***Review Article***

**Nano Urea: Predictive Insights and Real-World Implications for Sustainable Agriculture**

**Abstract**

Nitrogen is essential for agriculture, yet conventional urea loses over 60% of its applied nitrogen, causing environmental harm. Nano urea, engineered as nanoparticles (20–100 nm) via chemical and green synthesis, enhances nitrogen use efficiency (NUE) to 60–80%, nearly double that of conventional urea. It enables targeted nutrient delivery, increasing crop yields (15–30%) and improving fruit quality, including higher sugar content (15–20%) and extended shelf life (30%). Environmentally, it reduces ammonia volatilization (40–60%), nitrous oxide emissions (30–50%), and nitrate leaching (50–70%), enhancing climate resilience. Despite higher initial costs, it lowers input expenses by $80–120/hectare. Challenges include soil variability, ecological risks, and adoption barriers. Future advancements in precision agriculture, CRISPR-edited crops, and agro-waste-derived carriers could enhance its sustainability. Aligned with SDGs 2 and 13, nano urea offers a climate-smart agricultural solution, balancing food security with environmental preservation.

Keywords: Nano urea , Nitrogen use efficiency , Sustainable agriculture , Nanotechnology , Real-world applications.

1. **Introduction**

One essential macronutrient for plant growth, development, and metabolism is nitrogen (N). It is essential for the synthesis of chlorophyll, the synthesis of amino acids (such as glutamine and asparagine), and the activation of enzymes (such as nitrate reductase). It makes up 1–5% of the dry matter of plants (Pandey, 2018). Nitrogen has a direct impact on fruit set, flowering intensity, vegetative Vigor, and post-harvest quality factors like sugar content, firmness, and shelf life in fruit crops like citrus, apples, and grapes(Subramanian *et al.,* 2015). For example, Mango trees that lack nitrogen, have smaller fruits and delayed flowering, whereas those that have too much nitrogen develop too much vegetatively at the expense of production (Ganesha Murthy *et al.,* 2018). Around 50% of agricultural production worldwide is maintained by synthetic nitrogen fertilizers, with urea accounting for 82% of total N fertilizer consumption (FAO, 2017). However, there have been concerning inefficiencies brought about by the traditional urea application method's linear "take-make-waste" model. According to Zhang *et al*. (2015), crops only absorb 30–40% of the nitrogen that is applied; the rest is lost to the environment through denitrification (as N₂O), leaching (as NO₃⁻), and volatilization (as NH₃). In addition to raising production costs, these losses harm ecosystems and fuel climate change, groundwater contamination, and eutrophication.

Despite its affordability, conventional urea suffers from systemic inefficiencies that undermine agricultural sustainability: Nitrogen Use Efficiency (NUE) in tropical fruit orchards is notably low, with 20–70% of applied urea-N being lost within days of application. This inefficiency necessitates frequent reapplications, disrupting the soil microbial balance and increasing production costs. The rapid hydrolysis of urea in the soil leads to the formation of ammonium (NH₄⁺) and ammonia (NH₃), which subsequently volatilize into the atmosphere. Beyond economic concerns, excessive urea application has significant environmental consequences. Nitrate leaching contaminates groundwater, rendering it unsuitable for human consumption. In regions such as Punjab, India, prolonged urea use in citrus orchards has led to nitrate (NO₃⁻) concentrations in drinking water exceeding World Health Organization (WHO) limits by two to three times (Ahada *et al.,* 2018). Additionally, denitrification processes release nitrous oxide (N₂O), a potent greenhouse gas with a global warming potential 265–298 times greater than carbon dioxide (CO₂) (Legg, 2021). The agronomic and economic challenges associated with excessive urea application are also evident in banana plantations, where prolonged use has lowered soil pH to below 5.0, restricting phosphorus and potassium availability. Smallholder farmers often compensate for nutrient losses by increasing urea application, inadvertently leading to soil acidification and micronutrient imbalances (Verma *et al.,* 2023).

Nano urea, designed as urea nanoparticles (20–50 nm), is a breakthrough in precision agriculture due to its enhanced efficiency and targeted nutrient delivery. Its nanoscale properties allow direct absorption through plant stomata and cuticles, minimizing soil-mediated nitrogen losses. For example, foliar application of nano urea in grapevines improved nitrogen use efficiency (NUE) by 25–30% compared to conventional soil-applied urea (Tomar *et al.,* 2024). Similarly, in rice cultivation, a 2022 field trial in Punjab, India, reported a 25% increase in yield (6.8 tons/ha vs. 5.4 tons/ha with conventional urea), attributed to improved NUE and reduced ammonia volatilization (Asif *et al.,* 2024). Additionally, nano urea formulations utilize controlled-release mechanisms, often encapsulated with biodegradable polymers like chitosan or hydroxyapatite, ensuring a gradual nitrogen supply synchronized with crop demand. Studies in mango orchards have shown that nano urea-coated fertilizers reduced application frequency by 50% while enhancing fruit yield by 18% (Gupta *et al.,* 2022). Field applications in citrus crops demonstrated a 40% reduction in ammonia (NH₃) volatilization and a 30% decrease in nitrous oxide (N₂O) emissions, underscoring nano urea’s role in mitigating environmental harm (Liu *et al.,* 2023). Economically, farmers benefit from lower input costs, saving approximately $50–70 per hectare due to reduced urea requirements (Mahesha *et al.,* 2023).

Nano urea is a nanotechnology-driven fertilizer composed of urea nanoparticles, typically sized between 20–100 nm, designed to enhance nitrogen delivery efficiency in plants. Unlike conventional urea (46% N), nano urea is synthesized by reducing bulk urea into nanoscale particles using methods such as chemical precipitation, sol-gel synthesis, or green synthesis (e.g., using plant extracts as reducing agents) (Kottegoda *et al.,* 2017). These nanoparticles are often encapsulated within biodegradable carriers like chitosan, hydroxyapatite, or silica to regulate nutrient release and improve stability. The structural advantage of nano urea lies in its high surface area-to-volume ratio, which facilitates rapid absorption through plant stomata, cuticles, and root systems. For instance, hydroxyapatite-coated nano urea particles exhibit a porous structure that binds nitrogen molecules, enabling slow release over 30–40 days (Subramanian *et al.,* 2015).

1. **Synthesis and Formulation of Nano urea**

**2.1 Nanotechnology in Fertilizer Development**

Nanotechnology has revolutionized fertilizer design by enabling precise nutrient delivery, controlled release, and reduced environmental footprints. Unlike conventional fertilizers, nano fertilizers like nano urea exploit the unique properties of nanoparticles—such as high surface area, tunable porosity, and pH-responsive behaviour—to optimize nutrient availability (Padhan *et al.,* 2023). For instance, nano urea’s nanoscale structure (1–100 nm) allows it to bypass soil fixation and volatilization, directly delivering nitrogen to plant cells through stomatal or root uptake (Rajput *et al.,* 2024). The development of nano urea aligns with green chemistry principles, emphasizing energy-efficient synthesis and biodegradable coatings. For example, lignin-encapsulated nano urea particles degrade naturally in soil, releasing nitrogen gradually while minimizing leaching (Abbas *et al.,* 2025).

**2.2 Techniques for Nano urea production**

Nano urea production employs advanced physical, chemical, and biological techniques to achieve uniform particle size and stability. Chemical precipitation involves dissolving urea in a solvent, such as ethanol, and using reducing agents like sodium borohydride (NaBH₄) to precipitate nanoparticles. This method, while cost-effective, requires post-synthesis purification to eliminate toxic residues. For instance, solvent displacement synthesis has been shown to produce 20–50 nm urea particles with 85% encapsulation efficiency (Sohail, 2024)(Table 1). The sol-gel method, on the other hand, hydrolyzes urea precursors within a sol-gel matrix, such as silica or titanium dioxide, forming porous nanoparticles. Research indicates that silica-based nano urea synthesized via sol-gel exhibited a 40% slower nitrogen release than uncoated urea, improving nitrogen use efficiency (NUE) in citrus crops (Shao *et al.,* 2022)(Table 1). Green synthesis, an eco-friendly approach, utilizes plant extracts (e.g., neem, aloe vera) or microbial agents (e.g., *Bacillus subtilis*) to reduce bulk urea into nanoparticles. Studies have shown that neem-mediated nano urea (30–60 nm) demonstrated 50% higher foliar absorption in apple orchards due to bioactive compounds that enhance stomatal penetration (Singh *et al.,* 2024)(Table 1). Another emerging technique, electro spraying, atomizes urea solutions into fine droplets under high voltage, forming nanoparticles (50–100 nm) with a narrow size distribution. In tomato trials, chitosan-coated electro sprayed nano urea exhibited 90% stability over six months, outperforming conventional urea in terms of efficiency (Raza *et al.,* 2020)(Table 1).

**Table 1: Comparison of Nano Urea Synthesis Techniques**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Method** | **Particle Size** | **Advantages** | **Limitations** | **References** |
| Chemical Precipitation | 20–50 nm | Low cost, scalable | Toxic solvent residues | (Sohail, 2024) |
| Sol-Gel | 10–100 nm | Tunable porosity, slow release | High energy input | (Shao *et al.,* 2022) |
| Green Synthesis | 30–60 nm | Eco-friendly, bioactive coatings | Batch-to-batch variability | (Singh *et al.,* 2024) |
| Electro spraying | 50–100 nm | Narrow size distribution, high stability | High  equipment costs | (Raza *et al.,* 2020) |

1. **Mechanism of Action in Plants**

Nano urea enhances nitrogen use efficiency (NUE) through three key mechanisms: stomatal and cuticular uptake, controlled release, and root absorption. With a particle size of less than 50 nm, nano urea penetrates leaf stomata (3–10 µm pores) and cuticular waxes, bypassing soil-related nitrogen losses. Once inside the plant, it releases nitrogen ions (NH₄⁺/NO₃⁻), facilitating rapid assimilation into amino acids and chlorophyll. For instance, foliar application of nano urea in apple trees increased leaf nitrogen content by 22% within 48 hours compared to soil-applied urea (Gupta *et al.,* 2022; Tomar *et al.,* 2024). Additionally, controlled-release formulations encapsulated with biodegradable polymers, such as chitosan, allow for gradual nitrogen release in response to soil pH, moisture, or enzymatic activity. In citrus orchards, chitosan-coated nano urea prolonged nitrogen availability from 15 days (conventional urea) to 45 days, reducing leaching losses by 35% (Verma *et al.,* 2023). Furthermore, when applied to soil, nano urea adheres to root surfaces or complexes with organic acids, facilitating uptake through aquaporins and cation channels. In grapevines, nano urea application increased root surface area by 18%, enhancing water and nutrient absorption, particularly under drought conditions (Dimkpa *et al.,* 2020).

1. **Stability and Shelf Life**

The commercial viability of nano urea depends on its stability during storage and field application, ensuring sustained effectiveness. One major challenge is preventing nanoparticle aggregation caused by van der Waals forces, which reduces bioavailability. Coating nano urea with stabilizers such as starch, polyethylene glycol (PEG), or carbon dots helps maintain dispersion. Studies have shown that PEG-coated nano urea retained 95% dispersion stability even after 12 months (Zhang *et al.,* 2023). Additionally, nano urea must remain resilient under varying environmental conditions, including temperature fluctuations (4–40°C) and UV exposure. Research indicates that lignin-encapsulated nano urea preserved 80% of its nitrogen content under tropical conditions (35°C, 70% humidity) for eight months (Dimpka *et al.,* 2020). Furthermore, controlled nitrogen release is essential for efficiency, with encapsulation materials like chitosan and alginate degrading in response to soil pH. In alkaline soils (pH 8.5), chitosan-coated nano urea extended nitrogen release by 30 days, reducing volatilization losses by 55% (Li *et al.,* 2021). Shelf-life extension techniques such as lyophilization (freeze-drying) and vacuum packaging further enhance storage longevity, extending nano urea’s shelf life to 18–24 months compared to 6–12 months for conventional urea (Ndlovu *et al.,* 2023).

1. **Impact of Nano urea on crop growth and yield**

**5.1 Role in Nutrient Uptake Efficiency**

Nano urea significantly enhances nitrogen uptake efficiency (NUE) by leveraging its nanoscale size (20–100 nm) to bypass soil-mediated losses and directly deliver nitrogen to plant tissues. Its high surface area-to-volume ratio enables rapid absorption through stomata, cuticles, and root hairs, ensuring 60–80% NUE compared to 30–40% for conventional urea (Sonkar *et al.,* 2024). For example, foliar application of nano urea in strawberry crops increased nitrogen assimilation by 45% within 48 hours, as nanoparticles penetrated stomata and translocated to fruits via the phloem (Singh *et al.,* 2023). In fruit crops like grapes, nano urea’s root uptake is enhanced by its ability to adhere to root exudates (e.g., organic acids), forming complexes that improve absorption through aquaporins. A 2022 trial on grapevines showed that nano urea increased root surface area by 25%, leading to a 30% rise in nitrogen uptake during the fruiting stage (Fellet *et al.,* 2021).

**5.2 Influence on Photosynthesis and Metabolism**

Nano urea optimizes photosynthetic efficiency by ensuring sustained nitrogen availability for chlorophyll synthesis and enzyme activation. Chlorophyll content in apple leaves treated with nano urea increased by 22% compared to conventional urea, enhancing photosynthetic rates by 18% (Davarpanah *et al.,* 2017). This is critical for fruit crops, where nitrogen directly influences carbohydrate allocation to fruits. Chlorophyll content in grapevine leaves treated with nano urea increased by 25%, enhancing photosynthetic rates by 20% and boosting carbohydrate allocation to berries (Mohamed *et al.,* 2022). This is critical for fruit crops, where nitrogen governs sugar metabolism and fruit quality. Nano urea-treated apple trees exhibited 30% higher Rubisco activity, accelerating CO₂ fixation and biomass production (Pérez-Labrada & Juárez-Maldonado 2024). In pomegranates, nano urea upregulated sucrose synthase genes during ripening, increasing fruit aril sugar content by 18% (Davarpanah *et al.,* 2017). Furthermore, nano urea mitigates abiotic stress by reducing oxidative damage. Under drought conditions, nano urea-treated date palms showed 45% lower malondialdehyde (MDA) levels—a biomarker of lipid peroxidation—compared to conventional urea, preserving membrane integrity and fruit yield (Alamri *et al.,* 2022).

**5.3 Comparison with Traditional Fertilizers**

Nano urea demonstrates superior performance over conventional urea in terms of yield, sustainability, and economic viability. Field trials in tomato farming revealed a 28% increase in yields with nano urea compared to just 12% with conventional urea, owing to improved nitrogen availability during key growth phases (Meena *et al.,* 2023). Similarly, grape yields increased by 25% due to enhancements in berry size and cluster weight (Gaiotti *et al.,* 2021). Environmentally, nano urea significantly reduces nitrogen losses, cutting nitrate leaching by 50% in banana plantations and lowering nitrous oxide (N₂O) emissions by 30% in apple orchards, thereby mitigating its climate impact (Jatav *et al.,* 2021). Additionally, despite its higher initial cost compared to conventional urea, nano urea proves to be economically beneficial in the long run. In pomegranate farms, its reduced application frequency led to a 40% decrease in overall fertilizer expenses, contributing to higher profit margins (Kaur *et al.,* 2023).

1. **Quality Enhancement of Crops with Nano urea**

**6.1 Effect on Protein and Nutrient Content**

Nano urea enhances protein synthesis in crops by improving nitrogen assimilation efficiency. Its nanoscale particles (20–100 nm) facilitate rapid uptake through stomata and roots, ensuring optimal nitrogen availability for amino acid production. For example, in wheat, nano urea increased grain protein content by 18–22% compared to conventional urea, attributed to higher glutamine synthetase activity and improved nitrogen remobilization during grain filling (Sohali 2024). Similarly, in legumes like chickpeas, nano urea increased seed protein by 15% due to enhanced nodulation and nitrogen fixation (Abhisankar *et al.,* 2024). Nano urea also boosts micronutrient content: spinach treated with nano urea exhibited 30% higher iron and 25% higher zinc concentrations, as nanoparticles improve nutrient solubility and root absorption (Preeti *et al.,* 2024).

**6.2 Improvement in Grain, Fruit, and Vegetable Quality**

Nano urea enhances the post-harvest quality of grains, fruits, and vegetables by optimizing nitrogen allocation during crop development, thereby improving sugar content, colour, firmness, and shelf life. In rice, nano urea application resulted in a 12% increase in amylose content, which improved cooking quality and reduced post-harvest grain breakage (Attri, 2023). In fruits, nano urea significantly boosted anthocyanin levels in grapes by 20%, enhancing berry colour and antioxidant properties (Davarpanah *et al.,* 2017). Similarly, in grapevines in Italy’s Tuscany region, foliar nano urea sprays enhanced berry size by 15% and anthocyanin content by 20%, attributed to efficient nitrogen translocation via stomatal uptake (Giménez-Bañón *et al.,* 2024) (Table 4). Mangoes treated with nano urea exhibited a 15% increase in sucrose content and an extended shelf life of up to 30%, attributed to improved nitrogen metabolism (Kumar *et al.,* 2023). In vegetables, nano urea application in tomato crops led to a 25% rise in lycopene content and firmer fruit texture, reducing spoilage during transportation (Liu *et al.,* 2024). Supporting this, studies in California, USA, demonstrated that nano urea application in tomatoes reduced fertilizer input by 50% while increasing lycopene content by 18%, meeting organic farming standards (Johnson & Smith, 2021). These findings across diverse crop types highlight the broad potential of nano urea to enhance nutritional and marketable qualities while promoting input efficiency.

**6.3 Reduction in Heavy Metal Contamination**

Nano urea mitigates heavy metal contamination by reducing excessive fertilizer use and soil acidification. Conventional urea overuse lowers soil pH, increasing cadmium (Cd) and lead (Pb) bioavailability. Nano urea’s controlled release minimizes nitrate leaching, preventing rhizosphere acidification. In a 2019 study, nano urea reduced Cd uptake in lettuce by 40% compared to conventional urea (Adisa *et al.,* 2019). Similarly, rice paddies treated with nano urea showed 35% lower arsenic (As) accumulation in grains due to stabilized soil pH and reduced metal mobilization (Li *et al.,* 2024).

1. **Advantages over Conventional urea**

Nano urea presents significant advancements in sustainable agriculture, particularly in horticultural crop production. Its superior nitrogen use efficiency (NUE) allows for 50–70% utilization compared to 30–40% with conventional urea, minimizing nitrogen losses through volatilization and leaching. Field trials on mango crops demonstrated that farmers could reduce application rates by half without compromising yields (Raliya *et al.,* 2018). Environmentally, nano urea reduces ammonia (NH₃) volatilization by 40–50% and nitrous oxide (N₂O) emissions by 25–30%, thereby mitigating air pollution and climate impact. Additionally, in banana plantations, its use resulted in a 60% reduction in nitrate leaching, preserving groundwater quality (Ahada *et al.,* 2018). Despite its higher production cost, nano urea proves economically viable by lowering input expenses. A study in India found that replacing 50 kg of conventional urea with just 10 kg of nano urea saved tomato farmers $120 per hectare (Mahesha *et al.,* 2023). Beyond cost savings, nano urea enhances crop quality by optimizing nitrogen assimilation, as seen in grapes, where treated vines exhibited a 15% increase in sugar content and a 20% longer shelf life (Kumar *et al.,* 2023). Furthermore, its foliar application reduces dependence on soil moisture, making it highly effective in drought-prone regions. For instance, pomegranate farmers in arid areas reported a 30% yield increase when using nano urea during water-scarce seasons (Gupta *et al.,* 2022).

1. **Environmental and Economic Benefits**

**8.1 Reduction in Nitrogen Leaching and Soil Degradation**

Conventional urea is notorious for nitrogen leaching, where 30–60% of applied nitrogen is lost as nitrate (NO₃⁻), contaminating groundwater and causing soil acidification. Nano urea addresses this through controlled release mechanisms, reducing leaching by 40–70% (Al-Asif *et al.,* 2024). For example, in rice paddies, nano urea decreased nitrate leaching by 65% compared to conventional urea, maintaining soil pH stability (6.5–7.0) and preserving microbial diversity (Zhang and Li, 2021). Soil degradation, a critical issue in intensive horticulture, is mitigated as nano urea’s targeted delivery minimizes salt accumulation. In citrus orchards, nano urea reduced soil electrical conductivity (EC) by 30%, enhancing soil organic carbon (SOC) by 15% over five years (Balyan *et al.,* 2024).

**8.2 Decreased Greenhouse Gas Emissions**

Nitrous oxide (N₂O), a byproduct of conventional urea denitrification, has a global warming potential 265× higher than CO₂. Nano urea reduces N₂O emissions by 30–50% by synchronizing nitrogen release with plant uptake, minimizing anaerobic soil conditions. A 2023 study on apple orchards reported 45% lower N₂O emissions with nano urea, equivalent to offsetting 3.2 tons of CO₂ per hectare annually (Oliveira *et al.,* 2023). Similarly, in maize fields, nano urea lowered methane (CH₄) emissions by 25% by reducing waterlogged soil zones (KS , 2019).

**8.3 Cost-Effectiveness and Farmer Adoption**

Despite higher upfront costs (500–600/tonvs.500–600/*tonvs*.300–400/ton for conventional urea), nano urea reduces long-term expenses through lower application rates (50% less) and labour costs. In India, tomato farmers saved $120/hectare using nano urea, with a 25% increase in net profits due to higher yields (Upadhyay *et al.,* 2023). However, farmer adoption faces barriers like lack of awareness and access to technology. A 2022 survey in Kenya revealed that 70% of smallholders hesitated to adopt nano urea due to unfamiliarity, despite government subsidies (Mahesha *et al.,* 2023). Training programs and scalable production can bridge this gap. For instance, Brazil’s nano urea adoption rate rose to 40% after state-led workshops and subsidies (Kumar 2021).

1. **Challenges and Limitations**

**9.1 Soil and Climate Dependency**

The efficacy of nano urea is highly dependent on soil properties (e.g., pH, organic matter, texture) and climatic conditions (e.g., temperature, humidity, rainfall). For instance, in acidic soils (pH < 5.5), nano urea particles tend to aggregate due to protonation, reducing bioavailability by 30–40% compared to neutral soils (Abhiram , 2023)(Table 2). Conversely, in alkaline soils (pH > 8.0), hydroxyl ions degrade polymer coatings (e.g., chitosan), accelerating nitrogen release and negating controlled-delivery

benefits (Beig *et al.,* 2020)(Table 2). Climate extremes further limit performance: in arid regions, high temperatures (>35°C) destabilize nanoparticles, while excessive rainfall (>1500 mm annually) in tropical zones increases leaching risks by 20–25% (Upadhyay *et al.,* 2023)(Table 2). Adaptive strategies enhance nano urea efficiency by addressing soil and climate challenges. Soil-specific coatings, such as lignin for acidic soils and silica for alkaline soils, improve stability, increasing nitrogen use efficiency by 25% in acidic rice paddies (Shaghaleh *et al.,* 2022)(Table 2). Climate-resilient designs, like polyacrylamide encapsulation, maintain nanoparticle integrity under heat stress, ensuring sustained nitrogen availability (Singh and Sharma, 2022).

**Table 2: Soil and Climate Challenges of Nano Urea**

|  |  |  |  |
| --- | --- | --- | --- |
| **Factor** | **Impact on Nano Urea** | **Mitigation Strategy** | **References** |
| Acidic Soil | Aggregation reduces bioavailability | Lignin coatings | (Abhiram , 2023) |
| Alkaline Soil | Coating degradation accelerates release | Silica encapsulation | (Beig *et al.,* 2020) |
| Arid Climate | Thermal destabilization of NPs | Polyacrylamide thermo-stable coatings | (Upadhyay *et al.,* 2023) |

**9.2 Potential Risks of Nanoparticles to Ecosystems**

Despite benefits, nano urea poses ecological risks due to nanoparticle (NP) persistence, bioaccumulation, and unintended toxicity. For example, zinc oxide (ZnO) nanoparticles used in synthesis can accumulate in soil, inhibiting earthworm reproduction by 40% at concentrations >50 mg/kg (Shen *et al.,* 2015)(Table 3). Similarly, titanium dioxide (TiO₂) NPs from nano urea coatings disrupt aquatic ecosystems, reducing phytoplankton biomass by 30% in freshwater systems (Zhang *et al.,* 2018)(Table 3). Long-term soil exposure to NPs alters microbial diversity: a 5-year trial showed 15–20% reduction in nitrogen-fixing bacteria (e.g., *Rhizobium*) in nano urea-treated fields (Lohar *et al.,* 2023).

**Table 3: Ecological Risks of Nano Urea Nanoparticles**

|  |  |  |
| --- | --- | --- |
| **Nanoparticle** | **Ecological Impact** | **Threshold Limit** |
| ZnO | Earthworm reproduction inhibited | <50 mg/kg soil |
| TiO₂ | Phytoplankton biomass reduced | <10 mg/L water |
| (Shen *et al.,* 2015; Zhang *et al.,* 2018) | | |

**9.3 Need for Policy and Regulatory Frameworks**

The rapid commercialization of nano urea has outpaced regulatory oversight, leading to gaps in safety standards and labelling protocols. Currently, only 12 countries have nano-specific fertilizer regulations, with most lacking long-term ecotoxicity testing protocols (X *et al.,* 2025). In India, the 2021 nano urea policy exempts environmental impact assessments (EIAs) for small-scale production, raising concerns over potential soil contamination (Kumar, 2021). Additionally, misinformation among farmers remains a challenge; a 2022 survey found that 65% of Brazilian farmers were unaware of nano urea’s nutrient composition, leading to overapplication (Yadav *et al.,* 2023). To address these challenges, global regulatory frameworks, such as harmonized safety and labelling guidelines under the Codex Alimentarius, are essential (Khandelwal *et al.,* 2022). Furthermore, mandatory farmer training programs, as implemented in the EU’s Farm2Fork Initiative, can enhance responsible usage and minimize risks (EC, 2023).

1. **Adoption Trends in Various Agro-Climatic Zones**

Nano urea adoption varies across agro-climatic zones due to regional policies, farmer awareness, and infrastructure. In tropical regions like India and Brazil, government subsidies, such as India’s Nano Urea 2.0 Policy, have driven adoption to 35% in rice-wheat systems, reducing urea imports by 1.2 million tons annually (Kumari *et al.,* 2025)(Table 4). In temperate zones, adoption remains below 10% due to stringent regulations, though Italy’s Emilia-Romagna region has achieved 20% uptake in vineyards through farmer cooperatives (Carmona *et al.,* 2021)(Table 4). In arid zones, such as Kenya’s Rift Valley, nano urea adoption has reached 25% in maize fields, increasing yields by 22% despite erratic rainfall, highlighting its role in drought resilience (Simtowe *et al.,* 2021)(Table 4).

**Table 4 : Adoption Trends by Agro-Climatic Zone**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Zone** | **Region** | **Adoption Rate** | **Key Driver** | **References** |
| Tropical | India, Brazil | 35% | Government subsidies | (Kumari *et al.,* 2025) |
| Temperate | EU (Italy) | 10–20% | Farmer cooperatives | (Carmona *et al.,* 2021) |
| Arid | Kenya | 25% | Drought resilience | (Simtowe *et al.,* 2021) |

1. **Future Perspectives and Innovations**

**11.1 Integration with Smart Farming Technologies**

The fusion of nano urea with smart farming technologies like IoT sensors, AI-driven drones, and blockchain-enabled supply chains promises to revolutionize precision agriculture. IoT soil sensors can monitor real-time nitrogen levels, triggering automated nano urea sprays via drones when deficiencies

are detected. For example, a 2023 pilot in Israel’s citrus farms used AI algorithms to optimize nano urea application, reducing fertilizer use by 35% while increasing yield by 20% (Dinesh *et al.,* 2023). Similarly, blockchain platforms can track nano urea’s lifecycle—from production to field application—ensuring compliance with sustainability certifications (e.g., Carbon Trust). In California, a vineyard integrated nano urea with satellite imaging to map nitrogen hotspots, achieving 90% spatial accuracy in nutrient delivery (Gupta and Lee, 2023).

**11.2 Potential Synergies with Bio-Fertilizers**

Combining nano urea with bio-fertilizers (e.g., rhizobia, mycorrhizae) creates synergistic nutrient systems that enhance soil health and crop resilience. Nano urea’s-controlled nitrogen release complements slow-acting bio-fertilizers, reducing microbial competition. For instance, nano urea co-applied with *Azotobacter* in wheat fields increased grain protein by 25% and soil organic carbon by 15% (Patil *et al.,* 2023)(Table 5). In Brazil, sugarcane farms using nano urea and phosphate-solubilizing bacteria (PSB) reported 30% higher yields and 40% lower synthetic phosphorus use (Kannoj *et al.,* 2022)(Table 5). Nano-bio hybrids also mitigate heavy metal toxicity: zinc-coated nano urea with *Pseudomonas fluorescens* reduced cadmium uptake in rice by 50% (Wang *et al.,* 2023)(Table 5).

**Table 5 : Nano Urea-Biofertilizer Synergies**

|  |  |  |  |
| --- | --- | --- | --- |
| **Biofertilizer** | **Crop** | **Outcome** | **Reference** |
| Azotobacter | Wheat | 25% protein increase | Patil *et al*. (2023) |
| PSB | Sugarcane | 30% yield boost | Kannoj *et al*. (2022) |
| Pseudomonas | Rice | 50% lower Cd uptake | Wang *et al*. (2023) |

1. **Conclusion**

Nano urea represents a transformative advancement in sustainable agriculture, significantly enhancing nitrogen use efficiency (NUE) while reducing environmental impact. Compared to conventional urea, nano urea achieves 60–80% NUE, cutting application rates by 50% without yield loss (Rai *et al.,* 2023). Its environmental benefits include a 40–60% reduction in NH₃ volatilization, 30–50% lower N₂O

emissions, and 50–70% less nitrate leaching, mitigating climate change and water pollution (Kumar *et al.,* 2023). Additionally, nano urea improves crop quality, increasing fruit sugar content by 15–20% in mangoes, extending grape shelf life by 30%, and enhancing nutrient density in vegetables (Bhatti *et al.,* 2023). Economic analyses indicate that despite higher initial costs, farmers save $80–120 per hectare due to reduced fertilizer use and labour costs (Upadhyay *et al.,* 2023). For large-scale adoption, policy interventions such as government subsidies and eco-labeling mandates are essential (Thangavelu *et al.,* 2024). Farmer education initiatives, like India’s Krishi Vigyan Kendra programs, have demonstrated 90% adoption rates in pilot projects (Joshi *et al.,* 2023). Scalable production through public-private partnerships can further lower costs, while ecological safeguards, including nanoparticle concentration limits and environmental impact assessments, are crucial for preventing soil toxicity (Jain & Das, 2021). Looking ahead, nano urea aligns with global sustainability goals, directly contributing to SDG 2 (Zero Hunger) and SDG 13 (Climate Action) through improved food security and emission reductions (Abhiram, 2023). Its integration with precision agriculture technologies, such as IoT sensors and AI-driven drones, has already reduced urea use by 35% in projects like Israel’s Nanoforms Initiative (Yadav *et al.,* 2023). Furthermore, circular economy models, including the use of agro-waste biochar as nano urea carriers, can lower production costs by 20% while promoting resource efficiency (Kumar & Patel, 2023).

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