutrient delivery systems designed at the nanoscale to improve efficiency and sustainability in crop production. Unlike conventional fertilisers, which often suffer from poor nutrient use efficiency due to leaching, volatilisation, and fixation in soil, nano fertilisers

provide controlled release and targeted nutrient delivery.⁵ Their small particle size and large surface area improve solubility, absorption, and interaction with plant tissues.⁸

Nano urea is a liquid formulation containing nitrogen particles engineered at the nanoscale. When applied as a foliar spray, it penetrates leaf stomata and cuticular pores more effectively than bulk urea, leading to higher nitrogen

assimilation and reduced losses. Studies have shown that nano urea can partially substitute conventional nitrogen fertilisers, maintain yield while reducing input costs and environmental impacts.^{9,10}

Nano diammonium phosphate (nano DAP) is another innovation that delivers phosphorus and nitrogen in nano form. Its application improves phosphorus solubility and uptake, which is often limited in conventional fertilisers because soils fix it. Nano DAP enhances root development, photosynthetic activity, and grain filling in maize, while simultaneously reducing the required dose of conventional fertilisers.^{11, 12}

Together, nano urea and nano DAP represent a shift toward precision nutrient management. Integrating them into maize nutrient regimes has improved agronomic efficiency, nutrient recovery, and profitability, making them promising tools for climate-smart agriculture.^{13,14}

3. Agronomic Responses of Summer Maize

Nano-fertilisers provide notable agronomic advantages in maize cultivation. Field trials using nano DAP foliar sprays indicate that nitrogen and phosphorus inputs can be reduced by approximately 25% without affecting grain yield. This outcome

demonstrates the enhanced efficiency of nano-scale nutrient delivery, which facilitates improved uptake and utilisation relative to conventional fertilisers.¹⁵

Further, integrating nano DAP with soil test crop response (STCR) equations has proven effective in achieving targeted yields. Studies in Alfisols of Karnataka reported kernel yields of 9.7–9.9 t ha⁻¹, along with improved nutrient recovery efficiency. This approach not only optimises fertiliser use but also enhances productivity under site-specific nutrient management strategies.¹¹

Similarly, nano urea foliar sprays applied at critical growth stages such as knee-high and tasselling have been shown to enhance grain yield and nutrient uptake. Even at reduced nitrogen doses, maize plants maintained high productivity, indicating that nano urea can partially substitute conventional nitrogen fertilisers while sustaining crop performance.^{7,16}

Overall, these agronomic responses confirm that nano fertilisers can improve nutrient use efficiency, reduce input costs, and maintain yield stability, making them valuable tools for sustainable maize production systems (Table 2).

Table 2: Agronomic Responses of Maize to Nano Fertilisers

Treatment Approach /	Key Findings	Yield / Efficiency Outcomes	References
Nano DAP foliar spray	Reduced N & P inputs by ~25% without yield loss	Maintained grain yield; improved nutrient utilisation	15
Nano DAP + STCR equations (Alfisols, Karnataka)	Enhanced kernel yield and nutrient recovery efficiency	Kernel yield: 9.7–9.9 t ha ⁻¹ ; higher recovery rates	11
Nano urea foliar spray (knee-high & tasselling stages)	Improved grain yield and nutrient uptake even at reduced N doses	Sustained productivity with partial substitution	7,16
Integrated nano fertiliser regimes	Enhanced agronomic efficiency and reduced input costs	Yield stability maintained; improved profitability	7,15,16

4. Physiological and Biochemical Responses of Maize to Nano Fertilisers

Nano fertilisers affect maize physiology and biochemistry beyond yield and nutrient efficiency. Foliar application of nano urea has been shown to increase chlorophyll content, enhance photosynthetic activity, and improve nitrogen assimilation pathways. These improvements contribute to higher biomass accumulation and grain filling, even under reduced nitrogen regimes.¹⁷

Nano DAP also increases phosphorus availability, which is essential for energy transfer and

metabolic processes. Trials have reported improved root growth, higher ATP synthesis, and better enzymatic activity in maize plants treated with nano DAP compared to conventional fertilisers.¹⁸

Nano fertilisers also support stress tolerance. Studies indicate that maize plants receiving nano formulations exhibit improved antioxidant enzyme activity, reduced oxidative stress, and better water-use efficiency under drought and heat stress conditions. This suggests that nano fertilisers not only improve nutrient uptake but also strengthen plant resilience to abiotic stresses (Table 3).^{19,20}

Table 3: Physiological and Biochemical Responses of Maize to Nano Fertilisers

Treatment Approach	Physiological / Biochemical Effect	Key Outcomes in Maize Plants	References
Nano urea foliar spray	Increased chlorophyll content and enhanced photosynthetic activity	Higher biomass accumulation and improved grain filling	17
Nano urea (reduced N regime)	Improved nitrogen assimilation pathways	Sustained productivity under lower nitrogen inputs	17
Nano DAP application	Enhanced phosphorus solubility and uptake; improved ATP synthesis	Better root growth, enzymatic activity, and grain filling	18
Nano fertilisers under stress	Increased antioxidant enzyme activity; reduced oxidative stress	Improved drought and heat tolerance; better water-use efficiency	19,20

Collectively, these physiological and biochemical responses highlight nano fertilisers' potential to support sustainable maize production by improving plant metabolism, enhancing stress tolerance, and ensuring efficient nutrient utilisation.

5. Nutrient Regimes and Efficiency

Nano fertilisers have emerged as a promising innovation for optimising nutrient regimes in maize cultivation. Their ability to deliver nutrients in a controlled, targeted manner allows partial substitution of conventional nitrogen (N) and phosphorus (P) fertilisers, reducing dependence on bulk inputs while maintaining crop productivity.

Enhanced Agronomic Efficiency

Field trials show that nitrogen agronomic efficiency can increase by up to 26.9% when nano

DAP is integrated into maize nutrient regimes. Similarly, phosphorus recovery efficiency has been reported as high as 48.4%, reflecting improved nutrient uptake and utilisation compared to conventional fertilisers. These gains are attributed to the nanoscale particle size, which enhances solubility, root absorption, and translocation within plant tissues.^{6,21}

Integration with Organic Amendments

Combining nano fertilisers with farmyard manure (FYM) has proven particularly effective. FYM contributes organic matter and microbial activity, while nano fertilisers ensure precise nutrient delivery. Together, they improve nutrient contribution, soil fertility, and partial factor productivity (PFP), which measures yield per unit of nutrient applied. This integrated approach not only sustains yield but also enhances soil health and long-term

sustainability (Table 4).²²

Table 4: Nutrient Regimes and Efficiency Outcomes with Nano Fertilisers in Maize

Treatment Integration Approach	Key Findings / Efficiency Gains	Agronomic Outcomes	References
Nano DAP integration	Nitrogen agronomic efficiency ↑ up to 26.9%	Improved nutrient uptake and utilisation	6,21
Nano DAP (phosphorus recovery)	Phosphorus recovery efficiency ↑ up to 48.4%	Enhanced solubility, root absorption, and translocation	6,21
Nano fertilisers + FYM (organic amendments)	Improved soil fertility, microbial activity, and nutrient cycling	Higher partial factor productivity (PFP); sustained yield	22
Reduced fertiliser inputs with nano formulations	Lower N & P doses required without yield loss	Cost savings; maintained productivity	6,21,22
Integrated nutrient regimes	Balanced productivity, efficiency, and sustainability	Enhanced profitability and long-term soil health	6,21,22

Implications for Nutrient Management

Reduced fertiliser inputs: Nano fertilisers allow farmers to cut N and P doses without yield loss.

Improved nutrient efficiency: Higher agronomic efficiency and recovery rates ensure better nutrient utilisation.

Sustainable soil fertility: Integration with FYM and other organic amendments strengthens soil microbial activity and nutrient cycling.

Economic viability: Lower fertiliser costs and improved productivity enhance profitability for farmers.

Collectively, these findings highlight that nano fertiliser, when combined with conventional inputs and organic amendments, can redefine nutrient regimes in maize production by balancing productivity, efficiency, and sustainability.

6. Environmental and Economic Implications of Nano Fertilisers in Maize Systems

Adopting nano fertilisers in maize cultivation extends beyond agronomic and physiological benefits, offering substantial environmental and economic advantages. Conventional fertiliser use is often linked

to nutrient losses through leaching, volatilisation, and runoff, which contribute to greenhouse gas emissions, eutrophication, and declining soil health. In contrast, nano formulations deliver nutrients in a targeted, controlled way, reducing waste and minimising their ecological footprint.^{23,24}

Environmental Benefits

Field studies show that nano-DAP and nano-urea applications significantly lower nitrous oxide emissions compared with bulk fertilisers. This reduction is attributed to improved synchrony between nutrient release and crop demand, which curtails denitrification losses. Moreover, nano-fertilisers improve nutrient recovery efficiency, reducing residual nutrient loads in soils and water bodies.^{13,25} Nano-fertilisers also reduce energy use in fertiliser production and application. They reduce the number of conventional fertilisers needed, lowering the energy intensity of agricultural systems and aligning with the global objectives of climate-smart agriculture.²⁶

Economic Benefits

Economically, nano fertilisers reduce input costs while maintaining or even enhancing yield. Farmers benefit from lower expenditure on bulk fertilisers,

improved nutrient use efficiency, and higher profitability per hectare. Studies in India show that nano urea foliar sprays can reduce nitrogen fertiliser costs by up to 30% while sustaining grain yield and quality.²⁷ Additionally, nano fertilisers improve the cost-benefit ratio of maize cultivation. Economic analyses show that marginal returns from nano fertiliser adoption are higher than under conventional practices, especially in rainfed and resource-constrained systems. They are therefore especially valuable for smallholder farmers seeking inexpensive, sustainable solutions.²⁸

Policy and Sustainability Outlook

Integrating nano fertilisers into maize production systems supports national and international sustainability targets. Their role in reducing greenhouse gas emissions, improving nutrient efficiency, and enhancing farm profitability positions them as critical tools in achieving the UN Sustainable Development Goals related to food security, climate action, and sustainable agriculture.

7. Limitations and Challenges

Despite the promising agronomic, environmental, and economic benefits of nano fertilisers, several limitations and challenges must be acknowledged before their widespread integration into maize production systems.

Need for Long-Term Multi-Location Trials

Most current research on nano fertilisers consists of short-term studies conducted under controlled or restricted field conditions. To establish their consistency, safety, and scalability, long-term, multi-location trials across a variety of agro-ecological zones are required. These trials would provide information on effects on soil health, crop responses in different climates, and potential cumulative effects on ecosystems.²⁹

Regulatory Frameworks

Nano fertilisers have only recently entered agricultural practice, and regulatory frameworks remain underdeveloped. Clear guidelines on maximum particle size, nutrient release rates, and safe application levels are needed to secure farmer confidence and consumer safety. Without strong regulations, inconsistent product quality and misuse may undermine both productivity and sustainability objectives.³⁰

Farmer Awareness and Adoption Barriers

Farmer adoption of nano fertilisers remains limited because of limited awareness, accessibility, and affordability. Many smallholder farmers are unfamiliar with the technology or hesitant to replace conventional fertilisers. Extension services, demonstration plots, and participatory training programs are needed to bridge this knowledge gap.

Additionally, cost and supply-chain availability must be addressed to ensure equitable access.³¹

Summary of Challenges

Scientific validation: Need for long-term, multi-location trials.

Policy support: Development of regulatory frameworks and quality standards.

Farmer adoption: Awareness campaigns, training, and affordability measures.

Addressing these challenges will be critical for scaling nano fertilisers from experimental success to mainstream agricultural practice.

8. Future Prospects and Research Gaps in Nano Fertiliser Application

While nano fertilisers have shown promising agronomic, physiological, and environmental benefits in maize production, several future directions and research gaps remain before widespread adoption.

Long-Term Soil Health and Ecosystem Impact

The latest research mainly focuses on short-term yield and nutrient use efficiency. The long-term effects of nano fertilisers on soil microbial communities, nutrient cycling, and organic matter dynamics remain poorly understood. Research should explore whether continuous nano fertiliser use affects soil biodiversity or causes ecological imbalance.

Regulatory Frameworks and Standardisation

Nano fertilisers have only recently entered agricultural practice, and few regulatory guidelines currently address their production, quality assurance, and safe use. To build farmer confidence and protect consumer safety, international standards are needed for particle size, nutrient-release kinetics, and maximum allowable application rates.

Integration with Precision Agriculture

Future studies should investigate how nano fertilisers can be combined with precision farming technologies such as remote sensing, drones, and AI-based nutrient management systems. Improving nutrient delivery at the micro-scale would not only increase efficiency but also decrease environmental footprints.

Farmer Awareness and Adoption

Despite proven advantages, farmer uptake of nano fertilisers remains low because of limited awareness, limited accessibility, and cost concerns. Trust must be built and widespread acceptance encouraged by carrying out extension programmes, demonstration trials, and participatory research—especially when it comes to smallholder farmers in developing areas.

Research Gaps

There are not enough long-term trials in many locations across different farming environments.

Limited data on the interaction of nano fertilisers with other inputs such as biofertilisers and organic amendments.

Need for economic modelling to assess profitability under different scales of production.

There are not enough studies concerning climate resilience, in particular when drought and heat stress are involved.

9. Conclusion and Recommendations

From agronomic, physiological, environmental, and economic perspectives, nano fertilisers have strong potential for maize production. Nano urea and nano diammonium phosphate (DAP) have consistently improved yield stability, nutrient use efficiency, and profitability, even at reduced input rates. Because nutrient release is synchronised with crop demand, productivity increases while the environmental risks usually linked to conventional fertilisers are reduced.

Key Conclusions

Agronomic efficiency: Nano fertilisers can reduce nitrogen and phosphorus inputs by as much as 25 per cent without any reduction in yield, thus ensuring sustainable nutrient management.

Physiological benefits: Enhanced chlorophyll content, photosynthetic activity, and stress tolerance highlight their role in strengthening plant metabolism.

Environmental sustainability: Lower greenhouse gas emissions, reduced nutrient leaching, and improved soil health position nano fertilisers as climate-smart solutions.

Economic viability: Reduced fertiliser costs and improved cost-benefit ratios make nano fertilisers particularly valuable for smallholder farmers.

Recommendations

Scaling up field trials: Further research should investigate the interactions between soil microorganisms, the long-term effects on ecosystems, and the synergistic use in combination with biofertilisers to gain a deeper understanding of sustainability.

Policy support: Governments must set up regulatory frameworks and quality standards in order to make sure that production, distribution, and adoption are carried out safely.

Integration with precision agriculture: Combining nano fertilisers with digital tools such as drones, sensors, and AI-based nutrient models can maximise efficiency.

Farmer training and awareness: It is important to strengthen extension services and participatory research programs so that resource-poor farmers are more likely to adopt new practices.

Future research: Studying the interactions between soil micro-organisms, the long-term effects on ecosystems, and the synergistic application with biofertilisers will lead to a better understanding of sustainability.

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