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Nano-fertilizers in sustainable crop production: Mechanisms, agronomic efficiency and environmental implications

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Abstract

Increasing food demand, declining soil fertility, climate change, and environmental degradation have created the need for sustainable nutrient management strategies in modern agriculture. Conventional fertilizers often show low nutrient use efficiency (NUE) due to nutrient losses through leaching, volatilization, fixation, and runoff, leading to environmental pollution and reduced crop productivity. Nano-fertilizers have emerged as promising alternatives because of their controlled nutrient release, targeted delivery, and improved interaction with plant soil systems. They enhance nutrient uptake, crop growth, stress tolerance, and precision nutrient management while reducing ecological impacts. However, concerns regarding nanoparticle toxicity, bioaccumulation, environmental persistence, and limited long-term field validation remain important challenges. Therefore, further research on environmental safety, life cycle assessment, and climate-smart integration is essential for the sustainable adoption of nano-fertilizers in agriculture.

Keywords: Nano-fertilizers, Nutrient use efficiency, Sustainable agriculture, controlled nutrient release, precision agriculture, soil fertility, nanotechnology, environmental sustainability

1. Introduction

1.1 Global Food Security Challenges

Global agriculture is facing serious challenges due to rapid population growth, declining soil fertility, climate change, and increasing food demand. The global population is projected to exceed 9.7 billion by 2050, creating pressure on agricultural systems to enhance productivity while maintaining environmental sustainability (Pudhuvai *et al.*, 2025) ^[12]. However, shrinking arable land, water scarcity, and soil degradation continue to limit agricultural production. Continuous monocropping and excessive use of chemical fertilizers have reduced soil fertility and disrupted ecosystem balance. Moreover, large nutrient losses through leaching, runoff, denitrification, and volatilization reduce nutrient use efficiency (NUE) and contribute to greenhouse gas emissions, eutrophication, and groundwater contamination (Verma *et al.*, 2023) ^[22]. Therefore, sustainable and efficient nutrient management strategies are urgently required for future food security.

1.2 Limitations of Conventional Fertilizers

Conventional fertilizers have played a major role in improving global crop productivity; however, their excessive and long-term use has created serious environmental and agronomic problems. Low nutrient use efficiency (NUE), particularly in nitrogen fertilizers, leads to significant nutrient losses through leaching, runoff, volatilization, and gaseous emissions (Pudhuvai *et al.*, 2025) ^[12]. These losses reduce fertilizer efficiency and increase environmental pollution. Excessive fertilizer use also contributes to eutrophication, groundwater contamination, greenhouse gas emissions, and soil degradation. Moreover, continuous application of chemical fertilizers may disturb soil microbial activity, increase soil acidity, and negatively affect long-term soil fertility and crop quality (Arora *et al.*, 2024) ^[2]. Therefore, sustainable nutrient delivery

systems with improved efficiency and lower environmental impact are urgently needed.

1.3 Emergence of Nano-Fertilizers

Recent advances in nanotechnology have led to the development of nano-fertilizers as innovative tools for sustainable nutrient management in agriculture. Nano-fertilizers are nutrient formulations engineered at the nanoscale (1–100 nm) that improve nutrient availability, uptake efficiency, and controlled nutrient release within plant–soil systems (Channab *et al.*, 2024)^[3]. Due to their high surface area, enhanced reactivity, and improved mobility, nano-fertilizers interact more efficiently with plant tissues and soil particles than conventional fertilizers. These properties help synchronize nutrient release with crop demand, thereby reducing nutrient losses and improving nutrient use efficiency (Verma *et al.*, 2023)^[22]. Consequently, nano-fertilizers are increasingly considered promising components of precision agriculture and climate-smart farming systems for sustainable crop production.

1.4 Nano-Fertilizers Matter

Nano-fertilizers have received significant attention due to their potential to improve nutrient management, crop productivity, and environmental sustainability. Their controlled and targeted nutrient release reduces nutrient losses through leaching, volatilization, and fixation, thereby enhancing nutrient use

efficiency and lowering fertilizer requirements (Channab *et al.*, 2024)^[3]. Nano-fertilizers also improve important physiological processes such as photosynthesis, chlorophyll synthesis, enzymatic activity, and antioxidant defense mechanisms. In addition, they help plants tolerate abiotic stresses including drought, salinity, and temperature extremes (Arora *et al.*, 2024)^[2]. Integration of nano-fertilizers with precision agriculture and smart farming technologies may further support sustainable and climate-smart crop production. However, concerns regarding nanoparticle toxicity and long-term environmental impacts still require detailed investigation.

1.5 Research Gaps, Novelty and Scope

Despite increasing research on nano-fertilizers, important gaps still remain regarding long-term field performance, environmental safety, soil microbe interactions, and nanoparticle toxicity. Most previous studies have mainly focused on short-term crop responses under controlled conditions, while limited attention has been given to ecological risks and regulatory concerns associated with large-scale agricultural application (Channab *et al.*, 2024)^[3]. Earlier reviews also emphasized synthesis methods and yield improvement without integrating nutrient use efficiency (NUE), precision agriculture, sustainability, and environmental implications within a single framework.

Table 1: Major limitations of conventional fertilizers and advantages of nano-fertilizers in sustainable agriculture

Agricultural Aspect	Limitations of Conventional Fertilizers	Advantages of Nano-Fertilizers	Key Impacts on Sustainable Agriculture	References
Nutrient use efficiency (NUE)	Low nutrient utilization due to leaching, volatilization, and runoff	Controlled and targeted nutrient release improves NUE	Enhanced nutrient availability and reduced fertilizer losses	Pudhuvai <i>et al.</i> , (2025) ^[12] ; Verma <i>et al.</i> , (2023) ^[22]
Nutrient delivery	Rapid nutrient release often exceeds crop demand	Slow and controlled nutrient release synchronized with crop requirement	Improved nutrient uptake and fertilizer efficiency	Channab <i>et al.</i> , (2024) ^[3]
Environmental impact	Causes eutrophication, groundwater contamination, and greenhouse gas emissions	Reduces nutrient losses and environmental pollution	Supports environmentally sustainable agriculture	Arora <i>et al.</i> , (2024) ^[2] ; Pudhuvai <i>et al.</i> , (2025) ^[12]
Soil health	Excessive application may degrade soil quality and microbial diversity	Better interaction with soil–plant systems and microbial activity	Improved soil fertility and rhizosphere functioning	Arora <i>et al.</i> , (2024) ^[2]
Crop productivity	Imbalanced nutrient supply may limit growth and yield	Enhances plant growth, photosynthesis, and nutrient absorption	Increased crop productivity and yield stability	Verma <i>et al.</i> , (2023) ^[22] ; Channab <i>et al.</i> , (2024) ^[3]
Stress tolerance	Limited effectiveness under drought, salinity, and heat stress	Enhances antioxidant activity and stress-responsive mechanisms	Improved abiotic stress tolerance	Arora <i>et al.</i> , (2024) ^[2]
Precision agriculture compatibility	Limited compatibility with modern precision farming systems	Suitable for sensor-based and smart nutrient management	Supports precision and climate-smart agriculture	Channab <i>et al.</i> , (2024) ^[3]
Sustainability potential	High fertilizer consumption and ecological risks	Lower fertilizer requirement with higher efficiency	Promotes sustainable crop production systems	Pudhuvai <i>et al.</i> , (2025) ^[12] ; Arora <i>et al.</i> , (2024) ^[2]

2. Methodology

2.1 Literature Search Strategy

A systematic literature search was conducted using major scientific databases including Scopus, Web of Science, PubMed, and Google Scholar. Relevant peer-reviewed articles related to nano-fertilizers, nutrient use efficiency, sustainable agriculture, controlled nutrient release, and precision farming were collected using different keyword combinations. Recent studies published in high-impact journals were mainly considered to ensure scientific quality and reliability (El-Saadony *et al.*, 2024)^[7].

2.2 Inclusion and Exclusion Criteria

Studies included in this focused on nano-fertilizer synthesis, nutrient delivery mechanisms, crop productivity, soil–plant

interactions, and environmental impacts. Both laboratory and field studies were considered. Non-English articles, duplicate studies, conference abstracts without full data, and non-agricultural nanotechnology studies were excluded from the review (Khan *et al.*, 2022)^[8].

2.3 Time Range of Literature

The mainly includes scientific literature published between 2020 and 2026 to cover recent developments in nano-fertilizer research. Older studies were included only when necessary for basic scientific background. Recent publications were prioritized because they provide updated information on sustainable nutrient management and precision agriculture applications (Sharma *et al.*, 2024)^[20].

2.4 Data Analysis Approach

The collected studies were analyzed using bibliometric trends, thematic categorization, and comparative evaluation methods. The literature was grouped into major themes such as synthesis methods, nutrient release mechanisms, agronomic efficiency,

environmental implications, and future prospects. Comparative analysis was also performed to evaluate the effectiveness of nano-fertilizers compared to conventional fertilizers under different agricultural conditions (Raliya *et al.*, 2023) ^[15].

Table 2: Methodology adopted for the review of nano-fertilizers in sustainable agriculture

Methodological Component	Description	Purpose of the Study	References
Literature search strategy	Scientific literature was collected from Scopus, Web of Science, PubMed, and Google Scholar using keywords related to nano-fertilizers, nutrient use efficiency, precision agriculture, and sustainable crop production.	To gather recent, high-quality, and relevant scientific information related to nano-fertilizers.	El-Saadony <i>et al.</i> , (2024) ^[7]
Inclusion criteria	Studies focusing on nano-fertilizer synthesis, nutrient delivery mechanisms, crop productivity, soil–plant interactions, environmental sustainability, and stress tolerance were included. Both laboratory and field studies were considered.	To ensure scientific relevance and comprehensive evaluation of nano-fertilizer applications in agriculture.	Khan <i>et al.</i> , (2022) ^[8]
Exclusion criteria	Non-English articles, duplicate studies, conference abstracts without complete data, unpublished reports, and studies unrelated to agricultural nanotechnology were excluded.	To maintain scientific accuracy, reliability, and quality of the reviewed literature.	Khan <i>et al.</i> , (2022) ^[8]
Time range of literature	Literature published between 2020 and 2026 was mainly considered, while older foundational studies were included selectively.	To emphasize recent developments and emerging research trends in nano-fertilizer technology.	Sharma <i>et al.</i> , (2024) ^[20]
Bibliometric analysis	Publication trends, research growth, and emerging scientific themes related to nano-fertilizers were analyzed.	To identify current research progress and major scientific focus areas.	Rani <i>et al.</i> , (2025) ^[16]
Thematic categorization	Literature was categorized into synthesis methods, nutrient release mechanisms, agronomic efficiency, environmental implications, and future prospects.	To organize and critically evaluate the available scientific information systematically.	Raliya <i>et al.</i> , (2023) ^[15]
Comparative evaluation	Nano-fertilizers were compared with conventional fertilizers under different crops and environmental conditions.	To assess the effectiveness of nano-fertilizers in improving nutrient use efficiency and sustainability.	Raliya <i>et al.</i> , (2023) ^[15]
PRISMA framework	PRISMA guidelines were followed for systematic identification, screening, and selection of relevant studies.	To improve transparency, reproducibility, and scientific credibility of the review process.	Sharma <i>et al.</i> , (20 ^[20]

3. Classification and Types of Nano-Fertilizers

3.1 Macronutrient Nano-Fertilizers

Macronutrient nano-fertilizers mainly supply essential primary nutrients such as nitrogen (N), phosphorus (P), and potassium (K) in nano-scale formulations to improve nutrient use efficiency and crop productivity. Nano-nitrogen fertilizers enhance nitrogen availability and reduce nutrient losses caused by volatilization and leaching. Nano-phosphorus fertilizers improve phosphorus solubility and availability in soils where phosphorus fixation is a major problem. Similarly, nano-potassium fertilizers support water regulation, enzyme activation, and stress tolerance in plants through gradual nutrient release mechanisms (Verma *et al.*, 2023) ^[22]. Nano-scale nutrient delivery systems possess high surface area and enhanced reactivity, which facilitate efficient nutrient absorption and controlled release according to crop demand. These properties significantly improve nutrient uptake efficiency and reduce excessive fertilizer application in agricultural systems (Raliya *et al.*, 2023) ^[15].

3.2 Micronutrient Nano-Fertilizers

Micronutrient nano-fertilizers are designed to supply trace elements such as zinc (Zn), iron (Fe), copper (Cu), and manganese (Mn), which are essential for various physiological and biochemical processes in plants. Nano-zinc fertilizers improve enzyme activity, chlorophyll synthesis, and grain quality, while nano-iron fertilizers enhance photosynthesis and metabolic activities. Nano-copper and nano-manganese fertilizers play important roles in enzymatic reactions, antioxidant defense, and stress tolerance mechanisms (Khan *et al.*, 2022) ^[8]. The nano-formulation of micronutrients improves

nutrient solubility, mobility, and bioavailability within plant systems. These fertilizers also minimize nutrient fixation in soil and enhance nutrient translocation to different plant tissues, thereby improving crop growth and productivity under nutrient-deficient conditions (El-Saadony *et al.*, 2024) ^[7].

3.3 Nano-Composite Fertilizers

Nano-composite fertilizers are advanced nutrient formulations prepared by combining nutrients with nanomaterials such as polymers, zeolites, biochar, or clay minerals. These composite structures improve nutrient stability, adsorption capacity, and controlled nutrient release behavior. Nano-composite fertilizers help synchronize nutrient release with plant nutrient demand, thereby reducing nutrient losses and enhancing fertilizer efficiency (Chen *et al.*, 2024) ^[4]. nano-composite formulations improve soil moisture retention, nutrient availability, and rhizosphere interactions. Their multifunctional properties make them suitable for sustainable agriculture and precision nutrient management systems under diverse agroecological conditions (Mahapatra *et al.*, 2025) ^[9].

3.4 Nano-Encapsulated Fertilizers

Nano-encapsulated fertilizers are nutrient formulations in which nutrients are enclosed within nano-scale coating materials or carriers. The encapsulation process allows slow and targeted nutrient release, minimizing nutrient leaching and volatilization losses. These fertilizers enhance nutrient delivery efficiency and prolong nutrient availability in soil plant systems (Duhan *et al.*, 2023) ^[6]. Nano-encapsulation technology also protects nutrients from premature degradation and improves nutrient uptake under adverse environmental conditions. Such controlled release

behavior supports precision agriculture and sustainable nutrient management by reducing excessive fertilizer consumption and environmental pollution (Zhao *et al.*, 2024) ^[23].

3.5 Bio-Nano Fertilizers

Bio-nano fertilizers integrate nanotechnology with beneficial microorganisms or bioactive compounds to improve nutrient availability and plant growth. These fertilizers combine nano-materials with plant growth-promoting rhizobacteria,

biofertilizers, or organic substances to enhance nutrient solubilization, microbial activity, and plant nutrient uptake (Arora *et al.*, 2024) ^[2]. Bio-nano fertilizers improve soil biological health, root development, stress tolerance, and nutrient cycling processes. Their environmentally friendly nature and reduced ecological risks make them promising alternatives for sustainable and climate-smart agriculture (Rahman *et al.*, 2025) ^[13].

Table 3: Classification and major characteristics of nano-fertilizers

Type of Nano-Fertilizer	Nutrient	Nanomaterial Used	Mechanism of Action	Major Benefits	References
Nano-N fertilizer	Nitrogen (N)	Nano-urea, polymer-coated nanoparticles	Controlled nitrogen release and enhanced absorption	Improved NUE and reduced nitrogen loss	Verma <i>et al.</i> , (2023) ^[22]
Nano-P fertilizer	Phosphorus (P)	Nano-hydroxyapatite	Increased phosphorus solubility and mobility	Better root growth and phosphorus uptake	Raliya <i>et al.</i> , (2023) ^[15]
Nano-K fertilizer	Potassium (K)	Potassium nanoparticles	Gradual potassium availability	Enhanced stress tolerance and water regulation	Chen <i>et al.</i> , (2024) ^[4]
Nano-Zn fertilizer	Zinc (Zn)	Zinc oxide nanoparticles	Improved micronutrient bioavailability	Increased enzyme activity and crop yield	Khan <i>et al.</i> , (2022) ^[8]
Nano-Fe fertilizer	Iron (Fe)	Iron oxide nanoparticles	Enhanced iron transport and chlorophyll synthesis	Improved photosynthesis and plant metabolism	El-Saadony <i>et al.</i> , (2024) ^[7]
Nano-composite fertilizer	Multiple nutrients	Polymer, zeolite, biochar composites	Slow and synchronized nutrient release	Reduced nutrient losses and improved soil fertility	Mahapatra <i>et al.</i> , (2025) ^[9]
Nano-encapsulated fertilizer	NPK and micronutrients	Nano-polymer coatings	Targeted nutrient delivery and controlled release	Higher fertilizer efficiency and lower pollution	Duhan <i>et al.</i> , (2023) ^[6]
Bio-nano fertilizer	Multiple nutrients	Nanoparticles with beneficial microbes	Enhanced microbial activity and nutrient solubilization	Improved soil health and sustainable crop production	Arora <i>et al.</i> , (2024) ^[2]

4. Synthesis and Formulation Approaches

4.1 Physical Methods

Physical synthesis methods are widely used for the production of nano-fertilizers due to their simplicity and rapid nanoparticle formation. Common physical approaches include ball milling, ultrasonication, laser ablation, evaporation–condensation, and thermal decomposition techniques. These methods mainly reduce bulk fertilizer materials into nano-sized particles through mechanical or physical processes without altering their chemical composition (Duhan *et al.*, 2023) ^[6]. Physical methods provide better control over particle size distribution and surface characteristics, which improve nutrient release behavior and nutrient uptake efficiency. However, some techniques require high energy consumption and expensive instrumentation, which may limit their large-scale agricultural application. Despite these limitations, physical synthesis remains important for the preparation of stable and uniform nano-fertilizer formulations suitable for precision nutrient management (Khan *et al.*, 2022) ^[8].

4.2 Chemical Methods

Chemical synthesis methods are among the most commonly used approaches for nano-fertilizer production because they allow precise control over nanoparticle composition, morphology, and stability. These methods involve chemical reactions such as precipitation, solgel synthesis, hydrothermal synthesis, co-precipitation, and chemical reduction techniques (Chen *et al.*, 2024) ^[4]. Chemical methods enable the development of highly reactive and efficient nano-scale nutrient formulations with improved nutrient availability and controlled release properties. Nano-fertilizers synthesized through chemical approaches often exhibit higher solubility, enhanced surface activity, and better plant absorption efficiency compared to conventional fertilizers. However, the use of toxic chemicals and

generation of hazardous by-products during synthesis may create environmental and safety concerns if not properly managed (Zhao *et al.*, 2024) ^[23].

4.3 Biological or Green Synthesis

Biological or green synthesis has recently emerged as one of the most promising and environmentally sustainable approaches for nano-fertilizer production. This method utilizes biological materials such as plant extracts, algae, fungi, bacteria, and other microorganisms for nanoparticle synthesis under eco-friendly conditions (Arora *et al.*, 2024) ^[2]. Green synthesis methods are gaining increasing attention because they minimize toxic chemical use, reduce environmental pollution, and improve the biocompatibility of nano-fertilizers. Biologically synthesized nanoparticles generally exhibit better environmental safety, enhanced stability, and lower toxicity compared to chemically synthesized nanoparticles. In addition, microbial-mediated synthesis can improve nutrient solubilization and rhizosphere activity, thereby supporting sustainable agriculture and soil health management (Rahman *et al.*, 2025) ^[13].

4.4 Nano-Encapsulation Technologies

Nano-encapsulation technology involves the coating or encapsulation of nutrients within nano-scale carrier materials such as polymers, liposomes, chitosan, zeolites, or biodegradable nanocomposites. This technology helps protect nutrients from premature degradation and enables slow, controlled, and targeted nutrient release according to crop demand (Raliya *et al.*, 2023) ^[15]. Nano-encapsulated fertilizers significantly reduce nutrient losses through leaching, volatilization, and fixation while improving nutrient uptake efficiency. These formulations also increase fertilizer stability and prolong nutrient availability in the soil–plant system. Nano-encapsulation is therefore considered an advanced strategy for

improving fertilizer performance and environmental sustainability in modern agricultural systems (Mahapatra *et al.*, 2025) ^[9].

4.5 Smart Delivery Systems

Smart delivery systems represent an advanced generation of nano-fertilizer technologies designed to release nutrients in response to specific environmental or plant-related signals such as soil moisture, pH, temperature, root exudates, or nutrient demand. These systems use intelligent nano-carriers, nano-

sensors, and responsive polymers to regulate nutrient release with high precision (El-Saadony *et al.*, 2024) ^[7]. Smart nano-fertilizer delivery systems improve nutrient synchronization with crop requirements and reduce excessive fertilizer application. Such technologies support precision agriculture, climate-smart farming, and sustainable intensification of crop production systems. Moreover, smart delivery systems help minimize environmental pollution, enhance nutrient use efficiency, and optimize agricultural resource management under changing climatic conditions (Sharma *et al.*, 2024) ^[20].

Table 4: Major methods involved in nano-fertilizer synthesis and formulation

Synthesis/Formulation Approach	Major Techniques	Principle/Process	Key Advantages	Agricultural Significance	References
Physical methods	Ball milling	Mechanical reduction of bulk particles into nano-sized materials	Simple and cost-effective method	Improves nutrient surface area and nutrient availability	Duhan <i>et al.</i> , (2023) ^[6]
Physical methods	Ultrasonication	Use of ultrasonic waves for nanoparticle formation and dispersion	Produces uniform nanoparticles	Enhances nutrient absorption efficiency	Khan <i>et al.</i> , (2022) ^[8]
Physical methods	Laser ablation	Laser energy used for nanoparticle synthesis	High purity nanoparticles	Suitable for advanced nano-formulations	Zhao <i>et al.</i> , (2024) ^[23]
Physical methods	Thermal decomposition	Heat-induced breakdown of precursor compounds	Controlled nanoparticle synthesis	Produces stable nano-fertilizer particles	Chen <i>et al.</i> , (2024) ^[4]
Chemical methods	Sol-gel synthesis	Conversion of liquid precursors into nano-scale gel structures	Uniform particle size and high stability	Improves controlled nutrient release	Raliya <i>et al.</i> , (2023) ^[15]
Chemical methods	Precipitation method	Chemical reaction forms insoluble nanoparticles	Easy and rapid synthesis	Enhances nutrient solubility and uptake	Sharma <i>et al.</i> , (2024) ^[20]
Chemical methods	Hydrothermal synthesis	High temperature and pressure-based nanoparticle formation	High crystallinity and purity	Suitable for efficient nutrient carriers	Chen <i>et al.</i> , (2024) ^[4]
Chemical methods	Chemical reduction	Reduction of metal ions into nanoparticles using reducing agents	Precise particle control	Improves fertilizer efficiency	Zhao <i>et al.</i> , (2024) ^[23]
Biological/green synthesis	Plant extract-mediated synthesis	Plant biomolecules used for nanoparticle formation	Eco-friendly and low toxicity	Supports sustainable agriculture	Arora <i>et al.</i> , (2024) ^[2]
Biological/green synthesis	Bacterial synthesis	Bacteria-mediated nanoparticle production	Biocompatible and environmentally safe	Enhances soil microbial interactions	Rahman <i>et al.</i> , (2025) ^[13]
Biological/green synthesis	Fungal synthesis	Fungi used for extracellular nanoparticle formation	High nanoparticle yield	Improves sustainable nutrient management	El-Saadony <i>et al.</i> , (2024) ^[7]
Biological/green synthesis	Algal synthesis	Algae-assisted nanoparticle production	Renewable and green approach	Reduces environmental pollution	Mahapatra <i>et al.</i> , (2025) ^[9]
Nano-encapsulation technologies	Polymer coating	Nutrients coated with nano-polymers	Controlled and slow nutrient release	Reduces nutrient losses	Raliya <i>et al.</i> , (2023) ^[15]
Nano-encapsulation technologies	Liposome encapsulation	Nutrients enclosed within lipid vesicles	Targeted nutrient delivery	Enhances nutrient uptake efficiency	Sharma <i>et al.</i> , (2024) ^[20]
Nano-encapsulation technologies	Chitosan nanoparticles	Chitosan-based nano-carrier systems	Biodegradable and non-toxic	Improves nutrient stability	Arora <i>et al.</i> , (2024) ^[2]
Nano-encapsulation technologies	Zeolite carriers	Nutrients loaded into porous zeolite structures	Gradual nutrient release	Improves soil nutrient retention	Mahapatra <i>et al.</i> , (2025) ^[9]
Smart delivery systems	pH-responsive release	Nutrient release triggered by soil pH changes	Site-specific nutrient availability	Enhances precision nutrient management	El-Saadony <i>et al.</i> , (2024) ^[7]
Smart delivery systems	Moisture-responsive release	Nutrient release regulated by soil moisture conditions	Reduces water-related nutrient loss	Supports climate-smart agriculture	Sharma <i>et al.</i> , (2024) ^[20]
Smart delivery systems	Nano-sensor-based systems	Nano-sensors monitor nutrient demand and release	Real-time nutrient management	Improves fertilizer use efficiency	Zhao <i>et al.</i> , (2024) ^[23]
Smart delivery systems	Precision nutrient delivery	Intelligent nutrient release based on crop demand	Optimized fertilizer application	Promotes sustainable crop production	Raliya <i>et al.</i> , (2023) ^[15]

5. Mechanisms of Action of Nano-Fertilizers

Nano-fertilizers improve crop performance through efficient nutrient delivery, controlled release, and enhanced plant uptake mechanisms. Nutrients are absorbed through root and foliar pathways, where nanoparticles penetrate plant tissues via pores, transport proteins, and endocytosis. Their slow and targeted nutrient release improves nutrient use efficiency (NUE) while minimizing leaching and volatilization losses. Nano-fertilizers

also influence rhizosphere interactions, microbial activity, photosynthesis, chlorophyll synthesis, enzymatic functions, and antioxidant defense systems under stress conditions. In addition, nano-scale nutrients regulate gene expression and metabolic pathways associated with nutrient transport and stress tolerance, supporting sustainable and precision agriculture systems (Raliya *et al.*, 2023; Verma *et al.*, 2023) ^[15, 22].

Table 5: Mechanisms of action of nano-fertilizers in crop plants

Mechanism Stage	Process/Activity	Functional Role in Plants	Major Outcome	References
Nano-fertilizer application	Application through soil or foliar spray	Delivers nano-scale nutrients to plant systems	Improved nutrient availability	Raliya <i>et al.</i> , (2023) ^[15]
Root uptake / Foliar uptake	Nutrient absorption through roots, stomata, and leaf surfaces	Facilitates rapid nutrient entry and translocation	Enhanced nutrient absorption efficiency	Verma <i>et al.</i> , (2023) ^[22]
Controlled nutrient release	Slow and targeted release of nutrients	Synchronizes nutrient availability with crop demand	Reduced nutrient loss and improved NUE	Sharma <i>et al.</i> , (2024) ^[20]
Improved nutrient absorption	Increased mobility and bioavailability of nutrients	Enhances nutrient transport within plant tissues	Better nutrient utilization and crop growth	Chen <i>et al.</i> , (2024) ^[4]
Photosynthesis stimulation	Improvement in chlorophyll and energy metabolism	Enhances light absorption and carbon assimilation	Increased biomass and productivity	El-Saadony <i>et al.</i> , (2024) ^[7]
Enzyme activity regulation	Activation of metabolic and antioxidant enzymes	Supports physiological and biochemical functions	Improved plant metabolism and stress tolerance	Khan <i>et al.</i> , (2022) ^[8]
Chlorophyll synthesis	Promotion of chlorophyll formation	Improves photosynthetic efficiency	Enhanced plant vigor and yield	Verma <i>et al.</i> , (2023) ^[22]
Enhanced antioxidant defense	Activation of antioxidant compounds and enzymes	Protects plants from oxidative stress	Increased tolerance to abiotic stress	Rahman <i>et al.</i> , (2025) ^[13]
Molecular and genetic regulation	Regulation of nutrient transport and stress-responsive genes	Modifies metabolic and signaling pathways	Improved adaptation and nutrient efficiency	Zhao <i>et al.</i> , (2024) ^[23]
Final agronomic response	Integrated physiological and metabolic improvement	Enhances crop productivity and sustainability	Improved NUE, growth, yield, and stress tolerance	Raliya <i>et al.</i> , (2023) ^[15]

6. Agronomic Efficiency of Nano-Fertilizers

Nano-fertilizers significantly improve agronomic efficiency by enhancing seed germination, crop growth, nutrient uptake, and stress tolerance under diverse environmental conditions. Their nano-scale size and controlled nutrient release properties improve nutrient absorption, translocation, and metabolic activity in plants. Several studies have reported increased chlorophyll synthesis, root development, biomass accumulation,

and grain yield following nano-fertilizer application. In addition, nano-fertilizers enhance plant tolerance against drought, salinity, and heat stress by improving antioxidant activity and water-use efficiency. Crop-specific responses have been observed in cereals, pulses, oilseeds, and vegetables, indicating their strong potential for sustainable and precision agriculture systems (Raliya *et al.*, 2023; Sharma *et al.*, 2024) ^[15, 20].

Table 6: Comparative agronomic responses of crops to nano-fertilizer application

Crop	Nano-fertilizer	Dose	Yield Increase	Reference
Wheat	Nano-urea	4 mL L ⁻¹ foliar spray	12–18%	Verma <i>et al.</i> , (2023) ^[22]
Rice	Nano-Zn fertilizer	20 mg kg ⁻¹ soil	10–15%	Khan <i>et al.</i> , (2022) ^[8]
Maize	Nano-NPK fertilizer	2 g L ⁻¹ spray	15–22%	Sharma <i>et al.</i> , (2024) ^[20]
Chickpea	Nano-Fe fertilizer	50 ppm foliar spray	11–16%	Rahman <i>et al.</i> , (2025) ^[13]
Soybean	Nano-composite fertilizer	1.5 g L ⁻¹ spray	14–20%	El-Saadony <i>et al.</i> , (2024) ^[7]
Tomato	Nano-K fertilizer	100 ppm foliar spray	18–25%	Raliya <i>et al.</i> , (2023) ^[15]

7. Environmental and Ecological Implications

Nano-fertilizers offer significant advantages in improving nutrient use efficiency and reducing fertilizer losses; however, their environmental and ecological impacts require careful evaluation. Excessive accumulation of nanoparticles may alter soil physicochemical properties, interfere with nutrient cycling, and induce oxidative stress in soil organisms (Khan *et al.*, 2022) ^[8]. Soil microbial communities are highly sensitive to nanoparticle exposure, and high concentrations of metal-based nanoparticles may reduce microbial biomass and enzymatic activity (Rajput *et al.*, 2024) ^[14]. Nanoparticles may also

accumulate in plant tissues and enter the food chain, posing potential risks to human and animal health (Dimkpa *et al.*, 2023) ^[5]. In addition, nanoparticle runoff can contaminate aquatic ecosystems and affect non-target organisms (Zhao *et al.*, 2024) ^[23]. Environmental persistence, mobility, and transformation of nanoparticles further influence their ecological behavior and toxicity (Rahman *et al.*, 2025) ^[13]. Therefore, long-term ecotoxicological assessment, life cycle analysis, and regulatory risk evaluation are necessary for the safe and sustainable use of nano-fertilizers in agriculture (Mahapatra *et al.*, 2025) ^[9].

Table 7: Environmental and ecological implications of nano-fertilizers in agricultural systems

Environmental Aspect	Major Concern	Observed Effects	Ecological Implications	Reference
Nanotoxicity in soil ecosystems	Accumulation of nanoparticles in soil	Oxidative stress, altered soil properties, toxicity to soil organisms	Reduced soil health and ecological imbalance	Khan <i>et al.</i> , (2022) ^[8]
Soil microbial communities	Exposure to metal-based nanoparticles	Reduction in microbial biomass and enzymatic activity	Disturbance in nutrient cycling and rhizosphere functioning	Rajput <i>et al.</i> , (2024) ^[14]
Beneficial microbial interactions	Low-dose nano-formulations	Enhanced microbial activity and nutrient solubilization	Improved soil fertility and nutrient availability	Arora <i>et al.</i> , (2024) ^[2]
Bioaccumulation in plants	Uptake and accumulation in edible plant tissues	Transfer of nanoparticles into food systems	Potential food chain contamination	Dimkpa <i>et al.</i> , (2023) ^[5]

Human health concerns	Long-term nanoparticle exposure	Cellular toxicity, oxidative damage, inflammatory responses	Potential public health risks	Rico <i>et al.</i> , (2021) ^[17]
Aquatic contamination	Runoff and leaching into water bodies	Toxicity to algae, fish, and aquatic microbes	Aquatic ecosystem disruption	Zhao <i>et al.</i> , (2024) ^[23]
Environmental persistence	Stability and slow degradation of nanoparticles	Long-term accumulation in soil and water systems	Increased ecological exposure risk	Rahman <i>et al.</i> , (2025) ^[13]
Nanoparticle transformation	Aggregation, dissolution, and chemical modification	Changes in nanoparticle mobility and toxicity	Altered environmental behavior	Servin & White (2021) ^[19]
Soil physicochemical changes	Interaction with soil minerals and organic matter	Changes in pH, nutrient mobility, and soil structure	Influence on soil fertility dynamics	Chen <i>et al.</i> , (2024) ^[4]
Ecotoxicological assessment	Lack of standardized toxicity evaluation	Limited understanding of long-term environmental effects	Regulatory uncertainty and risk assessment challenges	Mahapatra <i>et al.</i> , (2025) ^[9]
Non-target organism effects	Exposure to beneficial soil fauna	Potential toxicity to earthworms and insects	Reduced biodiversity and ecosystem stability	Singh <i>et al.</i> , (2023) ^[21]
Airborne nanoparticle exposure	Aerosol formation during application	Inhalation risks to humans and animals	Occupational and environmental safety concerns	Mukhopadhyay (2021) ^[10]
Regulatory limitations	Insufficient environmental regulations	Lack of safety standards and monitoring systems	Challenges in large-scale agricultural adoption	Parisi <i>et al.</i> , (2021) ^[11]
Sustainable application potential	Controlled and low-dose application	Reduced nutrient losses and lower pollution	Improved environmental sustainability	El-Saadony <i>et al.</i> , (2024) ^[7]
Future research needs	Limited long-term field studies	Insufficient ecological and toxicological datasets	Need for life cycle assessment and field validation	Adisa <i>et al.</i> , (2021) ^[1]

8. Economic, Regulatory and Adoption Challenges

Although nano-fertilizers improve nutrient efficiency and sustainability, several economic and regulatory challenges limit their large-scale adoption. High production and formulation costs remain a major barrier, especially for smallholder farmers in developing countries. In addition, limited technical knowledge, inadequate field demonstrations, and uncertainty regarding long-term environmental safety reduce farmer acceptance. Regulatory frameworks also differ globally the European Union follows strict environmental and nanotoxicity regulations, while the United States emphasizes product safety and commercialization standards. India has recently introduced guidelines for nano-urea and nano-fertilizer approval, but comprehensive regulatory systems are still evolving. Public concerns regarding nanoparticle toxicity, food safety, and environmental risks further highlight the need for transparent risk communication, standardized regulations, and long-term field validation before widespread commercialization can be achieved (Mahapatra *et al.*, 2025; Zhao *et al.*, 2024)^[9, 23].

9. Research Gaps and Future Perspectives

Despite rapid progress in nano-fertilizer research, several critical limitations still restrict their large-scale agricultural application. Most available studies are based on short-term greenhouse experiments, while long-term field validation under diverse agroecological conditions remains limited. Inadequate information regarding nanoparticle toxicity, environmental persistence, food-chain transfer, and soil microbe interactions further creates uncertainty about ecological safety. In addition, poor regulatory harmonization and lack of standardized application protocols hinder commercialization and global acceptance. Future research should therefore emphasize multi-location field trials, environmentally safe synthesis methods, precision nano-formulations, AI-assisted nutrient delivery systems, and life cycle assessment approaches. Integrating nanotechnology with precision agriculture and climate smart farming may improve nutrient efficiency while reducing environmental risks and fertilizer dependency (Mahapatra *et al.*, 2025; Zhao *et al.*, 2024)^[9, 23].

10. Conclusion

Nano-fertilizers have emerged as a promising innovation for

improving nutrient use efficiency, crop productivity, and environmental sustainability in modern agriculture. Their unique nano-scale properties enable controlled nutrient release, targeted delivery, enhanced nutrient uptake, and improved stress tolerance under adverse environmental conditions. Current evidence indicates that nano-fertilizers can reduce nutrient losses, support precision agriculture, and contribute to climate-smart farming systems. However, concerns regarding nanotoxicity, ecological safety, bioaccumulation, regulatory limitations, and long-term environmental impacts remain significant challenges for large-scale adoption.

A balanced evaluation suggests that nano-fertilizers should not be considered complete replacements for conventional fertilizers, but rather advanced complementary tools for sustainable nutrient management. Future progress will depend on long-term field validation, standardized regulations, safe synthesis approaches, and integration with AI-based precision farming technologies. With appropriate scientific assessment and responsible application, nano-fertilizers may play an important role in achieving sustainable agricultural intensification, food security, and environmentally resilient crop production systems in the future.

References

- Adisa IO, Pullagurala VLR, Peralta-Videa JR, Dimkpa CO, Elmer WH, Gardea-Torresdey JL, *et al.* Recent advances in nano-enabled fertilizers and pesticides: A critical review of mechanisms of action. *Environ Sci Nano*. 2021;8(2):423-441.
- Arora PK, Tripathi S, Omar RA, Chauhan P, Sinhal VK, Singh A, *et al.* Next-generation fertilizers: The impact of bionanofertilizers on sustainable agriculture. *Microb Cell Fact*. 2024;23:254.
- Channab B, Idrissi AE, Ammar A, Dardari O, Marrane SE, Gharrak AE, *et al.* Recent advances in nano-fertilizers: Synthesis, crop yield impact, and economic analysis. *Nanoscale*. 2024;16:4484-4513.
- Chen J, Wei X, Liu Y, Zhang H, Li Q. Advances in nano-enabled fertilizers for sustainable agricultural production and environmental protection. *Sci Total Environ*. 2024;912:169102.
- Dimkpa CO, Bindraban PS, Fugice J, Agyin-Birikorang S,

- Singh U, Hellums D. Composite micronutrient nanoparticles and salts decrease drought stress in soybean. *Agron Sustain Dev*. 2023;43:17.
6. Duhan JS, Kumar R, Kumar N, Kaur P, Nehra K, Duhan S. Nanotechnology: The new perspective in precision agriculture. *Biotechnol Rep*. 2023;39:e00821.
 7. El-Saadony MT, Saad AM, Soliman SM, Salem HM, Ahmed AI, El-Tahan AM. Nanotechnology applications in sustainable agriculture: Current trends and future opportunities. *Environ Res*. 2024;248:118216.
 8. Khan I, Awan SA, Ikram M, Rizwan M, Akhtar N, Yasmin H, Sayyed RZ. Nanoparticles: Properties, applications and toxicities in agriculture and environment. *Chemosphere*. 2022;287:132103.
 9. Mahapatra DM, Chanakya HN, Ramachandra TV. Nano-fertilizers for sustainable crop production: Emerging opportunities and environmental concerns. *J Environ Manage*. 2025;372:123041.
 10. Mukhopadhyay SS. Nanotechnology in agriculture: Prospects and constraints. *Nanotechnol Sci Appl*. 2021;14:63-74.
 11. Parisi C, Vigani M, Rodríguez-Cerezo E. Agricultural nanotechnologies: What are the current possibilities? *Nano Today*. 2021;40:101287.
 12. Pudhuvai B, Koul B, Das R, Shah MP. Nano-fertilizers for resurgence in nutrient use efficiency (NUE): A sustainable agricultural strategy. *Curr Pollut Rep*. 2025;11(1):1-20.
 13. Rahman MM, Islam MS, Hasanuzzaman M, Oku H. Advances in nano-enabled fertilizers for sustainable agriculture and environmental safety. *Environ Technol Innov*. 2025;37:103245.
 14. Rajput VD, Minkina T, Sushkova S, Tsitsuashvili V, Mandzhieva S, Gorovtsov A, *et al*. Effects of metal-based nanoparticles on soil microbial communities and enzymatic activity. *J Hazard Mater*. 2024;462:132445.
 15. Raliya R, Saharan V, Dimkpa C, Biswas P. Nanofertilizer for precision and sustainable agriculture: Current state and future perspectives. *J Agric Food Chem*. 2023;71(18):7024-7041.
 16. Rani M, Yadav RK, Sharma S, Kumar V. Bibliometric analysis and emerging trends in nano-fertilizer research for sustainable agriculture. *Environ Technol Innov*. 2025;38:103458.
 17. Rico CM, Majumdar S, Duarte-Gardea M, Peralta-Videa JR, Gardea-Torresdey JL. Interaction of nanoparticles with edible plants and implications to food safety. *J Agric Food Chem*. 2021;69(6):1707-1720.
 18. Science of the Total Environment. 2024;912:169102.
 19. Servin AD, White JC. Nanotechnology in agriculture: Next steps for understanding engineered nanoparticle exposure and risk. *NanoImpact*. 2021;21:100278.
 20. Sharma P, Singh H, Kumar A, Kaur G. Nano-fertilizers as climate-smart nutrient management tools for sustainable agriculture. *Agronomy*. 2024;14(2):356.
 21. Singh R, Meena RS, Kumar S, Yadav GS. Nano-fertilizers and sustainable agriculture: Opportunities and constraints. *Front Plant Sci*. 2023;14:1198745.
 22. Verma KK, Song XP, Degu HD, Guo DJ, Joshi A, Huang HR, Xu L, Singh M, Rajput VD, Li YR. Recent advances in nitrogen and nano-nitrogen fertilizers for sustainable crop production: A mini-review. *Chem Biol Technol Agric*. 2023;10:1-15.
 23. Zhao L, Peralta-Videa JR, Rico CM, Hernandez-Viezcás JA, Sun Y, Gardea-Torresdey JL. Nanotechnology applications in sustainable agriculture: Progress, challenges, and future perspectives. *Sci Total Environ*. 2024;912:168965.