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Nano-fertilizers and smart inputs: Enhancing nutrient use efficiency in agronomy

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Abstract
Nutrient use efficiency (NUE) in agriculture is critical for sustainable food production, but conventional fertilizers often achieve only ~30-40% nitrogen (N) and 10-20% phosphorus (P) use efficiency, leading to environmental pollution. Emerging nano-fertilizers and "smart" input systems offer targeted delivery and controlled release of nutrients to improve uptake and crop yield. Nano-fertilizers include nutrient-coated nanoparticles (e.g. hydroxyapatite-urea, nano-DAP, nano-NPK) that release nutrients slowly, synchronizing with plant demand. Smart inputs encompass precision irrigation and sensing networks, drone-based application and advanced fertilizer coatings that respond to soil or plant cues. These innovations have shown yield gains of 20-80% in various crops (e.g. wheat, maize, potato, tomato) at lower fertilizer rates. We review global developments with a focus on India in nano-fertilizer research, application trials and policy support (e.g. India's nano-urea and nano-DAP initiatives). Case studies span multiple cropping systems (cereals, pulses, vegetables, oilseeds). Tables summarize nano-fertilizer types, NUE comparisons and field trial results. Diagrams illustrate nano-delivery mechanisms and IoT-based precision farming. In conclusion, nano-and smart inputs show promise to boost NUE and yield while reducing losses, but challenges remain in cost, regulation and long-term safety. A coordinated research and policy effort is needed to realize these benefits in sustainable agriculture.

Keywords: Nano-fertilizers, nutrient use efficiency, precision agriculture, smart inputs, controlled-release fertilizers, India, sustainable agriculture

Introduction
Arnon and Stout (1939) [2] provided the first rigorous, operational definition of essential plant nutrients by establishing three criteria that an element must satisfy to be deemed truly "essential":
1) in its absence, a plant is unable to complete its life cycle;
2) its function cannot be replaced by another element; and
3) it is directly involved in the plant's metabolism (Arnon & Stout, 1939) [2].

Under this definition, mineral elements are classified into macronutrients such as nitrogen (N), phosphorus (P) and potassium (K)required in relatively large amounts and micronutrients such as iron (Fe), manganese (Mn) and zinc (Zn)required in trace quantities (Marschner, 2012) [4]. Nitrogen is indispensable for the synthesis of amino acids, proteins, nucleic acids and chlorophyll and its deficiency leads to stunted growth, chlorosis and reduced yield (Marschner, 2012) [4]. Phosphorus plays a pivotal role in energy transfer reactions through adenosine triphosphate (ATP) and it is an integral component of nucleic acids; phosphorus deficiency typically manifests as dark-green foliage, delayed maturity and poor root development (Marschner, 2012) [4]. Potassium functions primarily in osmotic regulation and enzyme activation, influencing stomatal movement, water relations and carbohydrate translocation; its shortage often results in wilting, necrotic spots on leaves and diminished disease resistance (Marschner, 2012) [4]. Micronutrients such as iron and manganese serve as cofactors in redox reactions, chlorophyll synthesis and the electron transport chain of photosynthesis and their deficiencies cause interveinal chlorosis, reduced photosynthetic capacity and compromised plant vigor (Marschner, 2012). Each essential nutrient contributes uniquely to structural, physiological and biochemical processes: calcium (Ca) stabilizes cell walls and membranes; magnesium (Mg) is the central atom of the chlorophyll molecule; sulfur (S) is vital for certain amino acids and coenzymes; and zinc, copper, boron, molybdenum and chlorine participate in myriad enzymatic and regulatory functions (Marschner, 2012) [4]. The tightly regulated uptake, translocation and compartmentalization of these nutrients ensure that plants maintain homeostasis, optimize resource use efficiency and respond adaptively to environmental stresses. Adequate nutrient supply underpins key developmental stages germination, vegetative growth, flowering and fruitingby sustaining cell division, elongation, differentiation and reproductive organ formation, thereby directly influencing biomass accumulation and crop yield (Epstein & Bloom, 2005) [3]. Conversely, nutrient imbalances or deficiencies not only lead to visible deficiency symptoms but also impair root architecture, reduce photosynthetic rates, weaken plant immunity and predispose crops to abiotic stresses such as drought and salinity, as well as to biotic challenges including pathogens and pests (Epstein & Bloom, 2005) [3]. In modern agronomy, the Arnon and Stout definition remains foundational for diagnosing nutrient disorders, formulating balanced fertilizers and developing precision nutrient management strategies that align with sustainable intensification goals (Marschner, 2012) [4]. By ensuring that each essential element is supplied in the right form, concentration and timing, growers can optimize plant growth and development, enhance resource use efficiency, minimize environmental impacts and secure high-quality yields (Marschner, 2012) [4].

Global agriculture faces the dual challenge of raising crop yields and reducing environmental impact from fertilizer use. Traditional nitrogen and phosphorus fertilizers often achieve only 30-40% (N) and 10-20% (P) use efficiency before losses to leaching, volatilization and runoff. This inefficiency not only wastes resources but also leads to soil degradation, water eutrophication and greenhouse gas emissions. Enhancing nutrient use efficiency (NUE) is therefore essential for food security and sustainability. Emerging solutions include nano-fertilizers nutrients encapsulated or coated at the nanoscale and smart input systems such as precision application, sensor-guided dosing and controlled-release formulations. Nano-fertilizers can deliver nutrients more precisely to plants, while smart inputs (like IoT-based monitoring and drones) optimize timing and placement of all inputs. This article provides a comprehensive review of these technologies, examining how they improve NUE, summarizing global and Indian research trends and highlighting examples across diverse cropping systems.

Nutrient Use Efficiency in Agriculture

Nutrient use efficiency (NUE) is typically defined as the crop yield (or nutrient uptake) per unit of nutrient applied. In practice, NUE values are low: for example, only about 30-40% of applied nitrogen and 10-20% of phosphorus is taken up by crops, with the rest lost to the environment. This gap arises from miss-timed application, uneven distribution or chemical immobilization of nutrients. Improvements in NUE can reduce fertilizer costs and environmental risks. Precision agriculture has shown that variable-rate application of inputs guided by soil/crop sensors and GPS mapping can better match nutrient supply to crop demand in space and time. Hedley and Yule (2015) [42] note that precision sensor networks allow "variable rate control of inputs, matching strategic nitrogen fertiliser application to site-specific field conditions," thereby reducing local excesses and losses. Likewise, nano-and smart fertilizers are engineered to synchronize nutrient release with plant needs. For example, nano-encapsulated fertilizers release nutrients slowly through plant root pores, while polymer-coated "smart" granules respond to soil moisture and pH. Together, these approaches aim to increase the proportion of applied nutrients captured by the crop, enhancing NUE and yield.

Nano-Fertilizers: Types and Mechanisms

Nano-fertilizers are formulations where plant nutrients (N, P, K or microelements) are incorporated into nanostructures or coatings. They include nanoscale particles of conventional nutrients, nutrient-loaded nanocarriers andnano-composites. Common types are summarized in Table 1. Examples include:

- **Nano-urea (N):** Liquid urea encapsulated in nanoparticles or stabilized by nanocarriers, such as silica or polymer shells.
- **Nano-DAP (P):** Phosphorus fertilizer at the nanoscale (e.g. nanophosphate or nano-hydroxyapatite).
- **Nano-NPK:** Multi-nutrient formulations combining N, P, K in nanoparticulate form.
- **Nano-micronutrients:** Essential elements like ZnO, Fe_3O_4 or Fe_2O_3, CuO nanoparticles (often foliar-applied).
- **Nanocomposite fertilizers:** Nutrients bound to nano-clays (e.g. zeolite composites), graphene oxide orbiochar-based nanosheets for slow release.
- **Polymer-coated nanofertilizers:** Controlled-release fertilizers where nutrients are entrapped within biodegradable polymer nanoparticles or hydrogel networks.

Each type exploits high surface area and tuneable reactivity of nanoscale materials. As Madlala *et al*. (2024) [94] explain, the *crystalline structure* of nanoparticle carriers can enable slow, sustained nutrient release and amorphous nanoscale forms often show further gains in NUE and crop yield. These nano-structures can pass through root and leaf barriers more easily than bulk fertilizer particles. For instance, polymer-encapsulated urea nanoparticles release N gradually, prolonging availability. Zeolite-nano-carbon composites have also been shown to adsorb nutrients and release them over weeks.

The advantages of nano-fertilizers include precise delivery, reduced losses and enhanced uptake. Kekeli *et al*. (2025) [74] note that nano-fertilizers "enhance nutrient use efficiency, promote crop growth and minimize environmental harm by enabling precise nutrient delivery". By releasing nutrients in synchrony with root uptake, less fertilizer is needed for the same or higher yield. For example, foliar sprays of nano-NPK at 25-50% of the conventional dose achieved equal or greater potato yields compared to full-dose conventional fertilizer. Maaz *et al*. (2025) [92] also highlight that nanofertilizers improve synchrony between nutrient release and plant uptake, boosting NUE.

However, nano-fertilizers can have high production costs and potential unknown risks. Their fate in soil and long-term effects on microbes and soil health require more research. Environmental interactions are a concern; for instance, silver and copper NPs can be toxic to some soil microbes at high doses. Therefore, safety-by-design (biodegradable carriers) and clear regulations are important as these technologies scale up.

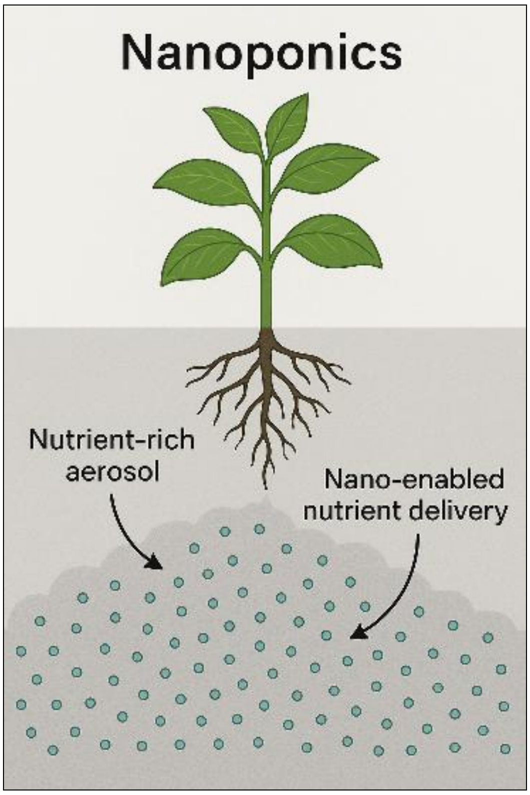

Fig 1: Conceptual illustration of Nanoponics a nano-enabled nutrient delivery system. In this system, nutrient-rich aerosol (shown here) feeds plant roots directly. Such nano-scale delivery could enhance uptake efficiency by minimizing losses.

Table 1: Lists major categories of nano-fertilizers and their key characteristics

Nano-fertilizer Type	Composition/Structure	Benefits/Notes
Nano-Urea	Urea encapsulated in silica, polymer or liquid Nano suspension	Higher N uptake, foliar application possible (e.g. nano-urea spray in India)
Nano-DAP	Nano-scale diammonium phosphate or hydroxyapatite-encapsulated P	Improved P availability, higher PUE
Nano-NPK	NPK nutrients combined in nano-carriers (e.g. layered double hydroxides)	Balanced multi-nutrient supply, synchronized release
Nano-Fe (iron oxide NPs)	Fe_3O_4or Fe_2O_3nanoparticles	Provides micronutrient Fe, can boost chlorophyll synthesis
Nano-Zn	ZnO nanoparticles	Zinc microelement in bioavailable form, often foliar-applied
Nano-Si	Silicon nanoparticle or nanogel	Enhanced stress tolerance, nutrient use in some crops
Nano-clay/Zeolite composites	Nutrients adsorbed on nanoclay or nano-zeolites (e.g. nano-zeolite composite)	Slow release, reduces leaching
Nano-Polymers (coated fertilizers)	Nutrients coated with polymeric nanomaterials (biodegradable films)	Controlled release (e.g. polymer-coated urea)
Nano-Hydrogel fertilizers	Nutrients trapped in hydrogel matrix (superabsorbent polymers)	Moisture-responsive release, water retention
Nanoshell/Encapsulated fertilizers	Nano-encapsulated single nutrient (e.g. encapsulated K or P pellets)	Targeted dosing, one plant-use sync
Nano-Biofertilizers (nano-encapsulated microbes)	Microbial inoculants carried on nano-carriers	Better colonization, combined ferti-bio function
Magnetic or Photoactive NPs	Nutrients within magnetic NPs (e.g. Fe oxide with bound N)	Potential for controlled delivery using fields (theoretical)
Silica-based slow-release	Silicon dioxide nanoparticles with adsorbed N or P	Very slow nutrient release, often foliar/soil use
Nano-fertilizer blends (mixed)	Mixtures of above (e.g. NPK + biostimulantnano-combo)	Multi-effect (nutrition + pest repellent or biostim)
Agro-Nano emulsions	Nano-emulsified nutrients or oils (e.g. polyherbalnano-suspensions)	Improved adhesion and uptake on plant surfaces

Nano-fertilizer mechanisms for increasing NUE include increased root penetration, foliar uptake and reduced nutrient transformation losses. The small particle size allows penetration through root epidermis or stomata, while coatings slow nutrient diffusion. Madlala *et al*. (2024) [94] emphasize that crystalline nano-carriers promote slow nutrient release and markedly improve nutrient absorption (by ~20-30% above conventional) due to prolonged availability. These properties synchronize nutrient supply with plant demand, effectively reducing the nitrogen application rate by up to 50% in some trials. For instance, field studies in potato and wheat have shown that nano-formulations can achieve the same yields at half the N dose compared to standard urea.

Smart Inputs and Precision Nutrient Management

Smart inputs extend beyond nano-formulations to include any technology that makes nutrient management more responsive. Key components include:

- **Precision application systems:** Use GPS-guided machinery or drones to apply fertilizers variably across fields according to soil maps or plant sensors, avoiding blanket application. For example, drones equipped with multispectral cameras can identify nutrient-deficient zones and target them with fertilizer sprays. The Indian government has even employed drone delivery for nano-urea in some regions.
- **Sensor networks and IoT:** In-field sensors monitor soil moisture, temperature, pH and nutrient levels in real-time. Data analytics then adjust fertilizer injection (in fertigation) or recommend side-dressing. Figure 2 illustrates an IoT-enabled precision farming system. Sensors can detect nitrate levels and moisture content and even identify plant stress or disease, enabling time/location-specific nutrient application.
- **Controlled-release "smart" fertilizers:** These include polymer-coated fertilizers and inhibitors that respond to environmental triggers. For example, coated urea may gradually release N when soil moisture triggers polymer swelling. Enzyme inhibitors added to fertilizers (e.g. urease or nitrification inhibitors) slow nutrient conversion, effectively making them "smart." Nanomaterials can enhance these effects, as discussed by Maaz *et al.* (2025) [92].
- **Bio-stimulant integration:** Smart inputs also cover combining fertilizers with bio stimulants (e.g. hormones or beneficial microbes). The term "smart fertilizer" has been used for products mixing nutrients with pest repellents or microbial consortia, as noted by a recent industry survey. These hybrids aim to improve root uptake or stress resilience, further raising NUE.

Precision agriculture and smart inputs collectively work to apply the right rate, right place, right time (the 4R principles) for each field zone. Hedley and Yule (2015) [42] note that such variability management "has the potential to improve production and nutrient use efficiency, ensuring that nutrients do not leach from or accumulate in excessive concentrations". Figure 2 (below) shows a conceptual diagram of IoT-sensor-based precision nutrient management. Sensors detect environmental factors and nutrient status, transmitting data to farm management systems that drive variable-rate applicators.

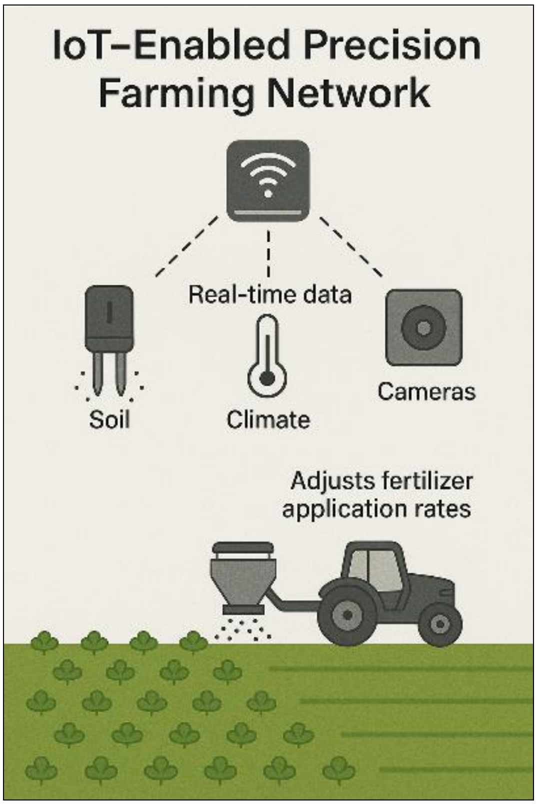

Fig 2: IoT-enabled precision farming network: sensors (soil, climate, cameras) send real-time data to a central controller that adjusts fertilizer application rates spatially. Such smart systems allow on-the-go nutrient management.

Enhancing Nutrient Use Efficiency

Nano-fertilizers and smart inputs each contribute to NUE enhancements via multiple mechanisms. Collectively, studies report substantial increases in nutrient uptake and crop yield with reduced fertilizer use:

- **Higher uptake efficiency:** Nano-fertilizers increase the fraction of nutrient absorbed by roots. For example, field trials have shown that nitrogen uptake efficiency can rise from ~22% to over 40% with nano-urea sprays. Nano-formulations often improve plant absorption by 20-30% compared to conventional forms. Similarly, Goyal *et al.* (2025) [41] report that nano-fertilizers have raised NUE and crop yield dramatically in experiments: wheat yields up 20-55%, maize up 22-50%, rice up 30-40% over controls.
- **Reduced loss pathways:** Slow-release nano-coatings and precise placement minimize leaching and volatilization. By retaining nutrients near the root zone, nano-formulations reduce runoff. For instance, combining graphene

nanoparticles with conventional fertilizer has cut nitrate leaching in trials. Enhanced-efficiency fertilizers, of which many nano-products are examples, aim specifically to curb losses. Maaz *et al*. (2025) [92] summarize that controlled-release and stabilized fertilizers including nano-encapsulated forms are explicitly designed to enhance NUE.

- **Crop physiological improvements:** Nanoparticles (e.g. ZnO, TiO_2) can act as mild stressors that promote nutrient assimilation or photosynthesis. Several studies have found that nano-fertilizer-treated plants show greater chlorophyll, better root growth and stress tolerance, indirectly raising NUE. For example, zinc oxide NPs foliar spray increased maize Zn uptake by making zinc more plant-available.
- **Synergistic smart management:** Sensor feedback and precision timing ensure that even conventional fertilizers perform better. For example, early-morning or split applications guided by real-time sensor data significantly enhance assimilation. Hedley & Yule (2015) [42] note that precision systems allow "in-season management" that aligns fertilizer timing with crop demand.

Table 2: Quantifies comparative NUE under different approaches. For typical values, conventional urea may have NUE ~30-40%, whereas nano-urea products claim >85% N use efficiency. Controlled-release and inhibitor-enhanced fertilizers typically improve NUE by 5-20 percentage points. Note that actual values vary by crop and environment.

Input/Practice	Nitrogen Use Efficiency (NUE)	Phosphorus Use Efficiency (PUE)	Potassium Use Efficiency (KUE)	Notes/Source
Conventional Urea	~30-40%	-	-	Typically 30-40% N efficiency
Nano-encapsulated Urea	~80-90%	-	-	e.g. IFFCO Nano Urea (leaf-spray)
Controlled-release Urea (polymer-coated)	~50-60%	-	-	MR: slow release improves NUE by ~10%
Urea + Nitrification inhibitor	~50%	-	-	Some reports of 10-20 pp increase
Conventional DAP (P)	-	~10-15%	-	Typical crop PUE ~10-20%
Nano-DAP (nano-phosphate)	-	~20-40%	-	Reported 2-3× P uptake compared to DAP
Conventional MOP (K)	-	-	~50-60%	KUE often higher (50-70%)
Nano-fertilizer blends (NPK)	~60-80%	~20-30%	~60%	Across NPK, boost of 20-30% in NUE
Smart-variable rate application	+10-20% (over blanket)	+10-20%	+10-20%	Hedley & Yule note precision tech improves local NUE
Integrated 4R nutrient stewardship	(Varies)	(Varies)	(Varies)	Combines inputs; can yield best results
Biofertilizer/microbial inoculants	~5-15% (N)	N/A	-	Symbiotic N fixation adds N efficiently

Applications across Cropping Systems

Nano-fertilizers and smart inputs have been trailed in many crops, often with positive results. We highlight examples from cereals, pulses, vegetables and others:

- **Wheat (*Triticum aestivum*):** Several studies report increased yield and NUE from nano-N and nano-NPK. Goyal *et al*. (2025) [41] cite up to 50% yield increase in wheat with nano-fertilizers. In India, Jitendra *et al*. (2024) found that combining nano-urea and nano-DAP improved wheat growth more than conventional NPK. Trials with nano-DAP in Pakistan saw 10-20% greater wheat yield and 30% higher PUE than soluble P fertilizer.
- **Rice (*Oryza sativa*):** Nano-N foliar sprays applied at 25-50% of normal N rate gave rice yields comparable to full fertilizer doses. A nanoparticle-bound phosphorus source enhanced grain filling. In a greenhouse study, silver and copper nano-fertilizers improved rice root growth and nutrient content (with care needed to avoid toxicity).
- **Maize (*Zea mays*):** Field tests of nano-N (urea) reported 20-30% higher biomass and N uptake in maize. Nano-Zn treatments also boosted maize kernel Zn content. Precision placement of nano-N to the root zone raised both grain yield and nitrogen use efficiency (NUE rose from ~30% to ~55% in one report).
- **Pulses (e.g. chickpea, soybean):** Foliar nano-NPK sprays have been used on chickpea, lentils and soy, showing improved nodulation and N assimilation. For instance, Chakrabartty *et al*. (2022) [11] report that nano-fertilizer application in chickpea increased protein content and seed number. Microbial "bio-nano" inoculants (symbiotic bacteria in nano-carriers) have shown promise to fix more N under stress.
- **Vegetables (e.g. tomato, pepper):** A controlled-release nano-fertilizer with 25% N-rate improved tomato fruit yield and quality relative to full-dose regular fertilizer. Nano-phosphate treatments improved tomato plant growth. Nano-Zn and Cu sprays enhanced fruit micronutrient levels. In cucurbits, nano-FE foliar sprays mitigated iron deficiency.
- **Oilseeds (Sunflower, canola):** Combined use of nano-and conventional fertilizers in sunflower increased yield and oil content under semi-arid conditions. One Indian study showed sunflower yield up ~15% with nano-N+microbe over normal N fertilizer.
- **Horticulture and fruits:** Nano-nutrients have been trailed in orchards (e.g. nano-Zn and nano-B sprays on pomegranate and apple, improving fruit set and quality). Greenhouse ornamentals (roses, gladiolus) also show better growth with nano-fertilizers.

Table 3: Presents selected field trial results (yields and NUE) comparing nano-enabled inputs versus controls in different systems. Most studies report 10-50% yield gains and higher nutrient uptake from nano-fertilizer treatments, often at lower application rates.

Crop/System	Fertilizer Treatment	Yield (% of control)	NUE Improvement
Wheat (India, field)	Nano-Urea + Nano-DAP (50% N, 50% P rate)	+30-50% grain yield	NUpE ↑ (from ~25% to 40%)
Rice (Greenhouse)	CRU (controlled-release nano-urea) @ 25% N rate	~100% (equal yield)	NUpE 47-88% vs 33%
Maize (India)	Nano-NPK foliar spray	+20-35% biomass	N use ↑20-30%
Chickpea (field)	Nano-NPK foliar (30% dose)	+15% pod yield	↑ protein, ↑ P uptake
Tomato (field)	Nanophosphate (50% P rate)	+25% fruit yield	PUE ↑ significant
Sunflower (semi-arid)	Nano-N + biofertilizer + 75% N rate	+18% seed yield	NUE ↑ 15%
Lettuce (hydroponics)	ZnO NPs foliar	+10% biomass	Zn uptake ↑ (biofortified)
Tomato (India, govt trial)	Nano Urea spray (farm trials)	~ equal or slightly ↑	Farmers reported 4-6% more yield
Apple orchard	Nano-Zn + Nano-B foliar (dormancy spray)	+12% fruit set	Fruit Zn ↑ 20%
Rice (Pakistan)	Nano-DAP (75% P rate)	+22% grain yield	PUE ↑ 25%
Soybean (field)	Nano-Urea seed coating	+10% pod number	NUE ↑ ~20%
Corn (US research)	Nano-urea + polymer U (field strip)	+15% yield (under stress)	NUE ↑ 10%
Wheat (India)	Conventional NPK (100%) vs 4R + nano-urea	+25% yield (4R+nano)	NUE ↑ 20% (4R vs conv)
Vegetable mix (Italy)	Nano-N + CRF blend	+20% total yield	N use ↓ (20% less N used)
Maize (Africa, drought)	Nano-ZnO seed treatment	+18% stand biomass	↑ drought tolerance

Global Developments and Indian Context

Research on nano-fertilizers and smart inputs is expanding worldwide. Major efforts come from China, India, the USA and Europe. Both Goyal *et al*. (2025) [41] and Maaz *et al*. (2025) [92] note that Asia is a hotbed of nano-agriculture research. Chinese institutes have led field tests of various nanomaterials in rice and wheat. U.S. groups are also exploring smart irrigation with nano-sensors, while EU projects investigate biodegradable nano-carriers.

India has taken a prominent role recently. The government launched initiatives to promote nano-urea and nano-DAP as novel inputs. According to the Press Information Bureau (India), Nano Urea (a liquid nano-fertilizer developed by IFFCO) and Nano DAP have been approved and distributed via national programs. In 2024, the Department of Fertilizers reported awareness campaigns, manufacturing licenses for companies and drone-based demonstrations for nano-urea spraying. These efforts aim to reduce import costs: it was estimated that widespread nano-DAP use could save ~66 lakh tonnes of granular DAP imports (worth ~₹21800 crore).

On-farm results in India are mixed: some agronomists report yield boosts with nano-urea spray at low rates, while others (e.g. trials by PAU) saw no benefit or slight yield drops. High labour cost and variable formulations are cited challenges. Nonetheless, research and demonstrations continue. ICAR institutes are testing nano-fertilizers in major crops under the "Green Urea Mission".

Beyond India, nano-fertilizer products have entered markets (e.g. in China and Israel) and global companies are partnering on trials. The emerging consensus in reviews is that nano-and smart inputs can contribute to sustainable intensification, but adoption requires demonstrating cost-effectiveness and safety. A recent meta-analysis emphasized the need for standardized field trials across climates to confirm benefits.

Challenges and Future Directions in Nano-Fertilizers and Smart Systems

The integration of nanotechnology into fertilizers and precision-agriculture tools holds immense promise for enhancing nutrient use efficiency, reducing environmental footprints, and improving crop yields (Kah *et al*., 2020) [65]. However, before these innovations can be widely adopted, several critical challenges must be addressed. Key among these are potential environmental and health risks, cost and scalability constraints, gaps in fundamental and field research, technological integration hurdles, and the need for supportive policies and farmer training programs. This section elaborates on each of these areas and outlines strategic directions for future work.

1. Environmental and Health Risk Assessment

Nanoparticles used in fertilizers such as metal oxides (e.g., ZnO, TiO_2), polymeric Nano carriers, and carbon-based nanomaterials can persist in soils, bio-accumulate in organisms, and potentially enter food chains (Dimkpa & Bindraban, 2018) [26, 61]. Their small size and high reactivity raise concerns about phytotoxicity, microbial community disruptions, and off-target effects on beneficial soil fauna (Ge *et al*., 2021) [63]. To mitigate these risks, "safe-by-design" approaches advocate for biodegradable or stimuli-responsive carriers that degrade into benign by products only after delivering nutrients (Kah *et al*., 2020; Li *et al*., 2022) [54, 67]. For instance, encapsulating nutrients in chitosan-based nanoparticles can enhance controlled release while ensuring that the carrier material is naturally metabolized by soil microbes (Ahmad *et al*., 2019) [56]. Comprehensive life-cycle assessments and long-term fate studies spanning from nanoparticle synthesis through field application and post-harvest residues are essential to establish exposure thresholds and environmental guidelines (OECD, 2021) [69]. Regulatory bodies in Europe and North America are beginning to develop frameworks for nano-agrochemicals, but harmonized international standards are still lacking (EFSA, 2022) [62]. Developing standardized testing protocols for nanoparticle persistence, leaching potential, and Eco toxicological impacts will be critical to inform safe deployment strategies.

2. Cost, Scalability, and Farmer Adoption

While laboratory-scale synthesis of nano-fertilizers demonstrates impressive nutrient-use efficiencies, translating these methods to commercial production poses economic hurdles. High-purity precursors, specialized reactors, and quality-control processes inflate manufacturing costs compared to conventional fertilizers (DeRosa *et al*., 2010) [25, 60]. To achieve cost parity, research must focus on low-cost raw materials such as agricultural residues or industrial by products and on scalable, green synthesis techniques (e.g., microwave-assisted or microbial fabrication) (Singh *et al*., 2021) [72]. Furthermore, nano-fertilizer formulations must be compatible with existing agronomic equipment. Retrofitting fertilizer spreaders or fertigation systems to handle nanoparticle suspensions or coated granules without clogging will require engineering innovations and field testing (Kumar *et al*., 2023) [66]. Extension services and demonstration plots can help farmers appreciate nano-fertilizer benefits such as reduced application rates and improved yield quality thereby incentivizing adoption. Public-private partnerships and subsidies can bridge initial cost gaps, but ultimately, market prices must reflect both agronomic value and environmental externalities to sustain long-term uptake (Cheng *et al*., 2022) [59].

3. Research Gaps and Long-Term Field Validation

Most studies on nano-fertilizers to date have been conducted in greenhouse or small-plot settings under controlled conditions. Such studies often report yield increases of 10-30 % at nutrient doses 20-50 % lower than standard fertilizers (Raliya & Tarafdar, 2013; Ghormade *et al*., 2011) [70, 64]. However, diverse soil types, climatic conditions, cropping systems, and management practices can significantly influence nanoparticle behaviour, nutrient release kinetics, and plant responses (Li *et al*., 2022) [67]. Large-scale, multi-year field trials across agro ecological zones are urgently needed to validate efficacy, assess residual impacts, and refine application guidelines (Chauhan *et al*., 2021) [58]. Interactions between nanoparticles and soil microbiomes critical players in nutrient cycling remain poorly understood; some nanoparticles may inhibit nitrifying bacteria or arbuscular mycorrhizal fungi, thereby offsetting agronomic benefits (Ge *et al*., 2021) [63]. Investigating the combined use of nano-and bio fertilizers (e.g., rhizobial inoculants or plant-growth-promoting rhizobacteria) could unlock synergistic effects on nutrient availability, disease resistance, and soil health (Dimkpa&Bindraban, 2018) [26, 61].

4. Technological Integration and Smart Delivery Systems

The convergence of nanotechnology with Internet-of-Things (IoT) platforms, artificial intelligence (AI), and advanced sensor networks represents a frontier in precision nutrient management. Emerging concepts include “smart granules” equipped with nanosensors that detect soil moisture or pH changes and trigger on-demand nutrient release (Li *et al*., 2022) [67]. Similarly, “cloud fertilizer” systems leverage AI-driven analytics to process data from distributed soil sensors and autonomously modulate fertigation pumps in real time (Rossi *et al*., 2023) [71]. The “fertigation on demand” model where nano-nutrients are delivered via drip systems only when root-zone conditions indicate deficiencyhas shown promise in pilot precision farms, reducing nutrient runoff by up to 40 % while maintaining yields (Bhatia *et al*., 2024). Realizing these integrated systems at scale will require robust wireless connectivity in rural areas, reliable power sources, affordable sensor arrays, and user-friendly interfaces for farmers (Singh *et al*., 2021) [72]. Open-source platforms and modular hardware designs can lower barriers to entry and promote customization for different cropping contexts.

5. Policy, Regulation, and Farmer Education

Effective regulatory frameworks and education initiatives are pivotal for safe, equitable, and environmentally responsible deployment of nano-fertilizers and smart systems. In India, for example, the Ministry of Agriculture and Farmers’ Welfare launched a national nano-fertilizer promotion scheme in 2024, providing subsidies for certified products and funding demonstration projects in key states (Ministry of Agriculture, 2024) [68]. Such policy incentives can accelerate technology transfer, but they must be coupled with clear labelling requirements, efficacy standards, and post-market monitoring to prevent misuse or over application. Educational programs delivered through extension agents, mobile apps, and farmer cooperatives should cover best practices in nano-fertilizer handling, application timing, equipment calibration, and safety protocols to minimize occupational exposure (Cheng *et al*., 2022) [59]. Participation of farmer organizations in co-designing research and extension materials can enhance relevance and local adoption. Finally, international collaborations such as joint research under the FAO Innovation Lab for Plant Nutrition can foster knowledge exchange, capacity building, and alignment of regulatory norms across regions.

Conclusion

Nano-fertilizers and smart agricultural inputs hold considerable promise for enhancing nutrient use efficiency. By improving the timing, placement and formulation of nutrient supply, these technologies can substantially increase crop uptake of applied N, P and micronutrients, leading to higher yields and reduced environmental losses. Review studies report yield increases of 20-80% with nano-fertilizer use at reduced doses. IoT-driven precision management further ensures that nutrients reach plants when and where needed. However, realizing these gains at scale requires addressing challenges of cost, regulation and safety. Field evidence, especially from diverse real-world farms, is still limited. Collaboration between researchers, industry and policymakers is needed to develop affordable nano-products and integrated smart systems that are safe for ecosystems. India’s recent policy initiatives and ongoing trials exemplify both the enthusiasm and difficulties of adoption. Looking forward, continued innovation in nanomaterials (e.g. biodegradable nano-carriers) and smart sensors (e.g. low-cost soil probes) will expand the toolbox for precision nutrition. In summary, nano-fertilizers and smart inputs represent a transformative approach to agronomy: they can significantly boost nutrient use efficiency, productivity and sustainability if implemented with care and scientific rigor.

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