

**Review Article****NANO FERTILIZERS IN CLIMATE-SMART AGRICULTURE: A COMPREHENSIVE REVIEW OF MECHANISMS, SOIL HEALTH, INNOVATION TRENDS, AND ECONOMIC PERSPECTIVES***Raju Kumar*Division of Soil Science, Mahatma Gandhi Kashi Vidyapith (MGKVP),  
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**Abstract**

The intensification of agriculture under changing climatic conditions has exposed critical inefficiencies in conventional fertilizer systems, particularly low nutrient use efficiency (NUE) and significant greenhouse gas (GHG) emissions. Nitrogen losses through volatilization, leaching, and denitrification not only reduce agronomic productivity but also contribute substantially to environmental degradation. In this context, nano fertilizers have emerged as a transformative innovation with strong relevance to climate-smart agriculture (CSA), which seeks to simultaneously enhance productivity, improve resilience, and mitigate emissions. This review critically evaluates the mechanistic basis, agronomic potential, environmental implications, and innovation trajectories of nano fertilizers. Nano fertilizers, engineered at dimensions of 1–100 nm, exhibit enhanced surface reactivity and controlled-release properties, enabling targeted nutrient delivery and improved crop performance under abiotic stress. Recent advances in nano-encapsulation and precision delivery systems demonstrate their growing integration within sustainable agricultural frameworks. Beyond yield enhancement, nano fertilizers can positively influence soil biological processes. Crucially, reduced nitrogen losses translate into lower nitrous oxide emissions, directly supporting CSA mitigation goals. However, uncertainties regarding nanoparticle persistence, ecotoxicological impacts, and regulatory governance necessitate comprehensive risk assessment. This review finds that while nano fertilizers hold immense promise for advancing CSA, their strategic and responsible adoption—guided by robust science and policy—is essential to realize a resilient, resource-efficient, and low-carbon food production system.

**Keywords:** Nano fertilizers; Climate-smart agriculture; Nutrient use efficiency; Soil health; Greenhouse gas mitigation; Sustainable agriculture

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## Introduction

Global agriculture is undergoing unprecedented pressure due to rapid population growth, increasing food demand, resource scarcity, and accelerating climate change. Rising global temperatures, irregular precipitation patterns, prolonged droughts, and extreme weather events are significantly affecting crop productivity and soil health. At the same time, agricultural intensification has led to excessive dependence on synthetic fertilizers to meet production targets. Although chemical fertilizers have played a pivotal role in boosting crop yields since the Green Revolution, their inefficient use has created serious environmental and sustainability challenges.

Nitrogen use efficiency (NUE) in conventional agricultural systems remains critically low, often below 50%, meaning that a substantial portion of applied nitrogen is lost through ammonia volatilization, nitrate leaching, runoff, and denitrification. These losses not only reduce agronomic efficiency but also contribute to groundwater contamination, eutrophication of aquatic ecosystems, soil degradation, and emission of nitrous oxide (N<sub>2</sub>O), a greenhouse gas with a global warming potential nearly 300 times greater than carbon dioxide. Similar inefficiencies exist for phosphorus and micronutrient fertilizers, further intensifying nutrient imbalances in soils.

This creates a fundamental paradox for agriculture: how can we intensify production to meet future food demands—projected to require a 60-70% increase by 2050—without further exacerbating climate change and environmental degradation? This challenge is compounded by the fact that agriculture currently contributes an estimated 20-30% of global greenhouse gas emissions. This "wicked problem" demands a fundamental shift from input-intensive practices to knowledge-intensive, precision-based strategies that can decouple food production from environmental harm.

In response to these challenges, the concept of Climate-Smart Agriculture (CSA) has gained global recognition as a holistic framework for sustainable agricultural development. CSA is built upon three interconnected pillars: (i) sustainably increasing agricultural productivity and incomes, (ii) enhancing resilience and adaptive capacity to climate variability, and (iii) reducing or removing greenhouse gas emissions where possible. Achieving these objectives requires innovative nutrient management strategies that improve resource use efficiency while minimizing environmental externalities.

Nanotechnology has emerged as a transformative scientific advancement with significant implications for agricultural sustainability. Nano fertilizers, engineered at nanoscale dimensions (1–100 nm), possess unique physicochemical properties such as high surface area-to-volume ratio, enhanced reactivity, tunable surface chemistry, and controlled-release capabilities. These characteristics distinguish nano fertilizers from conventional bulk fertilizers and provide opportunities to redesign nutrient delivery systems for improved efficiency and reduced environmental impact.

Unlike traditional fertilizers that release nutrients rapidly and often exceed plant demand, nano fertilizers can be formulated to enable slow and synchronized nutrient release. This targeted delivery enhances nutrient uptake efficiency, reduces leaching and volatilization losses, and improves crop physiological performance. Moreover, nano-scale particles can facilitate better interaction with root surfaces and enable efficient foliar penetration through stomatal openings, thereby increasing nutrient bioavailability.

Beyond nutrient delivery efficiency, nano fertilizers may also contribute to improved soil biological functioning. Soil microorganisms play a crucial role in nutrient cycling, organic matter decomposition, and soil structure stabilization. Emerging evidence suggests that

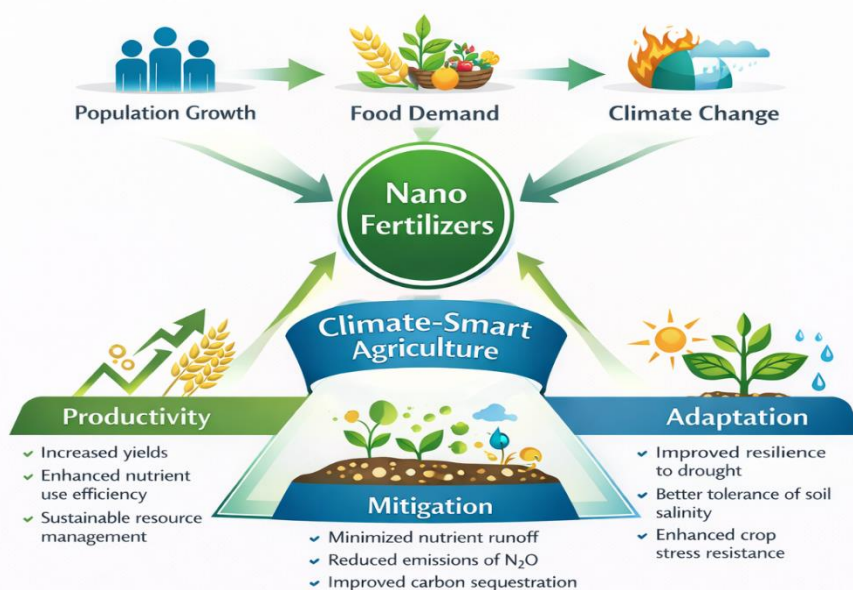
certain nano-formulations can stimulate beneficial microbial activity, enhance enzymatic functions such as urease and dehydrogenase, and improve rhizospheric interactions. These effects have direct implications for long-term soil fertility and resilience under climate stress conditions.

Recent years have witnessed rapid innovation and commercialization efforts in nano-enabled agricultural inputs. Patent landscape analyses reveal increasing global research and development activities in nano-encapsulation systems, nanomaterial-based fertilizers, precision nutrient delivery technologies, and microbe-assisted nano formulations. This growing technological interest reflects the strategic importance of nano fertilizers in supporting climate-smart and sustainable agriculture. However, despite promising agronomic and environmental benefits, concerns remain regarding nanoparticle persistence in soils, potential ecotoxicological effects, regulatory uncertainties, and long-term sustainability assessments.

Given the dual challenge of ensuring food security while mitigating environmental degradation, it is essential to critically evaluate the role of nano fertilizers within the CSA framework. A comprehensive understanding of their mechanisms of action, agronomic performance, soil biological impacts, innovation trends, and potential risks is necessary to guide responsible adoption and policy formulation.

Therefore, this review aims to synthesize current scientific knowledge on nano fertilizers and examine their relevance to climate-smart agriculture. Specifically, it evaluates (i) the conceptual basis and classification of nano fertilizers, (ii) mechanisms underlying enhanced nutrient use efficiency, (iii) contributions to productivity, adaptation, and mitigation, (iv) impacts on soil biological health, (v) emerging patent and innovation trends, (vi) environmental and regulatory considerations, and (vii) economic feasibility and adoption challenges. By integrating technological advancements with sustainability principles, this review seeks to provide a comprehensive perspective on the future prospects of nano-enabled nutrient management in resilient and low-carbon agricultural systems.

### Conceptual Framework of Nano Fertilizers in CSA



## **Classification and Types of Nano Fertilizers**

Nano fertilizers can be broadly classified based on their composition, mode of action, and nutrient delivery mechanism. Understanding this classification is crucial for evaluating the specific applications and benefits of these systems within climate-smart agriculture.

### **Based on Composition**

#### ***Macro-nutrient Nano Fertilizers***

These formulations deliver primary nutrients—nitrogen, phosphorus, and potassium—in nanoscale forms. Nano-nitrogen fertilisers, such as nano-urea, have garnered particular attention due to their ability to reduce application rates while maintaining or even improving crop yields. Nano-phosphorus fertilizers, often synthesized as hydroxyapatite nanoparticles, enhance phosphorus availability by reducing fixation in soils. Nano-potassium fertilizers improve potassium uptake efficiency and stress tolerance.

#### ***Micro-nutrient Nano Fertilizers***

These include formulations of essential micronutrients such as zinc oxide (ZnO), iron oxide (Fe<sub>2</sub>O<sub>3</sub>), copper oxide (CuO), manganese, and boron nanoparticles. Nano-zinc and nano-iron are particularly effective in correcting hidden deficiencies and enhancing crop physiological performance under stress conditions.

#### ***Nano-composite Fertilizers***

These combine multiple nutrients within a single nanoscale carrier, enabling simultaneous delivery of macro and micronutrients. Nano-composites may also incorporate growth promoters, bio-stimulants, or beneficial microorganisms to enhance overall crop performance.

### **Based on Mode of Delivery**

#### ***Controlled-Release Nano Fertilizers***

Nutrients are encapsulated within nanoscale carriers such as polymer matrices, zeolites, or clay minerals. Release is regulated by environmental triggers, including moisture, temperature, pH, or enzymatic activity, ensuring synchronization with plant demand.

#### ***Targeted Nano Fertilizers***

These formulations are designed for site-specific delivery to particular plant tissues or rhizosphere zones. Surface functionalization with specific ligands enables recognition by root cells or foliar structures, enhancing uptake efficiency.

#### ***Carrier-Based Nano Fertilizers***

Nanomaterials such as carbon nanotubes, graphene oxide, or silica nanoparticles serve as carriers for nutrient loading. These carriers protect nutrients from environmental losses and facilitate controlled release.

## **Mechanisms of Action of Nano Fertilizers**

Nano fertilizers improve nutrient delivery efficiency through multiple physicochemical and biological pathways. Unlike conventional fertilizers, which often release nutrients rapidly and exceed plant uptake capacity, nano fertilizers are engineered to

synchronize nutrient release with plant demand. Their nanoscale size (1–100 nm) provides unique properties that enhance nutrient absorption, translocation, and utilization within plant systems.

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

One of the most significant advantages of nano fertilizers is their controlled-release behavior. Nutrients can be encapsulated within nano-carriers such as polymer matrices, metal oxides, or biodegradable coatings. These nano-encapsulation systems regulate nutrient diffusion in response to environmental triggers, such as moisture, temperature, or root exudates.

This controlled release:

- Prevents sudden nutrient spikes
- Reduces nitrate leaching
- Minimizes ammonia volatilization
- Improves synchronization with crop nutrient demand

As a result, nutrient use efficiency (NUE) is substantially enhanced compared to conventional fertilizers.

### ***Enhanced Root Uptake Efficiency***

Due to their extremely small particle size, nano fertilizers exhibit higher surface reactivity and mobility in soil systems. Nano-scale particles can:

- Penetrate root epidermal layers more efficiently
- Increase contact area with root hairs
- Enhance nutrient diffusion across membranes

This improves nutrient absorption kinetics and facilitates efficient translocation to aerial plant parts. Increased root–nano interaction also enhances rhizospheric nutrient availability.

### ***Improved Foliar Penetration***

Nano fertilizers applied through foliar spray can enter plant tissues via:

- Stomatal openings
- Cuticular pores
- Trichomes

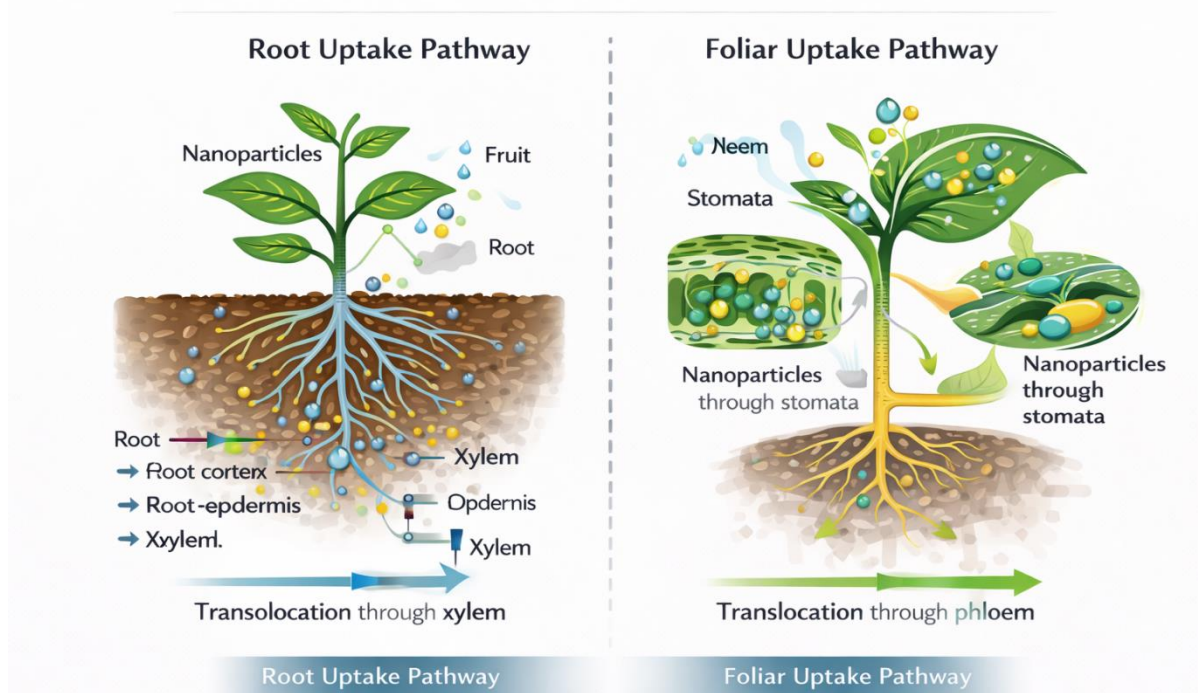
Their small size enables easier penetration compared to bulk fertilizers. Once inside, nano nutrients are translocated through phloem and xylem pathways, ensuring uniform distribution within plant tissues.

This mechanism is particularly effective for:

- Nano urea
- Nano zinc
- Nano iron

Foliar nano application often requires a lower dosage while achieving comparable or superior results.

## Mechanisms of Nano Fertilizer Uptake in Plants



### *Reduced Nutrient Losses and Environmental Emissions*

Conventional nitrogen fertilizers are prone to:

- Nitrate leaching into groundwater
- Ammonia volatilization
- Nitrous oxide (N<sub>2</sub>O) emission

Nano fertilizers reduce these losses through:

- Slow nutrient release
- Improved root uptake
- Reduced exposure to soil nitrification–denitrification pathways

Lower nitrogen losses translate directly into reduced greenhouse gas emissions, aligning nano fertilizers with climate mitigation strategies.

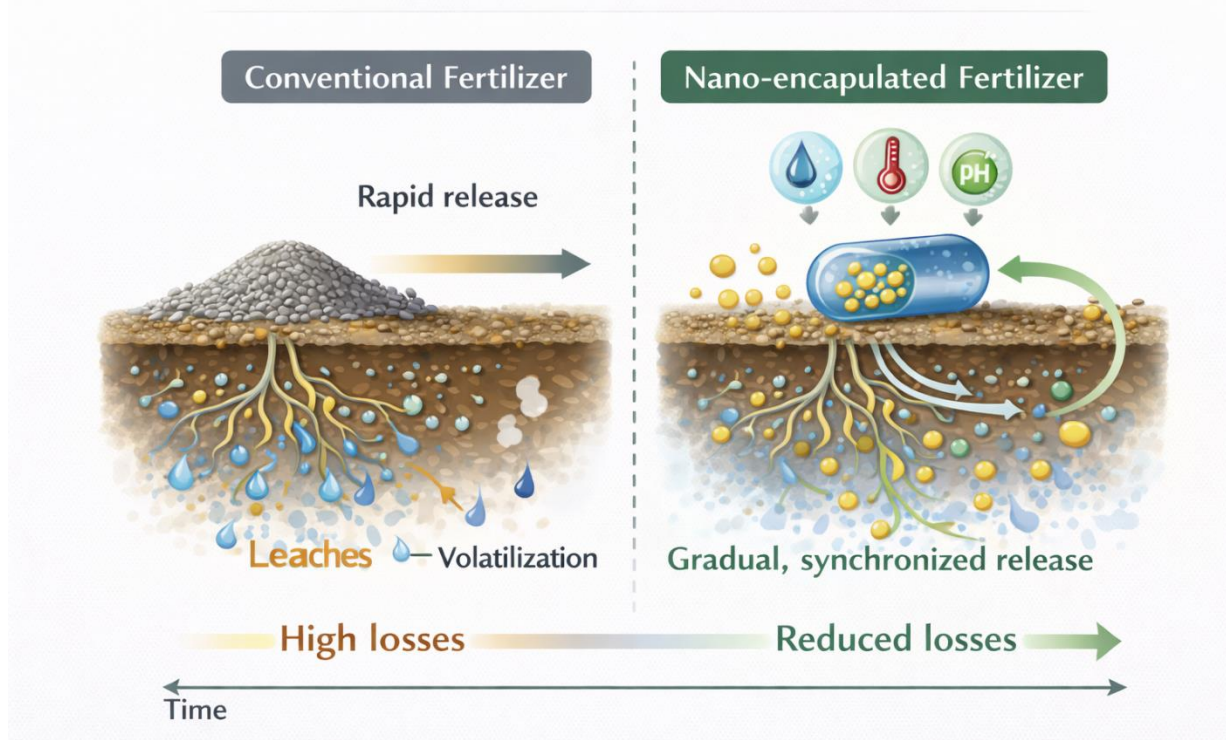
### *Interaction with Soil Microorganisms*

Nano fertilizers can influence soil biological processes in several ways:

- Stimulating beneficial microbial populations
- Enhancing enzymatic activities (e.g., urease, dehydrogenase)
- Improving nutrient mineralization
- Supporting rhizosphere stability

However, the effect is dose-dependent. At optimal concentrations, nano fertilizers enhance soil biological functioning; excessive concentrations may cause microbial toxicity.

## Controlled Release Mechanism



### **Improved Plant Stress Tolerance**

Certain Nano formulations, such as nano zinc and nano silicon, improve plant tolerance to abiotic stresses by:

- Enhancing antioxidant enzyme activity
- Improving osmotic balance
- Increasing chlorophyll stability
- Supporting stronger root architecture

This contributes to improved resilience under drought and heat stress conditions.

### **Role of Nano Fertilizers in Climate-Smart Agriculture**

Climate-Smart Agriculture (CSA) aims to address the dual challenge of ensuring global food security while responding to climate change. It is structured around three interlinked pillars: (i) increasing productivity, (ii) enhancing adaptation and resilience, and (iii) reducing greenhouse gas emissions (mitigation). Nano fertilizers have emerged as a promising technological innovation capable of supporting all three pillars simultaneously through improved nutrient management and environmental efficiency.

### **Enhancing Agricultural Productivity**

Productivity enhancement remains the primary objective of modern agriculture. Conventional fertilizers often fail to achieve optimal nutrient uptake due to rapid release and losses in soil systems. Nano fertilizers, by contrast, improve nutrient use efficiency (NUE) through controlled release and targeted delivery mechanisms.

Several studies report that nano formulations:

- Increase chlorophyll content (higher SPAD values)
- Improve photosynthetic efficiency

- Enhance root biomass and shoot growth
- Increase grain yield and harvest index

Nano nitrogen formulations, for example, have demonstrated improved nitrogen assimilation and reduced fertilizer requirement while maintaining or increasing yield levels. Similarly, nano zinc and nano iron enhance micronutrient availability, correcting hidden deficiencies that limit productivity.

By improving nutrient uptake efficiency, nano fertilizers reduce input waste and contribute to higher crop productivity per unit of fertilizer applied, aligning with the first pillar of CSA.

**Table 1: Comparison Between Conventional and Nano Fertilizers**

| Parameter                           | Conventional Fertilizers                                    | Nano Fertilizers                                         | Implication for CSA                                                           |
|-------------------------------------|-------------------------------------------------------------|----------------------------------------------------------|-------------------------------------------------------------------------------|
| Particle Size                       | Micron to millimeter scale                                  | 1–100 nanometers                                         | Enables unique uptake mechanisms                                              |
| Surface Area                        | Relatively low                                              | Very high surface area-to-volume ratio                   | Enhanced reactivity and interaction                                           |
| Nutrient Use Efficiency (NUE)       | 30–50% (Nitrogen)                                           | 60–90% (reported in various studies)                     | Higher productivity per unit input                                            |
| Nutrient Release Pattern            | Rapid and uncontrolled                                      | Controlled, slow, and demand-driven release              | Reduces N <sub>2</sub> O emissions (Mitigation) & improves NUE (Productivity) |
| Application Dose                    | Higher quantity required                                    | Lower dose required due to higher efficiency             | Reduced input costs and transport emissions                                   |
| Leaching Losses                     | High (especially nitrate)                                   | Significantly reduced                                    | Protects water quality (Adaptation)                                           |
| Volatilization Loss                 | High (NH <sub>3</sub> emission common)                      | Reduced due to controlled release                        | Lowers indirect GHG emissions                                                 |
| Greenhouse Gas Emissions            | Higher N <sub>2</sub> O emissions                           | Reduced N <sub>2</sub> O emissions                       | Direct climate mitigation benefit                                             |
| Target Specificity                  | Non-targeted nutrient distribution                          | Targeted and site-specific delivery possible             | Precision agriculture compatibility                                           |
| Interaction with Soil Microbes      | May disrupt microbial balance at high dose                  | Potential to enhance microbial activity (dose-dependent) | Supports long-term soil health (Resilience)                                   |
| Environmental Impact                | Risk of eutrophication and soil degradation                 | Lower environmental footprint (if properly regulated)    | Aligns with sustainability goals                                              |
| Cost Consideration                  | Lower production cost but high long-term environmental cost | Higher initial cost but improved long-term efficiency    | Economic trade-off requiring policy support                                   |
| Precision Agriculture Compatibility | Limited                                                     | Highly compatible with sensor-based systems              | Enables data-driven nutrient management                                       |

### ***Strengthening Climate Adaptation and Resilience***

Climate change exposes crops to multiple abiotic stresses, including drought, heat stress, salinity, and nutrient imbalances. Adaptation strategies require technologies that improve plant tolerance and resource efficiency under stress conditions.

Nano fertilizers contribute to adaptation through:

- Improved root architecture enabling better water uptake
- Enhanced antioxidant enzyme activity, reducing oxidative stress
- Stabilization of chlorophyll under heat stress
- Improved osmotic adjustment under drought conditions

Nano silicon and nano zinc have been shown to enhance plant stress tolerance by regulating reactive oxygen species (ROS) metabolism. Additionally, improved nutrient synchronization reduces physiological stress caused by nutrient deficiencies or imbalances. By increasing resilience at the physiological and soil levels, nano fertilizers strengthen crop stability under variable climatic conditions.

### ***Mitigation of Greenhouse Gas Emissions***

Agriculture contributes significantly to global greenhouse gas emissions, particularly nitrous oxide (N<sub>2</sub>O) derived from nitrogen fertilizers. Conventional nitrogen management practices are inefficient, resulting in substantial nitrogen losses through volatilization and denitrification.

Nano fertilizers mitigate emissions through:

- Controlled nitrogen release
- Reduced exposure to nitrification–denitrification processes
- Lower fertilizer application rates
- Improved synchronization between nutrient supply and plant demand

Reduced nitrogen losses directly decrease N<sub>2</sub>O emissions, thereby lowering the carbon footprint of agricultural production systems. Furthermore, enhanced root growth and microbial activity may contribute to improved soil carbon stabilization and sequestration. Thus, nano fertilizers help achieve climate mitigation goals by lowering emissions intensity per unit of crop production.

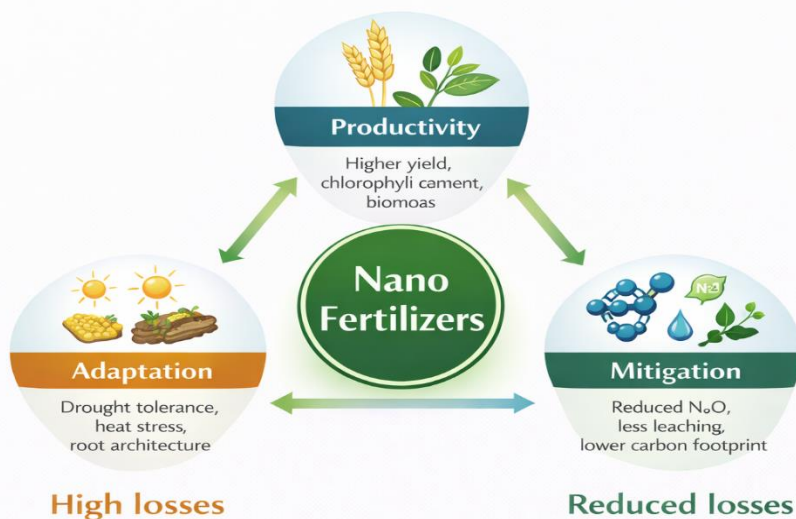
### ***Integration with Precision Agriculture***

Nano fertilizers are highly compatible with precision agriculture technologies. Their formulation allows integration with:

- Sensor-based nutrient monitoring systems
- Variable-rate application technologies
- Site-specific nutrient management strategies

Precision nano-delivery reduces excessive fertilizer application and ensures efficient nutrient distribution according to soil variability. This integration further strengthens the CSA framework by improving input efficiency and minimizing environmental impact.

### Nano Fertilizers Supporting All Three CSA Pillars



### Impact of Nano Fertilizers on Soil Health and Biological Functioning

Soil health is a fundamental determinant of long-term agricultural sustainability. It encompasses the physical, chemical, and biological properties of soil that collectively regulate nutrient cycling, water retention, organic matter dynamics, and crop productivity. While conventional fertilizer systems often focus primarily on nutrient supply, they may inadvertently disrupt soil microbial balance and accelerate soil degradation when applied excessively. In contrast, nano fertilizers are increasingly being evaluated not only for nutrient efficiency but also for their influence on soil biological processes and ecosystem stability.

#### *Influence on Soil Microbial Biomass*

Soil microorganisms are central to nutrient mineralization, nitrogen fixation, phosphorus solubilization, and organic matter decomposition. Emerging studies suggest that optimized nano fertilizer application can enhance microbial biomass carbon (MBC) and stimulate beneficial microbial populations in the rhizosphere.

Potential mechanisms include:

- Gradual nutrient availability supporting sustained microbial growth
- Reduced salt stress compared to high-dose conventional fertilizers
- Improved root exudation due to enhanced plant nutrition

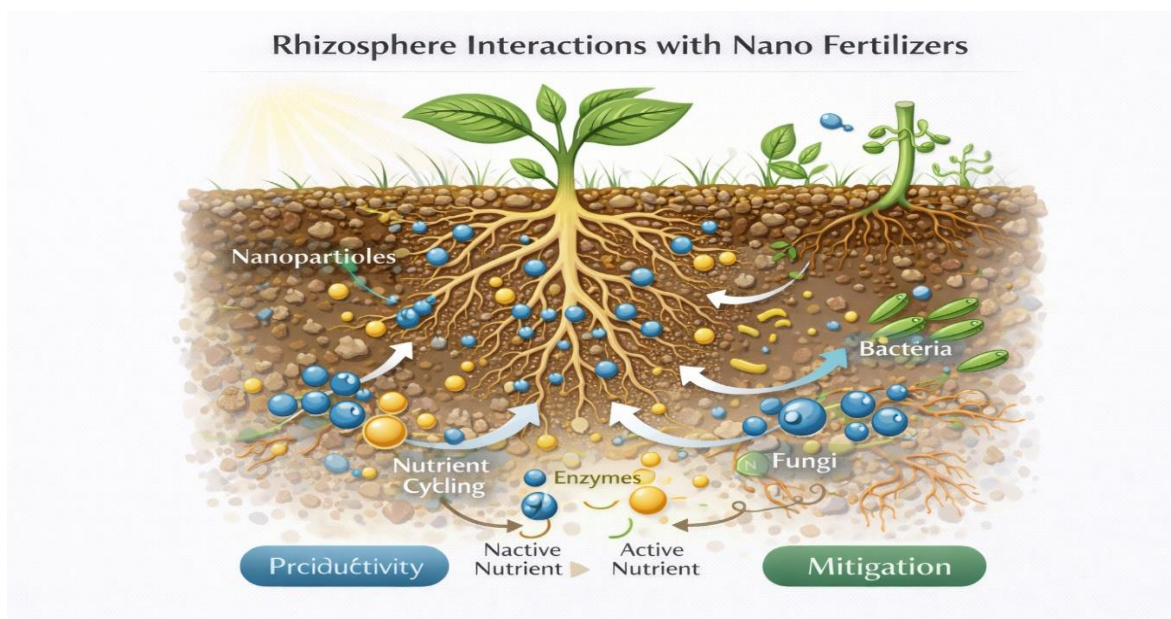
However, the microbial response is highly concentration-dependent. Low to moderate nano fertilizer doses tend to promote microbial activity, whereas excessive nanoparticle accumulation may suppress sensitive microbial groups.

#### *Effect on Soil Enzymatic Activities*

Soil enzymes serve as sensitive indicators of soil biological health. Nano fertilizers have been reported to influence key enzymatic activities, including:

- Dehydrogenase activity (indicator of overall microbial oxidative activity)
- Urease activity (nitrogen transformation)
- Phosphatase activity (phosphorus mineralization)
- Catalase activity (oxidative stress response)

Improved nutrient synchronization reduces nutrient shock in soil systems, thereby supporting stable enzymatic functioning. Enhanced dehydrogenase activity, in particular, reflects improved microbial metabolic intensity under balanced nano nutrient supply.



### ***Impact on Soil Organic Carbon Dynamics***

Soil organic carbon (SOC) plays a crucial role in climate mitigation and soil structural stability. Efficient nutrient use through nano fertilizers can indirectly influence SOC dynamics by:

- Increasing root biomass production
- Enhancing rhizospheric carbon inputs
- Supporting microbial carbon stabilization processes

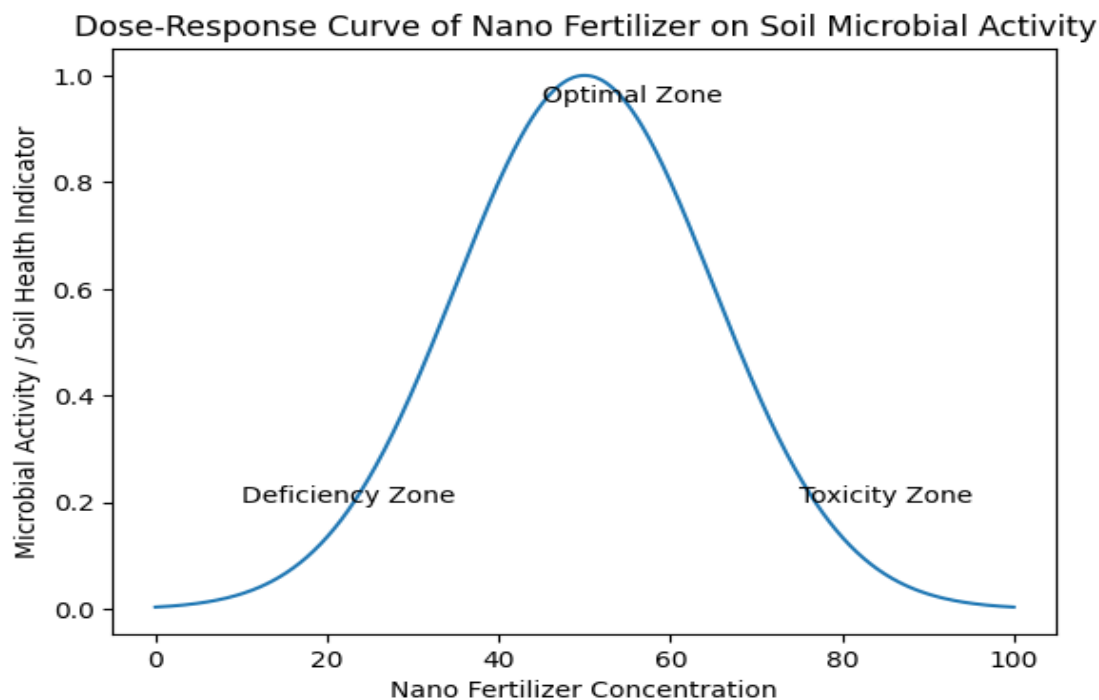
Improved plant growth leads to greater below-ground carbon deposition, potentially contributing to long-term carbon sequestration. When integrated with conservation practices, nano fertilizers may support carbon-positive agricultural systems.

### ***Interaction with Rhizosphere Processes***

The rhizosphere represents a biologically active interface between plant roots and soil. Nano fertilizers can modify rhizosphere processes by:

- Enhancing nutrient diffusion gradients
- Improving root surface contact
- Stimulating beneficial plant–microbe symbiosis
- Supporting mycorrhizal associations

Microbe-assisted nano formulations further enhance nutrient cycling and reduce dependency on high synthetic fertilizer inputs.



### ***Soil Physical and Chemical Stability***

In addition to biological parameters, nanoformulations may influence soil physical properties by:

- Reducing nutrient accumulation and salt build-up
- Reducing soil acidification caused by excessive nitrogen application
- Improving nutrient distribution uniformity

Better nutrient efficiency reduces secondary soil degradation problems often associated with conventional fertilizer overuse.

**Table 2: Effects of Nano Fertilisers on Soil Biological and Biochemical Indicators**

| Soil Indicator           | Observed Impact of Nano Fertilizers | Implication for Soil Health                  |
|--------------------------|-------------------------------------|----------------------------------------------|
| Microbial Biomass Carbon | Increased (dose-dependent)          | Improved nutrient cycling capacity           |
| Dehydrogenase Activity   | Enhanced                            | Higher microbial metabolic activity          |
| Urease Activity          | Regulated and stabilized            | Efficient nitrogen transformation            |
| Phosphatase Activity     | Moderately enhanced                 | Improved phosphorus mineralization           |
| Soil Respiration         | Improved                            | Active microbial processes                   |
| Soil Organic Carbon      | Potential increase (indirect)       | Enhanced carbon stabilization                |
| Rhizosphere Interaction  | Strengthened                        | Enhanced plant–microbe synergy               |
| Soil Aggregate Stability | Potentially improved                | Better soil structure and water infiltration |

## **Patent Landscape and Innovation Trends in Nano Fertilizers**

The rapid advancement of nano fertilizer technology is reflected in the increasing number of patent filings worldwide. Patent landscape analyses provide insight into innovation trajectories, commercialization potential, and emerging research priorities within nano-enabled nutrient management systems. Over the past decade, global research and development activities in nano fertilizers have expanded significantly, particularly in technologically advanced and agriculturally intensive regions.

Recent analyses of international patent databases indicate strong innovation activity in countries such as the United States, China, and India, demonstrating the strategic importance of nano fertilizers in sustainable agricultural transformation. The majority of patents fall within fertilizer chemistry (IPC Class C05) and agricultural applications (A01), highlighting a combined focus on material engineering and field-level nutrient management.

### ***Major Innovation Domains***

Patent trends reveal five dominant innovation clusters in nano fertilizer development:

#### **(i) Advanced Nutrient Delivery Systems**

Nano-encapsulation technologies represent one of the most prominent areas of innovation. These systems involve coating or embedding nutrients within biodegradable polymers or nanocarriers to enable controlled and sustained release. Such designs improve nutrient synchronization with plant demand, reducing environmental losses and improving nutrient use efficiency (NUE).

#### **(ii) Nanomaterial-Based Fertilisers**

Patents frequently describe the use of metal and metal oxide nanoparticles such as nano zinc oxide (ZnO), nano iron oxide (Fe<sub>2</sub>O<sub>3</sub>), nano silica, and nano hydroxyapatite. These materials enhance nutrient solubility, bioavailability, and plant absorption efficiency. Their nanoscale properties facilitate better interaction with root surfaces and soil colloids.

#### **(iii) Precision Agriculture Integration**

Emerging innovations integrate nano fertilizers with sensor-based monitoring systems and variable-rate application technologies. Smart nano delivery systems are designed to respond to soil moisture, pH, or plant nutrient status, thereby enabling site-specific nutrient management. This approach strengthens resource efficiency and reduces excessive fertilizer application.

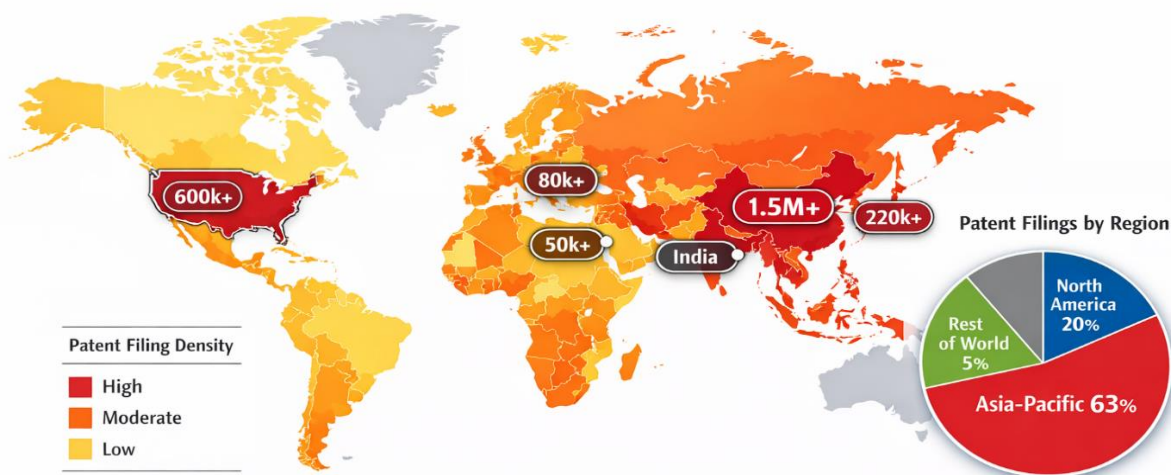
#### **(iv) Soil Remediation and Conditioning**

Some patented nano formulations focus on improving soil structure, detoxifying contaminated soils, and enhancing rhizosphere stability. Nano-enabled soil conditioners may contribute to carbon stabilization and restoration of degraded agricultural lands.

#### **(v) Plant–Microbe Interaction Enhancement**

Microbe-assisted nano formulations represent an emerging frontier in sustainable agriculture. These technologies combine nano nutrients with beneficial microorganisms to enhance nutrient cycling, stimulate root growth, and strengthen plant immune responses.

## Global Patent Distribution



### Commercialization and Strategic Implications

The growth in patent activity indicates a transition of nano fertilizers from laboratory research toward commercial-scale deployment. Large fertilizer industries and biotechnology firms are increasingly investing in nano-enabled nutrient systems to improve fertilizer efficiency and reduce environmental footprint.

**Table 3: Emerging Innovation Domains in Nano Fertilizer Development**

| Innovation Domain                     | Key Technological Focus                 | Relevance to CSA                                                   |
|---------------------------------------|-----------------------------------------|--------------------------------------------------------------------|
| Nano Encapsulation                    | Controlled nutrient release systems     | Reduced nutrient loss and improved NUE (Productivity & Mitigation) |
| Metal Oxide Nanoparticles             | Enhanced nutrient bioavailability       | Increased productivity and stress tolerance (Adaptation)           |
| Smart Precision Nano Systems          | Sensor-linked nutrient delivery         | Resource optimization and reduced environmental footprint          |
| Soil Conditioning Nanoagents          | Rhizosphere improvement and remediation | Long-term soil resilience (Adaptation)                             |
| Microbe–Nano Synergistic Formulations | Enhanced biological nutrient cycling    | Sustainable soil health (Productivity & Adaptation)                |
| Biodegradable Nanocarriers            | Eco-friendly polymer-based delivery     | Reduced ecotoxicity risk (Environmental safety)                    |

Commercial interest is driven by:

- Demand for higher nutrient efficiency
- Regulatory pressure to reduce nitrogen emissions
- Need for climate-resilient agricultural inputs
- Rising adoption of precision farming technologies

However, despite rapid technological development, regulatory frameworks for nano fertilizers remain evolving in many countries. Clear guidelines for environmental safety, dosage limits, and quality standards are essential for responsible commercialization.

### ***Implications for Climate-Smart Agriculture***

Innovation trends strongly align with the objectives of Climate-Smart Agriculture. Controlled-release nano systems reduce greenhouse gas emissions (mitigation), stress-tolerant formulations enhance crop resilience (adaptation), and improved nutrient efficiency increases productivity. The convergence of nanotechnology, precision agriculture, and biological systems represents a multidisciplinary pathway toward sustainable intensification.

### **Environmental and Safety Considerations**

Although nano fertilizers demonstrate significant potential for improving nutrient use efficiency and supporting climate-smart agriculture, their long-term environmental and ecological implications require careful evaluation. The small particle size and high reactivity that confer agronomic advantages may also raise concerns regarding nanoparticle persistence, mobility, and bioaccumulation in soil–plant systems.

### ***Nanoparticle Persistence and Soil Accumulation***

Unlike conventional fertilizers that dissolve or transform rapidly in soil, certain engineered nanoparticles may persist depending on their composition, coating material, and environmental conditions. Repeated applications over multiple cropping cycles could lead to gradual accumulation in soil matrices.

Potential concerns include:

- Alteration of soil physicochemical properties
- Disruption of microbial community structure
- Interaction with soil colloids and organic matter

The environmental fate of nanoparticles is influenced by soil pH, texture, moisture, and organic carbon content. Therefore, long-term field trials are essential to assess cumulative effects.

### ***Ecotoxicological Impacts***

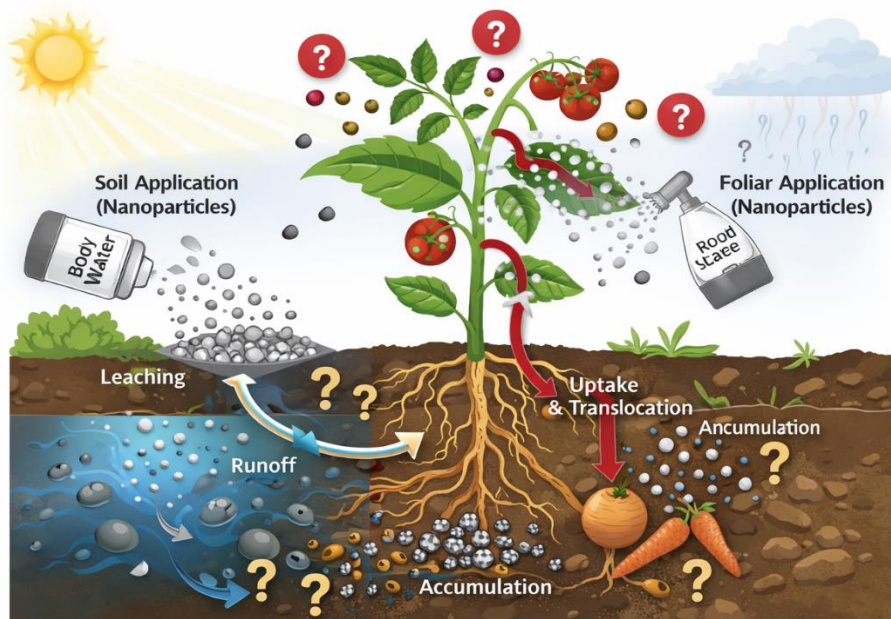
At optimal concentrations, nano fertilizers may stimulate microbial and plant growth; however, excessive doses can induce oxidative stress in soil microorganisms and plants. Certain metal-based nanoparticles, such as ZnO or Fe<sub>2</sub>O<sub>3</sub>, may generate reactive oxygen species (ROS) under high concentrations.

Possible ecotoxicological risks include:

- Microbial inhibition at high nanoparticle concentrations
- Root membrane damage under excessive exposure
- Bioaccumulation in plant tissues

Dose optimization and safe concentration thresholds must be scientifically established before widespread application.

## Environmental Fate of Nanoparticles in Soil-Plant Systems



### ***Risk of Food Chain Transfer***

Nanoparticles absorbed by plants may translocate to edible plant parts depending on size and chemical composition. Although many nanoformulations are designed for controlled nutrient release and biodegradability, the potential for nanoparticle entry into the food chain requires detailed investigation.

Research priorities include:

- Tracking nanoparticle movement within plant tissues
- Assessing human exposure risks
- Evaluating long-term health implications

Comprehensive food safety studies are necessary to address public concerns and regulatory requirements.

### ***Regulatory and Policy Challenges***

Regulatory frameworks for nano fertilizers are still evolving in many countries. Unlike traditional fertilizers, nano formulations require specialized risk assessment protocols due to their unique physicochemical properties.

Key regulatory challenges include:

- Lack of standardized toxicity testing guidelines
- Limited life cycle assessment (LCA) studies
- Absence of harmonized global nano-agriculture policies
- Difficulty in defining nano-specific labeling standards

Developing science-based regulatory policies is essential to ensure safe commercialization and farmer confidence.

### ***Need for Life Cycle Assessment (LCA)***

To fully evaluate sustainability, nano fertilizers must be assessed through life cycle analysis, considering:

- Production energy requirements
- Environmental footprint
- Transport and application efficiency
- End-of-life environmental impact

While nano fertilizers may reduce field-level emissions, manufacturing processes must also be environmentally responsible to achieve net climate benefits.

### ***Economic Feasibility and Adoption Challenges***

The large-scale adoption of nano fertilizers depends not only on agronomic performance but also on economic viability and accessibility for farmers. While nano fertilizers offer improved nutrient use efficiency (NUE) and reduced environmental losses, their economic implications must be carefully evaluated under field conditions.

### ***Cost Comparison***

The production cost of nano fertilizers is generally higher than that of conventional bulk fertilizers—usually 2-4 times more expensive per kg of nutrient—due to advanced manufacturing processes, nanomaterial synthesis, and quality control. However, nano fertilizers often require smaller application doses because of their higher efficiency. Lower nutrient loss, decreased transportation volume, and fewer repeat applications may offset the initial cost differences.

For example, nano nitrogen formulations have demonstrated comparable yield responses with 20–50% lower nitrogen application rates under optimized conditions. This reduction can partially compensate for higher per-unit product cost. When calculated as "cost per unit of nutrient taken up by the plant" or "cost per ton of yield," nano fertilizers often prove more economical.

### ***Return on Investment (ROI)***

Economic return depends on multiple factors:

- Increased crop yield (5-15% reported in some trials)
- Reduced fertilizer input quantity (20-50% reduction)
- Lower labor and transportation costs
- Reduced environmental compliance costs

Field studies indicate that improved NUE and yield stability may enhance profitability, particularly in high-value crops. However, ROI may vary depending on soil type, cropping system, and agro-climatic conditions. Long-term multi-season economic trials are necessary to establish consistent benefit–cost ratios.

### ***Risk Mitigation Value***

The higher initial cost of nano fertilizers can be viewed as an investment in risk reduction. Improved stress tolerance (drought, heat, nutrient deficiency) leads to more consistent yields, offering economic stability that is hard to measure but highly valued by

farmers. This resilience benefit is a crucial, yet often overlooked, part of the economic argument for adopting nano fertilizer.

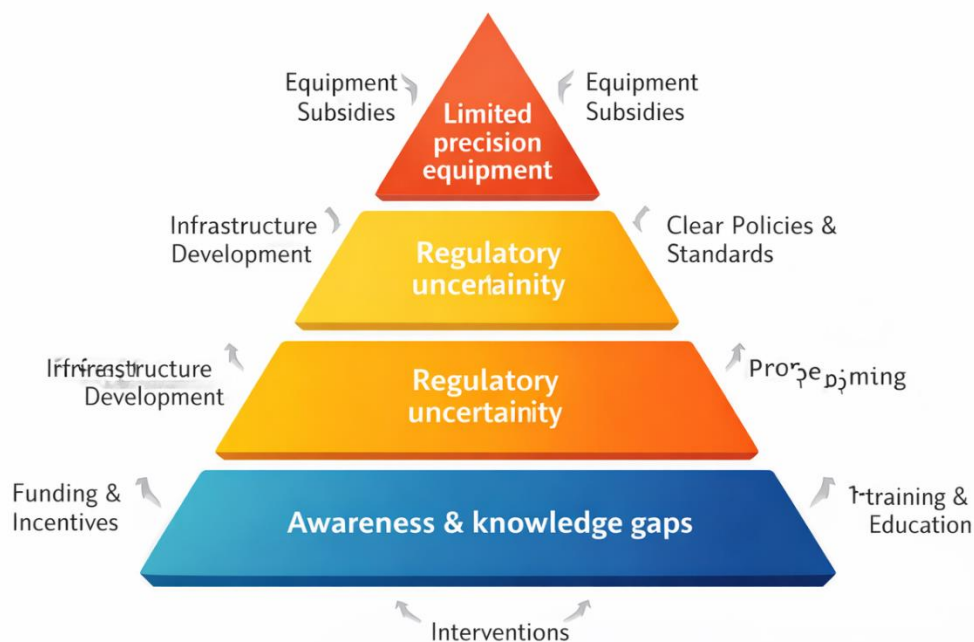
### ***Life Cycle Costing (LCC)***

A comprehensive economic analysis requires a Life Cycle Costing perspective, which considers:

- Production and manufacturing costs
- Distribution and application expenses
- Environmental externality costs
- Long-term soil health implications

While upfront costs favor conventional fertilizers, the full life cycle cost—including environmental remediation and productivity losses from soil degradation—may favor nano-enabled systems.

### **Adoption Barriers Pyramid**



### ***Adoption Challenges for Smallholder Farmers***

Despite technological promise, several constraints may limit adoption among small-scale farmers:

- Higher upfront product cost
- Limited awareness and technical knowledge
- Uncertainty regarding long-term safety
- Inadequate regulatory clarity
- Limited access to precision application equipment

To ensure inclusive adoption, policy interventions should include:

- Farmer training programs and extension services

- Subsidy support during transition phase
- Clear labeling and safety guidelines
- Public–private partnerships for distribution
- Risk-sharing instruments such as crop insurance with premium discounts for CSA technology adopters
- Carbon credit mechanisms that reward verified emission reductions

**Table 4: Quantitative Performance Comparison Between Conventional and Nano Nitrogen Fertilizers**

| Parameter                           | Conventional N Fertilizer | Nano N Fertilizer                                       | Implication                                          |
|-------------------------------------|---------------------------|---------------------------------------------------------|------------------------------------------------------|
| Nitrogen Use Efficiency (NUE, %)    | 30–50%                    | 60–90%                                                  | Doubled efficiency with same nutrient input          |
| N <sub>2</sub> O Emission Reduction | Baseline                  | 15–30% reduction (reported range)                       | Direct climate mitigation benefit                    |
| Nitrogen Dose Requirement           | 100% recommended dose     | 50–80% of recommended dose                              | 20-50% input reduction possible                      |
| Yield Response                      | Moderate                  | Comparable or increased (5–15% reported in some trials) | Productivity maintained or enhanced                  |
| Leaching Loss                       | High (variable)           | Reduced (20–40% reported range)                         | Water quality protection                             |
| Application Frequency               | Multiple splits           | Reduced frequency (controlled release)                  | Labor and fuel savings                               |
| Cost per kg of nutrient             | Low                       | High (2-4x)                                             | Apparent disadvantage                                |
| Cost per ton of yield               | Baseline                  | Potentially lower                                       | Actual economic advantage when efficiency considered |

### Future Prospects and Research Directions

Nano fertilizer technology is still evolving, and its full potential in climate-smart agriculture has yet to be realized. While current research highlights improvements in nutrient use efficiency, crop productivity, and environmental sustainability, future advancements must focus on interdisciplinary integration, long-term safety validation, and scalable implementation strategies.

### Development of Smart and Responsive Nano-Delivery Systems

Next-generation nano fertilizers are expected to move beyond passive controlled-release systems toward stimuli-responsive or smart delivery platforms. These systems may respond dynamically to:

- Soil moisture fluctuations
- Root exudate signals
- pH variations
- Plant nutrient demand

Such adaptive systems could optimize nutrient release in real time, significantly improving synchronization between nutrient supply and crop requirements.

### ***Integration with Precision Agriculture and Digital Technologies***

The convergence of nanotechnology with digital agriculture represents a transformative opportunity. Integration with:

- IoT-based soil sensors
- Remote sensing platforms
- Artificial intelligence (AI)-driven nutrient models
- Variable-rate fertilizer applicators

can enable data-driven nutrient management. Nano fertilizers combined with precision agriculture tools could reduce fertilizer wastage while maximizing crop productivity.

### ***Biodegradable and Eco-Friendly Nanocarriers***

A major research priority is the development of biodegradable nanocarriers derived from natural polymers such as chitosan, starch, lignin, and cellulose. These materials can minimize environmental persistence and reduce ecotoxicological concerns associated with synthetic nanoparticle accumulation.

Eco-friendly nano formulations should aim to:

- Enhance nutrient efficiency
- Reduce soil toxicity risks
- Support circular bio economy principles

### ***Long-Term Field Trials and Soil Health Monitoring***

Most current studies are short-term or conducted under controlled conditions. Long-term, multi-season field experiments across diverse agro-climatic zones are essential to:

- Evaluate cumulative nanoparticle effects
- Assess changes in soil microbial diversity
- Monitor soil organic carbon dynamics
- Measure greenhouse gas emission reductions
- Establish safe concentration thresholds

Robust field-based evidence will strengthen regulatory approval and farmer adoption.

### ***Policy Framework and Farmer Adoption***

Successful implementation of nano fertilizers requires:

- Clear regulatory guidelines and safety standards
- Standardized quality control protocols
- Harmonized international nano-agriculture policies
- Farmer awareness and training programs
- Cost-effective production technologies
- Risk-sharing mechanisms and carbon credit integration

Policy support and public–private partnerships will be crucial for scaling nano-enabled nutrient management systems.

### ***Contribution to Sustainable Development Goals (SDGs)***

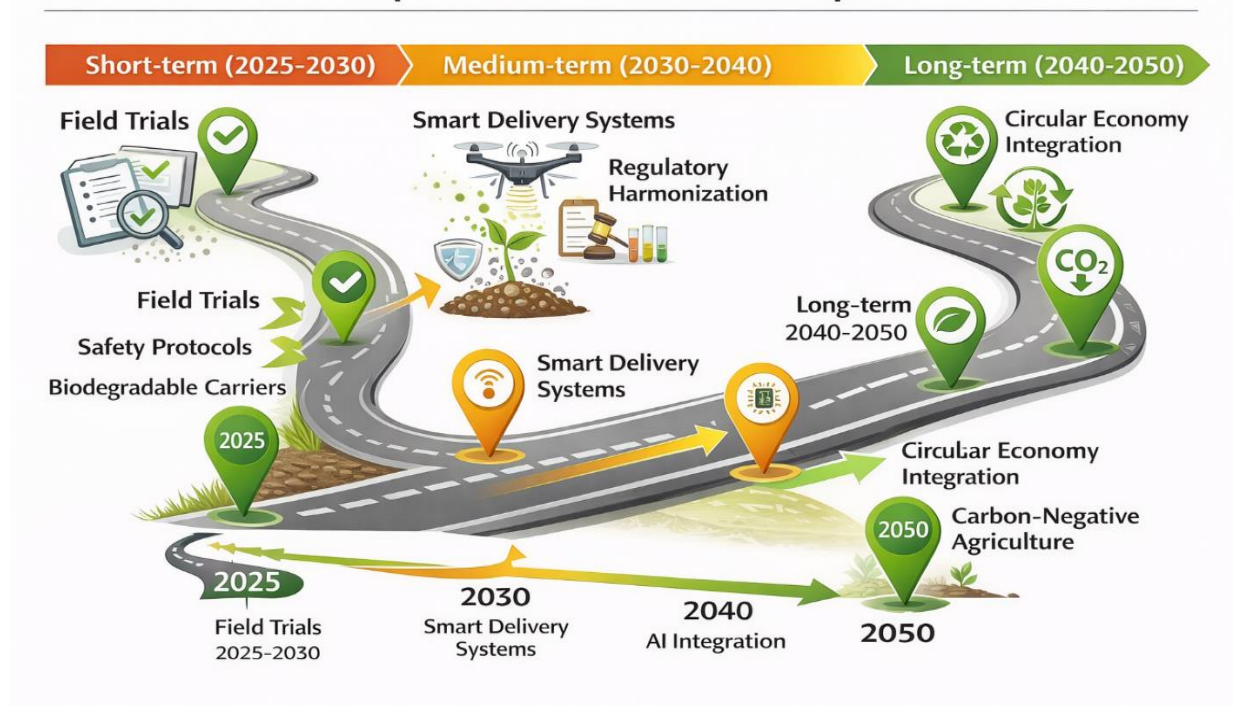
Nano fertilizers align with multiple Sustainable Development Goals, including:

- **SDG 2 (Zero Hunger):** Enhanced productivity and nutrient efficiency

- **SDG 6 (Clean Water and Sanitation):** Reduced nutrient leaching
- **SDG 12 (Responsible Consumption and Production):** Improved input efficiency
- **SDG 13 (Climate Action):** Reduced GHG emissions
- **SDG 15 (Life on Land):** Protection of soil ecosystems

By enhancing productivity while reducing environmental footprint, nano fertilizers may contribute to resilient and low-carbon agricultural systems.

### Roadmap for Nano Fertilizer Development



### Conclusion

The integration of nano fertilizers into the Climate-Smart Agriculture (CSA) framework represents a critical evolution in sustainable nutrient management. As global food systems face the compounding pressures of climate instability and resource depletion, the transition from conventional, high-loss fertilization to precision-targeted nano-delivery is no longer a luxury but a necessity. This review confirms that by leveraging their unique physicochemical properties, nano fertilisers can bridge the gap between high productivity and environmental stewardship—simultaneously boosting yields, priming crops for resilience to abiotic stress, and drastically reducing greenhouse gas emissions.

However, the journey from laboratory innovation to widespread field adoption is contingent on navigating a complex landscape of ecological uncertainty and economic reality. While the agronomic benefits are evident, the long-term impact of nanoparticle persistence in soil requires vigilant, science-based monitoring. The future of this technology lies in "Green Nanotechnology"—prioritising biogenic synthesis and biodegradable carriers to ensure that the tools we deploy to protect our soil today do not become tomorrow's pollutants.

### The Path Forward

The successful deployment of nano-enabled agriculture hinges on a coordinated, multi-disciplinary effort:

- **For Scientists:** The priority must shift from merely demonstrating efficacy to elucidating long-term fate and developing smart-release, biodegradable formulations. Research should focus on dose optimization, mechanistic understanding of plant–nanoparticle interactions, and development of eco-friendly synthesis methods.
- **For Policymakers:** The urgent task is to establish transparent, harmonized safety standards and certification protocols that build trust without stifling innovation. Regulatory frameworks must address nanoparticle characterisation, environmental fate assessment, and food safety evaluation, while enabling responsible commercialisation.
- **For Economists and Development Agencies:** The focus should be on innovative financing and extension models that bridge the initial cost-gap and knowledge barrier for smallholder farmers. Carbon credit mechanisms, risk-sharing instruments, and public–private partnerships can ensure equitable access to this transformative technology.
- **For the Agricultural Industry:** Investment in scalable, cost-effective manufacturing processes and farmer education programs will be essential for market development and responsible deployment.

By harmonizing these efforts, nano fertilizers can fulfill their potential as a cornerstone of a resilient, low-carbon, and food-secure future. The path forward requires balancing innovation with precaution, efficiency with equity, and productivity with sustainability. If navigated wisely, nano-enabled nutrient management may prove to be one of the most significant agricultural advancements of the twenty-first century.

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