Nanotechnology in Precision Agriculture: Applications of Nanosensors and Nano-inputs for Crop Production

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Abstract
Nanotechnology has been identified as a promising technology to revolutionize the field of precision agriculture through the development of innovative approaches to enhance crop productivity, resource utilization, and environmental sustainability. In the present review, the application of nanosensors and nano-enabled agricultural products has been assessed in the context of modern crop production systems. A systematic review and meta-analysis were undertaken following the PRISMA guidelines. A comprehensive literature search was undertaken through major scientific databases such as Scopus, Web of Science, ScienceDirect, Springer Link, Google Scholar, and others. The search yielded 1,765 publications, which were later reduced to 51 studies following the application of de-duplication and screening criteria. The results of the systematic review suggest that nanotechnology has the potential to contribute to the enhancement of the efficiency of agriculture through the application of nanosensors, nanofertilizers, nanopesticides, nano-carrier systems, and others. Nanosensors help to sense the nutrient availability in the soil, plant physiological parameters, environmental parameters, and pathogens in real-time, thus helping to make informed decisions in precision agriculture. Nano-enabled products help to enhance nutrient utilization, protect crops from pests and diseases, and promote plant growth through the targeted release of agrochemicals. Nanoparticles have the potential to enhance plant tolerance to abiotic stresses such as drought and salinity, thus helping to promote climate-resilient agriculture. However, the potential risks to the environment, accumulation of nanoparticles in the soil ecosystem, and their impact on non-target organisms have to be assessed to ensure the safe application of nanotechnology to precision agriculture.

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1. Introduction

Agriculture plays a fundamental role in sustaining global food security and supporting the livelihoods of billions of people. However, modern agricultural systems face numerous challenges including population growth, climate change, land degradation, water scarcity, and declining soil fertility (Iqbal, 2020) [14]. These factors collectively threaten the sustainability of crop production systems and require innovative technological solutions to enhance productivity while minimizing environmental impacts. Conventional agricultural practices often rely heavily on chemical fertilizers and pesticides to increase crop yields. While these practices have contributed significantly to global food production, excessive use of agrochemicals has resulted in soil degradation, water contamination, and loss of biodiversity (Ditta *et al*., 2015; Elemike *et al*., 2019) [9, 10]. Precision agriculture has emerged as an advanced farming approach that aims to optimize agricultural inputs and improve resource efficiency by using modern technologies such as sensors, geographic information systems, remote sensing, and automation. The core objective of precision agriculture is to apply the right input at the right place and time in order to maximize productivity and minimize environmental impacts. In this context, nanotechnology has emerged as a powerful tool that can significantly enhance the capabilities of precision agriculture Nanotechnology involves the manipulation of materials at the nanoscale, typically between 1 and 100 nanometers, where unique physicochemical properties such as high surface area, enhanced reactivity, and improved mobility can be exploited for various applications. In agricultural systems, nanotechnology has enabled the development of advanced tools such as nanosensors, nanofertilizers, nanopesticides, and nano-enabled delivery systems that can improve crop productivity and sustainability (Amir *et al*., 2019; Liu *et al*., 2021; Vuong, 2019; Hossain *et al*., 2020; Malukani *et al*., 2021) [2, 27, 48, 13, 29]. One of the most promising applications of nanotechnology in agriculture is the development of nanosensors. These sensors can detect chemical, biological, and environmental signals with high sensitivity and accuracy. Nanosensors allow real-time monitoring of soil nutrient levels, plant physiological conditions, pathogen infections, and environmental stresses, thereby enabling farmers to make informed management decisions (Kaushal & Wani, 2017) [20]. Through the integration of nanosensors with digital technologies, agricultural systems can become more intelligent and responsive to changing environmental conditions.

In addition to sensing technologies, nano-enabled agricultural inputs have also gained considerable attention. Nano-inputs such as nanofertilizers, nanopesticides, and nano-carriers are designed to improve the efficiency and effectiveness of agrochemicals by enhancing their delivery, stability, and controlled release (Khan & Ahmad, 2022; Singh *et al*., 2023) [21, 39]. These nanoformulations can significantly reduce nutrient losses, improve plant nutrient uptake, and decrease environmental pollution. Recent studies have demonstrated that nanoparticles such as zinc oxide, silver nanoparticles, and carbon-based nanomaterials can enhance plant growth and crop productivity under different environmental conditions (Jayarambabu *et al*., 2015; Seleiman *et al*., 2023; Xin *et al*., 2025; Vera-Reyes *et al*., 2024) [17, 36, 49, 46]. Furthermore, nanotechnology can contribute to climate-resilient agriculture by improving plant tolerance to abiotic stresses such as drought, salinity, and temperature extremes.

Despite the promising benefits of nanotechnology in agriculture, concerns have been raised regarding the potential ecological and environmental risks associated with nanoparticle applications. The accumulation of engineered nanomaterials in soil ecosystems may affect microbial communities, beneficial insects, and other organisms that are essential for maintaining soil health and ecosystem stability (Pérez-Hernández *et al*., 2020; Upadhyay *et al*., 2022) [32, 44]. Given the rapid growth of research in this field, there is a need for systematic evaluation of existing studies to understand the current progress, opportunities, and challenges associated with nanotechnology in precision agriculture. Therefore, this review aims to synthesize findings from selected scientific studies to provide a comprehensive overview of nanosensors and nano-inputs for crop production.

2. Objectives

The main objective of this review is to systematically examine the current state of knowledge on the applications of nanotechnology in precision agriculture, with particular emphasis on nanosensors and nano-enabled agricultural inputs for improving crop production. The study aims to provide an overview of how nanotechnology-based tools contribute to efficient resource management, enhanced productivity, and sustainable agricultural practices.

The specific objectives of this study are to evaluate the role of nanotechnology in supporting precision agriculture and sustainable crop production; to examine the applications of nanosensors in monitoring soil health, plant conditions, and environmental parameters; to analyze the effectiveness of nano-inputs such as nanofertilizers, nanopesticides, and nanocarrier systems in improving nutrient use efficiency and crop protection; to assess the potential benefits and limitations of nanotechnology in agricultural systems; and to synthesize existing scientific evidence through a systematic review and meta-analysis to identify future research directions in nano-enabled precision agriculture.

3. Methodology

3.1. Study Design

This study was conducted as a systematic review and meta-analysis to evaluate the role of nanotechnology in precision agriculture, particularly focusing on nanosensors and nano-enabled agricultural inputs used for crop production. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency, consistency, and methodological rigor throughout the literature selection process. PRISMA provides a structured framework that guides researchers in identifying, screening, and selecting relevant studies in a systematic manner. By adopting this framework, the present review ensured that only the most relevant and high-quality studies related to nanotechnology applications in crop production were included in the final dataset.

3.2. Literature Search Strategy

A comprehensive literature search was carried out across several major academic databases to identify studies related to nanotechnology applications in precision agriculture. The databases used for the search included Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar, which collectively cover a wide range of peer-reviewed scientific publications. The search focused on studies published between 2009 and 2026, a period during which research on nanotechnology in agriculture has expanded rapidly.

To ensure broad coverage of relevant literature, multiple search keywords and phrases were used during the database search. These included terms such as nanotechnology in agriculture, precision agriculture and nanotechnology, nanosensors in agriculture, nanofertilizers and nanopesticides, nano-inputs for crop production, and nanoparticles in plant growth. Boolean operators were used to combine these keywords and refine the search results. The main search query applied in the databases was: ("Nanotechnology" OR "Nanomaterials") AND ("Precision agriculture" OR "Smart agriculture") AND ("Nanosensors" OR "Nanofertilizers" OR "Nanopesticides" OR "Nano-inputs") AND ("Crop production" OR "Plant growth"). This search strategy resulted in the identification of 1,765 scientific publications related to nanotechnology applications in agriculture.

3.3. Prisma Screening Process

The selection of relevant studies was carried out through several stages following the PRISMA framework. In the identification stage, the initial database search produced 1,765 articles related to nanotechnology and agriculture.

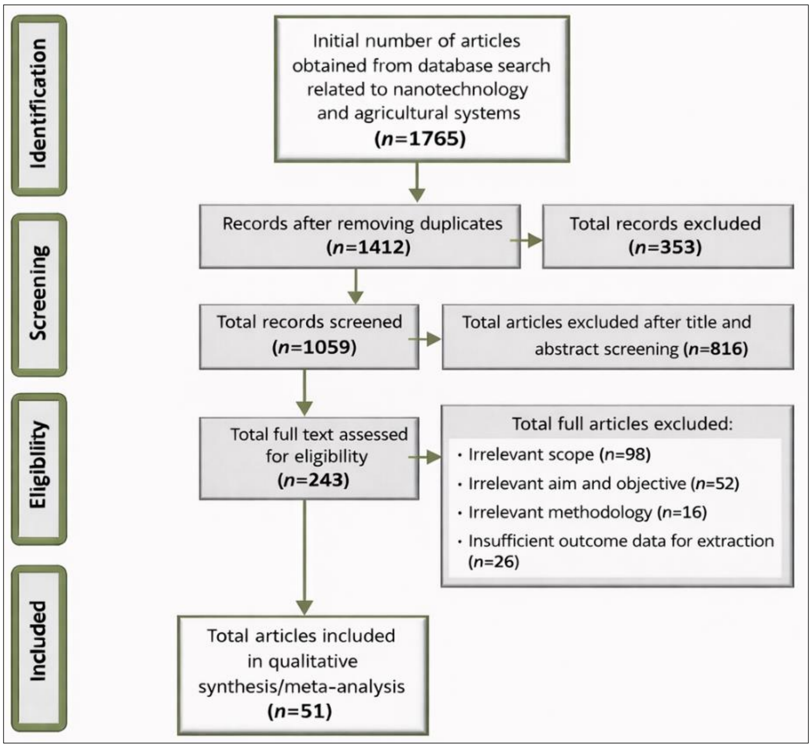

Fig 1: PRISMA flowchart for nanotechnology studies

During the duplicate removal stage, repeated records across different databases were removed, resulting in 1,412 unique publications. In the title and abstract screening stage, the relevance of each study was evaluated based on its title and abstract. Articles that were unrelated to agricultural applications, such as those focusing on biomedical nanotechnology, food packaging technologies, or industrial nanomaterials, were excluded. After this initial screening process, 243 articles remained for further evaluation.

The remaining studies were then subjected to full-text eligibility assessment based on predefined inclusion and exclusion criteria. The inclusion criteria consisted of peer-reviewed journal articles and scholarly book chapters focusing on nanotechnology applications in agriculture, studies involving nanosensors or nano-enabled agricultural inputs, and research reporting effects on crop growth, yield, or soil health. Conversely, the exclusion criteria included studies unrelated to crop production, articles focusing exclusively on food processing or packaging, and non-scientific reports such as editorials or opinion papers.

After applying these criteria, 51 articles were selected for qualitative synthesis and meta-analysis. These studies formed the final dataset used for detailed analysis and discussion in this review, providing a comprehensive overview of the role of nanosensors and nano-inputs in precision agriculture and crop production (Figure 1).

4. Results and Discussion

4.1. Overview of Nanotechnology in Agriculture

Nanotechnology has emerged as one of the most promising innovations in modern agriculture due to its ability to manipulate materials at extremely small scales and enhance their functional properties. At the nanoscale, materials often exhibit unique physicochemical characteristics such as increased surface area, enhanced catalytic activity, improved solubility, and higher reactivity compared with their bulk counterparts. These properties allow nanomaterials to perform specific functions more efficiently, making them highly suitable for agricultural applications. The application of nanotechnology in agricultural systems has led to the development of advanced tools and products that improve nutrient delivery, crop protection, environmental monitoring, and stress management, thereby supporting sustainable agricultural intensification (Yadav *et al*., 2025; Biswas *et al*., 2025; Kumar *et al*., 2021; Upinder & Kumar, 2021) [50, 4, 24, 45]. As global agricultural systems face increasing pressure from population growth, climate change, and limited natural resources, nanotechnology offers innovative solutions for improving productivity while minimizing environmental degradation.

Nanoparticles possess distinctive physical and chemical properties that enable them to interact with plant systems at molecular, cellular, and physiological levels. Nanoparticles may also influence cellular signaling pathways and nutrient transport mechanisms in plants (Jampílek & Kráľová, 2019; Anderson *et al*., 2017) [15, 3].

Table 1: Categorization of selected studies based on nanotechnology focus areas and their applications in agriculture

Nanotechnology focus	Application in Agriculture	References
General applications of nanotechnology in agriculture	Enhancing crop productivity, improving nutrient management, and supporting sustainable agricultural practices	Amir *et al*., 2019; Biswas *et al*., 2025; Hossain *et al*., 2020; Liu *et al*., 2021; Vuong, 2019; Kumar *et al*., 2021; Upinder & Kumar, 2021; Vishwakarma *et al*., 2023; Yadav *et al*., 2025; Yadu *et al*., 2021[2, 4, 13, 27, 48, 24, 45, 47, 50, 51]
Nanosensors for precision agriculture	Real-time monitoring of soil nutrients, plant health, environmental conditions, and pathogen detection	Kaushal & Wani, 2017; Srivastava *et al*., 2021; Tarafdar *et al*., 2025 [20, 41, 42]
Nanofertilizers and nano-enabled nutrient management	Controlled nutrient release, improved nutrient uptake efficiency, and reduced fertilizer losses	Gunasena *et al*., 2021; Jayarambabu *et al*., 2015; Akwu *et al*., 2026; Negi *et al*., 2023; Xin *et al*., 2025; Elemike *et al*., 2019 [12, 17, 1, 31, 49, 10]
Nanopesticides and crop protection technologies	Enhanced pest and disease control through improved delivery and antimicrobial activity	Jo *et al*., 2009; Churilov *et al*., 2020; Khan & Rizvi, 2017 [18, 7, 22]
Nanocarriers and smart nano-delivery systems	Targeted delivery of agrochemicals, improved stability of active compounds, and controlled release mechanisms	Khan & Ahmad, 2022; Singh *et al*., 2023 [21, 39]
Nanotechnology for plant growth and productivity enhancement	Improved seed germination, plant metabolism, photosynthesis, and crop yield	Anderson *et al*., 2017; Chaudhary *et al*., 2025; Jampílek & Kráľová, 2019; Vera-Reyes *et al*., 2024 [3, 6, 15, 46]
Nanotechnology for abiotic stress tolerance	Enhancing plant tolerance to drought, salinity, and other environmental stresses	Seleiman *et al*., 2023; Li *et al*., 2025; Singh *et al*., 2024; Khedr *et al*., 2026; Pramanik *et al*., 2023; Sabarivasan *et al*., 2025 [36, 26, 38, 23, 33, 35]
Environmental impacts and ecological risks of nanoparticles	Assessment of nanoparticle accumulation, effects on soil microbes, beneficial insects, and ecosystem health	Pérez-Hernández *et al*., 2020; Li *et al*., 2021; Upadhyay *et al*., 2022; Kannan *et al*., 2020 [32, 26, 44, 19]
Green nanotechnology and sustainable nano-agriculture	Environmentally friendly nanoparticle synthesis and sustainable crop protection strategies	Martin *et al*., 2026; Maity *et al*., 2022 [30, 28]
Emerging technologies and future research directions	Integration of nanotechnology with genomics, digital agriculture, and innovation management	Javaid *et al*., 2024; Dabare *et al*., 2025; Upadhayay *et al*., 2023; Singh *et al*., 2026; Chandan *et al*., 2026; Malukani *et al*., 2021; Reddy *et al*., 2025 [16, 8, 44, 40, 5, 29, 34]

Due to their extremely small size, nanoparticles can penetrate plant tissues through roots, stomata, or cuticular pathways, allowing direct interaction with cellular structures and metabolic processes. These interactions can influence a variety of plant physiological mechanisms, including nutrient absorption, photosynthetic efficiency, enzyme activation, hormone regulation, and stress tolerance mechanisms. As a result, nanoparticles have been reported to enhance plant growth, improve nutrient uptake efficiency, and stimulate beneficial metabolic responses under both normal and stress conditions (Maity *et al*., 2022; Reddy *et al*., 2025) [28, 34]. In addition, nano-enabled formulations often provide controlled release of active ingredients, which improves the efficiency of agrochemicals while reducing losses due to leaching, volatilization, or degradation.

The integration of nanotechnology with agricultural practices has also facilitated the development of innovative nano-enabled agricultural inputs, commonly referred to as nano-inputs. These include nanofertilizers, nanopesticides, nanoherbicides, nanocarriers, and nanosensors, which are designed to enhance the efficiency and precision of agricultural operations. Nanofertilizers can deliver nutrients in a controlled and targeted manner, improving nutrient use efficiency and reducing environmental contamination associated with excessive fertilizer use. Similarly, nanopesticides provide improved stability, enhanced bioavailability, and more effective delivery of active compounds to pests and pathogens. Nanosensors, another important component of nano-enabled agriculture, allow real-time monitoring of soil conditions, crop health, and environmental factors, enabling farmers to make informed decisions regarding irrigation, fertilization, and pest management. Together, these nano-based technologies contribute to the development of more precise, efficient, and sustainable agricultural systems.

Furthermore, nanotechnology plays an important role in supporting global sustainability initiatives and climate-resilient agricultural practices. By improving resource use efficiency and reducing the environmental footprint of agricultural activities, nano-enabled technologies can contribute to achieving several Sustainable Development Goals (SDGs), particularly those related to food security, environmental protection, and sustainable production systems. Nanotechnology-based agricultural inputs can significantly reduce the excessive use of fertilizers and pesticides, which are major contributors to soil degradation, water pollution, and greenhouse gas emissions. Additionally, nanomaterials can enhance plant resilience to abiotic stresses such as drought, salinity, and temperature extremes, which are becoming increasingly common due to climate change (Elzein, 2024) [11]. Consequently, the integration of nanotechnology into precision agriculture represents a promising pathway toward achieving sustainable crop production while ensuring environmental protection and long-term agricultural productivity.

The selected studies can be categorized into ten major nanotechnologies focus areas based on their primary research themes and applications in agriculture. These categories include nanosensors, nano-inputs, stress tolerance, environmental safety, and emerging nano-enabled technologies, as summarized in Table 1.

4.2. Nanosensors in Precision Agriculture

Nanosensors represent one of the most advanced technological tools supporting the development of precision agriculture. These devices are capable of detecting extremely small concentrations of chemical, biological, and environmental signals due to the unique sensitivity and responsiveness of nanomaterials. In agricultural systems, nanosensors can be integrated into soil, plant tissues, irrigation systems, or monitoring platforms to collect real-time information related to crop health and environmental conditions. The high sensitivity of nanomaterials enables nanosensors to detect minute variations in nutrient concentrations, soil moisture, pH levels, and the presence of pathogens or pollutants. Consequently, nanosensor-based monitoring systems provide accurate and rapid detection capabilities that can significantly improve agricultural management practices (Kaushal & Wani, 2017) [20]. These sensing technologies are considered an essential component of smart farming systems because they enable site-specific crop management and precision monitoring of field conditions (Hossain *et al*., 2020; Tarafdar *et al*., 2025) [13, 42].

One of the primary applications of nanosensors in agriculture is the monitoring of soil health and nutrient availability. Soil nutrients such as nitrogen, phosphorus, and potassium play critical roles in plant growth and productivity, but conventional soil testing methods are often time-consuming and may not reflect real-time nutrient dynamics in agricultural fields. Nanosensors can provide rapid and continuous monitoring of nutrient concentrations, allowing farmers to apply fertilizers more efficiently and reduce nutrient losses due to leaching or runoff. This targeted nutrient management approach improves nutrient use efficiency while minimizing environmental contamination caused by excessive fertilizer application.

Nanosensors are also increasingly being used for plant health monitoring and early detection of diseases. Plant pathogens often trigger biochemical changes within plant tissues before visible symptoms appear. Nanosensors can detect these biochemical signals, including volatile organic compounds, plant hormones, or stress-related metabolites, enabling early diagnosis of plant diseases. Early detection is particularly important for preventing large-scale crop losses and reducing the need for excessive pesticide application. By identifying plant stress or pathogen infection at an early stage, nanosensor technologies enable timely and targeted interventions that support more sustainable crop protection strategies. Another important application of nanosensors is in the monitoring of environmental conditions that affect crop growth, including temperature, humidity, soil moisture, and atmospheric gases. These environmental factors strongly influence plant physiological processes and crop productivity. Nanosensor-based monitoring systems can continuously track these parameters and provide real-time feedback to farmers or automated agricultural systems. Such systems allow precise irrigation scheduling, improved water management, and optimized crop management decisions, which are essential components of precision agriculture.

The integration of nanosensors with digital technologies, such as wireless communication systems, artificial intelligence, and Internet of Things (IoT) platforms, further enhances their capabilities in agricultural monitoring. Through wireless networks, nanosensors can transmit real-time data to centralized monitoring systems or mobile devices, enabling farmers to make informed decisions quickly and efficiently. This integration contributes to the development of smart agricultural systems where automated monitoring and decision-making processes can optimize resource use and improve crop productivity (Srivastava *et al*., 2021) [41]. In addition to improving agricultural productivity, nanosensors also contribute to environmental sustainability by reducing the excessive use of fertilizers, pesticides, and irrigation water. Accurate monitoring of field conditions allows farmers to apply agricultural inputs only when necessary, thereby minimizing resource wastage and environmental pollution. Furthermore, nanosensor technologies can be used to detect contaminants such as heavy metals or pesticide residues in soil and water systems, providing valuable information for environmental protection and sustainable land management.

Despite these advantages, several challenges remain in the practical implementation of nanosensors in agricultural systems. These challenges include high production costs, technical complexity, durability issues in field conditions, and the need for reliable calibration methods. Moreover, large-scale adoption of nanosensor technologies requires the development of affordable and user-friendly systems that can be easily implemented by farmers in diverse agricultural environments. Continued research and technological development are therefore necessary to improve the reliability, affordability, and scalability of nanosensor-based agricultural monitoring systems (Upadhayay *et al*., 2023) [43].

4.3. Nano-inputs for Crop Production

Nano-inputs represent an important category of nanotechnology applications in agriculture, designed to enhance the efficiency and effectiveness of agricultural inputs such as fertilizers, pesticides, and plant growth regulators. Unlike conventional agrochemicals, nano-inputs utilize nanoscale materials that provide improved solubility, enhanced reactivity, and controlled release mechanisms. These properties enable nano-inputs to deliver active ingredients more precisely to target sites within plants or soil systems, thereby improving their efficiency while reducing environmental losses.

4.4. Nanofertilizers

Nanofertilizers are among the most widely studied nano-inputs in agricultural research. These formulations are designed to improve nutrient use efficiency by providing controlled and targeted delivery of essential nutrients to plants. Conventional fertilizers often suffer from low nutrient use efficiency due to processes such as volatilization, leaching, and runoff, which result in significant nutrient losses and environmental pollution. In contrast, nanofertilizers release nutrients gradually, ensuring sustained nutrient availability for plant uptake while minimizing losses to the surrounding environment (Gunasena *et al*., 2021) [12].

Nanofertilizers can be formulated using various nanomaterials, including metal oxide nanoparticles, polymer-based nanoparticles, and nanocomposite materials. Among these, zinc oxide nanoparticles have received considerable attention due to their beneficial effects on plant growth and development. Zinc is an essential micronutrient involved in enzyme activation, protein synthesis, and photosynthesis. Studies have shown that zinc oxide nanoparticles can enhance seed germination, root development, and biomass accumulation in various crop species (Jayarambabu *et al*., 2015) [17]. In addition, zinc oxide nanoparticles may improve plant tolerance to environmental stresses by enhancing antioxidant defense mechanisms. Several studies also report that nano-based fertilizers can enhance soil nutrient availability and improve nutrient delivery efficiency compared with conventional fertilizers (Akwu *et al*., 2026; Negi *et al*., 2023) [1, 31].

Furthermore, nanofertilizers have been reported to enhance nutrient uptake efficiency by increasing the interaction between nutrients and plant root surfaces. The small size and high surface area of nanoparticles facilitate their penetration into plant tissues and allow more efficient nutrient absorption. As a result, crops treated with nanofertilizers often exhibit improved growth performance, higher yields, and enhanced nutrient content (Chaudhary *et al*., 2025) [6].

4.5. Nanopesticides

Nanopesticides represent another important group of nano-inputs designed to improve crop protection against pests and diseases. These formulations utilize nanoscale materials to enhance the delivery and effectiveness of pesticide active ingredients. Conventional pesticides often suffer from rapid degradation, low solubility, and poor target specificity, which reduce their effectiveness and increase environmental contamination. Nanopesticides address these limitations by improving the stability, solubility, and controlled release of pesticide compounds (Khan & Rizvi, 2017) [22].

Silver nanoparticles have been widely investigated for their antimicrobial and antifungal properties. These nanoparticles exhibit strong inhibitory effects against a wide range of plant pathogens, including bacteria, fungi, and viruses. The antimicrobial activity of silver nanoparticles is primarily attributed to their ability to disrupt microbial cell membranes, generate reactive oxygen species, and interfere with cellular metabolic processes. Consequently, silver nanoparticles have been explored as effective agents for plant disease management in various crops (Jo *et al*., 2009) [18]. Biogenic metal nanoparticles synthesized through biological processes have also shown promising results in plant disease control and crop protection (Churilov *et al*., 2020) [7].

Nanoformulated pesticides also allow lower application rates compared with conventional pesticides, thereby reducing environmental contamination and minimizing risks to non-target organisms. Additionally, nanoencapsulation techniques can protect pesticide active ingredients from degradation caused by environmental factors such as sunlight, temperature, and microbial activity.

4.6. Nanocarriers and Smart Delivery Systems

Nanocarriers are nanoscale delivery systems designed to transport agricultural inputs such as nutrients, pesticides, or genetic materials to specific target sites within plant systems. These carriers improve the efficiency of agrochemical delivery by protecting active compounds from degradation and enabling controlled release mechanisms. Nanocarriers can be composed of various materials, including polymers, liposomes, carbon-based nanomaterials, and metal nanoparticles.

One of the major advantages of nanocarrier systems is their ability to deliver agrochemicals precisely to target tissues, thereby reducing the required dosage and minimizing environmental exposure. Controlled release systems ensure that nutrients or pesticides are released gradually over time, maintaining optimal concentrations within plant tissues. This targeted delivery approach enhances the effectiveness of agricultural inputs while reducing waste and environmental contamination (Khan & Ahmad, 2022) [21]. The integration of nanocarriers with advanced agricultural technologies also opens new possibilities for precision farming applications. For example, nanocarriers can be designed to respond to specific environmental triggers such as pH changes, temperature variations, or enzymatic activity, enabling smart and responsive delivery of agrochemicals.

Overall, nano-inputs represent a promising strategy for improving crop productivity while promoting sustainable agricultural practices. However, further research is needed to evaluate their long-term environmental impacts, optimize their formulation, and ensure safe implementation in large-scale agricultural systems.

4.7. Nanotechnology for Stress Tolerance

Environmental stresses such as drought, salinity, extreme temperatures, and nutrient deficiencies are major constraints to crop productivity worldwide. These abiotic stresses disrupt plant physiological processes, reduce photosynthetic efficiency, and ultimately lead to significant yield losses. In recent years, nanotechnology has emerged as a promising approach for enhancing plant tolerance to environmental stresses and improving crop resilience under adverse conditions. Nanotechnology has also been investigated for improving productivity and stress resilience in major food crops including potatoes and cereals (Sabarivasan *et al*., 2025) [35].

Nanoparticles can influence plant physiological and biochemical processes that are involved in stress responses. When applied in appropriate concentrations, nanoparticles may enhance antioxidant enzyme activity, regulate plant hormone levels, and improve water use efficiency. These effects help plants maintain cellular stability and metabolic activity under stressful environmental conditions. Consequently, nano-enabled technologies are increasingly being explored as potential tools for improving crop resilience in changing climatic conditions (Pramanik *et al*., 2023) [33]. One of the most widely studied nanoparticles in stress tolerance research is zinc oxide nanoparticles. Zinc plays an essential role in plant metabolism, including enzyme activation, protein synthesis, and membrane stabilization. Studies have demonstrated that zinc oxide nanoparticles can improve plant growth and physiological performance under salinity stress conditions. These nanoparticles enhance chlorophyll content, photosynthetic efficiency, and nutrient uptake, thereby supporting plant growth even in saline environments (Seleiman *et al*., 2023) [36].

Nanotechnology has also shown significant potential in improving plant tolerance to drought stress. Water scarcity is one of the most critical challenges affecting global agriculture, particularly in arid and semi-arid regions. Nanoparticles may improve plant water retention capacity and enhance root development, allowing plants to access water more efficiently from soil systems. Additionally, nanoparticles can stimulate antioxidant defense systems that protect plant cells from oxidative damage caused by drought-induced stress.

Meta-analysis studies have provided quantitative evidence supporting the beneficial effects of nanoparticles on crop productivity under drought conditions. These analyses indicate that nanoparticle treatments can significantly improve plant biomass accumulation, yield components, and overall crop productivity in water-limited environments (Li *et al*., 2025) [25]. Such findings highlight the potential of nanotechnology as a valuable tool for climate-resilient agriculture.

Furthermore, nanotechnology can contribute to improving plant resistance against multiple stresses simultaneously. For example, nanoparticles may enhance plant tolerance to both abiotic stresses such as drought and salinity, as well as biotic stresses caused by pathogens or pests. This multifunctional capability makes nanotechnology particularly attractive for developing integrated crop management strategies that address multiple agricultural challenges. Despite these promising benefits, the application of nanoparticles in stress management must be carefully evaluated to ensure environmental safety and sustainability. The physiological responses of plants to nanoparticles may vary depending on nanoparticle type, concentration, plant species, and environmental conditions. Therefore, further research is needed to determine optimal application rates, evaluate long-term ecological impacts, and develop safe and effective nano-enabled agricultural technologies (Sheteiwy *et al*., 2021; Singh *et al*., 2024) [37, 38].

4.8. Environmental Risks and Safety Concerns of Nano-Agriculture

Although nanotechnology offers significant benefits for improving agricultural productivity and sustainability, concerns regarding the environmental and ecological impacts of engineered nanomaterials have received increasing attention. The introduction of nanoparticles into agricultural systems may lead to complex interactions with soil, plants, microorganisms, and other living organisms within agroecosystems. These interactions can influence the stability, mobility, and toxicity of nanoparticles in soil and water environments. Consequently, understanding the environmental fate and potential ecological risks associated with nano-enabled agricultural inputs is essential for ensuring their safe and sustainable application (Li *et al*., 2021; Upadhyay *et al*., 2022) [26, 44].

One of the primary concerns related to nano-agriculture is the accumulation of engineered nanomaterials in soil systems. Nanoparticles applied through nanofertilizers, nanopesticides, or other nano-inputs may persist in soil environments and interact with soil microorganisms that play critical roles in nutrient cycling and soil fertility. Studies have shown that nanoparticles can influence microbial activity and alter the composition of microbial communities, potentially affecting important soil functions such as nitrogen fixation, organic matter decomposition, and nutrient mineralization (Pérez-Hernández *et al*., 2020) [32,]. While some nanomaterials may stimulate microbial activity at low concentrations, excessive accumulation of nanoparticles could disrupt soil microbial balance and negatively affect soil health.

In addition to soil microorganisms, nanoparticles may also impact beneficial insects and other organisms that contribute to agricultural ecosystem stability. Beneficial insects such as pollinators, predators, and parasitoids play essential roles in crop pollination and biological pest control. Exposure to certain nanomaterials may affect insect physiology, reproduction, and survival, thereby potentially disrupting ecological interactions within agroecosystems (Kannan *et al*., 2020) [19]. Such ecological disturbances could indirectly affect crop productivity and biodiversity in agricultural landscapes.

Another important concern involves the potential transfer of nanoparticles through the food chain. Nanoparticles absorbed by plants may accumulate in edible plant tissues and subsequently enter the food chain when consumed by animals or humans. The long-term implications of nanoparticle accumulation in food systems remain insufficiently understood. Research on the uptake, translocation, and accumulation of nanomaterials in plant tissues indicates that nanoparticles can move through plant vascular systems and accumulate in leaves, fruits, or seeds depending on their physicochemical properties (Li *et al*., 2021) [26]. Therefore, comprehensive risk assessment studies are necessary to evaluate potential food safety implications associated with nano-enabled agricultural technologies.

The toxicity of nanoparticles also depends on factors such as particle size, surface chemistry, concentration, and exposure duration. Some nanoparticles may generate reactive oxygen species that cause oxidative stress in plants and other organisms when applied at high concentrations. Consequently, determining optimal dosage levels and application methods is essential to avoid negative biological effects (Upadhyay *et al*., 2022) [44]. In addition, the development of environmentally friendly and biodegradable nanomaterials may help reduce potential environmental risks associated with nano-agriculture. Despite these concerns, many researchers emphasize that the environmental risks of nanotechnology can be minimized through careful design, responsible application, and appropriate regulatory frameworks. The development of green nanotechnology approaches, such as plant-based synthesis of nanoparticles, may reduce toxicity and environmental hazards while maintaining the beneficial properties of nanomaterials (Martin *et al*., 2026) [30]. Furthermore, interdisciplinary research involving agronomy, environmental science, toxicology, and nanotechnology is necessary to ensure the safe integration of nanotechnology into agricultural systems.

Overall, while nano-enabled technologies offer promising solutions for improving crop production and resource efficiency, their environmental implications must be carefully evaluated through long-term ecological studies and comprehensive risk assessments. Establishing clear regulatory guidelines and monitoring frameworks will be essential to ensure that the benefits of nanotechnology in agriculture are realized without compromising environmental sustainability.

4.9. Future Prospects and Research Directions

The rapid advancement of nanotechnology has opened new opportunities for transforming agricultural systems and addressing global food security challenges. As the global population continues to grow and climate change intensifies environmental stresses on agricultural production, innovative technologies such as nano-enabled agricultural inputs and nanosensor-based monitoring systems are expected to play increasingly important roles in sustainable farming practices. The integration of nanotechnology with precision agriculture technologies offers significant potential for improving crop productivity, enhancing resource efficiency, and reducing the environmental impacts of conventional agricultural practices (Biswas *et al*., 2025; Vishwakarma *et al*., 2023) [4, 47]. One promising future direction involves the development of smart nano-delivery systems capable of responding to environmental signals and releasing nutrients or agrochemicals in a controlled manner. These intelligent delivery systems may respond to specific triggers such as soil moisture levels, pH changes, or plant physiological signals, allowing more precise and efficient application of agricultural inputs. Such technologies could significantly improve nutrient use efficiency and reduce excessive fertilizer and pesticide applications, thereby promoting environmentally sustainable agriculture (Singh *et al*., 2023) [39]. Integration of nanotechnology with biological inputs such as biofertilizers is also being explored as a sustainable strategy for improving soil fertility and crop productivity (Singh *et al*., 2026) [40].

Another important area of future research involves the integration of nanotechnology with other emerging technologies such as biotechnology, genomics, and digital agriculture. Combining nanotechnology with genomic tools and plant biotechnology may enable the development of crops with enhanced nutrient uptake efficiency, improved stress tolerance, and greater productivity under challenging environmental conditions (Javaid *et al*., 2024) [16]. Additionally, integrating nanosensors with digital agriculture platforms and data analytics systems can create advanced decision-support tools that assist farmers in managing crops more efficiently. Green nanotechnology is also expected to play a crucial role in the future development of sustainable agricultural nanomaterials. Traditional nanoparticle synthesis methods often involve chemical processes that may produce toxic by-products. In contrast, plant-based and biologically mediated nanoparticle synthesis techniques offer environmentally friendly alternatives that reduce toxicity and environmental risks. These green synthesis approaches utilize plant extracts, microorganisms, or other biological materials to produce nanoparticles in a more sustainable manner (Maity *et al*., 2022; Martin *et al*., 2026) [28, 30].

Furthermore, nanotechnology has significant potential for improving climate-resilient agriculture. Nanoparticles can enhance plant tolerance to environmental stresses such as drought, salinity, and temperature fluctuations by improving physiological and biochemical responses within plant systems. As climate change continues to affect agricultural productivity worldwide, nano-enabled technologies may help farmers adapt to changing environmental conditions and maintain stable crop yields (Khedr *et al*., 2026; Pramanik *et al*., 2023) [23, 33]. However, the successful adoption of nanotechnology in agriculture requires addressing several challenges related to scalability, cost, regulation, and public acceptance. Large-scale production of nano-enabled agricultural inputs must be economically feasible for farmers, particularly in developing countries where resource constraints may limit the adoption of advanced technologies. Additionally, regulatory frameworks must be established to evaluate the safety, environmental impacts, and long-term effects of nano-agricultural products before their widespread commercialization (Dabare *et al*., 2025) [8].

Education and knowledge dissemination will also play a critical role in promoting the adoption of nanotechnology in agriculture. Training programs and educational initiatives can help farmers, researchers, and agricultural professionals understand the benefits and safe use of nano-enabled technologies. Integrating nanotechnology concepts into agricultural education and research programs may facilitate the development of skilled professionals capable of advancing this emerging field (Chandan *et al*., 2026) [5]. Overall, nanotechnology is expected to become a key component of next-generation agricultural systems by enabling more precise, efficient, and sustainable crop production. Continued research, interdisciplinary collaboration, and responsible technological development will be essential for realizing the full potential of nanotechnology in precision agriculture while ensuring environmental safety and long-term sustainability.

5. Conclusion

Nanotechnology is increasingly recognized as a transformative approach for improving the efficiency and sustainability of modern agricultural systems. This systematic review synthesized findings from 51 peer-reviewed studies to evaluate the role of nanosensors and nano-enabled agricultural inputs in precision agriculture. The results highlight that nanotechnology offers significant potential to enhance crop productivity, improve nutrient use efficiency, and support environmentally sustainable farming practices. Nanosensors enable highly sensitive and real-time monitoring of soil nutrients, plant physiological conditions, and environmental parameters, allowing farmers to make more accurate and timely management decisions. Such technologies contribute to precision farming by optimizing the application of fertilizers, irrigation water, and pesticides, thereby reducing input waste and environmental contamination. In addition to monitoring technologies, nano-inputs such as nanofertilizers, nanopesticides, and nanocarriers play an important role in improving crop production efficiency. These nanoformulations provide controlled and targeted delivery of nutrients and agrochemicals, which enhances nutrient uptake, improves crop protection, and reduces losses associated with conventional agricultural inputs. Furthermore, several studies demonstrate that nanoparticles can stimulate plant physiological processes and strengthen plant tolerance to abiotic stresses such as drought and salinity, which are major constraints to agricultural productivity under changing climatic conditions. Despite these advantages, the widespread application of nanotechnology in agriculture requires careful consideration of environmental safety and ecological sustainability. Potential risks associated with nanoparticle accumulation in soil systems, impacts on soil microorganisms and beneficial organisms, and possible entry into the food chain remain areas of concern that require further investigation. Therefore, future research should focus on developing environmentally friendly nanomaterials, improving field-level application strategies, and establishing clear regulatory frameworks to ensure safe and responsible implementation. As a whole, nanotechnology has the potential to become a key component of next-generation precision agriculture. With continued interdisciplinary research, technological innovation, and appropriate regulatory oversight, nano-enabled agricultural technologies can contribute significantly to sustainable crop production, improved resource management, and global food security.

References

1. Akwu NA, Mwinga JL, Ajose DJ, Fawole OA, Aremu AO. Nanotechnology for Soil Remediation and Nutrient Delivery: Innovations in Sustainable Agriculture. In: Nanotechnology in Pre-and Postharvest Horticulture. 2026;pp. 137-165. CRC Press.
2. Amir L, Maryam B, Anvar G, Meisam Z. The role of nanotechnology for improving crop production. Вестник Российского университета дружбы народов.

Серия: Агрономия и животноводство. 2019;14(4):297-305.
3. Anderson AJ, McLean JE, Jacobson AR, Britt DW. CuO and ZnO nanoparticles modify interkingdom cell signaling processes relevant to crop production. J Agric Food Chem. 2017;66(26):6513-6524.
4. Biswas A, Ghorai S, Kanthal S, Chatterjee A, Pramanick M, Ghosh PK, *et al*. Nanotechnology for Sustainable Agriculture and Global Food Systems. In: Handbook of Nanotechnology in Agriculture. Singapore: Springer Nature Singapore; 2025. p. 1-37.
5. Chandan S, Bhargavi CP, Sulakiya P, Sathish KM, Raja Naika H. Educating the Future: Integrating Nano-Harvest in Agricultural Curricula. In: Plant-Based Nanotechnology for Proteomic and Genomic: Current Trends, Approaches and Applications. Singapore: Springer Nature Singapore; 2026. p. 383-413.
6. Chaudhary KB, Trivedi AP, Pandya MM, Baria K, Rathwa RI. Effect of Botanical Based Nano Formulations on the Morphological Growth and Yield of Okra (Abelmoschus esculentus L.). J Exp Agric Int. 2025;47(7):394-406.
7. Churilov D, Polischuk S, Churilov G, Shemyakin A, Churilova V, Andreev K, *et al*. The possibility of using biopreparations based on nanoparticles of biogenic metals in crop production and plant protection. IOP Conf Ser Earth Environ Sci. 2020;433(1):012001.
8. Dabare S, Rajapaksha S, Munaweera I. Exploring the intersection of innovation management and nanotechnology in sustainable agriculture. Int J Innov Sci. 2025:1-37.
9. Ditta A, Arshad M, Ibrahim M. Nanoparticles in sustainable agricultural crop production: applications and perspectives. In: Nanotechnology and plant sciences: nanoparticles and their impact on plants. Cham: Springer International Publishing; 2015. p. 55-75.
10. Elemike EE, Uzoh IM, Onwudiwe DC, Babalola OO. The role of nanotechnology in the fortification of plant nutrients and improvement of crop production. Appl Sci. 2019;9(3):499.
11. Elzein B. Nano Revolution: "Tiny tech, big impact: How nanotechnology is driving SDGs progress. Heliyon. 2024;10(10).
12. Gunasena MDKM, Alahakoon AMPD, Polwaththa KPGDM, Galpaya GDCP, Priyanjani HASA, Koswattage KR, *et al*. Transforming plant tissue culture with nanoparticles: a review of current applications. Plant Nano Biol. 2024;10:100102.
13. Hossain A, Kerry RG, Farooq M, Abdullah N, Tofazzal Islam M. Application of nanotechnology for sustainable crop production systems. In: Nanotechnology for food, agriculture, and environment. Cham: Springer International Publishing; 2020. p. 135-159.
14. Iqbal MA. Crop Production under Changing Climate: A Global Perspective. Sustainable crop production. 2020;293.
15. Jampílek J, Kráľová K. Beneficial effects of metal-and metalloid-based nanoparticles on crop production. In: Nanotechnology for agriculture: advances for sustainable agriculture. Singapore: Springer Singapore; 2019. p. 161-219.
16. Javaid A, Hameed S, Li L, Zhang Z, Zhang B, Rahman MU. Can nanotechnology and genomics innovations trigger agricultural revolution and sustainable development? Funct Integr Genomics. 2024;24(6):216.
17. Jayarambabu N, Kumari BS, Rao KV, Prabhu YT. Beneficial role of zinc oxide nanoparticles on green crop production. Int J Multidiscip Adv Res Trends. 2015;2(1):273-282.
18. Jo YK, Kim BH, Jung G. Antifungal activity of silver ions and nanoparticles on phytopathogenic fungi. Plant Dis. 2009;93(10):1037-1043.
19. Kannan M, Elango K, Tamilnayagan T, Preetha S, Kasivelu G. Impact of nanomaterials on beneficial insects in agricultural ecosystems. In: Nanotechnology for food, agriculture, and environment. Cham: Springer International Publishing; 2020. p. 379-393.
20. Kaushal M, Wani SP. Nanosensors: frontiers in precision agriculture. In: Nanotechnology: an agricultural paradigm. Singapore: Springer Singapore; 2017. p. 279-291.
21. Khan A, Ahmad F. Nanomaterials as unique carriers in agricultural practices for plant growth and development: A state of current knowledge. In: Plant and nanoparticles. Singapore: Springer Nature Singapore; 2022. p. 281-314.
22. Khan MR, Rizvi TF. Application of nanofertilizer and nanopesticides for improvements in crop production and protection. In: Nanoscience and plant–soil systems. Cham: Springer International Publishing; 2017. p. 405-427.
23. Khedr EH, Khedr N, Al-Dossary O, Al-Khayri JM. Nano-innovations for Enhancing Climate Resilience in Millets. In: Improving Crops for Future Sustainability and Climate Resilience. Singapore: Springer Nature Singapore; 2026. p. 361-380.
24. Kumar A, Nagar S, Anand S. Nanotechnology for sustainable crop production: recent development and strategies. In: Plant-microbes-engineered nano-particles (PM-ENPs) nexus in agro-ecosystems: Understanding the interaction of plant, microbes and engineered nano-particles (ENPS). Cham: Springer International Publishing; 2021. p. 31-47.
25. Li H, Wang Z, Zhou C, Wang H, Chen L, Yang H, *et al*. Harnessing nanoparticles to enhance crop production under drought stress: a quantitative meta-analysis. Agric Water Manag. 2025;315:109550.
26. Li Q, Ma C, White JC, Xing B. Fate and effects of engineered nanomaterials in agricultural systems. In: Nanomaterial Biointeractions at the Cellular, Organismal and System Levels. Cham: Springer International Publishing; 2021. p. 269-292.
27. Liu C, Zhou H, Zhou J. The applications of nanotechnology in crop production. Molecules. 2021;26(23):7070.
28. Maity D, Gupta U, Saha S. Biosynthesized metal oxide nanoparticles for sustainable agriculture: next-generation nanotechnology for crop production, protection and management. Nanoscale. 2022;14(38):13950-13989.
29. Malukani KK, Gaur N, Patel HK. Application of nanobiotechnology in agriculture: novel strategy for food security. In: Omics Technologies for Sustainable Agriculture and Global Food Security (Vol II). Singapore: Springer Singapore; 2021. p. 247-265.
30. Martin C, Garay AG, Pintos B. Green Nanotechnology in Sustainable Agriculture: Plant-Based Synthesis of Metallic Nanoparticles for Crop Protection and

Productivity. 2026.
31. Negi M, Sharma S, Sharma U, Kumar P, Sharma U, Sharma K. Aspects of the current and prospective sustainable usage of nanofertilizers in agriculture and their effects on health of the soil: An updated review. J Soil Sci Plant Nutr. 2023;23(1):594-611.
32. Pérez-Hernández H, Fernández-Luqueño F, Huerta-Lwanga E, Mendoza-Vega J, Álvarez-Solís JD. Effect of engineered nanoparticles on soil biota: Do they improve the soil quality and crop production or jeopardize them? Land Degrad Dev. 2020;31(16):2213-2230.
33. Pramanik B, Sar P, Bharti R, Gupta RK, Purkayastha S, Sinha S, *et al*. Multifactorial role of nanoparticles in alleviating environmental stresses for sustainable crop production and protection. Plant Physiol Biochem. 2023;201:107831.
34. Reddy LJ, Ghosh K, Panwar A. Transcriptomic Approaches to Examine the Nanomaterials' Impact on the Physiological and Molecular Responses of Plants. In: Nanobiostimulants in Innovative Agriculture. Singapore: Springer Nature Singapore; 2025. p. 169-201.
35. Sabarivasan R, Infanta SC, Srimathi K, Varghese G, Jeevanraj R, Gokul S. Nanotechnology Applications for Enhancing Potato Productivity, Stress Resilience, and Post-Harvest Quality. Am J Potato Res. 2025:1-17.
36. Seleiman MF, Ahmad A, Battaglia ML, Bilal HM, Alhammad BA, Khan N. Zinc oxide nanoparticles: A unique saline stress mitigator with the potential to increase future crop production. S Afr J Bot. 2023;159:208-218.
37. Sheteiwy MS, Shaghaleh H, Hamoud YA, Holford P, Shao H, Qi W, *et al*. Zinc oxide nanoparticles: potential effects on soil properties, crop production, food processing, and food quality. Environ Sci Pollut Res. 2021;28(28):36942-36966.
38. Singh A, Agrawal S, Rajput VD, Ghazaryan K, Yesayan A, Minkina T, *et al*. Nanoparticles in revolutionizing crop production and agriculture to address salinity stress challenges for a sustainable future. Discov Appl Sci. 2024;6(6):317.
39. Singh SP, Keswani C, Minkina T, Ortiz A, Sansinenea E. Nano-inputs: a next-generation solution for sustainable crop production. J Plant Growth Regul. 2023;42(9):5311-5324.
40. Singh S, Dubey A, Singh PK, Sahoo C, Saini A. The Synergy of Nanotechnology and Biofertilisers: A Pathway to Sustainable Growth. In: Biofertilizers for Sustainable Agriculture in Africa. Singapore: Springer Nature Singapore; 2026. p. 309-334.
41. Srivastava P, Singh R, Bhadouria R, Bahadur Pal D, Singh P, Tripathi S. Engineered nanoparticles in smart agricultural revolution: An enticing domain to move carefully. In: Plant-microbes-engineered nano-particles (PM-ENPs) nexus in agro-ecosystems: Understanding the interaction of plant, microbes and engineered nano-particles (ENPS). Cham: Springer International Publishing; 2021. p. 3-18.
42. Tarafdar JC, Kumar D, Singh SK, Singh KP, editors. Nanobiotechnology for Agricultural Sciences: Nano-Agri-Input Products for Crop Production and Environmental Protection. CRC Press; 2025.
43. Upadhayay VK, Naitam MG, Ghosh S, Patel VK, Sharma A, Chandra AK, *et al*. Techniques for integrating nanotechnology in agriculture. In: Advances in nanotechnology for smart agriculture. CRC Press; 2023. p. 19-40.
44. Upadhyay SK, Kumar S, Rout C, Vashistha G, Aggarwal D. Risks and concerns of use of nanoparticles in agriculture. In: The role of nanoparticles in plant nutrition under soil pollution: Nanoscience in nutrient use efficiency. Cham: Springer International Publishing; 2022. p. 371-394.
45. Upinder, Kumar R. Nanotechnology: advancement for agricultural sustainability. In: Plant-Microbes-Engineered Nano-Particles (PM-ENPs) Nexus in Agro-Ecosystems: Understanding the Interaction of Plant, Microbes and Engineered Nano-Particles (ENPS). Cham: Springer International Publishing; 2021. p. 19-27.
46. Vera-Reyes I, López-García M, Ruiz-Torres N, Méndez-Arguello B, Lira-Saldivar RH. Graphene oxide nanoparticles and graphite microparticles on seeds germination and growth of Solanum lycopersicum seedlings. Mundo nano. Revista interdisciplinaria en nanociencias y nanotecnología. 2024;17(32).
47. Vishwakarma V, Ogunkunle CO, Rufai AB, Okunlola GO, Olatunji OA, Jimoh MA. Nanoengineered particles for sustainable crop production: potentials and challenges. 3 Biotech. 2023;13(5):163.
48. Vuong LD. Nanoparticles for the improved crop production. In: Nanotechnology for agriculture: crop production & protection. Singapore: Springer Singapore; 2019. p. 85-106.
49. Xin X, Nepal J, Shohag JI, de Souza Junior JC, He S, Ahmad W, *et al*. Enhancing corn growth and nutrient uptake using carbon nanoparticles derived from carbon black: a two-year field study. J Soil Sci Plant Nutr. 2025;25(1):1159-1174.
50. Yadav MK, Kumar M, Yadav SK, Ranebennur H, Yadav S, Tiwari RK, *et al*. Nanobiotechnology for Sustainable Agriculture. In: Nanobiotechnology for Postharvest Management. Singapore: Springer Nature Singapore; 2025. p. 21-50.
51. Yadu B, Xalxo R, Chandra J, Kumar M, Chandrakar V, Keshavkant S. Applications of nanomaterials to enhance plant health and agricultural production. In: Plant Responses to Nanomaterials: Recent Interventions, and Physiological and Biochemical Responses. Cham: Springer International Publishing; 2021. p. 1-19

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