**Nano-Fertilizers: A Frontier in Sustainable Yield and Quality Improvement of Paddy Crop**

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**Abstract**

The rapid intensification of agriculture has raised significant concerns regarding soil health, environmental degradation, and nutrient use efficiency. In this context, nano-fertilizers, particularly **Nano Urea and Nano DAP (Nano Di-Ammonium Phosphate)**, have emerged as transformative tools in sustainable crop production. These next-generation fertilizers are engineered at the nanoscale to deliver nutrients with higher efficiency, reduced losses, and minimal environmental impact compared to conventional fertilizers. This chapter explores the role of nano-fertilizers in enhancing crop yield, improving grain quality, and promoting resource-use efficiency. It examines the physicochemical properties, mechanisms of nutrient delivery, and physiological responses of crops to Nano Urea and Nano DAP applications. Furthermore, recent field trials and case studies are presented to highlight their effectiveness across various agro-climatic conditions. The chapter also addresses challenges related to large-scale adoption, regulatory considerations, and future research needs. By integrating nano-fertilizer technology into precision and sustainable farming systems, there lies great potential to meet global food demands while safeguarding environmental and soil health.

**Keywords**: Nano Urea, Nano DAP, Nano Material (NM), Nano Particles (NPs), Sustainable Agriculture, Nutrient Use Efficiency, Crop Yield, Grain Quality, Nanotechnology in Farming.

**Introduction**

The fast expanding world population is expected to reach 9.6 billion by 2050 (UN, 2013), a 30% increase from the 2010s. Furthermore, consumer preferences for meat-based diets and rising demand for bioenergy crops are driving an increase in worldwide agricultural production. Consequently, the FAO (2009) anticipated that world grain output would need to expand by 70% by 2050 to satisfy the needs. Given the world's limited extra arable areas and restricted water supplies, increasing agricultural fertilizer application is one strategy for achieving the required huge rise in global food supply. However, in order to maintain current levels of grain output, the agricultural sector has employed a wide range of conventional fertilizers at high rates and for an extended period of time, resulting in major environmental challenges around the world. For example, high usage of nitrogen (N) and phosphorus (P) fertilizers has become a key anthropogenic component increasing global issues with eutrophication in coastal habitats and surface freshwater bodies (Conley et al., 2009; Correll, 1998), even harming people's daily lives: A significant algal bloom occurred in Lake Erie in 2014, forcing one of Ohio's largest communities (440,000 people) to limit the use of drinking water for two days (Bacon, 2014). A USGS report (Dubrovsky and Hamilton, 2010) found that 83% of shallow groundwater in agricultural zones in the US contains nitrates at levels above the USEPA's maximum contaminant level (MCl) of 10 mg L−1 due to intensive use of N fertilizers and manures. According to Rosenstock et.al. (2014), increased fertilizer applications in local intensive agriculture have resulted in an estimated N loading of 163 kilo tonne N yr−1 in Californian groundwater in the 2010s, which is twice the N loading in the 1970s (81 kilo tonne N).

For crop nutrition, farmers are using imbalance dose of granular nitrogenous & phosphatic fertilizers regularly since last few years which leads to diminishing crop yield year after year and most importantly imparts toxic effect on soil & crop health, reduces soil fertility & having high residual effect up to 2-3 years. But due to lack of awareness, farmers are used to apply new dose of fertilizers for every succeeding crop in the new crop season, they didn’t think to mobilize (re-use) previous applied dose (as residual amount) of fertilizer in the soil. Gradually soils getting toxic & unfertile which cause great loss in yield & poor quality grain. These fertilizers have low (30-40%) fertilizer use efficiency which leads to high cost of cultivation, required large amount to accomplish the nutritional supply per unit area as recommended. Nitrogenous fertilizers have great loss due to leaching & volatilization which cause low fertilizer use efficiency. Especially in the case of paddy cultivation, Rice plants require a precise number of nutrients in a specific form to be fed at the appropriate time for growth and development. Rice cultivation relies heavily on nitrogen. Nitrogen is an essential plant nutrient found in chlorophyll, amino acids, nucleotides, nucleic acids, hormones and enzymes. N accelerates plant vegetative growth and enhances yield and quality of grain by increasing; protein synthesis and tillering, leaf area/ canopy development, grain formation, grain filling. N is extremely mobile within the plant and soil. Nitrogen is the most confining element in nearly all Indian soils. Thus, effective use of N fertilizers is critical for improving vegetative growth and grain yields, particularly in intensive agricultural systems. Nitrogen is mostly supplied via urea fertilizer, which is extremely mobile in soil, causing volatilization and surface runoff issues. Urea emits dangerous pollutants into the air and soil water. It increases the concentration of ammonia in the soil, making it more acidic and reducing the soil's fertility. Urea use in the country has reached over 35 million tons, with 70% produced in India. Thus, the usage of urea pollutes water and soil and places a financial strain on farmers. As a result, there is an urgent need for research into developing new fertilizers to raise crop yields, improve plant nutrient usage efficiency, and reduce environmental disruptions for global sustainable development.

In terms of sustainable agriculture, incorporating creative nanotechnology into agriculture (including fertilizer creation) is seen as one of the most promising options to dramatically increasing crop productivity and feeding the world's fast growing population (Lal, 2008). Concerned about the low efficiency (only 30-50%) of conventional fertilizers and the lack of management alternatives to increase rates, DeRosa et al. (2010) advocated for the application of nanotechnology to fertilizer research and development. Several of these agricultural experts have been interested in the creation and implementation of nanomaterial-based fertilizers. (Ghormade et al., 2011; Khot et al., 2012; Lal, 2008; Nair et al., 2010), directly connected research is lacking. However, current nanotechnology research has shown a potential future for nanofertilizer development and application. For example, the ability of C nanotubes (CNTs) and zinc oxide nanoparticles (NPs) to penetrate tomato (Lycopersicon esculentum) plant roots or seed tissues suggests that a new nutrient delivery system can be developed by leveraging nanoscale porous domains on plant surfaces (DeRosa et al., 2010). Thus, the primary goal of this study is to collect, analyze, and synthesize the most recent information on these NPs and nanomaterials (NMs) that can boost plant development and yields while also reducing environmental hazards (such as those produced by N and P applications). These NMs are intriguing candidates for a new type of fertilizer (nanofertilizers) to address the looming concerns of food security and environmental protection.

**1. Nano fertilizers**

Nano fertilizers have lately emerged as a feasible substitute for granular chemical fertilizer in India. Nano fertilizers are nutrients that have been encapsulated or coated with nanomaterial, allowing for controlled release and delayed diffusion into the soil. Nanofertilizers can be classed as macronutrients or micronutrients. Nanofertilizers are projected to greatly boost crop growth and yields, increase fertilizer efficiency, reduce nutrient losses, and/or mitigate negative environmental impacts.

**Mechanisms of nanofertilizer uptake by plants**

If NPs are smaller than the diameters of cell wall pores (5 to 20 nm), they can enter plant cells directly through sieve-like cell wall features. However, the subsequent passage of NPs through the cell membrane, interactions with the cytoplasm, and use of NP carrying nutrients are too involved and beyond the scope of this review, in part due to a lack of related research (Nair et al., 2010). However, no research has excluded nanoparticle dispersion in water/soil solution as one of the key pathways for nutrient absorption by plant root systems.

* 1. **Macronutrient nanofertilizers**

Macronutrient nanofertilizers are chemically composed of one or more macronutrient components (for example, N, P, K, Mg, and Ca), allowing plants to get these critical macronutrients. Macronutrient fertilizers, primarily N and P, are widely utilized to boost food and fiber production. The total global usage of macronutrient fertilizer (N + P2O5 + K2O) was 175.7 million tons in 2011 and is expected to rise to 263 million tons by 2050 (Alexandratos and Bruinsma, 2012). Smil (2002) calculated that N fertilizers generated nearly 40% of the growth in per-capita food production over the last 50 years, demonstrating the importance of these macronutrient fertilizers in world food supply. Furthermore, due to the low effectiveness (30-50%) and widespread use of these macronutrient fertilizers, considerable amounts of these nutrients (N and P) are carried into surface and groundwater bodies, altering aquatic ecosystems and endangering human and aquatic life. As a result, an important and practically necessary research direction is to produce highly efficient and environmentally friendly macronutrient (N and P) nanofertilizers to replace conventional N and P fertilizers and assure sustained food production while safeguarding the environment. Thus, the development of macronutrient nanofertilizers is a top goal in fertilizer research. A brief summary of some promising macronutrient nanofertilizers is provided below:

* + 1. **Phosphorus (P) NP**s

In a greenhouse experiment, Liu and Lal (2014) produced hydroxyapatite (Ca5 (PO4)3OH) NPs of around 16 nm size and evaluated their fertilizing activity on soybean (Glycinemax) in an inert growth medium (50% perlite and 50% peat moss). Applying NPs enhanced growth rate and seed yield by 33% and 20%, respectively, compared to using a normal P fertilizer (Ca(H2PO4)2).

* + 1. **Calcium (Ca) NPs**

Liu et al. (2005) found that when CaCO3 NPs (20–80 nm, 160 mg L−1 as Ca) were applied as a Ca nutrient to peanut (Arachis hypogaea) seedlings grown in sand with Hoagland solution for 80 days, the seedlings' growth was significantly improved compared to the control (no Ca application) (e.g., dry biomass weight increased from 4.42 g per plant to 5.07 g per plant, a 15% increase). However, the improvements in dry biomass were comparable to those obtained when soluble Ca (200mg L−1 Ca(NO)3 as Ca) was applied.

* + 1. **Magnesium (Mg) NPs**

Delfani et al. (2014) found that applying 0.5 g L−1 of Mg-NP and Fe-NP solutions to black-eyed pea (Vigna unguiculata) increased 1000-seed weight by 7%, from 216 g (without Mg and Fe) to 232 g, which was higher than 191 g with regular Fe and Mg applications.

**1.2 Micronutrient nanofertilizers**

Plant micronutrients include iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and molybdenum (Mo), among others. Micronutrients are not as important for crop and plant growth as macronutrients (N, P, and K), as demonstrated by the Hoagland solution composition (Hoagland and Arnon, 1950). Micronutrients are commonly given to N, P, and K fertilizers (combined fertilizers) at modest rates (b5mgL−1) as soluble salts for crop uptake. Micronutrients in these composite fertilizers usually supply adequate nutrients while posing minimal environmental hazards. However, plant access of the applied micronutrients may be reduced, and micronutrient insufficiency may arise in some soils with an alkaline pH, coarse texture, or low soil organic matter (SOM) (Fageria, 2009). Micronutrient nanofertilizers may improve the bioavailability of these nutrients to plants even in the worst-case conditions. Because nanofertilizer production and implementation are still in their early phases, there are few, if any, particular or systematic investigations on the effects and benefits of using micronutrient nanofertilizers in the field.

### ****1.2.1 Nano-Zinc Fertilizer****

## **Nano-Zinc Fertilizer is a fertilizer prepared using zinc oxide (ZnO) or zinc sulphate (ZnSO₄) particles that are less than 100 nanometers in size. It is utilized as a micronutrient supplement in crops to address zinc deficiency and improve plant metabolic activities more effectively than traditional zinc fertilizers.**

## **1.2.2 Mode of Action of Nano-Zinc Fertilizer**

### ****Enhanced Absorption and Mobility****

* **Nanoscale particles** have a larger surface area and better solubility, facilitating **rapid uptake** through stomata (foliar application) or root pores (soil application).
* Once absorbed, **Zn ions are transported via xylem and phloem** to various plant parts.

### ****Controlled and Targeted Release****

* Nano-Zn fertilizers often exhibit **slow and sustained release**, ensuring a **longer availability** of zinc throughout the crop growth period.
* This helps maintain **optimal zinc concentration** in plant tissues without the risk of toxicity.

### ****Participation in Enzymatic and Metabolic Processes****

* Zinc acts as a **co-factor for over 300 enzymes**, including those involved in **photosynthesis, auxin synthesis, protein synthesis, and antioxidant defense**.
* Nano-Zn enhances **carbonic anhydrase activity**—essential for CO₂ fixation and photosynthesis efficiency.

### ****Improvement in Root Architecture****

* Zinc influences the production of **growth hormones (auxins)**, leading to **improved root growth**, better nutrient uptake, and drought resistance.

### ****Stimulation of Seed Formation and Grain Quality****

* It plays a key role in **pollen formation, fertilization, and seed development**, contributing to better grain filling and **enhanced nutritional quality (Zn content)** in edible parts.

## **1.2.3 Utility of Nano-Zinc Fertilizer in Agriculture**

### ****Correcting Zinc Deficiency****

* Widely used to treat **zinc-deficient soils**, especially in **alkaline, sandy, or intensively cultivated soils**, where conventional Zn becomes unavailable due to fixation.

### ****Enhancing Crop Yield and Quality****

* Improves **flowering, fruit set, seed development**, and final grain yield.
* Enhances **nutritional quality** by increasing zinc content in grains (e.g., bio fortification in rice, wheat).

### ****Boosting Stress Tolerance****

* Nano-Zn improves **plant resistance to abiotic stresses** (drought, salinity, heat) and **biotic stresses** by strengthening plant defense systems.

### ****Reducing Fertilizer Dose and Environmental Impact****

* Due to its high efficiency, **less quantity is required** (5–10 times lower than conventional Zn fertilizers).
* Reduces **residue build up, soil toxicity**, and **metal contamination**.

### ****Compatibility in Integrated Nutrient Management****

* Suitable for **soil, foliar, or fertigation use**.
* Can be **combined with other nano or conventional fertilizers**, making it flexible in nutrient schedules.

Nowadays, there are two types of nano fertilizers accessible on the market, which comprise:

**1.3 Nano Urea (Liquid):** Nano Nano Urea is a cutting-edge agricultural input based on nanotechnology that delivers nitrogen to plants. Nanourea is a sustainable choice for farmers to achieve smart agriculture and prevent climate change. These meet the plant's fertilizer requirements since nano urea is bioavailable to plants due to its desired particle size of 20-25 nm and larger surface area (1,000 times that of 1 mm urea prill). As a result, Nano Urea increases crop availability by more than 80%, resulting in better nutrient use efficiency. Furthermore, by lowering the amount of nutrients lost from agricultural fields through leaching and volatilization loss—which formerly contributed to environmental degradation and climate change—nano urea helps to lessen its impact on the environment. A bag of urea fertilizer (45 kg) is equal to one bottle of nano urea (500 ml), which is 10% less than a bag of traditional urea. It has the potential to reduce urea fertilizer imports. In contrast to conventional urea, foliar application of nano urea liquid during key stages of a plant's growth efficiently satisfies its nitrogen needs and increases crop output and quality. IFFCO (2022).

**1.3.1 Mode of Action of Nano Urea**

Nano Urea is a nitrogenous fertilizer developed using nanotechnology, where nitrogen is encapsulated in nanoparticles (typically <50 nm in size). It enhances nutrient use efficiency, minimizes nitrogen losses, and supports sustainable agriculture. Its mode of action involves **both physiological and biochemical pathways**, distinct from conventional urea.

**1.4 Nano DAP (Liquid):** Nano DAP is an effective source of accessible nitrogen and phosphorus for all crops, assisting in the correction of nitrogen and phosphate shortages in standing crops. Nitrogen (8%N w/v) and phosphorus (16% P2O5 w/v) are present in the Nono DAP formulation. Because its particles are smaller than 100 nanometers (nm), Nano DAP (Liquid) has an edge in terms of surface area to volume. It can readily enter through stomata and other plant openings or inside the seed surface thanks to this special characteristic. Bio-polymers and other excipients are used to functionalize the nitrogen and phosphorus nono clusters in Nano DAP. Better Nano DAP dispersion and assimilation within the plant system results in increased seed vigour, chlorophyll, photosynthetic efficiency, quality, and crop yields. Aside from that, Nano DAP meets crop nutritional needs through precise and targeted application while minimizing environmental impact. IFFCO (2022).

Source: <https://www.iffco.in/en/nano-fertilisers>

**Mode of Action of Nano DAP (Di-Ammonium Phosphate)**

**Nano DAP** is an advanced nano-formulation of Di-Ammonium Phosphate (NH₄)₂HPO₄, designed to supply both **nitrogen (N)** and **phosphorus (P)** in a highly efficient and targeted manner. Developed using nanotechnology, it ensures **greater nutrient use efficiency**, **minimal losses**, and **enhanced crop productivity**, especially in phosphorus-deficient soils. The following outlines the **mode of action** of Nano DAP:

### ****1.4.1 Nano-Scale Size Enables Efficient Uptake****

* Nano DAP particles are extremely small (typically <100 nm), allowing **easy penetration through plant stomata and cuticle** when applied as a foliar spray.
* Unlike conventional granular DAP, which relies on root absorption, Nano DAP enables **direct foliar uptake**, bypassing phosphorus fixation in the soil.

### ****1.4.2Targeted and Controlled Nutrient Release****

* Nano DAP provides **slow and sustained release** of nitrogen and phosphorus, synchronizing with the crop’s nutrient demand.
* This reduces the risk of nutrient leaching, volatilization, and runoff, particularly in phosphorus which tends to get fixed in soil.

### ****1.4.3 Improved Phosphorus Availability****

* Conventional DAP often becomes unavailable due to **chemical fixation in soils**, especially in alkaline or acidic conditions.
* Nano DAP, due to its nanoscale particle size and increased surface area, **remains more bioavailable** and mobile in the soil-plant system.
* Phosphorus in Nano DAP is more **soluble and accessible**, supporting early root development and energy metabolism.

### ****1.4.4 Enhanced Nitrogen Uptake and Utilization****

* The ammonium (NH₄⁺) nitrogen in Nano DAP is efficiently absorbed and **directly assimilated into amino acids and proteins**.
* It enhances **chlorophyll synthesis**, **photosynthetic efficiency**, and overall vegetative growth.

### ****1.4.5 Promotes Root and Shoot Development****

* Phosphorus is critical for **root initiation and growth**, and Nano DAP ensures adequate supply during early growth stages.
* It improves **root surface area and nutrient foraging capacity**, indirectly boosting uptake of other macro- and micronutrients.

### ****1.4.6 Activates Energy-Related Metabolism****

* Phosphorus is vital for **ATP (adenosine triphosphate) formation**, which powers all energy-driven processes in the plant.
* Nano DAP supports **faster cell division, flowering, and grain development** due to sustained phosphorus supply.

### ****1.4.7 Compatibility with Sustainable Practices****

* Nano DAP reduces the total amount of fertilizer required, aligning with **climate-smart and sustainable agriculture**.
* It is **compatible with integrated nutrient management (INM)** and can be used in combination with other foliar sprays.

**1.5 Time & Method of Application**

Nano fertilizers can be applied to paddy crops in three main ways:

**Seed treatment**

Dissolve 3–5 ml of nano fertilizer per kg of seeds in water to create a thin film on the seeds. Let it sit for 20–30 minutes, then dry in the shade and sow.

**Root treatment**

Mix 3–5 ml of nano fertilizer per liter of water. Dip the seedling roots in the solution for 20–30 minutes. Then dry in the shade and transplant.

**Foliar spray**

Mix 2–4 ml of nano fertilizer per liter of water and spray on the crop canopy/ leaves during its active growth stages. For better results, you can apply two foliar sprays. The first spray should be applied 30–35 days after germination or 20–25 days after transplanting. If it rains within 12 hours, you should repeat the spray. 2nd spray should be applied 20-25 days after 1st spray or before flowering in the crop.

**1.6 Role of Nano fertilizers:**

Nano fertilizers have many roles in agriculture, including:

**Nutrient absorption:** Nano fertilizers help plants absorb nutrients and essential compounds more efficiently. This is because the nutrients are encapsulated with nanomaterials, which allows for controlled delivery.

**Environmental impact:** Nano fertilizers are released directly to plant roots, which reduces the need for excessive fertilizer use and the risk of soil and water contamination. This helps preserve soil fertility and promote sustainable farming practices.

**Precision farming:** Nanotechnology can help predict environmental problems like drought and soil moisture, and detect seeds and pests. This helps make agriculture more sustainable.

**Crop quality and yield:** Nano fertilizers deliver macronutrients and micronutrients in a controlled manner for a longer duration, which improves crop quality and yield.

**Reducing heavy metal toxicity:** Nanobiochar can help reduce heavy metals uptake in plants, which can alleviate toxicity.

**1.7 Impact of Nano fertilizer on yield of paddy:**

The application of nano urea and nano DAP can increase the yield of paddy by 3–24%:

**Nano urea** A field experiment found that nano urea sprays resulted in a 15–21% higher yield than chemical fertilizers. The experiment also found that a 4% concentration of nano spray had a significant impact on plant growth and yield.

**Nano DAP** Field experiments conducted by the Indian Council of Agricultural Research (ICAR) and state agricultural universities found that nano DAP can increase crop yield by up to 2.4%.

**Nano DAP and nano urea** A study found that the highest grain yield was recorded when rice seedlings were dipped in nano-DAP and then sprayed with nano-DAP during the tillering stage.

Nano-sized urea particles are more easily absorbed by plant roots, which can lead to increased nitrogen uptake and improved plant growth.

**1.8 Impact of Nano fertilizer on rice quality:**

**Nutritional content:** Non-nano fertilizers can also affect the nutritional content of rice grains. Organic fertilizers, in particular, have been associated with higher protein, amino acid, and micronutrient concentrations in rice compared to chemical fertilizers.

**Grain appearance and milling quality:** The application of non-nano fertilizers can influence rice grain appearance and milling quality, which are crucial factors for market acceptance and consumer preferences. A study found that rice grains treated with organic fertilizers exhibited better grain appearance, higher head rice recovery, and lower chalkiness compared to those treated with chemical fertilizers.

**Taste and aroma:** Taste and aroma are important sensory attributes that determine the acceptability and palatability of rice among consumers. Non-nano fertilizers can influence these attributes by affecting the concentrations of flavor compounds, such as 2-acetyl-1-pyrroline, which is responsible for the characteristic aroma of aromatic rice varieties.

**1.9 Conclusion**

Based on the above listed facts, it may be concluded that The nutrient uptake, enzyme activity, soil microbial biomass, yield and post-harvest soil characteristics of rice are all greatly influenced by the use of nano-formulated N2 and P2O5 fertilizers in conjunction with seedling root dipping and soil application. Nano fertilizers are cost effective, easy to carry and apply, conserve natural resources, eco-friendly and lead to sustainability in crop production (Paddy cultivation).

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