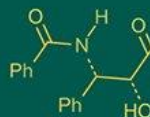


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Suparna Kishore Jana
M.Sc. (Ag.) Agronomy student,
Dr. Rajendra Prasad Central
Agricultural University, Bihar,
India

Nano-urea in crop production: mechanisms, agronomic performance, nitrogen use efficiency, environmental implications and future prospects: A critical review

Suparna Kishore Jana

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Abstract

Nano-urea has emerged as a promising approach for improving nitrogen management and reducing dependence on conventional urea fertilizers. This review summarizes recent research on the mechanisms, agronomic performance, nutrient-use efficiency, and economic potential of nano-urea in crop production. Due to its nanoscale characteristics, nano-urea can enhance foliar nitrogen delivery and support nitrogen assimilation within plants. The reviewed studies indicate that nano-urea can improve crop growth, yield attributes, nitrogen uptake, and nitrogen-use efficiency when applied in combination with an adequate dose of conventional nitrogen. In several crops, particularly cereals, partial replacement of conventional nitrogen with foliar nano-urea maintained yields comparable to full conventional nitrogen application while reducing fertilizer requirements. However, excessive replacement of soil-applied nitrogen may reduce nitrogen uptake, recovery efficiency, and crop yield. Economic benefits also depend on the level of nitrogen reduction, application method, and crop response. Overall, nano-urea appears more effective as a supplementary nitrogen source than as a complete replacement for conventional urea. Further multi-location and long-term studies are required to establish crop-specific application strategies and assess its agronomic, economic, and environmental sustainability.

Keywords: Nano-urea, nitrogen use efficiency, nitrogen uptake, foliar application, crop productivity, conventional urea, nutrient management, sustainable agriculture

Introduction

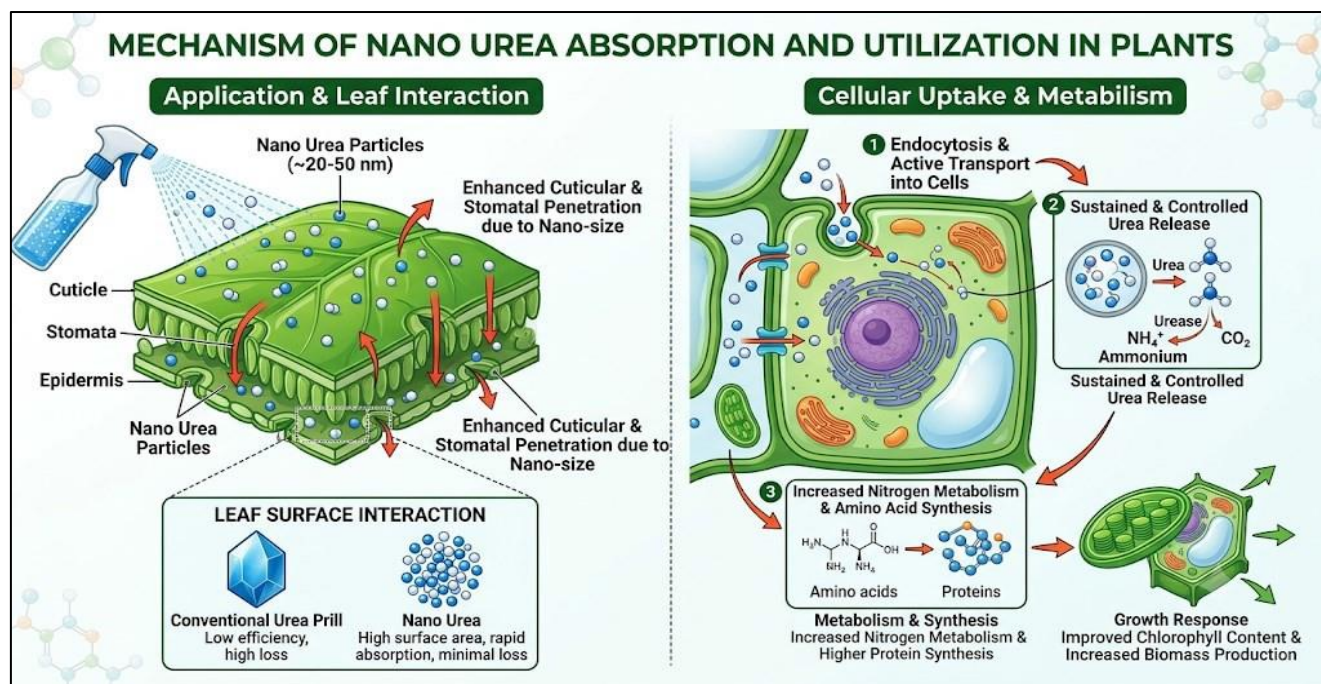
The increasing global population and the continuous decline in agricultural land available per person are creating new challenges for agriculture. Along with this, the cost of farm inputs is also rising steadily. To produce enough food for the growing population, agriculture needs improved and cost-effective methods that can increase crop production while reducing the use and cost of inputs, particularly fertilizers and other nutrient sources. Out of all nutrient sources nitrogen is important for plant growth and development. It plays important for amino acid formation which is major consistent for protein synthesis, chlorophyll formation, support enzyme and hormone (cytokinin) production (Takei *et al.*, 2002) ^[13]. For nutrient source like nitrogen; urea is mostly used by farmers and its consumption in India has increased substantially from 0.25 million tonnes in 1961 to 22.15 million tonnes in 2024, reflecting the growing dependence on nitrogen fertilizers to sustain crop productivity (FAOSTAT, 2024) ^[5]. But conventional urea shows low nutrient use efficiency (40-50%); means a large fraction of the applied nitrogen is lost through ammonia volatilization, nitrate leaching, denitrification and surface runoff rather than being taken up by the crop (Govindasamy *et al.*, 2023) ^[6]. Besides, government use nearly ₹1.32 lakh crore annually for subsidy expenditure in nitrogenous fertilizer alone (Department of Fertilizers, 2023-24) ^[4]. Altogether it burdens on both environmental and economic aspect. Furthermore, the application of conventional urea supplies a large flush of readily available inorganic nitrogen to the soil, which relieves the nitrogen limitation of the soil microorganisms and thereby stimulates their activity and biomass. To meet the energy demand of this heightened microbial activity, the microbes draw upon the soil organic carbon as their carbon and energy

Corresponding Author:
Suparna Kishore Jana
M.Sc. (Ag.) Agronomy student,
Dr. Rajendra Prasad Central
Agricultural University, Bihar,
India

source, accelerating the decomposition and mineralization of soil organic matter (Chen *et al.*, 2016) [1]. This urge to develop new and smart fertilizer which has higher efficiency with minimal disadvantage. It can possible through nanotechnology; it is application of nanoscience (study of material and phenomena at the nanoscale 1-100 nm) to create product and devices. Due to small particle size (30-50 nm) of nanofertilizer particularly nano urea can enter plant system more easily rather than conventional urea which potentially increase nutrient uptake; hence nutrient use efficiency will increase (Nongbet *et al.*, 2022) [9]. Current study suggests that one or two foliar sprays of IFFCO nano urea (4% w/v) with 75% conventional urea can achieve yield comparable with 100% conventional urea (Dass *et al.*,

2024) [3]. However, the effectiveness of nano-urea can vary depending on crop, soil conditions, nitrogen requirement, method of application, and the amount of conventional urea used. Therefore, further field-based studies are needed to evaluate suitable combinations of nano-urea and conventional urea for improving crop growth, yield, nitrogen-use efficiency, and economic returns while reducing the dependence on conventional nitrogen fertilizer. Hence, the present study was undertaken to evaluate the combined effect of nano-urea and conventional urea on crop productivity, nitrogen-use efficiency, and profitability under field conditions.

Mechanism of nano urea



Due to their very small particle size, nano-urea particles can potentially interact with and penetrate the leaf cuticle and epidermal tissues more efficiently than conventional urea. Following foliar application, the nitrogen supplied by nano-urea does not remain confined to the leaf surface but becomes available within the plant and is associated with enhanced nitrogen movement and mobilization along the root-shoot-leaf axis (Mondal *et al.*, 2026) [8]. NH_4 is assimilated primarily through the GS-GOGAT pathway, where glutamine synthetase (GS) converts NH_4^+ into glutamine, followed by glutamate synthase (GOGAT) producing glutamate for the synthesis of other amino acids and proteins. Consequently, enhanced nitrogen assimilation promotes protein synthesis and reduces the accumulation of free amino acids, thereby contributing to increased chlorophyll content and improved photosynthetic activity.

Effect on crop growth and yield

Nano-urea application has shown a generally positive but dose-and management-dependent effect on crop growth and yield. Several studies in maize and wheat reported improvements in plant height, leaf area index, dry matter accumulation, crop growth rate, tiller number, yield attributes, and grain yield when nano-urea was applied along with conventional nitrogen (Vasanth *et al.*, 2025, Dadmal *et al.*, 2024) [15, 2]. In maize, 75% recommended

nitrogen + two foliar sprays of nano-urea often produced growth and yield comparable to 100% recommended nitrogen, suggesting that nano-urea can partially compensate for reduced soil-applied nitrogen.

However, the response was not consistent across all treatments. Higher soil nitrogen levels combined with nano-urea, such as 100% RDN + 4 ml L^{-1} nano-urea, produced the highest growth and yield in some rabi maize studies (Srivastava and Singh, 2023) [12]. In contrast, excessive substitution of conventional nitrogen with nano-urea reduced crop performance; replacement beyond 50% resulted in progressive yield reduction in a rice-wheat system (Sikka *et al.*, 2025) [11], while 50% soil-applied nitrogen could not be adequately compensated by nano-urea in rice (Peramaiyan *et al.*, 2026) [10].

Overall, the evidence indicates that nano-urea is more effective as a supplementary nitrogen source than as a complete substitute for conventional urea. Its performance depends on the nitrogen dose, spray concentration and frequency, application stage, irrigation, crop, and agro-climatic conditions. Moderate integration, particularly around 75% conventional nitrogen with foliar nano-urea, appears to be a promising strategy for maintaining crop growth and yield while reducing conventional nitrogen requirements.

Effect on crop nutrient uptake and use efficiency

Nano-urea application has generally shown potential to improve nitrogen use efficiency (NUE) when combined with an adequate level of conventional nitrogen fertilizer. In a multi-location maize-wheat system, application of 75% recommended nitrogen through conventional fertilizer along with foliar nano-urea increased NUE by about 6-9%, reduced energy requirement by 8-11%, and lowered the overall nitrogen input by approximately 25% without reducing yield (Upadhyay *et al.*, 2023) ^[14].

Similarly, nano-formulated nitrogen combined with microbial inoculants increased apparent nitrogen recovery and agronomic efficiency compared with conventional urea, with total nitrogen uptake increasing by approximately 20-25% in maize and wheat (Kumar *et al.*, 2024) ^[7]. In rainfed maize, 50% recommended nitrogen through conventional urea combined with two nano-urea sprays produced NUE indices statistically comparable to 75% nitrogen + nano-urea, although higher nano-urea concentration improved growth and yield attributes.

However, NUE does not increase linearly with increasing nano-urea substitution. Higher replacement of soil-applied urea can reduce nitrogen assimilation and recovery. In rice, greater dependence on nano-urea reduced the activity of nitrogen-assimilating enzymes such as glutamine synthetase and glutamate synthase, indicating reduced nitrogen assimilation efficiency when conventional nitrogen was excessively reduced (Sikka *et al.*, 2025) ^[11]. Similarly, substantial replacement of prilled urea with nano-urea reduced nitrogen recovery and post-harvest soil nitrogen status in wheat.

Overall, the evidence suggests that partial replacement of conventional nitrogen, particularly around 25% with foliar nano-urea, can improve nitrogen use efficiency while maintaining productivity. However, excessive reduction of soil-applied nitrogen may compromise nitrogen uptake and recovery. Thus, the efficiency benefit of nano-urea depends on maintaining an adequate basal nitrogen supply, along with appropriate dose, spray timing, frequency, crop demand, and environmental conditions.

Effect of nano urea on economics

Nano-urea can improve the economic efficiency of nitrogen management by reducing conventional fertilizer use while maintaining crop yield. Studies have reported higher net returns and benefit-cost ratios with 75% recommended nitrogen + foliar nano-urea compared with lower nitrogen levels, while some treatments with 100% nitrogen + nano-urea produced the highest gross returns. Overall, the evidence suggests that partial replacement of conventional urea with nano-urea can reduce input costs and maintain profitability, although the economic advantage depends on fertilizer cost, application method, yield response, and agro-climatic conditions.

Limitations and research gaps

Despite the promising potential of nano-urea, its effectiveness remains inconsistent across crops, nitrogen levels, and growing environments. A major limitation is that nano-urea cannot consistently compensate for large reductions in soil-applied nitrogen, and excessive substitution may decrease nitrogen uptake, recovery efficiency, and crop yield.

Further research is required to establish crop-specific optimum doses, foliar concentrations, spray frequency, and application stages. The interaction between nano-urea and conventional nitrogen also needs greater attention, as NUE does not necessarily increase with increasing nano-urea substitution. In addition, the strong variation in NUE among agro-climatic zones indicates the need for multi-location and multi-season field trials before developing generalized recommendations.

There is also a need for greater understanding of the physiological and biochemical mechanisms of nano-urea uptake, nitrogen assimilation, and utilization, particularly under reduced conventional nitrogen supply. Long-term studies should further evaluate its effects on soil nitrogen availability, nutrient balance, and soil biological properties. Finally, research should integrate agronomic performance, nutrient-use efficiency, environmental impacts, and economic returns to identify nano-urea strategies that are both productive and economically viable.

Conclusion

Nano-urea can serve as an effective supplementary nitrogen source for improving crop growth, yield, and nitrogen-use efficiency. Its benefits are generally greater when combined with an adequate dose of conventional nitrogen, particularly at moderate replacement levels. However, excessive substitution may reduce crop performance. Therefore, site-specific and crop-specific recommendations are needed to optimize nano-urea use for productive and sustainable agriculture.

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