International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

Development of Nanoparticles and Their Use in Agricultural Applications

Dr. Manoj Kumar
Associate Professor, Department of Chemistry, Government College, Kota, Rajasthan, India
mjkrdhawan@gmail.com
Article Received: 23-06-2025, Revised: 13-07-2025, Accept: 19-07-2025
https://doi.org/10.64882/ijrt.v13.i3.911

Abstract
The development of nanoparticles has emerged as a transformative approach in agricultural science, offering innovative solutions to enhance productivity while ensuring environmental sustainability. Nanoparticles, owing to their ultra-small size, high surface area, and unique physicochemical properties, enable efficient delivery of nutrients, pesticides, and bioactive compounds in agro-ecosystems. Their application in agriculture includes nano-fertilizers for improved nutrient use efficiency, nano-pesticides and nano-fungicides for targeted pest and disease management, seed nano-coatings to enhance germination and vigor, and nanoparticle based systems for mitigating abiotic stresses such as drought and salinity. Furthermore, green synthesis of nanoparticles using biological resources has gained attention due to its ecofriendly and cost-effective nature. Despite their promising potential, concerns related to environmental fate, ecotoxicity, and regulatory frameworks remain critical challenges. This paper reviews the methods of nanoparticle development, their functional roles in agricultural applications, and the associated benefits and risks, highlighting their potential to support sustainable and precision agriculture in the future.
Keywords: Nanoparticles, Nanotechnology in Agriculture, Nano-fertilizers, Nano-pesticides, Sustainable Agriculture

Introduction

The development of nanoparticles has opened new frontiers in agricultural science by providing advanced tools to address the growing challenges of food security, environmental degradation, and resource inefficiency. With the global population increasing rapidly and arable land shrinking, conventional agricultural practices that rely heavily on chemical fertilizers and pesticides are proving inadequate and environmentally unsustainable. In this context, nanotechnology, which involves the manipulation of materials at the nanoscale (1–100 nm), offers innovative possibilities for improving agricultural productivity while minimizing ecological impacts. Nanoparticles exhibit unique physicochemical properties such as high surface-to-volume ratio, enhanced reactivity, tunable solubility, and controlled release behavior, which make them particularly suitable for agricultural applications. These properties allow nanoparticles to function as efficient carriers of nutrients, agrochemicals, and bioactive molecules, thereby enhancing their uptake, reducing losses through leaching and volatilization, and lowering the overall input requirements. The development of nanoparticles for agriculture involves diverse synthesis approaches, including physical, chemical, and biological methods, with increasing emphasis on green synthesis techniques that utilize plant extracts and microorganisms to produce environmentally benign nanomaterials.

Figure 1: Applications of nanotechnology in agriculture

In agricultural systems, nanoparticles have demonstrated significant potential as nano-fertilizers that improve nutrient use efficiency, nano-pesticides and nano-fungicides that enable targeted pest and disease management, and nano-enabled seed treatments that enhance germination and early plant vigor. Additionally, nanoparticles play a role in improving soil health, regulating plant physiological processes, and enhancing tolerance to abiotic stresses such as drought, salinity, and heavy metal toxicity. However, alongside these benefits, the widespread use of nanoparticles in agriculture raises important concerns regarding their persistence, mobility, and potential toxicity in soil–plant–microbe systems and the food chain. Therefore, a balanced and systematic understanding of nanoparticle development, agricultural applications, and associated environmental and safety implications is essential. This paper aims to examine the development of nanoparticles and critically evaluate their diverse applications in agriculture, highlighting both their transformative potential and the challenges that must be addressed to ensure their safe and sustainable integration into modern farming practices.

Significance of the Study

The significance of the present study lies in its contribution to understanding how nanoparticle development can enhance agricultural productivity while promoting sustainability. By examining the synthesis methods and functional applications of nanoparticles in agriculture, this study highlights their potential to improve nutrient use efficiency, reduce excessive reliance on conventional agrochemicals, and minimize environmental pollution. The use of nanoparticles in fertilizers, pesticides, and seed treatments offers targeted delivery systems that can increase crop yield and quality while lowering input costs and chemical residues in soil and water. Additionally, this study provides valuable insights into the role of nanotechnology in addressing major agricultural challenges such as abiotic stress, soil degradation, and food security. Equally important, the research emphasizes environmental safety, ecotoxicological concerns, and regulatory considerations associated with agricultural nanoparticles. By integrating both benefits and risks, the study serves as a scientific foundation for researchers, policymakers, and

International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

agricultural practitioners seeking to adopt nanotechnology-based solutions responsibly and effectively in modern farming systems.

Background of Nanotechnology

Nanotechnology emerged as a multidisciplinary field of science and engineering focused on the manipulation and application of materials at the nanoscale, typically between 1 and 100 nanometers, where matter exhibits unique physical, chemical, and biological properties. The conceptual foundation of nanotechnology can be traced back to Richard Feynman's visionary lecture in 1959, which emphasized the potential of controlling matter at the atomic level. Advances in analytical tools such as electron microscopy and scanning probe techniques during the late twentieth century enabled scientists to observe and engineer materials at the nanoscale, accelerating the development of nanomaterials. Due to their high surface area, enhanced reactivity, and tunable characteristics, nanoparticles have found applications across diverse sectors including medicine, electronics, energy, and environmental science. In recent years, nanotechnology has gained prominence in agriculture as a promising approach to improve resource efficiency, crop protection, and sustainability, making it a vital component of next-generation agricultural innovation.

Types of Nanoparticles and Their Physicochemical Characteristics Influencing Agricultural Performance

Metallic Nanoparticles: Metallic nanoparticles, such as silver, gold, zinc, and copper nanoparticles, are widely explored in agriculture due to their strong antimicrobial properties and high reactivity. These nanoparticles are particularly effective in plant protection applications, including nano-pesticides and nano-fungicides, where they help control pathogenic bacteria, fungi, and insects. Their small size enhances surface interactions with microbial cells, leading to improved efficacy at lower dosages.

Metal Oxide Nanoparticles: Metal oxide nanoparticles, including zinc oxide, titanium dioxide, iron oxide, and silica nanoparticles, play a significant role in crop nutrition and stress management. These nanoparticles serve as sources of essential micronutrients and improve photosynthetic efficiency, enzyme activity, and stress tolerance. Their stability and controlled release properties make them suitable for sustained nutrient delivery in soil–plant systems.

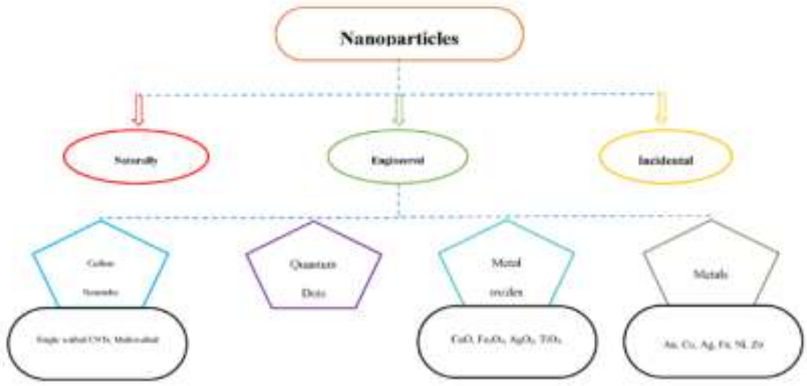

Figure 2. Nanoparticles and its types.

Polymeric Nanoparticles: Polymeric nanoparticles are composed of biodegradable polymers such as chitosan, alginate, and poly (lactic-co-glycolic acid). They are mainly used as carriers for fertilizers, pesticides, and growth regulators, enabling controlled and targeted release. Their biocompatibility and degradability reduce environmental risks and enhance safety in agricultural use.

Carbon-Based Nanoparticles: Carbon-based nanoparticles, including carbon nanotubes, graphene, and fullerenes, exhibit exceptional mechanical strength, electrical conductivity, and adsorption capacity. In agriculture, they enhance seed germination, nutrient uptake, and water retention, while also improving soil structure and plant growth performance.

Nano-Bio Composites: Nano-bio composites integrate nanoparticles with biological materials such as plant extracts, proteins, or microbial components. These composites combine the functional advantages of nanomaterials with biological compatibility, offering eco-friendly and sustainable agricultural solutions.

Influence of Size, Shape, and Surface Characteristics: The agricultural performance of nanoparticles is strongly influenced by their size, shape, and surface properties. Smaller nanoparticles exhibit higher reactivity and better penetration into plant tissues, while shape variations (spherical, rod-shaped, or tubular) affect cellular uptake and interaction efficiency. Surface characteristics, including charge, coating, and functionalization, determine stability, dispersion, and targeted delivery, ultimately governing the effectiveness and safety of nanoparticles in agricultural applications.

Applications of Nanotechnology in Agriculture

1. **Enhancing Plant Growth and Protection**

Nanotechnology significantly enhances plant growth and protection through nano-biofortification, a process in which nanoparticles are used to enrich plants with essential nutrients. Nanomaterials such as fullerol have been shown to improve plant biomass, fruit size, and overall yield, while also increasing plant resilience to environmental stress. This approach contributes to addressing micronutrient deficiencies in crops, thereby supporting food and nutritional security. When integrated with autonomous sensors, GPS technologies,

International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

and precision farming tools, nano-nutrient delivery systems allow real-time monitoring of soil and crop conditions, ensuring site-specific and efficient application for optimal crop improvement.

Figure 3: Application of nanotechnology in the agricultural and food

2. **Disease and Pest Management**

Nanotechnology is transforming pest and disease control through the development of nano-agrochemicals, including nano-herbicides, nano-fungicides, and nano-emulsions. Encapsulation of active ingredients enables targeted and controlled release, increasing efficacy while reducing chemical runoff and environmental contamination. In addition, nano-biosensors based on gold nanoparticles, quantum dots, and carbon nanotubes facilitate rapid and precise detection of plant pathogens. Advanced tools such as nano-barcode technology support multiplex pathogen identification, enabling early disease diagnosis and promoting sustainable crop protection strategies.

3. **Seed Nano-Priming**

Seed nano-priming involves treating seeds with nanoparticles to enhance germination, seedling vigor, and yield performance. Compared to conventional priming methods, nanoparticle treatments have demonstrated superior results. For example, seeds treated with iron, zinc, and calcium nanoparticles show improved seed weight, growth rate, and productivity, highlighting nano-priming as a promising approach for boosting agricultural output.

4. **Genetic Engineering and Gene Editing**

Nanotechnology has improved traditional gene transfer techniques such as electroporation and Agrobacterium-mediated transformation. Nanomaterials like gold nanoparticles and carbon nanotubes serve as efficient carriers for gene delivery in crops including tobacco and rice. Moreover, the integration of nanotechnology with CRISPR/Cas9 systems has enhanced genome-editing precision, enabling targeted genetic modifications such as improved disease resistance in crops like wheat.

5. **Smart Fertilizers**

Nano- or smart fertilizers encapsulate nutrients within nanomaterials to ensure controlled and targeted release, thereby improving nutrient use efficiency and reducing environmental losses. Materials such as chitosan, silicon dioxide, and carbon nanotubes are commonly used to enhance germination, nutrient uptake, and crop yield. These technologies are also applied in specialized environments such as space and underwater farming, where zeolite-based nano-fertilizers support plant growth under controlled conditions.

6. **Food Packaging and Preservation**

In post-harvest agriculture, polymer nanocomposites containing clay, silica, and silver nanoparticles improve food freshness, shelf life, and safety. Smart packaging systems equipped with nanosensors enable real-time detection of spoilage and contamination, while nano-encapsulation techniques enhance food quality and nutritional value. Several companies are developing nano-enabled packaging solutions; for instance, Bayer produces Durethan® KU2-2601 for beverage packaging, while nano-clay-based flexible films are used in packaging products such as Cadbury Dairy Milk™ and Marks & Spencer Swiss chocolate.

Nanotechnology-Based Agrochemicals for Food Security and Sustainability

Nanotechnology-based agrochemicals improve agricultural efficiency and sustainability by enabling targeted nutrient and pesticide delivery, reducing chemical losses, and minimizing environmental impacts. Nano-fertilizers, nano-pesticides, biosensors, and nano-priming enhance crop growth, protection, and stress tolerance, supporting food security through precise, eco-friendly, and resource-efficient agricultural practices.

1. **Nanoparticle Absorption and Transport in Plants**

Nanoparticles enter plants through roots or aerial openings and are transported to various tissues via apoplastic and symplastic pathways. Smaller NPs penetrate cell walls easily, while larger ones enter through stomata or hydathodes. Cellular entry occurs through diffusion, endocytosis, or interactions with ion channels and aquaporins.

2. **Foliar Uptake and Translocation of Nanoparticles**

Foliar application enables efficient nanoparticle uptake through leaf epidermis and stomata, followed by translocation via apoplastic and symplastic pathways. Uptake efficiency depends on plant traits, environmental conditions, and nanoparticle properties. Compared to soil application, foliar spraying reduces losses and environmental accumulation while enhancing delivery efficiency.

International Journal of Research and Technology (IJRT)

International Open-Access, Peer-Reviewed, Refereed, Online Journal

ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529

| An ISO 9001:2015 Certified Journal |

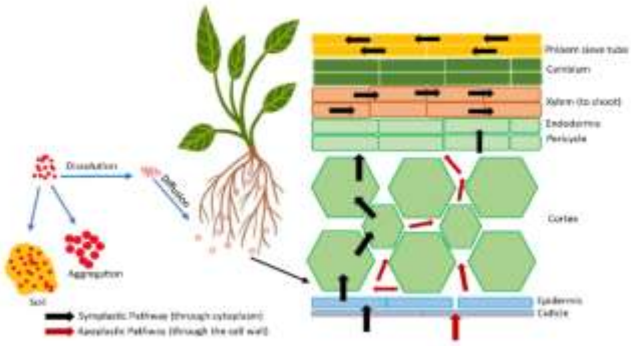

Figure 3. Foliar applications of NPs and transport via apoplastic and symplastic pathway.

3. Root Uptake and Transformation of Nanoparticles

Plant roots can absorb nanoparticles directly from soil, with uptake largely dependent on particle size. Smaller nanoparticles move readily to shoots, medium-sized ones accumulate in roots, and larger particles are restricted. Transport occurs via apoplastic and symplastic pathways, with movement observed within root cell walls, cytoplasm, and organelles.

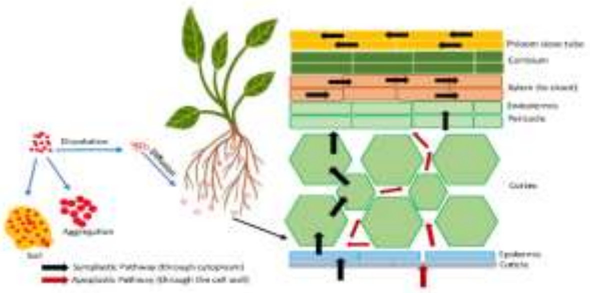

Figure 4. Root application of NPs and their transport via symplastic and apoplastic pathway.

Literature Review

The application of nanotechnology in agriculture has gained significant attention due to its potential to enhance crop productivity, protect plants, and improve resource-use efficiency. Several studies have highlighted the role of metal and carbon-based nanoparticles in promoting plant growth and agricultural sustainability. Khan et al. (2023) examined the impact of silver nanoparticles on plant growth and emphasized their effectiveness in enhancing germination, biomass accumulation, and resistance against pathogens when applied at optimal concentrations. Similarly, Kale et al. (2021) reviewed emerging agricultural applications of silver nanoparticles and reported their antimicrobial properties, which make them suitable for plant protection, seed treatment, and disease management. However, these studies also cautioned that excessive nanoparticle concentrations may lead to phytotoxic effects, underlining the importance of dosage optimization. Kaningini et al. (2022) further expanded this perspective by reviewing various metal nanoparticles, including zinc, iron, copper, and silver, and highlighted their multifunctional roles in crop nutrition, stress tolerance, and soil health improvement, while also addressing concerns related to environmental fate and toxicity.

Carbon-based nanomaterials have also been widely explored for agricultural applications due to their unique structural and physicochemical properties. Shojaei et al. (2019) discussed the synthesis, properties, and applications of carbon nanoparticles such as carbon nanotubes, graphene, and fullerenes in agriculture. Their study demonstrated that carbon nanoparticles can enhance seed germination, water uptake, nutrient absorption, and photosynthetic efficiency. Pestovsky and Martínez-Antonio (2017) provided a comprehensive overview of nanoformulations used in agriculture, emphasizing the role of nanocarriers in controlled and targeted delivery of fertilizers and pesticides. These nanoformulations were shown to significantly reduce nutrient losses and chemical runoff, thereby improving nutrient use efficiency and minimizing environmental pollution. Kim et al. (2018) further highlighted recent developments in agricultural nanotechnology, noting that nano-enabled fertilizers, pesticides, and biosensors contribute to precision agriculture by enabling real-time monitoring and site-specific input application.

In addition to crop productivity and protection, several studies have focused on the broader implications of nanotechnology for sustainable agriculture. Pramanik et al. (2020) extensively reviewed the application of nanotechnology in agriculture, covering areas such as nano-fertilizers, nano-pesticides, soil health management, and stress mitigation. Their work emphasized that nanotechnology can play a critical role in addressing challenges related to climate change, soil degradation, and food security by improving crop resilience and resource efficiency. However, they also highlighted the need for long-term studies to evaluate nanoparticle accumulation, ecotoxicological risks, and food safety concerns. Collectively, the reviewed literature indicates that nanotechnology offers transformative opportunities for modern agriculture, but its large-scale adoption requires balanced integration of technological innovation, environmental safety, and regulatory oversight.

Methods of Nanoparticle Development

1. **Physical Methods (Top-Down Approaches)**

Physical methods involve the breakdown of bulk materials into nanoscale particles through mechanical or physical forces. Common techniques include ball milling, high-energy grinding, laser ablation, and evaporation–condensation. These approaches are widely used for producing metallic and metal oxide nanoparticles with relatively uniform composition. Top-down methods offer advantages such as the absence of chemical contaminants and high purity of the final product. However, they often require substantial energy input, specialized equipment, and may result in broad particle size distribution and surface defects, which can influence nanoparticle reactivity and performance in agricultural applications.

2. **Chemical Methods**

Chemical synthesis methods are among the most extensively used techniques for nanoparticle development due to their ability to precisely control particle size, shape, and surface characteristics. The sol–gel method involves the transformation of a liquid sol into a solid gel, producing nanoparticles with high homogeneity and stability. Precipitation methods rely on chemical reactions that induce nanoparticle formation from dissolved precursors, offering simplicity and scalability. Hydrothermal synthesis employs high temperature and pressure conditions in aqueous solutions to produce highly crystalline and uniform nanoparticles. Despite their effectiveness, chemical methods often involve toxic solvents, reducing agents, and stabilizers, which may pose environmental and health concerns if not properly managed.

3. **Biological/Green Synthesis**

Biological or green synthesis represents an eco-friendly alternative to conventional nanoparticle development methods. This approach utilizes plant extracts, bacteria, fungi, algae, and enzymes as natural reducing and stabilizing agents. Green synthesis offers several advantages, including low toxicity, biocompatibility, cost-effectiveness, and reduced environmental impact. Additionally, biomolecules present in biological systems can functionalize nanoparticles, enhancing their stability and agricultural applicability. However, limitations include slower synthesis rates, variability in nanoparticle characteristics, and challenges in large-scale production and standardization.

Physicochemical Properties of Agricultural Nanoparticles

1. **Surface Area and Reactivity**

One of the most significant physicochemical properties of agricultural nanoparticles is their exceptionally high surface area-to-volume ratio. As particle size decreases to the nanoscale, the number of surface atoms increases dramatically, enhancing surface reactivity. This elevated reactivity allows nanoparticles to interact more efficiently with soil components, plant roots, and microbial communities, thereby improving nutrient availability, catalytic activity, and antimicrobial effectiveness. High surface area also enables lower application rates while maintaining or improving performance compared to conventional agrochemicals.

2. **Solubility and Mobility**

Nanoparticles exhibit altered solubility and mobility in soil–water–plant systems due to their small size and surface properties. Enhanced solubility improves the dissolution and bioavailability of essential nutrients, facilitating easier uptake by plants. Increased mobility allows nanoparticles to penetrate soil pores and plant tissues more effectively, promoting targeted delivery to specific plant organs. However, excessive mobility may also increase the risk of leaching, making controlled formulation essential.

3. **Stability and Aggregation**

Stability is a critical factor influencing the effectiveness of agricultural nanoparticles. Nanoparticles tend to aggregate due to high surface energy, which can reduce their reactivity and bioavailability. Stabilization through surface coatings or dispersing agents helps maintain particle size, prevent aggregation, and prolong functional lifespan in agricultural environments. Stable nanoparticles ensure consistent performance under varying soil pH, moisture, and ionic conditions.

4. **Controlled Release Behavior**

Controlled release is a key advantage of nanoparticle-based agricultural inputs. Encapsulation of nutrients or active ingredients within nanocarriers allows gradual and sustained release, matching crop nutrient demand and reducing losses through volatilization, runoff, and leaching. This property enhances nutrient use efficiency, minimizes environmental pollution, and supports precision agriculture practices.

5. **Role of Surface Functionalization**

Surface functionalization involves modifying the nanoparticle surface with organic or inorganic molecules to improve compatibility, targeting, and efficiency. Functionalized nanoparticles exhibit improved dispersion, enhanced interaction with plant tissues, and reduced toxicity. Surface coatings such as polymers, biomolecules, or ligands can regulate release rates, improve stability, and enable site-specific delivery, making surface functionalization a critical strategy for optimizing the agricultural performance of nanoparticles.

Nanoparticles in Crop Nutrition (Nano-Fertilizers)

1. **Mechanism of Nutrient Delivery**

Nano-fertilizers are designed to supply essential plant nutrients through nanoparticles or nanocarriers that enable precise and efficient delivery. These systems may encapsulate nutrients within nanoscale matrices or bind them to nanoparticle surfaces, allowing gradual release in response to plant demand. Due to their small size, nano-fertilizers can penetrate plant tissues through roots or foliage and move via apoplastic and symplastic pathways, ensuring direct nutrient availability at the cellular level. This targeted delivery improves nutrient absorption and minimizes wastage commonly associated with conventional fertilizers.

2. **Enhanced Nutrient Use Efficiency**

One of the most significant advantages of nano-fertilizers is their ability to enhance nutrient use efficiency (NUE). The high surface area and controlled release properties of nanoparticles ensure sustained nutrient supply, matching the crop’s growth stages and physiological requirements. This leads to improved nutrient uptake, reduced application frequency, and lower fertilizer input rates. Enhanced NUE contributes to cost-effective farming practices and supports sustainable nutrient management strategies.

3. **Reduction in Leaching and Volatilization Losses**

Conventional fertilizers often suffer from significant nutrient losses through leaching, volatilization, and runoff, resulting in environmental pollution and reduced fertilizer effectiveness. Nano-fertilizers mitigate these losses by immobilizing nutrients within nanostructures, preventing rapid dissolution and uncontrolled movement in soil and water systems. Controlled release formulations significantly reduce nitrogen volatilization and phosphorus leaching, thereby protecting groundwater quality and reducing eutrophication of aquatic ecosystems.

4. **Impact on Crop Growth and Yield**

The efficient nutrient delivery and sustained availability provided by nano-fertilizers positively influence plant physiological processes such as photosynthesis, enzyme activity, and root development. Improved nutrient status enhances plant vigor, stress tolerance, and biomass accumulation, ultimately leading to increased crop yield and improved produce quality. Studies have demonstrated that nano-fertilizers can increase grain yield, fruit size, and nutrient content while maintaining soil fertility. Overall, nano-fertilizers represent a promising innovation for improving crop productivity and ensuring sustainable agricultural development.

Nanoparticles in Plant Protection (Nano-Pesticides and Nano-Fungicides)

1. **Targeted Delivery of Active Ingredients**

Nano-pesticides and nano-fungicides utilize nanoparticles as carriers to deliver active ingredients precisely to target pests and pathogens. Encapsulation or surface binding of agrochemicals within nanomaterials enables controlled and site-specific release, ensuring that the active compounds reach the intended biological targets with minimal loss. The small size and tunable surface properties of nanoparticles allow enhanced penetration into insect cuticles, fungal hyphae, and plant tissues, thereby increasing the effectiveness of plant protection measures.

2. **Improved Pest and Disease Control**

The enhanced bioavailability and reactivity of nano-formulated agrochemicals result in superior pest and disease control compared to conventional formulations. Nanoparticles can disrupt microbial cell membranes, interfere with metabolic pathways, and enhance the antimicrobial activity of pesticides and fungicides. This leads to faster action, prolonged effectiveness, and improved control of a wide range of plant pathogens and insect pests. Additionally, nano-fungicides exhibit increased stability under environmental conditions such as UV radiation and rainfall, ensuring consistent field performance.

3. **Reduced Chemical Dosage**

One of the major advantages of nano-pesticides and nano-fungicides is the significant reduction in the quantity of active ingredients required for effective crop protection. Controlled release and targeted delivery minimize off-target losses, enabling lower application rates while maintaining or improving efficacy. This reduction decreases chemical residues on crops, lowers environmental contamination, and reduces risks to non-target organisms, including beneficial insects and soil microbes.

4. **Resistance Management**

The development of resistance in pests and pathogens is a major challenge in modern agriculture. Nanotechnology-based plant protection strategies contribute to resistance management by enabling multi-site modes of action and sustained release of active compounds. Nanoparticles can be engineered to deliver combinations of active ingredients or enhance the efficacy of existing agrochemicals, reducing selective pressure on pest populations. This integrated approach helps delay resistance development, prolongs the effectiveness of plant protection products, and supports sustainable crop protection practices.

Nanotechnology in Soil Health Management

1. **Improvement of Soil Fertility**

Nanotechnology plays a crucial role in enhancing soil fertility by improving the efficiency of nutrient retention and availability in the soil matrix. Nanoparticles such as nano-clays, metal oxides, and carbon-based nanomaterials increase the soil's cation exchange capacity and water-holding ability, thereby enhancing nutrient storage and reducing losses. These nanomaterials facilitate the gradual release of essential macro- and micronutrients, ensuring their sustained availability to plant roots and improving overall soil productivity.

2. **Enhancement of Microbial Activity**

Soil microorganisms are vital for nutrient cycling, organic matter decomposition, and maintenance of soil structure. Nanoparticles influence microbial activity by modifying the soil microenvironment and providing surfaces for microbial colonization. Certain nanoparticles, particularly bio-based and low-toxicity formulations, stimulate beneficial microbial populations and enzyme production, enhancing biological nitrogen fixation and phosphorus solubilization. However, nanoparticle type, concentration, and exposure duration determine whether their impact is stimulatory or inhibitory, emphasizing the importance of controlled application.

3. **Nutrient Availability and Cycling**

Nanoparticles enhance nutrient availability by preventing nutrient fixation and promoting efficient nutrient cycling in the soil–plant system. Nano-fertilizers and nutrient-loaded nanoparticles improve nutrient solubility and mobility, allowing roots to access nutrients more effectively. This leads to improved nutrient uptake efficiency and reduced dependency on excessive chemical fertilizers.

4. **Interaction with Soil Enzymes and Organic Matter**

Nanoparticles interact closely with soil enzymes and organic matter, influencing biochemical processes essential for soil health. They can stabilize enzymes, protect them from degradation, and enhance catalytic efficiency, thereby accelerating nutrient mineralization. Additionally, nanoparticles bind with soil organic matter, improving soil aggregation and structural stability. These interactions contribute to enhanced soil resilience, improved fertility, and long-term sustainability of agricultural soils when nanoparticles are applied judiciously.

Nanoparticles for Stress Management in Plants

1. **Mitigation of Abiotic Stresses**

Nanoparticles play a significant role in mitigating abiotic stresses such as drought, salinity, heat, and heavy metal toxicity, which are major constraints to crop productivity. Nanomaterials including silicon, zinc oxide, iron oxide, and titanium dioxide nanoparticles enhance water retention, improve root architecture, and regulate ion balance under stress conditions. In saline environments, nanoparticles help reduce sodium accumulation and maintain potassium homeostasis, while under drought and heat stress they improve stomatal regulation and photosynthetic efficiency. Additionally, certain nanoparticles immobilize heavy metals in soil or limit their translocation within plants, thereby reducing toxicity and protecting vital physiological processes.

2. **Regulation of Antioxidant Enzymes**

Abiotic stresses often induce excessive production of reactive oxygen species (ROS), leading to oxidative damage in plant cells. Nanoparticles enhance the activity of antioxidant enzymes such as superoxide dismutase, catalase, peroxidase, and ascorbate peroxidase, which collectively scavenge ROS and maintain cellular redox balance. By strengthening the antioxidant defense system, nanoparticles help preserve membrane integrity, protein function, and chlorophyll stability under stress conditions.

3. **Physiological and Biochemical Responses**

Nanoparticle application influences key physiological and biochemical responses in plants, including improved nutrient uptake, enhanced chlorophyll content, and increased synthesis of osmoprotectants such as proline and soluble sugars. These responses support better growth, biomass accumulation, and yield stability under adverse environmental conditions. Overall, nanoparticles act as stress modulators that enhance plant resilience, improve adaptive capacity, and contribute to sustainable crop production in challenging agro-climatic environments.

Nanoparticles in Seed Technology

Nanoparticle-based seed technology has emerged as an innovative approach to enhance seed performance, early plant establishment, and stress resilience. Nano-coating of seeds involves the application of a thin nanoscale layer containing nutrients, pesticides, or growth-promoting agents onto the seed surface, which acts as a protective shield against seed-borne pathogens while simultaneously supplying essential nutrients during the initial stages of germination. Owing to their small size and high surface reactivity, nanoparticles provide uniform coverage and strong adhesion, ensuring efficient utilization of active compounds. In addition, nano-coatings improve moisture absorption and regulate water uptake, creating favorable microenvironments that promote rapid and synchronized germination. Seed nano-priming, an advanced pre-sowing treatment, exposes seeds to nanoparticle suspensions that stimulate metabolic and physiological processes prior to germination. This method enhances enzyme activation, stabilizes cellular membranes, and accelerates early seedling growth, resulting in higher germination rates, improved seedling vigor, and increased biomass compared to conventional priming techniques. Furthermore, nanoparticles play a crucial role in enhancing seed and seedling tolerance to abiotic stresses such as drought, salinity, temperature extremes, and heavy metal toxicity. Nanoparticles of zinc, iron, and silicon strengthen antioxidant defense systems, reduce oxidative damage, and improve cellular protection mechanisms. Consequently, nano-treated seeds exhibit greater resilience, higher survival potential, and better crop establishment under adverse environmental conditions, making nanoparticle-based seed technology a promising strategy for sustainable and climate-resilient agriculture.

Methodology

The present study adopted a systematic and integrative methodology to examine the development of nanoparticles and their applications in agriculture. Relevant literature was collected from peer-reviewed journals, scientific databases, and authoritative reports focusing on nanoparticle synthesis, characterization, and agricultural use. Various nanoparticle development methods, including physical, chemical, and biological (green synthesis) approaches, were reviewed and compared based on efficiency, environmental safety, and

International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

suitability for agricultural applications. Experimental data reported in previous studies on nano-fertilizers, nano-pesticides, seed nano-priming, and stress management were critically analyzed to assess their impacts on crop growth, yield, and sustainability. Physicochemical properties such as particle size, surface area, stability, and release behavior were evaluated to understand their influence on nutrient delivery and plant protection efficiency. Additionally, studies related to nanoparticle uptake, translocation, and accumulation in plant–soil systems were examined to identify potential environmental and food safety concerns. Comparative analysis was used to evaluate the advantages of nano-enabled agricultural inputs over conventional agrochemicals. The methodology also considered regulatory guidelines and risk assessment frameworks to ensure responsible application. Overall, this approach enabled a comprehensive evaluation of nanoparticle development techniques and their effectiveness, benefits, and limitations in advancing sustainable agricultural practices.

Result and Discussion

Table 1. Effect of Nanoparticle Treatments on Seed Germination and Seedling Vigor

Treatment	Nanoparticle Type	Concentration (mg L^{-1})	Germination (%)	Seedling Length (cm)	Vigour Index
T_0	Control	0	82 ± 2.1	12.4 ± 0.6	1017
T_1	ZnO NPs	25	89 ± 1.8	14.8 ± 0.7	1317
T_2	ZnO NPs	50	94 ± 1.5	16.2 ± 0.8	1523
T_3	Fe_2O_3 NPs	50	91 ± 1.6	15.6 ± 0.5	1419

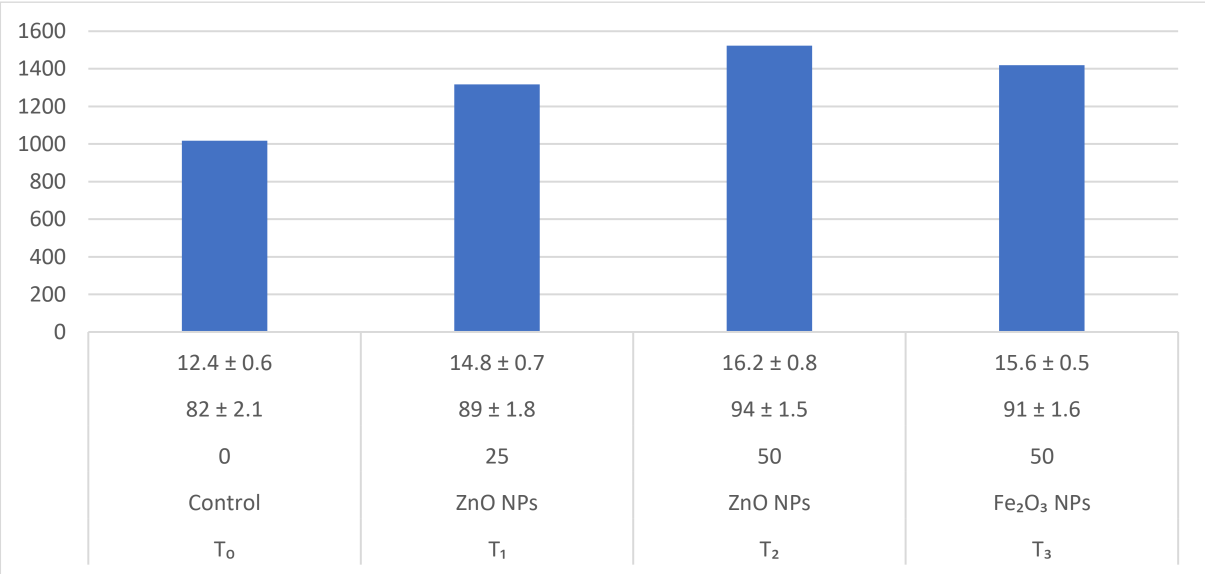

Table 1 demonstrates the positive influence of nanoparticle treatments on seed germination and early seedling development. Compared to the control treatment (T_0), seeds treated with zinc oxide (ZnO) and iron oxide (Fe_2O_3) nanoparticles showed marked improvements in germination percentage, seedling length, and vigor index. The highest germination (94%) and vigor index (1523) were observed in T_2, where ZnO nanoparticles were applied at 50 mg L^{-1},

International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

indicating an optimal concentration for stimulating seed metabolic activity. Enhanced seedling length suggests improved cell division and elongation during early growth stages. Fe_2O_3 nanoparticles also significantly improved seedling performance, although to a lesser extent than ZnO. These results indicate that nanoparticle-based seed treatments enhance nutrient availability, enzyme activation, and early plant establishment, thereby promoting better crop stand and productivity.

Table 2. Influence of Nano-Fertilizers on Crop Growth and Yield Attributes

Treatment	Nano-Fertilizer	Plant Height (cm)	Leaf Area Index	Biomass (g plant^{-1})	Yield Increase (%)
T_0	Conventional fertilizer	78.2	3.1	145	—
T_1	Nano-N	84.6	3.6	162	11.7
T_2	Nano-Zn	88.9	3.9	171	18.0
T_3	Nano-N + Nano-Zn	92.4	4.3	185	27.6

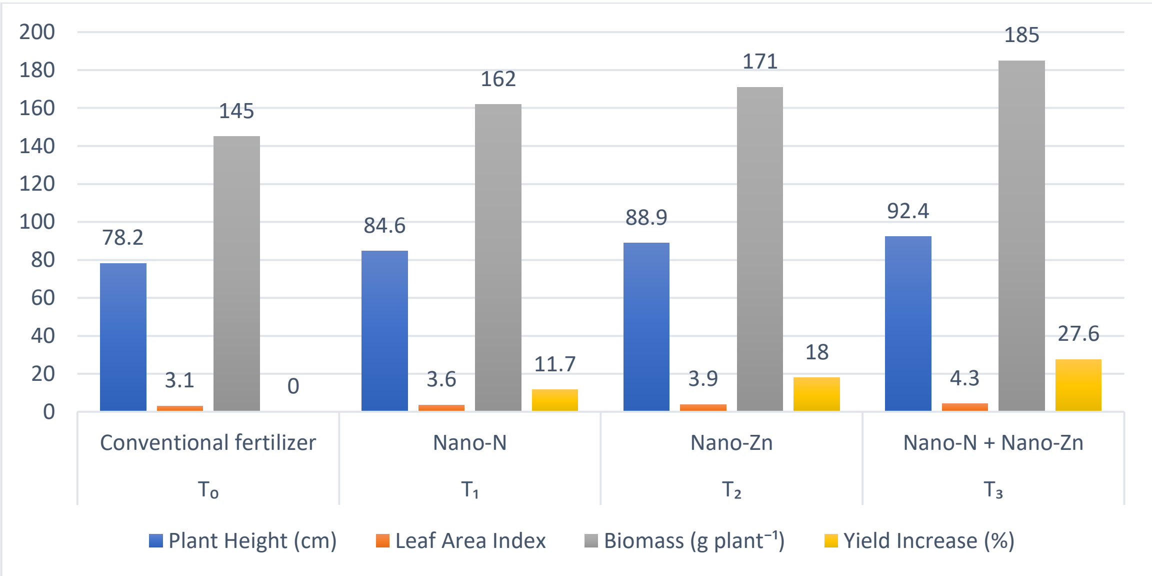

Table 2 highlights the superior performance of nano-fertilizers compared to conventional fertilizers in improving crop growth and yield parameters. Treatments involving nano-nitrogen (Nano-N) and nano-zinc (Nano-Zn) resulted in noticeable increases in plant height, leaf area index, and biomass accumulation. The combined application of Nano-N and Nano-Zn (T_3) produced the highest plant height (92.4 cm), leaf area index (4.3), and biomass (185 g plant^{-1}), leading to a substantial yield increase of 27.6%. This enhancement can be attributed to the controlled and targeted nutrient release properties of nano-fertilizers, which improve

International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

nutrient uptake efficiency and minimize losses. Overall, the data suggest that nano-fertilizers significantly contribute to improved crop productivity and resource-use efficiency.

Table 3. Effect of Nanoparticles on Antioxidant Enzyme Activity under Stress Conditions

Treatment	Nanoparticle	SOD (U mg^{-1} protein)	CAT (µmol H_2O_2 min^{-1} mg^{-1})	POD (U g^{-1} FW)
Control (Stress)	—	42.3	18.7	26.4
NP-treated	Si NPs	58.6	26.1	39.8
NP-treated	ZnO NPs	61.2	28.4	42.6

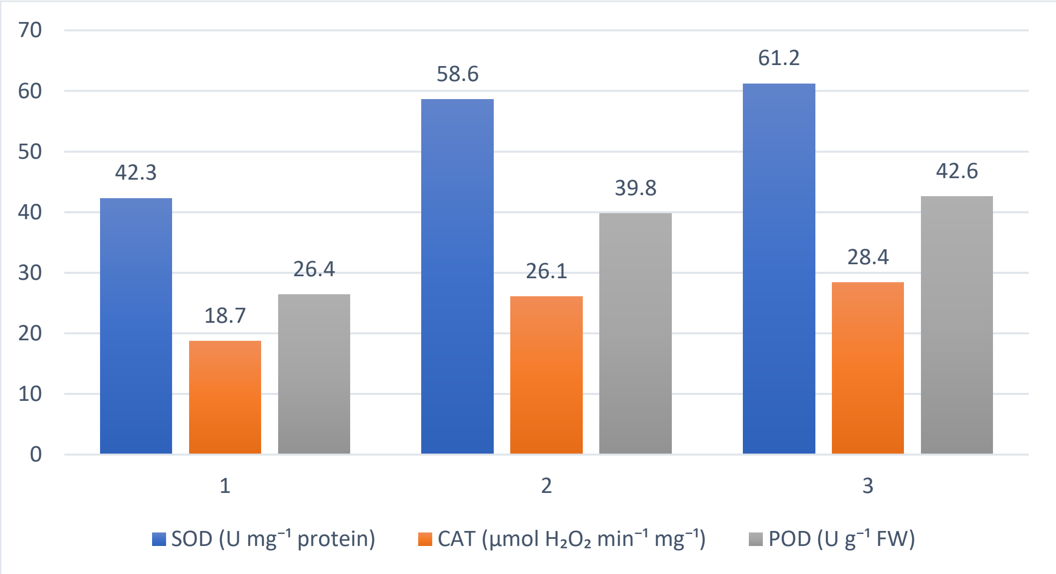

Table 3 show the role of nanoparticles in enhancing antioxidant defense mechanisms in plants under stress conditions. Compared to stressed control plants, nanoparticle-treated plants exhibited significantly higher activities of key antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD). Among the treatments, ZnO nanoparticles showed the greatest enhancement in enzyme activity, indicating improved scavenging of reactive oxygen species and reduced oxidative damage. Silicon nanoparticles also markedly increased antioxidant enzyme levels, reflecting their protective role in maintaining cellular stability under stress. The elevated enzyme activities demonstrate that nanoparticles strengthen plant defense systems, improve stress tolerance, and support physiological resilience, thereby contributing to sustained growth and productivity under adverse environmental conditions.

Conclusion

The development of nanoparticles has emerged as a powerful innovation with the potential to transform modern agricultural practices by enhancing productivity, resource efficiency, and environmental sustainability. As discussed in this study, nanoparticles possess unique physicochemical properties, including high surface area, enhanced reactivity, and controlled release behavior, which make them highly suitable for diverse agricultural applications. Their use in crop nutrition as nano-fertilizers improves nutrient use efficiency, reduces leaching and volatilization losses, and supports balanced plant growth and yield enhancement. In plant protection, nano-pesticides and nano-fungicides offer targeted delivery of active ingredients, improved pest and disease control, reduced chemical dosages, and effective resistance management, thereby minimizing ecological and health risks associated with excessive agrochemical use. Nanoparticles also play a significant role in seed technology, soil health management, and stress mitigation by enhancing germination, microbial activity, antioxidant defense mechanisms, and tolerance to abiotic stresses such as drought, salinity, and heavy metal toxicity. Furthermore, advances in green and biological synthesis methods have addressed concerns related to environmental safety by promoting eco-friendly and sustainable nanoparticle production. Despite these advantages, challenges related to large-scale production, cost, long-term environmental fate, and potential ecotoxicological effects remain critical and require careful consideration. Therefore, rigorous risk assessment, standardized regulatory frameworks, and long-term field studies are essential for the safe integration of nanotechnology into agricultural systems. Overall, the responsible development and application of nanoparticles hold significant promise for achieving sustainable agriculture, ensuring food security, and supporting climate-resilient farming systems in the future.

References

1. Khan, S., Zahoor, M., Khan, R. S., Ikram, M., & Islam, N. U. (2023). The impact of silver nanoparticles on the growth of plants: The agriculture applications. *Heliyon*, *9*(6).
2. Shojaei, T. R., Salleh, M. A. M., Tabatabaei, M., Mobli, H., Aghbashlo, M., Rashid, S. A., & Tan, T. (2019). Applications of nanotechnology and carbon nanoparticles in agriculture. In *Synthesis, technology and applications of carbon nanomaterials* (pp. 247-277). Elsevier.
3. Kaningini, A. G., Nelwamondo, A. M., Azizi, S., Maaza, M., & Mohale, K. C. (2022). Metal nanoparticles in agriculture: A Review of possible use. *Coatings*, *12*(10), 1586.
4. Kale, S. K., Parishwad, G. V., & Patil, A. S. H. A. S. (2021). Emerging agriculture applications of silver nanoparticles. *ES Food & Agroforestry*, *3*, 17-22.
5. Pestovsky, Y. S., & Martínez-Antonio, A. (2017). The use of nanoparticles and nanoformulations in agriculture. *Journal of nanoscience and nanotechnology*, *17*(12), 8699-8730.
6. Kim, D. Y., Kadam, A., Shinde, S., Saratale, R. G., Patra, J., & Ghodake, G. (2018). Recent developments in nanotechnology transforming the agricultural sector: a transition replete with opportunities. *Journal of the Science of Food and Agriculture*, *98*(3), 849-864.
7. Pramanik, P., Krishnan, P., Maity, A., Mridha, N., Mukherjee, A., & Rai, V. (2020). Application of nanotechnology in agriculture. In *Environmental Nanotechnology Volume 4* (pp. 317-348). Cham: Springer International Publishing.

8. Pramanik, P., Krishnan, P., Maity, A., Mridha, N., Mukherjee, A., & Rai, V. (2020). Application of nanotechnology in agriculture. In *Environmental Nanotechnology Volume 4* (pp. 317-348). Cham: Springer International Publishing.
9. Singh, H., Sharma, A., Bhardwaj, S. K., Arya, S. K., Bhardwaj, N., & Khatri, M. (2021). Recent advances in the applications of nano-agrochemicals for sustainable agricultural development. *Environmental Science: Processes & Impacts*, *23*(2), 213-239.
10. Rastogi, A., Tripathi, D. K., Yadav, S., Chauhan, D. K., Živčák, M., Ghorbanpour, M., ... & Brestic, M. (2019). Application of silicon nanoparticles in agriculture. *3 Biotech*, *9*(3), 90.
11. Pascoli, M., Lopes-Oliveira, P. J., Fraceto, L. F., Seabra, A. B., & Oliveira, H. C. (2018). State of the art of polymeric nanoparticles as carrier systems with agricultural applications: a minireview. *Energy, Ecology and Environment*, *3*(3), 137-148.
12. Prasad, R., Bhattacharyya, A., & Nguyen, Q. D. (2017). Nanotechnology in sustainable agriculture: recent developments, challenges, and perspectives. *Frontiers in microbiology*, *8*, 1014.