



Exploring the Integration of Nano Urea in Linseed Cultivation: A Comprehensive Agricultural Review

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This work was carried out in collaboration among all authors. Authors VS and AKS designed the study, performed the statistical analysis and wrote the manuscript. Authors HS and IA managed the literature searches, and Author LTL managed the overall manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Agriculture in the 21st century faces the challenge of increasing food production to meet the demands of a growing population, while addressing soil nutrient depletion, reduced NUE, and the environmental impacts of conventional fertilizers. Nitrogen, a macronutrient, is often lost through leaching and volatilization when applied in traditional form. Nanotechnologies, offer a promising solution by enhancing nitrogen delivery and uptake efficiency in crops. This review examines the

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global agricultural context, the role of nitrogen in crop productivity and plant development. Recent studies, especially in linseed cultivation, have demonstrated that integrating nano urea with reduced doses of conventional nitrogen significantly improves seed yield, nutrient uptake, and economic returns. However, the widespread adoption of nano fertilizers requires further investigation into long-term soil impacts, residue effects on oil quality, and integration with precision agriculture. Overall, nano urea stands as a pivotal innovation for sustainable agriculture, offering a scalable strategy to enhance productivity while preserving environmental integrity in a resource-constrained world.

Keywords: Urea; sustainable agriculture; nutrient; cultivation; climate change impact on agriculture.

1. INTRODUCTION

1.1 Global Agriculture Challenges Scenario

The present 21st century agriculture faces numerous challenges, including the need to increase the production of food and fibre for a rapidly growing global population, despite a declining rural workforce. It must also supply raw materials for an expanding bioenergy sector, support development in agriculture-dependent developing nations, implement more sustainable and efficient farming practices, and respond to the impacts of climate change. Between the year 2009 and 2050, the global population is projected to rise by over 2.3 billion people, representing an increase of more than one-third (Global agriculture towards 2050) where around 90% of global crop production growth (80% in developing countries) is projected to come from increased yields and cropping intensity, with less than 5% from land expansion—about 70 million ha globally. While developing countries may see a 120 million ha increase in arable land, this will be offset by a 50 million ha decline in developed nations. Crop yields are expected to rise more slowly, with annual growth rates dropping to 0.8% (down from 1.7%), and cereal yields slowing to 0.7% annually and by 2050, average cereal yields could reach 4.3 t ha⁻¹, up from 3.2 t ha⁻¹ today. While the demand increases, soil nutrient depletion is a critical issue closely tied to food insecurity in developing and least developed nations and this challenge has risen largely from the intensified use of agricultural land without the adequate supplementation of external nutrients. The persistent failure to replenish essential nutrients in already exhausted soils, coupled with nutrient losses caused by wind and water erosion, is accelerating soil degradation and threatening the long-term viability of agriculture in these regions (Sheldrick et al., 2002). Poor land management and undervaluing farmland lead to soil erosion, degradation, and fertility loss,

ultimately reducing crop productivity and threatening long-term agricultural sustainability and thus soil nutrient depletion is further intensified by unbalanced fertilizer use, largely due to limited knowledge and restricted access to nutrient resources, as evidenced by long-term fertilizer usage data from the FAOSTAT database (FAO 2001).

1.2 Significance of Nitrogen in Crop Productivity

With the rapid increase in global population intensifying, the demand on agricultural land to deliver more food and energy per unit area is increasing and to ensure sustainability, farming systems must boost productivity while also safeguarding the environment and the health of humans and animals. According to global estimates, soils contain approximately 65 petagrams (Pg) of nitrogen in the top 30 cm, and between 92 and 140 Pg down to a depth of 1 meter (Batjes 2014). The majority of this nitrogen exists in organic forms, which are not immediately accessible to plants. Each year, around 200 teragrams (Tg) of nitrogen are added through chemical fertilizers and animal manure (Potter et al., 2010), while biological nitrogen fixation contributes another 258 Tg.

1.3 Impact of Nitrogen in Plant Growth and Development

Nitrogen (N) is a vital nutrient for crop growth and development, and its deficiency can significantly restrict plant productivity (Fathi et al., 2013). Plant growth is a multifaceted process influenced by both nutrient uptake and water availability and as one of the most heavily utilized nutrients, nitrogen plays a critical role in assimilation and transport to developing plant tissues (Fathi & Zeidali 2021) and the availability of nitrogen generally enhances plant growth and productivity by facilitating water absorption. Furthermore, high levels of soil nitrogen stimulate the

formation of new leaves from both the terminal meristem and the lateral buds of older leaves, which ultimately leads to increased yield of above-ground plant parts (Fathi 2020). Nitrogen (N) being a key element in essential organic compounds like amino acids, proteins, and nucleic acids, with the deficiency of nitrogen, it can delay both vegetative and reproductive developmental stages (Fathi and Zeidali 2021). Proper application of nitrogen fertilizer can greatly enhance biomass production, as achieving high biomass typically depends on adequate nitrogen availability.

1.4 Impact of Nitrogen in Yield

Proper management of nitrogen (N) intake is essential for maximizing plant productivity, as N plays a critical role in plant development (Taheri et al., 2021). Inadequate nitrogen reduces leaf size, which in turn limits light absorption and photosynthetic efficiency, ultimately lowering biological yield; the opposite is true when sufficient N is available (Nasim et al. 2012). Therefore, nitrogen application should align with the actual needs of the plant at the same time over application can lead to increased nitrogen loss through leaching and reduced nitrogen use efficiency, especially when plants are unable to absorb the excess (Ghobadi et al. 2018).

Effective nitrogen (N) management involves supplying the plant with the optimal amount it requires for efficient uptake and use. Nitrogen positively influences grain yield by enhancing various morphological characteristics, and maximum yield is often achieved when N is applied at different growth stages throughout the plant's development (Fageria et al. 2013). However, many farmers tend to apply more N fertilizer than recommended, under the assumption that more nitrogen will always result in higher yields. This practice can negatively impact the sustainability of agricultural systems and increase production costs (Djaman et al. 2018). While the ideal nitrogen level for biomass and yield is the amount that promotes the highest growth rate and productivity, in practice, factors such as product quality and safety—especially nitrate levels in the final crop—often guide decisions on appropriate nitrogen use (Goodarzi et al. 2020).

1.5 Impact of Nitrogen in NUE

Resource use efficiency is crucial for plant growth and adaptation to changing environmental conditions. However, improving

the efficiency of one resource can sometimes reduce the efficiency of another—for instance, there is often a trade-off between nitrogen use efficiency and light use efficiency.

2. NANO UREA: A TECHNOLOGICAL OVERVIEW

Agricultural nutrient balances vary significantly with levels of economic development, highlighting the importance of improving soil fertility, particularly in developing nations (Campbell et al. 2014) and in recent times, food and nutritional security have become deeply integrated with emerging knowledge systems. Agricultural progress is also closely linked to factors such as social inclusion, public health, climate change, energy, ecosystem functions, natural resources, and effective governance—all of which should be addressed through clearly defined, goal-oriented strategies and as a result, sustainable agriculture offers a practical pathway to alleviate poverty and hunger. As agriculture moves toward recovery, enhancing environmental performance and involving food chain ecosystems in the agricultural production process are increasingly essential (Thornhill et al., 2016).

The use of renewable materials in manufacturing processes is advantageous, as it results in minimal environmental impact (Prasad et al. 2016). Nano-materials are considered environmentally sustainable, and considerable progress has been made in the area of green nanotechnology and in recent years, there has been a rapid shift toward adopting green nanotechnology for various applications (Rop et al., 2019). However, the path to achieving long-term environmental sustainability through green nanotechnology remains uncertain and therefore, it is essential to address and mitigate the potential risks associated with its advancement (Kandasamy and Prema 2015).

A key benefit of using nanoparticles for nutrient delivery is their ability to lessen environmental impact. Traditional fertilizers frequently lead to nutrient runoff, which can cause water pollution and eutrophication in aquatic ecosystems. In contrast, nanoparticles provide a slow and controlled nutrient release, significantly reducing the chances of leaching and runoff (Pandorf et al. 2020). This approach not only helps safeguard water quality but also decreases the reliance on excessive fertilizer use, thereby reducing overall production costs.

Nanotechnology plays a vital role in enhancing agricultural productivity by enabling precise nutrient management (Mukhopadhyay 2014). Additionally, it contributes to monitoring water quality and pesticide levels, supporting the sustainable development of agriculture. Due to the diverse properties and functions of nano-materials, providing a universal evaluation of their health and environmental risks remains challenging (Prasad et al., 2014). Although nano-fertilizers have become increasingly available in recent years, most conventional agricultural fertilizers are still not produced by major chemical manufacturers (Prasad et al., 2017) (Table 1). These nano-fertilizers may include components such as nano zinc, silica, iron, titanium dioxide, ZnCdSe/ZnS core-shell quantum dots (QDs), InP/ZnS core-shell QDs, Mn/ZnSe QDs, gold nanorods, and other core-shell QDs. They are designed to enhance controlled nutrient release and improve overall fertilizer quality. Extensive research has been conducted over the past decade on the uptake, biological behaviour, and toxicity of various metal oxide nanoparticles—such as Al₂O₃, TiO₂, CeO₂, FeO, and ZnO NPs—in the context of agricultural applications (Dimkpa, 2014; Zhang et al., 2016).

Integrating nanotechnology into agriculture marks the beginning of a new wave of innovation, where nanoscale manipulation of materials holds the potential for groundbreaking solutions. However, like any emerging technology, this agricultural nano revolution comes with both significant opportunities and challenges that require thorough evaluation. One

notable advancement is the nanoencapsulation of agrochemicals, including pesticides and fertilizers, which enable controlled and targeted release (Shukla et al., 2019) and this approach not only enhances the effectiveness of these inputs but also minimizes their environmental impact.

2.1 Mechanism of Action

Over the past decades, nanotechnology has emerged as a significant innovation with diverse applications in the agricultural sector (Marchiol et al., 2020). It encompasses a broad range of uses within agriculture (Kumar et al. 2022). One notable advancement is nano urea, which, due to its smaller particle size and improved solubility, represents a groundbreaking method for nutrient management. Traditional urea, a commonly used nitrogen fertilizer, often results in nutrient losses through volatilization and leaching, leading to soil and water contamination. In contrast, nano urea utilizes controlled-release mechanisms to improve nutrient use efficiency and reduce environmental harm and can be applied in various ways, including foliar spraying, fertigation, and soil incorporation. Foliar application involves spraying nano urea directly on plant foliage, enabling fast nutrient uptake and fertigation integrates nano urea into irrigation systems, allowing targeted nutrient delivery to the roots and hence, soil incorporation involves blending of nano urea into the soil during planting or tillage, ensuring a slow and steady nutrient release (Lohar et al., 2023).

Table 1. Commercial product of nanofertilizers

Commercial product	Content	Company
Nano-Gro™	Plant growth regulator and immunity enhancer	Agro Nanotechnology Corp., FL, United States
Nano Green	Extracts of corn, grain, soybeans, potatoes, coconut, and palm	Nano Green Sciences, Inc., India
Nano-Ag Answer®	Microorganism, sea kelp, and mineral electrolyte	Urth Agriculture, CA, United States
Biozar Nano-Fertilizer	Combination of organic materials, micronutrients, and macromolecules	Fanavar Nano-Pazhoohesh Markazi Company, Iran
Nano Max NPK Fertilizer	Multiple organic acids chelated with major nutrients, amino acids, organic carbon, organic micro nutrients/trace elements, vitamins, and probiotic	JU Agri Sciences Pvt. Ltd, Janakpuri, New Delhi, India
Master Nano Chitosan Organic Fertilizer	Water soluble liquid chitosan, organic acid and salicylic acids, phenolic compounds	Pannaraj Intertrade, Thailand
TAG NANO (NPK, PhoS, Zinc, Cal, etc.) fertilizers	Proteino-lacto-gluconate chelated with micronutrients, vitamins, probiotics, seaweed extracts, humic acid	Tropical Agrosystem India (P) Ltd, India

2.2 Mechanisms of Enhanced Nutrient Uptake

The improved nutrient absorption associated with nano urea is largely attributed to its smaller particle size and superior solubility and these nanoscale properties increase the surface area available for interaction with both soil particles and plant roots, thereby promoting more efficient nutrient absorption. Additionally, the controlled and gradual release of nutrients from nano urea ensures that nutrient availability is better synchronized with the growth requirements of the plant and this reduces nutrient losses and enhances overall uptake efficiency (Lohar et al. 2023).

2.3 Conventional vs. Nano Urea

Traditional nitrogen fertilizers like urea are harmful to the environment, contributing to soil acidification, water pollution, and greenhouse gas emissions. Liquid nano urea, on the other hand, is considered a more sustainable alternative due to its lower potential for nutrient loss (Rop et al. 2019). Nano urea particles, ranging from 20 to 50 nanometers, are more precise in delivering nitrogen to crops. Each nano particle has a surface area-to-volume ratio about 10,000 times greater than conventional urea granules, improving its interaction with plant surfaces. While the nitrogen use efficiency of conventional urea is low (around 30% in rice), nano urea shows better absorption by plants, especially in foliar applications (Vijayakumar et al., 2022, Midde et al., 2022). Overuse of traditional nitrogen fertilizers can degrade crop quality, lower nitrogen use efficiency, and harm the environment (Hanifuzzaman et al., 2022).

Advantages of Nano Urea: Nano urea offers significant advantages over conventional urea, particularly in nutrient release and efficiency. Traditional urea suffers from rapid volatilization and leaching, causing nitrogen losses and reduced plant uptake. In contrast, nano urea employs controlled release mechanisms—such as polymer coatings or encapsulation—that minimize these losses, providing nutrients more precisely to plants. Several studies have shown that nano urea improves nutrient retention in the soil and enhances plant uptake, leading to higher crop yields and a reduced environmental footprint. This increased efficiency is essential for addressing resource wastage and supports the sustainable intensification of agriculture (Lohar et al. 2023).

2.4 Rethinking Nitrogen: The Nano-Fertilizer Solution

With the global population on the rise and the availability of arable land declining, the demand for chemical fertilizers—particularly nitrogen-based ones—continues to grow (Wen et al., 2017). In 2019–20, global nitrogen fertilizer demand reached 107.4 million tons, with urea accounting for approximately 76.5% of this total (FAO 2022). Despite its widespread application, urea production is linked to several environmental concerns, including greenhouse gas emissions, significant water and energy consumption, and pollution risks (Fiamelda et al. 2020). To mitigate these impacts, researchers have suggested lowering urea consumption through the adoption of more energy-efficient fertilizers (Bartolucci 2022). Conventional fertilizers, including urea, are known for their low nutrient use efficiency—often just 30–35%—which leads to over application and negative environmental effects (Kumar et al. 2019, Kumar et al. 2022). Nutrient losses through nitrate leaching (NO_3^-) and the emission of ammonia (NH_3) and nitrous oxide (N_2O) further contribute to environmental degradation (Mahmud et al., 2021).

In response to these challenges, there is growing interest in alternative nutrient delivery systems, with nano-fertilizers gaining attention as promising solutions (Verma et al., 2022). These fertilizers, distinguished by their nanoscale size and slow-release capabilities, act as efficient nutrient carriers. Their high surface area-to-volume ratio enhances nutrient absorption while reducing losses through leaching and gaseous emissions (Mishra et al., 2022). However, more in-depth research is still needed to fully understand their advantages over traditional fertilizers.

3. INTRODUCTION TO LINSEED

Linseed is an erect annual herb that grows to a height of 30-120 cm and has a slender, glabrous, grayish-green stem. Linseed varieties are cultivated so that the oil can be extracted from the seeds. The flax varieties are planted so that the stems can be harvested for fibre. The flax varieties have straight culms, fewer secondary branches near the top of the stem, and are comparatively taller (80–120 cm). The old (linseed) variety grew 60–80 cm tall and has a short tap-tote branching structure while the shoot has several branches and a bushy

appearance. The spectacular, different-shaped, regular, hermaphrodite, pentamerous, and hypogynous flowers are borne in a loose terminating raceme or open cyme and are coloured blue, white, or pink. Five ovate, acuminate persistent sepals make up the calyx. The corolla is made up of five free, clawed, fugacious, imbricate, bluish, or white, deciduous petals that fall before midday, the androecium has five stamens that have been transformed into staminodes make up the outer whorl, however, the base of the gynoecium is surrounded by a fused ring made up of the inner five fertile stamens that have been expanded. The petals fit within this ring and are narrow at the base. At the enlarged bases of the stamens are glands that secrete nectar. The anthers encircle and extend over the stigma in the majority of *Linum usitatissimum* L. flowers, but in some variants, the stigma protrudes slightly beyond the anthers. The two-celled,

longitudinally dehiscent, introrse anthers. There are five connected carpels in the upper gynoecium. Because each carpel has a fake septum, the ovary is ovoid and ten celled, and it can produce up to two ovules in each carpel. The ovaries have an axile placentation, five filiform, free, or united styles that are twisted together to form a stigmatic surface with a small club-like shape, and the ovules are succulent and anatropous and the fruit is a 5- to 9-mm-diameter spherical, smooth globular capsule. The only species of the Linaceae family having non-dehiscent or semi-dehiscent capsules for modern cultivation is *Linum usitatissimum* L. and the capsule is of the indehiscent form in the majority of types. Linseed contains 33% to 45% oil, rich in unsaturated fatty acids—especially α -linolenic acid (ALA)—making it valuable for diverse industries such as paints and varnishes. Both the entire plant and its processed seeds have notable commercial uses (Mandal et al. 2025).



Fig. 1. Flowering of linseed plants



Fig. 2. Capsules bearing seeds of *Linum usitatissimum* L. plant c. Seeds after cleaning from the capsules (the images are from the authors trial on linseed)

3.1 Economic Importance

Flax fibre: Flax fibre is recognized as one of the most eco-friendly and natural fibres available for textile use and is valued for its notable properties such as high strength, fineness, and durability. Compared to cotton and jute, flax is shinier, stronger, less elastic, longer-lasting, and more resistant to environmental changes. It blends easily with other natural fibres like wool, silk, and cotton. When bundled, flax fibres resemble blonde hair, and the threads produced are exceptionally strong, making them suitable for use in footwear, fishing lines, and nets. It is widely applied in the production of items such as canvas, twine, carpets, blankets, and mats and the coarser and rougher varieties are ideal for making sturdy ropes, shipping cords, twines, and other cordage materials, which are crucial in the aeronautics and defense sectors. High-quality flax fibres are used to produce textiles known as 'linen' or 'linso-fabrics,' which include products like suiting, shirting, bed linens, laces, damasks, and curtains. Blended fabrics such as flax-jute (Linju) and flax-cotton (Linco) have shown to offer superior quality compared to 100% jute or cotton fabrics (Pandey and Dayal 2003).

Geotextiles (Insulation): Flax fibres, both coarse and fine, can be blended and processed into insulation batts—sheets of wadded fibre—that exhibit insulation properties comparable to those of fiberglass batts. These batts are effectively used for insulating ceilings and walls (Jacobsz and Vander Merwe 2012).

Plastic Composites: Due to their light weight and cost-effectiveness, flax fibres serve as a viable alternative to fiberglass in the production of plastic composites. These composites are used in various applications such as car dashboards, fencing materials, and septic tanks. Flax is often referred to as the "plastic crop" because of its significant role in promoting eco-friendly alternatives for paper and plastic production (Vittal et al., 2005).

Commercial Wax Applications: Wax is extracted from the cortical tissues of flax using various organic solvents. This wax is commonly utilized in the production of shoe polishes (Charles, 2019).

Industrial Uses of Linseed Oil: Linseed oil, derived from flax seeds, is a highly versatile drying oil owing to the presence of di- and tri-unsaturated fatty acids, which allow it to

polymerize when exposed to air. This property enables linseed oil to harden into a solid form, making it suitable for use on its own or in blends with other oils, solvents, and resins. Raw linseed oil dries slowly and has a tendency to yellow over time with poor color retention. To enhance its drying speed and colour stability, raw linseed oil undergoes heat modification (heating at high temperatures). It can also be blended with chemical dryers—such as linoleates or resinates of metals like lead, manganese, cobalt, or zinc—to meet specific needs in the dyeing and coatings industries.

Nutritional Value: Flax seeds are rich in essential nutrients and have considerable nutraceutical value, offering health benefits for both humans and animals. They contain all eight essential amino acids—namely isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine—along with carbohydrates, vitamins, minerals, and crude fibre. Flax is also the richest plant-based source of omega-3 and omega-6 fatty acids (Anonymous 2006). Health professionals often recommend these nutrients for improved wellness. A single cup (130 grams) of ground flax seeds provides approximately 585 kcal of energy, 26 grams of protein, 53 grams of total fat, 36 grams of dietary fibre, 38 grams of carbohydrates, and a full spectrum of essential vitamins and minerals necessary for the human body (Anonymous 2003).

As Fodder: After extracting oil from linseed seeds, the remaining residue, known as cake, is typically brown in colour. Before the extraction of oil (defatting), this cake contains several valuable components, including 21.78% non-nitrogenous extract, 29.37% lipids, 27.78% protein, 7.02% fibre, 3.40% ash, and 10.65% total moisture content (Gutierrez et al. 2010). Due to its high protein content, linseed cake serves as a nutritious and palatable feed for livestock. It is commonly fed to cattle to enhance their health, promote the shine and gloss of their coats, and improve overall well-being. Additionally, linseed meal is sometimes used as an additive in baking products (Coskuner and Karababa 2007).

4. NANO UREA: IMPACT ON CROPS

Panday et al. (2022) conducted a field experiment during the Rabi season of 2022 at the Instructional Farm, Department of Agronomy, College of Agriculture, Dapoli, Ratnagiri, Maharashtra, to examine the effect of nitrogen

levels and nano urea on the growth, yield, and quality of mustard (*Brassica juncea*) in the lateritic soils of Konkan. The treatments involved varying nitrogen levels (0, 100, 75% of RDN) and nano urea concentrations (0, 20, 40, 60, 80 ppm) applied at 30 and 60 DAS. The results showed significant improvements in plant height, number of branches, number of functional leaves, and dry matter production at 40, 60, and 80 DAS when 75% RDN (F₃) and two sprays of nano urea at 40 ppm (N₃) were applied. The highest seed yield (2083.57 kg ha⁻¹) and straw yield (3646.24 kg ha⁻¹) were observed with this combination, while the untreated control (F₁N₁) had the lowest yields.

Gayathri et al. (2023) conducted a split-plot field experiment to evaluate the effects of nano urea and conventional urea on the growth and development of safflower. The results indicated that applying 100% nitrogen as urea topdressing during the vegetative stage, followed by two foliar sprays of nano urea at the flowering and seed-filling stages, significantly improved physiological parameters such as plant height and primary branches. The use of 100% nitrogen fertilizer enhanced safflower growth and yield, while halving the nitrogen supply led to reduced growth and yield. The foliar application of nano urea and 2% urea at the reproductive stages provided the plants with necessary nutrients, boosting yield attributes and seed yield. The study concluded that foliar application of nano urea is an effective solution to mitigate nutrient deficiencies when soil nutrient absorption is limited, offering better nutrient release control, improving nutrient use efficiency, reducing urea costs, and minimizing pollution from conventional fertilizers.

Siddiqui (2023) conducted a field experiment at the Students' Instructional Farm, C.S. Azad University of Agriculture and Technology, Kanpur, to study the effect of foliar applications of nano urea and nano zinc on the growth, quality, and productivity of Indian mustard (*Brassica juncea*) under timely sown irrigated conditions. The experiment, set in a Randomized Block Design with 10 treatments, included variations of the recommended dose of N:P:K:ZnSO₄ (RDF) and combinations with nano urea (4 ml litre⁻¹ at 30 and 45 DAS) and nano zinc (2 ml litre⁻¹ at 30 DAS). Results showed that the treatment with 100% RDN and ZnSO₄, along with nano urea and nano zinc sprays, resulted in the highest plant height (201.41 cm), number of branches (Primary 8.2, Secondary 10.4, Tertiary 4.3), dry matter accumulation (46.38 g/plant), leaf

area index (4.46 at 90 DAS), and significant grain (18,564 kg ha⁻¹) and straw yields (45,686 kg ha⁻¹). The highest number of siliqua plant⁻¹ (268.85) and oil content (41.64%) were achieved with this treatment, which led to oil yield of 773.01 kg ha⁻¹. The high yield was attributed to increased dry matter accumulation and LAI. The oil extracted from this treatment had a low erucic acid content (<2%), making it suitable for edible purposes.

4.1 Impact on Linseed

The use of nano-nitrogen through foliar spraying has been shown to increase the dry weight of plants, likely due to enhanced growth and increased branch development. This improvement in plant structure could lead to higher levels of photosynthetic activity, ultimately boosting the production of photosynthates. Since nitrogen plays a critical role in the metabolic processes that contribute to dry matter accumulation in plants, its application via nano-urea has demonstrated positive effects. These findings align with previous research conducted by Varsha et al. (2020).

Reddy et al. (2023) concluded that the soil application of 100% nitrogen in two splits (50% as basal and 50% as top dressing) resulted in the highest leaf and plant nitrogen content, as well as the most significant nitrogen, phosphorus, and potassium (NPK) uptake by both the seed and stover. This approach also exhibited superior agronomic efficiency and nutrient recovery, ultimately leading to better yield attributes and higher seed and stover yields. Among the various foliar spray treatments with different nitrogen doses, two sprays of Nano-urea at 3 ml litre⁻¹—applied at the flower initiation and capsule development stages—resulted in the highest nutrient uptake by linseed plants. This in turn led to the highest seed and stover yields, demonstrating the effectiveness of Nano-urea in improving the overall nutrient efficiency and crop productivity (Table 2).

Ramesh et al. (2023) reported that the highest grain yield (1434.23 kg ha⁻¹) in linseed was obtained with treatment T₇, which involved 50% nitrogen (RDN), 100% phosphorus and potassium through the soil, along with two foliar applications of nano-N at 0.4% concentration at 20 and 40 days after sowing (DAS). This was similar to T₈, which included 25% nitrogen (RDN), 100% phosphorus and potassium, and three foliar sprays of nano-N at 0.4% at 20, 40, and 60 DAS, yielding 1395.76 kg ha⁻¹.

Table 2. Influence of nano urea in yield parameters in linseed

Treatments	Capsules plant ⁻¹	Seed capsule ⁻¹	Seed yield (Kg ha ⁻¹)	Stover yield (Kg ha ⁻¹)	Agronomic efficiency (AE)	Recovery efficiency (RE)
Main plot						
F ₁	42.42	9.74	996.98	3037.92	6.47	6.09
F ₂	36.69	8.32	830.65	2751.20	5.53	5.63
F ₃	32.16	7.17	673.55	2272.89	3.95	5.25
F ₄	29.19	6.38	567.68	2223.23	2.99	4.92
Sem±	0.52	0.15	12.81	60.08	0.12	0.09
CD (0.05)	1.81	0.54	44.33	235.60	0.44	0.34
Sub plot						
N ₁	28.71	6.60	577.13	1952.22	2.63	4.37
N ₂	34.66	8.09	770.13	2581.37	4.44	5.03
N ₃	41.47	8.73	932.56	3073.96	7.46	7.52
N ₄	32.15	7.63	729.65	2440.63	4.02	4.65
N ₅	38.58	8.48	826.58	2803.34	5.13	5.80
Sem±	0.56	0.12	13.03	56.87	0.14	0.10
CD (0.05)	1.61	0.34	37.55	163.83	0.40	0.30

The observed increase in yield was due to nano fertilizers that enhanced nutrient uptake, expanding the plant's surface area for metabolic activities, improving photosynthesis, and boosting both source and sink strength. This allowed better nutrient absorption and higher photosynthate production, leading to improved seed and stover yields.

Kumar et al. (2024) reported that two foliar sprays of nano-urea (3 ml L⁻¹) at flowering and capsule development significantly boosted seed yield (838 kg ha⁻¹), straw yield (1669 kg ha⁻¹), harvest index (33%), and profitability (net returns Rs. 25,894 ha⁻¹; B:C ratio 2.60). The highest productivity and returns were achieved with 100% recommended nitrogen dose (split 50% basal, 50% top dressing) plus nano-urea sprays, yielding 984 kg ha⁻¹ of seed, 1827 kg ha⁻¹ of straw, and a B:C ratio of 2.91 and henceforth foliar sprays, whether nano-urea or 2% urea, combined with full nitrogen application, significantly improved yield and economic gains.

Durgeshwari et al. (2024) concluded that nano-urea significantly enhanced linseed yield and its attributes. The highest number of capsules per plant, seed yield, stover yield, and oil yield were observed with two sprays of nano-urea at 3 ml L⁻¹ at flower initiation and capsule development stages (N₃). This treatment also resulted in the highest seed number per capsule. Nano-urea exhibited a similar effect to 2% urea on yield attributes. The combination of 100% nitrogen (F₁) and two nano-urea sprays (N₃) resulted in significantly higher seed yield, stover yield, and oil yield, compared to the interaction of 75%

nitrogen (F₂) and two sprays of 2% urea (N₅). Nano-urea thus proved to be an effective alternative to traditional nitrogen sprays, improving nutrient uptake, growth, and yield in linseed production.

Harode et al. (2024) conducted a field experiment to study the effect of nano-urea on the growth and yield of linseed during the 2023-2024 rabi season in Nagpur. They used three nitrogen doses (50% basal + 50% top dressing) as the first factor and four foliar nitrogen supplementation treatments as the second factor. Among the various treatments, two sprays of nano-urea at 3 ml L⁻¹ during the flower initiation and capsule development stages (N₂) resulted in the highest plant height (68.91 cm), number of branches (4.36), dry matter accumulation (8.86 g plant⁻¹), chlorophyll content (SPAD value: 25.53), and the number of days to 50% flowering (58.56 days) and physiological maturity (113 days). This treatment also recorded the highest yield attributes, including the number of capsules per plant (36.33), seed yield per plant (2.53 g), straw yield per plant (5.37 g), and test weight (8.25 g). The positive effects on growth and yield were attributed to higher branch numbers, dry matter, and chlorophyll content. However, the number of seeds per capsule was not significantly influenced by foliar nitrogen treatments, as this trait is genetically determined and these results are consistent with those reported by Kikon et al. (2024).

Dehury et al. (2024), based on a year-long experiment, concluded that applying 75% nitrogen (22.5 kg ha⁻¹) along with one spray of

nano-urea (3 ml litre⁻¹) at the flower initiation stage resulted in higher nitrogen availability and nutrient uptake, making it the most productive and economical option for linseed production in Jharkhand. Moreover, the combination of 100% nitrogen (N₁) soil application and two foliar sprays of nano-urea at 3 ml litre⁻¹ during flowering and capsule development stages (F₃) resulted in the highest seed and straw yields, B:C ratio, nitrogen use efficiency, nitrogen content in grain and straw, and NPK uptake in grain and straw compared to other treatments.

5. CONCLUSION

In the face of mounting global agricultural challenges—including soil nutrient depletion, reduced nitrogen use efficiency (NUE), and the pressing need to sustainably increase crop yields—nano urea emerges as a transformative innovation in nutrient management. Its application in linseed cultivation, as reaffirmed by recent findings (Kumar et al. 2024, Reddy et al. 2023), has demonstrated significant improvements in seed and stover yield, nutrient uptake, and economic returns. The enhanced nitrogen delivery through foliar nano-urea sprays, particularly when integrated with recommended nitrogen doses, underscores its superior efficiency and reduced environmental impact compared to conventional fertilizers.

At the core of 21st-century agricultural sustainability is the need to produce more with less—less land, less labor, and fewer synthetic inputs—while ensuring food security and environmental resilience. Nano urea aligns seamlessly with this vision. Its controlled-release mechanism and increased absorption efficiency not only reduce fertilizer losses but also mitigate pollution, making it a critical tool in sustainable intensification.

Thus, nano urea represents a key step toward rethinking nitrogen management in linseed and broader cropping systems. It supports the dual goals of sustainability and productivity, offering a scalable, eco-friendly solution that addresses both the agronomic and environmental demands of modern agriculture. As such, it holds enormous potential to reshape input strategies and reinforce the future of global food systems under climate and resource constraints.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models

(ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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