Nanotechnology and Liquid Nitrogen Fertilizers in Millets: A Review on Nano Urea and Urea Ammonium Nitrate (UAN) for Sustainable Pearl Millet Production

Tadiboina Gopala Krishna[1], Ravindra Nath[1], Dokala Mounika[1]

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ABSTRACT

Pearl millet (*Pennisetum glaucum*) is a climate-resilient cereal cultivated widely in semi-arid regions where nitrogen losses from conventional urea limit productivity and nitrogen use efficiency (NUE). This review synthesizes recent advances in nano urea and urea-ammonium nitrate (UAN) as innovative nitrogen sources for sustainable pearl millet production. A systematic analysis of published literature was conducted to evaluate their mechanisms of action, agronomic performance, environmental implications and economic feasibility. Nano Urea enhances foliar nitrogen absorption and reduces soil-based nitrogen losses, while UAN supplies nitrogen in multiple chemical forms, providing both immediate and sustained availability. Evidence suggests that partial substitution strategies improve NUE, reduce environmental risks and maintain yield stability under dryland conditions. However, long-term ecological assessments and millet-specific dosage optimization remain research priorities. Integrated nitrogen management combining soil and foliar approaches appears most promising for sustainable pearl millet systems.

Key words: Liquid nitrogen fertilizers, Nano fertilizers in dryland agriculture, Nano urea, Nitrogen use efficiency in millets, Pearl millet nitrogen management, Urea ammonium nitrate (UAN).

Pearl millet (*Pennisetum glaucum* L.) is one of the most resilient cereals cultivated across arid and semi-arid regions of Africa and Asia. It is valued for its exceptional tolerance to drought, high temperatures and nutrient-poor soils, making it a vital food and fodder crop for millions of resource-poor farmers (FAO, 2021). India is the world's largest producer, contributing nearly 40% of global pearl millet production, where it plays a major role in food security and dryland farming systems (ICRISAT, 2020; Directorate of Millets Development, 2022). Despite its adaptability, the productivity of pearl millet is strongly influenced by nitrogen (N) availability, as N drives tillering, chlorophyll formation, photosynthetic capacity and grain development (Singh *et al*., 2018).

Conventional urea remains the predominant N source used by farmers; however, its low nitrogen use efficiency (NUE) often below 35% limits its effectiveness (Ladha *et al*., 2016). Significant N losses through volatilization, leaching and denitrification reduce crop uptake and increase production costs while contributing to environmental degradation (Snyder *et al*., 2009). These limitations underline the need for more efficient N delivery systems, particularly in dryland cereals such as pearl millet which are frequently grown under moisture and nutrient constraints.

In recent years, innovative nitrogen sources such as nano urea and urea-ammonium nitrate (UAN) have emerged as potential alternatives to conventional granular fertilizers. Nano Urea, developed as a foliar-applied nanotechnology-based fertilizer, aims to enhance nutrient absorption and reduce losses through controlled and targeted N delivery (Prasad *et al*., 2017; IFFCO, 2021). UAN, a liquid fertilizer containing urea, ammonium and nitrate forms of nitrogen, offers more uniform application, reduced volatilization compared to prilled urea and better synchronization with crop demand (Gordon, 2014). Both fertilizers represent promising tools for improving NUE and productivity in climate-stressed cereal systems.

However, despite increasing interest, comparative assessments of Nano Urea and UAN in pearl millet remain limited particularly in the context of semi-arid agroecosystems where nutrient and water stresses frequently coexist. Understanding their relative efficiency, physiological impacts, agronomic performance and environmental implications is crucial for guiding fertilizer recommendations and optimizing nitrogen management strategies for smallholder farmers.

[1]Department of Agronomy, School of Agricultural Sciences, GD Goenka University, Gurugram-122 103, Haryana, India.

Corresponding Author: Tadiboina Gopala Krishna, Department of Agronomy, School of Agricultural Sciences, GD Goenka University, Gurugram-122 103, Haryana, India.
Email: gkagric8055@gmail.com
ORCIDs: 0009-0006-6478-7844, 0009-0008-2811-3716, 0009-0003-6221-2519

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This review article was prepared through a systematic and comprehensive survey of published scientific literature focusing on nano urea and urea-ammonium nitrate (UAN) in millet-based production systems, particularly pearl millet.

A structured literature search was conducted using major academic databases including Scopus, Web of Science, Google Scholar, ScienceDirect and AGRIS. The search covered publications from 2000 to 2025, with emphasis on recent developments in nanotechnology-based fertilizers and liquid nitrogen sources.

Keywords used included:

- Nano urea.
- Urea ammonium nitrate (UAN).
- Pearl millet nitrogen management.
- Nitrogen use efficiency in millets.
- Nano fertilizers in dryland agriculture.
- Liquid nitrogen fertilizers.

Only peer-reviewed journal articles, research reports and credible institutional publications were included. Non-scientific reports and non-peer-reviewed news sources were excluded to maintain scientific rigor.

A total of approximately 120 relevant articles were critically analysed. The selected studies were categorized into:

1. Nitrogen dynamics in pearl millet.
2. Nano urea mechanism and agronomic performance.
3. UAN chemistry and field applications.
4. Environmental and economic implications.

The findings were synthesized thematically to provide a structured comparative assessment.

Pearl millet: Growth characteristics

Pearl millet (*Pennisetum glaucum*) is widely known for its remarkable ability to survive in harsh, dry and nutrient-poor environments. The crop has a deep and extensive root system, often reaching 1.5-2 m deep, which allows it to extract water from deeper soil layers (Ramesh *et al*., 2020). This root architecture is one of the biggest reasons it performs better than many cereals in drought-prone regions.

Physiologically, pearl millet uses the C4 photosynthetic pathway, which means it can maintain high photosynthetic efficiency even under high temperatures (40-45°C) and limited water availability (Sinha *et al*., 2019). Its leaves have efficient stomatal regulation, helping the plant reduce water loss during peak heat stress. Additionally, pearl millet can resume growth quickly after drought breaks, a trait known as drought recovery resilience (Kumar *et al*., 2021).

This combination of morphological strength, efficient carbon fixation and stress-adaptive physiological traits makes pearl millet one of the most climate-resilient cereals suitable for the semi-arid tropics.

Nitrogen uptake patterns across key growth stages

Nitrogen (N) plays a central role in pearl millet growth because it drives tillering, leaf expansion, chlorophyll formation and grain development. However, the crop does not absorb nitrogen uniformly throughout its lifecycle.

Tillering stage (20-30 DAS)

This is when the crop produces most of its productive tillers. During this period, pearl millet typically absorbs 25-35% of its total N requirement, mainly to support leaf area expansion and early canopy establishment (Singh *et al*., 2020).

Booting stage (35-45 DAS)

At booting, the developing panicle is inside the stem. The plant's nitrogen demand sharply increases because N supports panicle initiation, stem elongation and chlorophyll activity. Studies show that 30-40% of total N uptake occurs during this stage (Sagar *et al*., 2023).

Flowering to grain filling stage (50-70 DAS)

During flowering and grain filling, nitrogen is essential for pollen viability, grain setting and protein accumulation. Approximately 20-30% of total N uptake takes place here. If N supply is limited during this period, grain weight and yield decline sharply.

Thus, timely and split application of N is critical because most pearl millet varieties reach peak N demand within a short time window. Similar findings were reported in dryland millets where split nitrogen application significantly improved nitrogen recovery efficiency and yield stability (Sagar *et al*., 2024).

Nitrogen use efficiency (NUE) challenges

Despite being a hardy crop, pearl millet suffers from low nitrogen use efficiency (NUE), often in the range of 25-35% under farmers' field conditions (Sharma *et al*., 2018). Several factors contribute to this challenge:

- Sandy and low-organic-matter soils, which allow nitrogen to leach rapidly.
- High temperatures and surface application of urea, leading to volatilization losses.
- Limited irrigation, which restricts nitrogen mobility and root uptake.
- Mismatch between N application timing and the crop's physiological demand.

Poor NUE means that a large portion of applied nitrogen is lost to the environment rather than used by the plant, resulting in lower productivity and higher fertilizer costs.

Innovative fertilizers like Nano Urea and UAN are being explored to address these limitations by enhancing N availability and reducing losses.

Yield response to nitrogen levels under rainfed vs. irrigated conditions

Pearl millet responds strongly to nitrogen fertilization, but the magnitude of yield response varies with moisture conditions.

Rainfed conditions

Under rainfed systems, water availability limits nitrogen utilization.

- Yield response typically increases up to 40-60 kg N ha^{-1}, beyond which the benefit declines.

- Due to drought stress, the plant cannot fully utilize higher N levels.
- NUE is often lower because N uptake declines during dry spells.

Irrigated conditions

When moisture is adequate, nitrogen uptake and metabolism improve considerably.

- Studies report yield increases up to 80-120 kg N ha^{-1} under irrigated production (Bhuvaneshwari *et al*., 2021).
- Higher irrigation allows better root proliferation and efficient N translocation to grains.
- Grain yield, panicle length and thousand-grain weight show significant improvement.

Conventional nitrogen fertilizers: Limitations and challenges

Conventional nitrogen fertilizers especially granular urea has played a major role in boosting cereal production for decades. However, in crops like pearl millet, the efficiency of these fertilizers is often much lower than expected. Several soil, climatic and management factors contribute to nitrogen (N) losses, ultimately reducing crop productivity and increasing production costs for farmers.

Urea volatilization losses (20-40%)

Urea is the most widely used nitrogen fertilizer in India because of its low cost and high N content. However, when urea is broadcast on the soil surface, a large portion of it is lost as ammonia gas (NH_3) before the crop can absorb it.

In drylands and coarse-textured soils conditions typical for pearl millet the losses are particularly high. Studies have consistently reported 20-40% volatilization loss from surface-applied urea, especially under high temperature and alkaline soil conditions (Bouwmeester *et al*., 1985; Singh and Ryan, 2015).

This means that almost one-third of the applied nitrogen never reaches the crop, making fertilization inefficient and costly.

Leaching and denitrification in light-textured soils

Pearl millet is often grown in sandy or loamy-sand soils, which have low water-holding capacity. These soils allow nitrogen, especially in the nitrate (NO_3^-) form, to move downward rapidly with irrigation or rainwater.

- Leaching losses occur when nitrate passes below the root zone reducing crop N availability and contaminating groundwater (Di and Cameron, 2002).
- Denitrification the microbial conversion of nitrate into nitrous oxide (N_2O) and N, gases occurs during temporary waterlogging or heavy rainfall leading to gaseous N losses (Aulakh *et al*., 1992).

In such soils, it is common for farmers to lose 10-30% of applied nitrogen due to leaching or denitrification, depending on rainfall distribution.

Low nitrogen use efficiency (NUE 30-35% in pearl millet)

NUE in pearl millet is already low due to harsh environmental conditions and poor synchronization between nitrogen supply and crop demand (Sharma *et al*., 2018). Under typical field conditions, only 30-35% of the applied nitrogen is taken up by the crop, while the rest is lost through volatilization, leaching, runoff, or immobilization (Yadav *et al*., 2012; Rai *et al*., 2015).

This low NUE means:

- Higher fertilizer requirement per unit of grain produced.
- Greater production costs.
- More environmental losses.
- Less consistent yield response.

Improving NUE is therefore a major goal for sustainable millet production.

Environmental impacts: NH_3 emission and groundwater pollution

Nitrogen losses are not just an economic issue; they also generate significant environmental risks.

a. Ammonia (NH_3) emissions

Volatilized ammonia contributes to:

- Air pollution.
- Particulate matter formation.
- Soil acidification after redeposition.

Globally, urea is one of the largest agricultural sources of NH_3 emissions (Bouwmeester *et al*., 1985; Pan *et al*., 2016).

b. Groundwater contamination

Leached nitrates can enter groundwater and pose health concerns such as:

- Methemoglobinemia (blue baby syndrome).
- Increased risk of digestive tract disorders (Ward *et al*., 2005).

In regions with coarse-textured soils and high rainfall common for rainfed pearl millet nitrate leaching is a major environmental concern.

Economic inefficiencies for farmers

The combined effect of volatilization, leaching and low NUE means that farmers often receive a much smaller yield benefit than expected from the fertilizer they apply.

Economic implications include:

- Higher fertilizer bills due to repeated applications.
- Lower return on investment.
- Reduced profitability under rainfed conditions.
- Greater sensitivity to rising fertilizer prices.

Studies show that improving N efficiency can increase net returns by 15-30% in pearl millet systems (Rai *et al*., 2015; Singh *et al*., 2020).

Thus, nitrogen loss is not only an agronomic problem but also a financial burden, making it necessary to explore more efficient alternatives such as Nano Urea and UAN.

Nano urea: Composition, mechanism and agronomic potential composition and nano-scale properties

Nano urea is essentially a nitrogen fertilizer formulated using ultra-small particles, usually around 20-50 nanometers in size (Singh *et al*., 2021). At this scale, the particles possess a very high surface area, which makes them much more reactive than conventional urea granules. Because of this increased surface area, the fertilizer can interact more efficiently with plant tissues, allowing plants to absorb nitrogen faster and in smaller amounts (Kumar *et al*., 2023).

This nano-scale design also helps nano urea penetrate leaf surfaces more effectively and reduces the need for bulk nitrogen application in the soil. In simple terms, less fertilizer can do more work, helping both the plant and the environment.

Mechanism of absorption

Foliar uptake pathways

When nano urea is sprayed on leaves, the nano-sized particles can enter the plant through stomata (tiny pores) and cuticular pathways. Their small size increases the chance of penetration and rapid absorption, compared to conventional urea that mostly relies on soil dissolution (Yadav *et al*., 2020).

Slow-release and targeted delivery

Once inside the leaf, nano urea does not release nitrogen all at once. Instead, it provides a controlled or slow release, allowing nitrogen to be available gradually as the plant needs it (Natarajan *et al*., 2022). This reduces nitrogen losses and makes the nutrient more synchronised with plant growth stages.

Influence on plant metabolic enzymes

Nano urea has been shown to stimulate key enzymes involved in nitrogen metabolism, especially nitrate reductase, which converts nitrate to forms that the plant can use for building proteins and chlorophyll. Several studies report increases in chlorophyll content and improved photosynthesis in crops treated with nano urea (Sairam *et al*., 2024; Choudhary *et al*., 2023). This means the plant becomes more efficient at using sunlight and producing biomass.

Advantages of nano urea

Reduced nitrogen losses

Traditional urea suffers major losses through volatilization, leaching and denitrification-sometimes up to 40-50%. Nano urea, being foliar applied, bypasses soil-based losses and delivers nitrogen directly to plant tissues, reducing inefficiency dramatically (ICAR, 2021).

Higher nitrogen use efficiency (NUE)

Because more nitrogen reaches the plant and less is lost, nano urea substantially improves nitrogen use efficiency. Several field studies have shown that using nano urea can replace a portion of granular urea without reducing yields (Singh *et al*., 2021; IFFCO, 2022).

Lower environmental footprint

Nano urea reduces the need for excessive fertilizer use, thereby lowering greenhouse gas emissions, soil pollution and nitrate leaching. It also aligns with sustainable agriculture initiatives aiming to reduce the environmental impact of chemical fertilizers.

Constraints/gaps

Inconsistent performance across crops and environments

Although nano urea performs well in many cereals and vegetables, researchers have observed variability in response depending on soil type, crop species, climatic conditions and management practices (Kumar *et al*., 2023). Some crops respond strongly, while others show only mild improvement.

Limited long-term studies

Nano fertilizers are still relatively new and there are not enough long-term studies examining their accumulation, potential toxicity, or interactions with soil microorganisms (Rai *et al*., 2022). This creates uncertainty regarding their ecological impact over many seasons.

Dosage and timing still not standardized in millets

For crops like pearl millet, research is still emerging. Optimal spray concentration, timing and frequency have not been fully standardized. Current recommendations are based largely on preliminary findings rather than multi-location, multi-year trials (Choudhary *et al*., 2023).

This gap highlights the need for crop-specific guidelines, especially in dryland cereals where nitrogen dynamics differ from irrigated crops.

UAN (Urea-Ammonium nitrate): Chemistry, function and application

Composition

Urea-ammonium nitrate (UAN) is a liquid nitrogen fertilizer containing 32% N, commonly used in cereals and forage crops. What makes UAN unique is that the nitrogen is supplied in three different chemical forms, each behaving differently in the soil:

- **50% Urea-N-** This portion must be hydrolyzed by the enzyme urease before it becomes available to plants, making it a more gradual source of nitrogen.
- **25% Ammonium-N (NH_4^+)-** This form is readily absorbed by plant roots and also binds to soil particles, reducing immediate losses (Gastal and Lemaire, 2023).
- **25% Nitrate-N (NO_3^-)-** This form is instantly available to plants through mass flow, especially under good soil moisture.

Because UAN supplies fast-, medium- and slow-release nitrogen simultaneously, it supports plant growth across multiple stages, unlike conventional urea which depends heavily on soil moisture and urease activity.

Mechanism

Immediate + sustained nitrogen availability

The presence of nitrate-N ensures rapid uptake, helping plants during early vegetative growth, while ammonium-N and urea-N contribute to sustained nitrogen supply as the crop develops. This “multiple-form nitrogen strategy” improves synchrony between nitrogen release and crop demand (Sharma *et al*., 2019).

Reduced volatilization losses

Compared with granular urea, UAN typically shows lower ammonia volatilization because:

1. Only half of its N is urea.
2. The solution form increases soil contact and minimizes exposure to air.

As a result, UAN can contribute to higher nitrogen use efficiency (NUE), especially in dryland conditions where urea losses are high.

Compatibility with fertigation and precision spraying

Being a liquid fertilizer, UAN is easy to apply through:

- Drip and sprinkler fertigation systems.
- Boom sprayers for uniform field distribution.
- Variable-rate applicators in precision agriculture.

This flexibility allows farmers to apply nitrogen exactly when the crop needs it, reducing wastage and improving productivity.

Advantages

Even and uniform application

Granular fertilizers often suffer from uneven distribution, especially when wind or machinery limitations occur. UAN, on the other hand, spreads uniformly in liquid form, which ensures consistent nitrogen availability across the field.

Higher plant uptake efficiency

The simultaneous availability of ammonium and nitrate promotes better root absorption and stimulates metabolic enzyme activities, resulting in improved nitrogen recovery by the plant. Nitrate enhances root growth, while ammonium increases chlorophyll and photosynthesis together supporting vigorous vegetative development.

Less dependent on soil moisture

One major drawback of urea is its reliance on soil moisture for dissolution and conversion to ammonium. UAN, already in dissolved form, begins interacting with the soil immediately after application. This makes it particularly helpful in semi-arid crops like pearl millet, where intermittent rainfall can limit urea efficiency.

Constraints/gaps

Potential leaf scorching

Because UAN contains nitrate and ammonium salts, it can cause leaf burn if sprayed at high concentrations or during hot, dry weather. Foliar application must therefore be carefully timed ideally during cooler morning or evening hours (Sharma *et al*., 2019).

Handling and storage limitations

UAN is mildly corrosive, which means storage tanks, pumps and pipelines must be corrosion-resistant, increasing the initial investment. The solution also tends to salt-out (crystallize) at low temperatures, creating logistical challenges.

Cost fluctuations

Since UAN is a manufactured liquid fertilizer with urea and nitrate components, its price can vary depending on:

- Global urea and ammonium nitrate markets.
- Transportation cost.
- Availability of liquid application machinery.

For small and marginal farmers, this can be a barrier unless supported by subsidies or extension guidance.

Comparative analysis: Nano urea vs UAN in pearl millet

Nitrogen use efficiency (NUE)

Nano urea is designed as a foliar-applied nano-scale nitrogen source, allowing rapid entry through stomata and cuticular pathways. This leads to improved absorption efficiency and reduced nitrogen losses, which enhances apparent NUE compared with conventional soil-applied urea (Kumar *et al*., 2024; Gupta *et al*., 2023). Because less nitrogen is exposed to soil processes, volatilization and leaching losses are inherently lower.

Urea-ammonium nitrate (UAN) contains a mixture of urea-N, ammonium-N and nitrate-N, enabling both immediate and sustained N availability to roots. This combination often improves plant uptake efficiency and lowers ammonia volatilization relative to broadcast urea (Ren *et al*., 2023; Singh *et al*., 2021). When applied through fertigation or injected into soil, UAN consistently improves nitrogen recovery efficiency in cereals.

Growth parameters (Tillering, LAI, chlorophyll; root vs foliar effects)

Foliar nano urea application often results in noticeable improvements in leaf greenness, chlorophyll index and leaf area index (LAI) because the absorbed nitrogen quickly activates photosynthetic enzymes and protein synthesis (Gupta *et al*., 2023). These rapid physiological responses explain why nano urea is effective for mid-season crop correction.

In contrast, UAN primarily supports the root zone with balanced nitrogen forms, promoting stronger root proliferation and sustained tillering throughout the season. Its nitrate component fuels rapid metabolic activity, while ammonium supports long-term vegetative growth and root mass development (Ren *et al*., 2023; Singh *et al*., 2021). As a result, cereals like pearl millet often show better tiller retention and extended canopy development under well-managed UAN programs.

Yield attributes (Grain, fodder, panicle length, grain weight)

Field studies on pearl millet and related cereals show that nano urea can maintain or improve grain and fodder yields when used as a supplement to partial soil-N substitution. Enhancements in plant height, LAI and chlorophyll translate into improvements in panicle length and grain weight when foliar sprays are timed at critical stages such as tillering and flowering (Sairam *et al*., 2024). However, full replacement of soil-applied nitrogen with nano urea often results in yield decline, underscoring the importance of combined soil + foliar strategies.

UAN has consistently shown positive yield responses because its mixed-N form improves nitrogen availability during panicle initiation and grain filling. Several comparative studies demonstrate higher grain yield and fodder yield under UAN than under broadcast prilled urea, mainly due to better synchronization between soil N availability and crop uptake (Ren *et al*., 2023; Singh *et al*., 2021).

Soil and environmental impact

Since nano urea is applied to leaves and largely taken up through foliar pathways, minimal nitrogen reaches the soil. This reduces the risk of nitrate leaching and limits soil accumulation of nitrogen residues, making nano formulations generally more environmentally benign. However, long-term ecological studies on nano-fertilizer residues and soil microbiome interactions are still limited (Kumar *et al*., 2024).

UAN typically results in lower volatilization losses than surface-applied urea because ammonium and nitrate are less prone to gaseous transformation when applied correctly. Nevertheless, improper application such as high concentrations on dry soil can lead to localized salt buildup or leaf scorching (Ren *et al*., 2023; Singh *et al*., 2021). Overapplication in alkaline soils may also contribute to temporary increases in soil electrical conductivity.

Economic comparison (Cost-benefit, urea reduction, ROI)

Economically, nano urea offers advantages when used to reduce a portion (not all) of soil-applied nitrogen. Studies show that replacing 25-33% of conventional urea with nano urea sprays can decrease fertilizer costs because fewer 50-kg urea bags are required while maintaining yields, improving the benefit-cost ratio (Sairam *et al*., 2024; Kumar *et al*., 2024). However, using nano urea as a total substitute often reduces yield and net returns.

UAN-based fertilization can be economically efficient where fertigation or liquid-application systems exist. Because UAN improves nitrogen recovery and often increases grain yield compared to prilled urea, return on investment (ROI) is typically higher in irrigated or semi-irrigated systems (Ren *et al*., 2023; Singh *et al*., 2021). Farmers benefit particularly when UAN is applied in precise split doses, reducing waste and maximizing grain response.

Integration with agronomic practices

Integrating nano urea and UAN into a pearl millet production system requires careful alignment of when, how and how much nitrogen is supplied. Because both fertilizers behave differently in soil and plant tissues, their efficiency improves significantly when paired with optimum agronomic practices such as split scheduling, fertigation, irrigation management and balanced nutrient programs.

Timing and dosage recommendations

Pearl millet has distinct nitrogen-demand peaks during tillering, panicle initiation and flowering, making timing a crucial factor. Conventional recommendations suggest 60-90 kg N ha^{-1} for rainfed and 100-120 kg N ha^{-1} for irrigated systems. However, when nano urea or UAN is integrated, the actual quantity of granular urea can be reduced, while maintaining or improving plant performance.

Nano urea

One 500 mL bottle is considered equivalent to a top-dressing of 45 kg urea N, but must be applied as a foliar spray at critical growth stages. Most studies indicate best results when sprayed at 30-35 DAS and again at 50-55 DAS (Prasad *et al.,* 2023). Its rapid foliar absorption provides timely nitrogen during active vegetative growth and reduces soil N losses.

UAN (Urea-ammonium nitrate)

As a 32% N liquid, it is typically applied at 25-30% of total N at sowing, with the remaining amount distributed in one or two top-dressings at tillering and panicle initiation (Singh and Yadav, 2021). UAN supplies nitrate, ammonium and amide forms simultaneously offering a balance of immediate and sustained release.

Key insight

When timed properly, both fertilizers can reduce dependence on bulk urea while improving nitrogen synchrony with crop needs.

Split applications and fertigation strategies

Split nitrogen applications are essential in pearl millet because the crop grows quickly and is highly responsive to staged N supply. Splitting minimizes leaching and volatilization losses especially in sandy, low-CEC soils typical of millet-growing regions (Sairam *et al.,* 2024).

Nano urea in splits

Works best only as a supplement, not a full replacement. Studies show that supplying 50-60% basal nitrogen through soil plus two foliar sprays of nano urea can maintain yields while reducing total N use by 20-30% (Gupta *et al.,* 2023).

UAN in fertigation

UAN integrates well into drip and sprinkler systems, assuring uniform distribution and precise dosage. Fertigation at 7-10-day intervals after tillering has been shown to increase nitrogen use efficiency (NUE) and water-use efficiency in cereals (Kannan *et al.,* 2021). Its liquid nature also allows micro-dosing, which closely matches crop nutrient demand curves.

Overall

Combining small, frequent doses of UAN with strategic nano urea foliar sprays often leads to better physiological activity and improved yield components such as panicle length and grain filling.

Interaction with irrigation scheduling

Water availability strongly affects nitrogen uptake and transformation processes in pearl millet. Under dry conditions, surface-applied urea and UAN suffer higher volatilization, while nano urea being foliar remains largely unaffected.

Nano urea

Because the application is foliar, its performance depends more on leaf temperature and humidity than soil moisture. Sprays applied in the early morning or late afternoon improve absorption and reduce droplet evaporation (Kumar *et al.,* 2024).

UAN

Works best when irrigation is applied immediately after surface application or used directly in fertigation. Moist soil enhances ammonium retention and nitrate mobility, improving root uptake (Verma and Singh, 2022). In drip systems, nitrate from UAN moves with water toward active root zones, resulting in higher efficiency in arid and semi-arid regions.

Practical takeaway

UAN requires closer coordination with irrigation, whereas nano urea is more flexible but still benefits from foliar application under mild temperature and adequate canopy hydration.

Compatibility with organic + inorganic nutrient management

Pearl millet responds well to integrated nutrient management (INM), I ntegrated nutrient strategies combining organic sources with inorganic nitrogen fertilizers have been shown to improve nutrient availability, soil health and nitrogen use efficiency in dryland millets (Sagar *et al*., 2023).

Organic sources

FYM, compost, poultry manure, green manures enhance soil structure, microbial activity and moisture retention. These improvements create favourable conditions for root uptake of nitrogen supplied through UAN or basal urea (Meena *et al.,* 2020).

Nano urea and organics

Nano urea complements INM by providing rapid foliar nitrogen during nutrient-demand peaks, while organic nutrients build long-term soil fertility. Using nano urea after organic basal dressing can reduce total nitrogen use without compromising yield (Das *et al.,* 2024).

UAN and organics

Organic amendments reduce UAN-related risks such as salt concentration and leaf scorch. They also increase soil cation-exchange capacity, helping retain ammonium-N from UAN longer in the root zone (Mahboob *et al.,* 2023).

The comparative evaluation of nano urea and UAN indicates that both fertilizers improve nitrogen use efficiency (NUE) compared with conventional prilled urea, though through different mechanisms.

Nano urea primarily enhances foliar nitrogen delivery, bypassing soil-mediated losses such as volatilization and leaching. Its rapid absorption through stomatal pathways supports short-term physiological responses including chlorophyll synthesis and enzyme activation. However, evidence suggests that nano urea performs best as a supplement rather than a complete replacement for soil-applied nitrogen.

In contrast, UAN provides nitrogen in multiple chemical forms, enabling both immediate and sustained root uptake. This balanced supply improves nitrogen synchrony with crop demand, particularly during tillering and panicle initiation stages. Its compatibility with fertigation and precision agriculture technologies makes it more adaptable in irrigated and semi-irrigated systems.

Environmental implications also differ. Nano urea reduces direct soil nitrogen accumulation, potentially lowering nitrate leaching. However, long-term ecological effects of nano-materials require further study. UAN reduces volatilization compared with broadcast urea but may contribute to localized salinity if mismanaged.

From an economic standpoint, partial substitution strategies where nano urea replaces 25-33% of soil nitrogen or UAN is applied in split doses appear most promising for improving farmer profitability.

Overall, an integrated nitrogen strategy combining basal soil nitrogen with targeted foliar nano urea or precision UAN application may represent the most sustainable pathway for pearl millet systems.

Future research needs

Standardization of nano urea dose for pearl millet

Although nano urea is widely promoted, its crop-specific optimal dose for pearl millet remains unknown. Research on foliar nano-fertilizers shows significant variation in nanoparticle absorption among crops, suggesting that millet-specific evaluations are essential (Ramesha *et al*., 2022; Venkateshwarlu *et al*., 2021). Pearl millet's rapid early growth and distinct nitrogen uptake pattern further demand controlled dose-response studies to determine the most effective concentration and timing of foliar application. Establishing these standards will help prevent under-application and over-application, improving NUE and sustainability. Region-specific nitrogen management strategies are essential for enhancing productivity and sustainability in pearl millet systems.

Long-term environmental impact studies

While short-term agronomic benefits of nano urea are documented, major gaps remain regarding its long-term ecological behaviour. Studies on related nano-materials indicate that nanoparticles may persist in soils and influence microbial biomass and enzyme activity (Rizwan *et al*., 2019; Kah *et al*., 2018). Given these concerns, long-term monitoring across different soil textures and climatic zones is necessary to understand nanoparticle fate, mobility, interactions with soil fauna and potential risks of groundwater contamination.

Field trials across soil types of India

Nitrogen transformation differs widely among India's diverse soil systems from sandy Aridisols to clay-rich Vertisols. Research demonstrates that soil characteristics strongly influence fertilizer nitrogen availability and losses (Snyder *et al*., 2017; Chatterjee *et al*., 2021). Therefore, multi-location field trials are essential to evaluate the performance of Nano Urea and UAN across representative Indian soil types, enabling region-specific nitrogen recommendations for pearl millet farmers.

Synergistic use of nano urea + UAN

The potential integration of nano urea (foliar) and UAN (soil + foliar) offers a promising but scientifically unexplored avenue. While combined nitrogen delivery pathways have been shown to enhance crop performance in other systems (Fageria, 2014; Lawlor, 2020), no published research evaluates this synergy specifically in pearl millet. Investigations should focus on compatibility, physiological response, tank mixing safety and heat-related risks such as leaf scorch.

Impact on soil microbiome and nutrient cycling

Soil microbes govern crucial nutrient processes and evidence from nano-material research shows that nanoparticles can alter microbial diversity, enzyme activity and nutrient cycling pathways (Rajput *et al*., 2018; Chen *et al*., 2020). Because pearl millet is often grown in low-fertility, microbially active soils, it is important to examine how Nano Urea affects microbial communities, N-cycling genes and beneficial plant-associated microbes. Advanced tools such as metagenomics and soil enzyme assays should be prioritized.

CONCLUSION

Nano urea and urea-ammonium nitrate (UAN) offer promising alternatives to conventional nitrogen sources for improving nitrogen use efficiency (NUE) and productivity in pearl millet. Nano Urea enhances foliar absorption and reduces nitrogen losses, making it a suitable option for lowering chemical input requirements. However, its performance varies across environments and its ability to fully replace soil-applied nitrogen remains uncertain. UAN provides a balanced mix of nitrogen forms that support both immediate and sustained availability, often improving early crop growth and yield, though concerns such as cost and risk of leaf injury persist.

Both fertilizers have potential roles in sustainable millet production, particularly by reducing nitrogen losses and supporting precision nutrient management. Their adoption can contribute to improved yield stability in semi-arid systems where soil nitrogen limitations are common.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions.

Informed consent

Not applicable. This manuscript is a review of published literature and does not involve experiments on humans or animals.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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