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Nanotechnology Applications in Agriculture for Crop Protection and Nutrient Delivery: A Review

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This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Nanotechnology has emerged as a revolutionary tool in modern agriculture, offering precision solutions for crop protection and nutrient management. The applications of nanotechnology in agriculture for crop protection and nutrient delivery. The application of engineered nanomaterials, including nano-fertilisers, nano-pesticides, and smart nanosensors, enables enhanced agricultural productivity, resource efficiency, and environmental sustainability. Nano-fertilisers, such as nano-urea, zinc oxide, and iron oxide nanoparticles, exhibit controlled release and improved bioavailability, resulting in up to 30–50% reduction in input use with comparable or superior yield outcomes. Nano-pesticides formulated with polymeric or metallic carriers enhance pest control efficacy at lower dosages through targeted delivery and reduced volatilisation. Nanosensors based on carbon nanotubes, quantum dots, and gold nanoparticles provide real-time monitoring of soil moisture, nutrient levels, and plant health, enabling site-specific management through integration with Internet of Things (IoT) platforms. Physiologically, nanoparticles modulate plant metabolic pathways, improve photosynthetic efficiency, and enhance abiotic stress tolerance by activating antioxidant defence mechanisms. Despite these advantages, environmental and biosafety concerns persist due to the potential mobility, persistence, and bioaccumulation of nanoparticles in soil, water, and food chains. Studies have confirmed nanoparticle translocation from roots to shoots and even into edible plant parts, raising the need for long-term ecotoxicological assessments. Regulatory bodies such as the OECD, FAO, and national agencies have developed initial safety, emphasising particle characterisation, exposure assessment, and lifecycle analysis. Field validation, transparent labelling, and stakeholder engagement remain key components for public acceptance and ethical deployment. As global agriculture faces increasing challenges from climate variability, resource depletion, and food insecurity, nanotechnology offers a scientifically grounded approach to optimise input use, reduce environmental footprints, and sustain crop productivity. Through interdisciplinary research, policy support, and inclusive education, nanotechnology can redefine the future of farming systems, contributing to climate-resilient, economically viable, and ecologically balanced agricultural practices.

Keywords: Nanotechnology; Nano-fertilisers; Nano-pesticides; nanosensors; bioavailability; precision; biosafety.

1. INTRODUCTION

1.1 Nanotechnology in Agriculture

Recently, agriculture is facing several concerns, including climate change, soil degradation, decreasing land holding, urbanisation, unsustainable use of natural resources, excessive use of agrochemicals, biodiversity loss, air pollution, etc., are some of the alarming issues which demand immediate interventions. Conventional agricultural practices could not handle these challenges (Yadav et al., 2023). Nanotechnology refers to the manipulation and application of materials at the nanometre scale (1–100 nm), where unique physicochemical properties emerge due to the high surface-area-to-volume ratio and quantum (Behera et al. 2019). In agriculture, nanotechnology involves the engineering of nanomaterials and nano-enabled devices aimed at enhancing agricultural productivity, improving crop protection, ensuring precise nutrient delivery, and minimising resource wastage (Chowdhury et al., 2023). These nanomaterials include nanoparticles, nanoemulsions, nanocomposites, and nano biosensors, which have the potential to revolutionise traditional farming methods by improving the delivery efficiency of agrochemicals, reducing environmental contamination, and enabling early diagnosis of diseases. The field is interdisciplinary in nature, combining inputs from materials science, chemistry, biology, and agricultural engineering to address the challenges of sustainable food production.

1.2 Significance of Nanotechnology in Modern Crop Management

The global agricultural sector faces challenges such as reduced arable land, climate stress, nutrient depletion, pest resistance, and the need to ensure food security for a projected 9.7 billion population by 2050 (Kaur et al. 2023). Nanotechnology offers solutions by enabling smart delivery of fertilisers and pesticides, thus increasing nutrient use efficiency (NUE) and reducing the need for frequent applications. Nanomaterials can be used in agriculture today to increase fertiliser use efficiency, increase yield and reduce the need for pesticides, rapid detection of pathogens, detection of toxic chemicals in food, and regulate agricultural food security (Qarachal et al., 2023). Moreover, nano-fertilisers such as zinc oxide, iron oxide, and nano-urea formulations have demonstrated improved crop growth and yield under both field and greenhouse conditions, reducing nutrient losses through leaching and volatilisation. In crop protection, nanoencapsulation of active ingredients ensures controlled release and targeted delivery to pests and pathogens, minimising off-target toxicity and residues in food. Moreover, nanobiosensors and nano-enabled diagnostic devices are being developed for real-time monitoring of soil nutrients, pathogens, and environmental pollutants, enhancing precision agriculture practices (Bharti et al. 2024). These advancements are essential in aligning agriculture with the goals of environmental sustainability and productivity enhancement.

2. FUNDAMENTALS OF NANO-TECHNOLOGY IN AGRICULTURE

A. Definition and characteristics of nanoparticles

Nanoparticles are defined as particles having at least one dimension in the range of 1–100 nanometers. Their small size imparts unique physicochemical properties, which are not present in their bulk counterparts (Thakur & Thakur, 2022). These include enhanced surface reactivity, high surface-area-to-volume ratio, quantum mechanical effects, and superior solubility or dispersion potential in aqueous and organic media. These traits make nanoparticles particularly suitable for agricultural applications involving efficient delivery of active ingredients, sensing mechanisms, and catalytic interactions at the biological interface. The physical dimensions of nanoparticles influence their interaction with biological systems, penetration into plant tissues, and rate of dissolution or degradation (Mu et al. 2014). Spherical nanoparticles typically offer lower aggregation tendencies and better mobility compared to rod or irregular-shaped particles. A nanoparticle with a 10 nm diameter exhibits a surface-area-to-volume ratio 100 times greater than its micron-sized counterpart, enabling higher contact with plant surfaces or cellular membranes (Mekuye & Abera, 2023). Their high surface energy also facilitates catalytic and redox reactions critical to pest control and nutrient delivery. Surface functionalization allows nanoparticles to carry ligands, polymers, or biomolecules that can guide them to specific plant parts, cells, or biochemical targets. Functionalization with peptides, antibodies, or polymers like polyethylene glycol (PEG) enhances biocompatibility, stability in soil or water, and specific binding to receptors or plant stomata. This targeted delivery mechanism minimises off-target losses and improves agrochemical use efficiency while reducing phytotoxicity and ecological disruption.

B. Types of nanomaterials used in agriculture

Agricultural nanotechnology incorporates diverse nanomaterials tailored for specific functions, including disease control, nutrient enhancement, and environmental remediation (Yadav et al. 2023). These materials vary in composition, structure, and biocompatibility (Table 1). Silver nanoparticles (AgNPs) exhibit strong antimicrobial activity against a broad spectrum of phytopathogens by generating reactive oxygen species (ROS) and disrupting cell membranes (Fareed et al., 2023). Zinc oxide (ZnO) and copper oxide (CuO) nanoparticles serve dual roles as micronutrient fertilisers and antimicrobial agents. ZnO nanoparticles enhance seedling vigour and chlorophyll content in maize, tomato, and wheat. Titanium dioxide (TiO_2) nanoparticles are photoactive agents that can degrade pesticide residues and promote photosynthesis by enhancing light absorption in chloroplasts. Biodegradable polymers such as polylactic acid (PLA), chitosan, and polycaprolactone are used to develop nanocarriers for pesticides and fertilisers (Shakiba et al. 2020). These particles allow sustained release, environmental protection of active ingredients, and compatibility with biological systems. Lipid-based nanoparticles like solid lipid nanoparticles (SLNs) and nanoemulsions provide hydrophobic cores for encapsulating poorly soluble agrochemicals, improving dispersion and penetration through plant cuticles. Single-walled and multi-walled carbon nanotubes (SWCNTs, MWCNTs) are employed to enhance seed germination and promote root elongation through improved water and nutrient uptake (Solorio-Rodriguez et al., 2023). Graphene oxide (GO) and reduced graphene oxide (rGO) act as carriers for fertilisers and pesticides due to their high

Table 1. Types of nanomaterials used in agriculture

Type of Nanomaterial	Examples	Applications in Agriculture
Metal-based Nanoparticles	Silver (Ag), Gold (Au), Zinc oxide (ZnO), Iron oxide (Fe_2O_3)	Antimicrobial agents, nanofertilizers, crop protection, soil remediation
Carbon-based Nanomaterials	Carbon nanotubes (CNTs), Graphene oxide, Fullerenes	Seed germination enhancement, biosensors, delivery of agrochemicals, stress tolerance
Polymeric Nanomaterials	Chitosan nanoparticles, Poly(lactic-co-glycolic acid) (PLGA)	Controlled release of fertilizers, pesticides, biostimulants, improved nutrient uptake
Silica-based Nanomaterials	Mesoporous silica nanoparticles (MSNs)	Smart delivery systems for agrochemicals, slow release of nutrients, pathogen control
Lipid-based Nanoparticles	Liposomes, Solid lipid nanoparticles (SLNs)	Encapsulation of pesticides and herbicides, gene delivery, protection of biomolecules
Quantum Dots	CdSe, ZnS, Carbon quantum dots	Fluorescent labeling, plant imaging, biosensing of toxins and pathogens
Nanoclays	Montmorillonite, Halloysite nanotubes	Soil conditioning, pesticide carriers, slow release of agrochemicals
Magnetic Nanoparticles	Fe_3O_4, $CoFe_2O_4$	Targeted delivery of agrochemicals, magnetic-assisted separation, pathogen detection

(Source - Fareed et al., 2023, Yadav et al. 2023)

adsorption capacity and tunable surface chemistry. These materials also hold promise for soil pollutant remediation and biosensor development.

C. Nanofabrication and delivery mechanisms

The production and application of nanomaterials in agriculture involve precision-engineering methods that control particle size, distribution, and surface chemistry for optimal functionality (Wahab et al. 2024). The bottom-up approach involves self-assembly from atomic or molecular precursors through chemical synthesis, sol-gel processing, or green synthesis methods using plant extracts or microbial agents. Top-down techniques include mechanical milling, lithography, and laser ablation to reduce bulk materials into nanoscale dimensions. Bottom-up methods offer better control over morphology and purity, while top-down techniques are suitable for producing large volumes at an industrial scale. Nanoencapsulation involves enclosing active ingredients within nanocarriers such as liposomes, micelles, or polymeric matrices, ensuring protection against environmental degradation and enabling controlled release. Nanogels are hydrogel nanoparticles with high water content and biocompatibility, suitable for moisture-responsive nutrient delivery. Nanosuspensions consist of nanosized agrochemical particles dispersed in liquid media with the help of stabilisers, improving solubility and bioavailability. These delivery systems collectively aim to reduce input wastage, enhance bioavailability, and prolong the duration of field efficacy.

3. NANOTECHNOLOGY FOR CROP PROTECTION

A. Nano-pesticides

Nanotechnology has enabled the development of nano-pesticides, which offer improved pest control by enhancing the bioavailability, stability, and specificity of active compounds (Anandhi et al. 2020). These formulations are designed to reduce environmental contamination and mitigate the health risks associated with conventional pesticide overuse. Nano-pesticides increase the active surface area of insecticidal compounds, leading to enhanced penetration and prolonged activity at lower concentrations. Studies have shown that nano-encapsulated chlorpyrifos, when applied at just 25% of the recommended field dose, can achieve similar pest mortality as conventional formulations. Similarly, polymer-based nano-formulations of lambda-cyhalothrin have demonstrated up to 90% reduction in required application rates without compromising pest control efficacy. Nanocarriers enable controlled and sustained release of active ingredients, minimising degradation by UV light or microbial activity (Natarajan et al. 2014). Mesoporous silica nanoparticles, chitosan nanoparticles, and polymeric micelles are widely studied for their ability to encapsulate pesticides and release them in response to environmental triggers such as pH or moisture levels. Site-specific delivery using magnetic nanoparticles or ligand-functionalized nanocarriers ensures that the pesticide reaches the intended pest population with minimal off-target effects. Several nano-pesticide products have been developed and tested in field conditions. A commercial formulation, “Ourofino Nano” (Brazil), uses nanostructured particles to deliver imidacloprid with improved systemic action and rainfastness. Another formulation, “AgroNano” (Argentina), delivers copper and sulfur in nano-form for use in integrated pest and disease management. Research on nano-hexaconazole, nano-carbendazim, and nano-pyrethroids has shown promising results in reducing pest damage across crops such as cotton, rice, and vegetables.

B. Nano-fungicides and nano-bactericides

Nano-enabled antifungal and antibacterial agents play a crucial role in crop protection, especially against resistant strains of phytopathogens (Noman et al. 2023). Nanoparticles act through multiple mechanisms, including cell wall disruption, oxidative stress induction via reactive oxygen species (ROS), DNA damage, and protein denaturation. Silver nanoparticles (AgNPs) are particularly effective, exhibiting broad-spectrum fungicidal activity against pathogens such as *Fusarium oxysporum*, *Rhizoctonia solani*, and *Alternaria alternata*. Copper nanoparticles disrupt fungal respiration and membrane integrity, leading to cell lysis. Traditional fungicides often result in the evolution of resistant pathogen strains due to repetitive use of single modes of action. Nanomaterials, with their multiple and nonspecific pathways of toxicity, are less likely to induce resistance. Nano-formulations allow for synergistic combinations of antifungal compounds and bioactives, reducing the selective pressure on pathogen populations. Additionally, integrating nanomaterials with biocontrol agents such as *Trichoderma spp.* and *Bacillus subtilis* further diversifies the disease management toolbox.

C. Nanomaterials as insect repellents and attractants

Insect management using nanotechnology includes not only insecticidal activity but also behavioural manipulation via repellency or attractancy (Kannan et al. 2022). Nanoemulsions—oil-in-water formulations with droplet sizes <200 nm—improve the dispersion, stability, and bioactivity of botanical oils like neem, citronella, and clove oil. Neem oil nanoemulsion has shown 70–80% repellent efficacy against *Spodoptera litura* larvae, with improved shelf life and reduced phytotoxicity compared to conventional emulsions. Their rapid absorption and systemic movement also enable translaminar action, deterring pests feeding on both upper and lower leaf surfaces. Functionalized nanoparticles can target specific pathways in insect physiology, such as neurotransmission, cuticular integrity, or endocrine balance (Shahzad et al. 2021). Silica nanoparticles cause mechanical abrasion of the insect exoskeleton, leading to desiccation and mortality. Zinc oxide and magnesium oxide nanoparticles interfere with enzyme systems and calcium ion signalling, resulting in paralysis or death. RNAi delivery using nanocarriers has also been explored to silence essential insect genes selectively, providing precision pest control without harming beneficial organisms.

D. Disease diagnostics using nanobiosensors

Nanotechnology contributes to rapid, sensitive, and portable diagnostics for early detection of plant diseases, enabling timely interventions. Nanobiosensors utilise functionalized nanoparticles, quantum dots, or carbon nanotubes to detect specific nucleic acids, proteins, or metabolites associated with pathogens (Sharma et al. 2020). Gold nanoparticle-based colourimetric assays can detect *Pseudomonas syringae* or *Xanthomonas oryzae* within minutes with a detection limit as low as 10^2 CFU/mL. Electrochemical sensors using ZnO and graphene oxide have also been developed for real-time detection of *Phytophthora infestans* and *Tobacco mosaic virus* at picomolar concentrations. Lab-on-a-chip platforms and lateral flow devices incorporating nanomaterials are being commercialised for field-level use by farmers and extension workers (Yadav et al. 2025). Devices based on magnetic nanoparticles, quantum dots, or colourimetric gold nanoparticles are designed for ease of operation, low cost, and robust performance under diverse agro-climatic conditions. For example, a graphene-based paper sensor has been developed to detect *Xanthomonas campestris* in cabbage with high accuracy, suitable for integration into smartphone-based diagnostics. These devices significantly reduce reliance on laboratory infrastructure and enable real-time disease surveillance for precision crop management.

4. NANOTECHNOLOGY FOR NUTRIENT DELIVERY AND SOIL HEALTH

A. Nano-fertilizers

Nano-fertilisers are engineered formulations designed to enhance the efficiency of nutrient delivery to crops by using nanomaterials with slow-release and site-specific properties (Table 2) (Singh et al. 2024). These fertilisers are typically composed of nutrients encapsulated within or coated onto nanocarriers such as polymers, silica, or carbon-based particles. Nano-fertilisers are formulated to provide a controlled and gradual release of nutrients, aligning with the plant's growth cycle and metabolic needs (Mahesha et al. 2023). This reduces nutrient losses caused by leaching, volatilisation, or fixation. For instance, urea encapsulated in hydroxyapatite nanoparticles exhibited sustained nitrogen release over 20 days, compared to less than 5 days in conventional formulations. Nanostructured zinc oxide and iron oxide fertilisers have demonstrated improved solubility and greater root uptake efficiency due to their enhanced surface activity and interaction with root exudates. The application of nano-fertilisers has shown significant improvements in nutrient use efficiency (NUE). Zinc oxide nanoparticles applied to maize increased zinc uptake by 44% and dry biomass by 35% under greenhouse conditions. Nano-urea has demonstrated a 30–50% reduction in application rates without compromising yield outcomes. These improvements are critical in mitigating nutrient losses that are typically seen with conventional fertilisers, where only 30–50% of applied nitrogen is utilised by crops, with the remainder lost to the environment. Studies comparing nano-fertilisers with bulk formulations have consistently shown superior outcomes in terms of nutrient absorption, plant growth, and yield (Iqbal et al. 2019). For instance, rice plants treated with nano-encapsulated phosphorus exhibited 2.5 times higher biomass than those treated with traditional phosphorus sources. Similarly, chitosan-coated nitrogen nanoparticles applied to wheat improved grain yield by 18% and reduced nitrate leaching losses. These findings indicate the potential of nano-fertilisers to meet agronomic demands with reduced environmental impact.

B. Micronutrient and macronutrient nano-carriers

Nanocarriers facilitate the transport of essential micro- and macronutrients into plant systems with high bioavailability and targeted delivery. Nanoparticles such as ZnO, Fe_2O_3, and nano-hydroxyapatite are widely studied for the delivery of zinc, iron, and phosphorus (Saxena et al. 2018). Zinc oxide nanoparticles at 25 mg/L significantly increased shoot length and chlorophyll content in mung bean, compared to bulk $ZnSO_4$. Iron oxide nanoparticles enhanced iron translocation from root to shoot in soybean, correcting chlorosis in Fe-deficient soils. Nitrogen-based nanofertilizers such as nano-urea enable slow hydrolysis, extending nitrogen availability during critical crop stages. Phosphorus-loaded nanoparticles have addressed phosphorus fixation issues in acidic and calcareous soils by maintaining P in plant-available form for longer durations. Micronutrient deficiencies, especially of zinc, boron, and iron, are widespread and limit crop productivity (Singh et al. 2010). Nano-formulations offer effective tools for correcting these imbalances due to their solubility in diverse pH ranges and their capacity to chelate and transport nutrients directly into plant cells. For example, boron nano-chelates showed 30% higher efficacy in enhancing reproductive growth in tomato compared to conventional boric acid. The localised delivery also minimises toxicity risks, a common concern with micronutrient over-application.

C. Soil amendments and nanoclays

Nanomaterials have shown promise as soil amendments due to their structural and chemical properties that influence soil texture, water holding capacity, and pollutant adsorption (Zaib et al. 2023). Nanoclays such as montmorillonite and kaolinite possess high cation exchange capacities and interlayer swelling properties that improve soil porosity and aggregate stability. These amendments help buffer soil pH and increase microbial habitat suitability. Application of halloysite nanotubes has been shown to enhance soil aeration and retain water up to 15% more than untreated soils, aiding crop resilience during dry spells. Nanoscale zero-valent iron (nZVI), graphene oxide, and biochar nanoparticles are highly effective in immobilising toxic metals such as arsenic, cadmium, and lead (Shaheen et al. 2022). These nanomaterials adsorb or reduce metals into less mobile and bioavailable forms, thereby protecting crops and soil microbial diversity. For example, biochar-loaded nano-Fe reduced arsenic uptake in rice by 60% when applied at 0.5% soil concentration. These materials are vital for remediating contaminated soils and restoring productivity.

D. Role of nanomaterials in microbial interactions

The interaction between nanomaterials and soil microbiota is a critical aspect of soil health, influencing nutrient cycling, organic matter decomposition, and nitrogen fixation (Khan et al. 2021). Nanoparticles at appropriate doses can promote microbial growth and enzymatic activity. ZnO and TiO_2 nanoparticles have been reported to enhance microbial biomass and phosphatase activity in rhizosphere soils under moderate concentrations. However, at high concentrations, some nanoparticles may exert toxicity by generating ROS or disrupting cell membranes. Careful dose calibration and material selection are therefore essential to support beneficial microbial communities. Chitosan nanoparticles and silica nanogels have been used as carriers for microbial inoculants such as *Azospirillum* and *Rhizobium*, promoting biofilm formation and increasing root colonisation efficiency (Arora et al. 2024). These nanocarriers protect microbes during storage and delivery while facilitating root attachment and symbiotic interactions. Application of nano-encapsulated *Rhizobium* increased nitrogenase activity in legumes by 30–40%, contributing to higher nitrogen fixation rates. This technology offers an eco-friendly route to reduce synthetic nitrogen inputs.

5. MECHANISMS OF ACTION AND PHYSIOLOGICAL IMPACT

A. Nanoparticle uptake, translocation, and accumulation in plants

Nanoparticles enter plants through multiple pathways and undergo translocation to different tissues, influencing physiological functions depending on their size, charge, composition, and surface chemistry (Rahman et al. 2022). Once internalised, they interact with plant biomolecules and organelles, impacting metabolism and development. Nanoparticles can be absorbed via roots from soil solution or applied directly to leaves through foliar sprays (Hong et al. 2021). Root uptake primarily occurs through the apoplastic or symplastic pathways. Particles smaller than 40 nm may penetrate through root epidermal cell walls and pass into the vascular system. Foliar uptake occurs through stomata, cuticle pores, or damaged epidermis. Stomatal openings, which range from 10–100 μm, allow particles under 100 nm to penetrate and enter mesophyll tissues. Hydrophilic nanoparticles like nano-silica and metal oxides exhibit higher foliar permeability due to better dispersion and solubility. Once internalised, nanoparticles are translocated via xylem and phloem to aerial organs including stems, leaves, and fruits (Shukla et al. 2016). Studies using labelled TiO_2 nanoparticles revealed systemic movement from roots to shoots, accumulating in leaf mesophyll and chloroplasts. Carbon nanotubes and metal nanoparticles have also been detected in vacuoles, nuclei, and intercellular spaces, suggesting active or passive transport mechanisms across cell membranes. Their mobility depends on particle size, surface charge, and plant species.

B. Physiological and biochemical responses to nanoparticles

Nanoparticles can induce positive or negative responses in plants depending on concentration, exposure time, and particle properties (Goswami et al. 2019). Their interaction with physiological pathways influences photosynthesis, stress signalling, enzyme activity, and nutrient metabolism. Metal oxide nanoparticles like TiO_2 and ZnO can enhance photosynthetic rate and chlorophyll synthesis under optimal concentrations. TiO_2 nanoparticles increase Rubisco activity, stomatal conductance, and light absorption, improving net photosynthesis by 12–30% in crops like spinach, wheat, and tomato. ZnO nanoparticles stimulate auxin biosynthesis and chlorophyll content, supporting higher leaf area index and biomass accumulation. These effects are linked to improved nutrient uptake and chloroplast integrity. Nanoparticles can boost plant tolerance to abiotic stresses by activating antioxidant defence systems (Jalil et al. 2019). Silver, cerium oxide, and silicon nanoparticles enhance the activity of superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), reducing oxidative damage under drought and salinity stress. Silica nanoparticles improve osmotic adjustment and water retention, promoting membrane stability under water-limited conditions. Iron oxide nanoparticles have been reported to mitigate salinity-induced chlorosis and lipid peroxidation in soybean and rice, contributing to yield stability under stress.

C. Toxicity concerns and threshold levels

While nanomaterials offer significant agronomic benefits, their misuse or overapplication poses toxicity risks to plants and surrounding ecosystems (Singh et al. 2022). Understanding dose-response relationships and establishing safety thresholds is essential for sustainable application. Phytotoxic effects of nanoparticles emerge at high concentrations or prolonged exposure (Jogaiah et al. 2021). Symptoms include inhibited germination, reduced root elongation, chlorosis, and membrane damage. For instance, ZnO nanoparticles above 200 mg/L inhibited seed germination and induced oxidative stress in wheat and maize. AgNPs at 100 ppm caused DNA fragmentation and mitochondrial dysfunction in *Arabidopsis thaliana*. Toxicity is influenced by particle aggregation, dissolution rate, and plant sensitivity. The accumulation of nanoparticles in edible plant parts raises concerns about trophic transfer and food chain contamination. Studies have detected TiO_2 and ZnO nanoparticles in grains and fruits, necessitating assessment of their bioavailability and transformation during digestion. Long-term exposure to nano-copper and nano-silver also alters soil microbial diversity and enzyme function, affecting nutrient cycling and ecosystem stability. Establishing regulatory frameworks and safe application guidelines is imperative to minimise unintended impacts.

Table 2. Nanotechnology for Nutrient Delivery and Soil Health in a multiple-column table format

Category	Nanomaterials/Examples	Applications in Nutrient Delivery	Impact on Soil Health	Challenges/Limitations
Nanofertilizers	Nano-hydroxyapatite, Urea-coated nanoparticles	Slow and controlled nutrient release, enhanced nutrient use efficiency (NUE)	Improves soil nutrient retention, reduces nutrient leaching	Cost of production, lack of large-scale field validation
Metal-based Nanoparticles	ZnO, FeO, MnO nanoparticles	Supply of essential micronutrients (Zn, Fe, Mn) directly to crops	Restores micronutrient balance, enhances microbial activity	Possible toxicity to beneficial microbes if overdosed
Silica Nanoparticles	Mesoporous silica nanoparticles (MSNs)	Smart carriers for nitrogen, phosphorus, and potassium delivery	Improves soil porosity and cation exchange capacity	Risk of bioaccumulation in soil environment
Polymeric Nanocarriers	Chitosan nanoparticles, PLGA nanoparticles	Encapsulation and controlled delivery of fertilizers and bio-stimulants	Enhances soil biological activity, supports root–microbe interactions	Biodegradability and stability issues under field conditions
Magnetic Nanoparticles	Fe_3O_4 nanoparticles	Targeted delivery of nutrients with magnetic guidance	Helps in localized soil nutrient enrichment	Requires specialized application techniques

Category	Nanomaterials/Examples	Applications in Nutrient Delivery	Impact on Soil Health	Challenges/Limitations
Carbon-based Nanomaterials	Carbon nanotubes, Graphene oxide	Facilitates efficient nutrient absorption and water retention	Improves soil aeration and structural stability	Long-term environmental safety concerns
Lipid-based Nanoparticles	Liposomes, Solid lipid nanoparticles (SLNs)	Encapsulation of hydrophobic nutrients and plant hormones	Protects sensitive biomolecules in soil environment	Limited scalability and high production costs

(Source: Singh et al. 2010, Singh et al. 2024)

6. NANOTECHNOLOGY AND PRECISION AGRICULTURE

A. Smart nano sensors for real-time monitoring

Nanotechnology has transformed precision agriculture through the development of nano sensors capable of monitoring soil and plant conditions in real time with exceptional sensitivity and speed (Yadav et al. 2023). These smart nano sensors detect a variety of environmental and physiological parameters that guide timely interventions for improved crop productivity. Nano sensors embedded in soil or applied on plant surfaces can measure key agronomic variables such as soil moisture, nitrate and phosphate levels, pH, temperature, and ethylene production. Carbon nanotube-based electrochemical sensors have demonstrated the ability to detect nitrate concentrations at levels below 1 ppm, which is significantly lower than the detection limit of conventional sensors. Gold nanoparticle-based sensors functionalized with DNA or aptamers enable rapid detection of stress-related metabolites such as abscisic acid and hydrogen peroxide, which serve as early indicators of plant health. Fluorescent quantum dot-based sensors have been developed to track nutrient uptake patterns and water stress in crops, with spatial resolution reaching individual root zones. Nanosensors integrated with microcontrollers and wireless modules form the backbone of real-time decision-making systems in smart farms (Khondakar et al. 2024). Data collected by nanosensors can be transmitted wirelessly to central databases using Bluetooth, ZigBee, or LoRaWAN protocols. For instance, nano-enabled field-deployable sensor platforms linked with Internet of Things (IoT) architectures allow farmers to monitor pH fluctuations, nutrient profiles, and irrigation needs remotely. These platforms offer automation through cloud computing and AI-based analytics, reducing human error and improving input use efficiency. The scalability and miniaturisation of nanosensors allow their placement across large field areas with minimal disturbance, enabling spatial and temporal precision.

B. Decision support systems for resource optimisation

Nano-enabled data acquisition supports advanced decision support systems (DSS) that guide the precise application of agricultural inputs, thereby optimising resource use and minimising environmental footprints (Ashique et al. 2025). Data from nanosensors can be fed into DSS models to create geo-referenced nutrient and pest maps. These maps direct variable-rate applicators to apply the exact quantity of fertilisers or pesticides needed in specific field zones, improving nutrient use efficiency and reducing excess chemical application. Studies have shown that variable-rate nitrogen application based on nanosensor feedback reduced fertilizer use by up to 30% while maintaining or increasing crop yields. Similarly, site-specific herbicide application guided by nano-sensing of weed density resulted in a 25–40% reduction in herbicide input without compromising efficacy. Nanosensor-derived big data allows for predictive modelling of crop growth, disease outbreaks, and nutrient deficiencies using machine learning algorithms. These models can forecast irrigation requirements, pest emergence, and optimal harvesting windows. For example, nanosensors monitoring canopy temperature and soil conductivity were used to develop algorithms predicting water stress in wheat with 90%

accuracy. Predictive analytics enhances proactive decision-making and reduces dependence on manual scouting or reactive interventions. The integration of remote sensing data with nano sensor inputs further strengthens the reliability of predictive models, offering a multidimensional view of crop and field dynamics (Yadav, & Yadav, 2025, Omia et al. 2023).

7. REGULATION, ETHICAL, AND SAFETY

A. Environmental fate and behaviour of nanoparticles

The increasing deployment of nanomaterials in agriculture raises critical questions about their environmental behaviour, persistence, and impact on ecosystems. Understanding how nanoparticles interact with soil, water, and biological organisms is vital to ensure their safe and sustainable application. Nanoparticles exhibit distinct behaviour in agroecosystems due to their high reactivity, colloidal stability, and tendency to aggregate (Pradhan et al. 2017). Their mobility in soil is influenced by particle size, surface charge, coating, and soil characteristics such as pH, organic matter, and cation exchange capacity. Studies have shown that uncoated silver and zinc oxide nanoparticles can leach through sandy soils and reach groundwater within days of application, whereas coated nanoparticles exhibit slower transport. The degradation of nanoparticles is often limited, with metal oxides like TiO_2 and CeO_2 remaining stable in soil for extended periods due to low solubility and resistance to microbial breakdown. Their persistence may interfere with natural biogeochemical cycles, affecting nutrient dynamics and microbial diversity. Nanoparticles can be absorbed by plants and transferred through trophic levels, raising concerns about their bioaccumulation and toxicity in the food web (Dang et al. 2021). Experiments have demonstrated the uptake of CeO_2 and ZnO nanoparticles in edible plant parts such as lettuce, wheat, and rice, with particle sizes as small as 5–10 nm translocating into grains and leaves. Upon consumption, these particles can accumulate in animal tissues, potentially inducing oxidative stress, inflammation, or genotoxicity. Risk of bioaccumulation varies with nanoparticle properties and exposure levels, requiring detailed toxicokinetic studies to assess long-term risks to both human and environmental health.

B. Risk assessment and biosafety

To guide the responsible use of nanomaterials in agriculture, international and national institutions have developed regulatory frameworks and protocols for safety evaluation (Kumari et al. 2023). The Organisation for Economic Co-operation and Development (OECD) has proposed test guidelines and guidance documents for the safety assessment of manufactured nanomaterials, focusing on physical-chemical characterisation, environmental fate, ecotoxicology, and human health impacts (Nielsen et al. 2021). The Food and Agriculture Organisation (FAO) and World Health Organization (WHO) jointly published guidance on nanotechnologies in food and agriculture, emphasising the precautionary principle, lifecycle analysis, and stakeholder transparency. National regulatory bodies such as the US Environmental Protection Agency (EPA) and the European Food Safety Authority (EFSA) have also issued position papers and technical requirements for nanomaterial registration, addressing data gaps and encouraging tiered risk assessment models. Most current studies on nanoparticle toxicity and efficacy are conducted under controlled laboratory or greenhouse settings (Cox et al. 2016). There is a critical need for long-term, multi-season field studies to capture the realistic exposure scenarios, interactions with complex soil matrices, and cumulative ecological effects. Only through extended trials can researchers understand chronic toxicity, delayed impacts, and the influence of environmental variables such as rainfall, temperature, and microbial activity on nanoparticle behaviour. These studies are essential for establishing maximum permissible application limits and post-application monitoring protocols.

C. Public perception and stakeholder engagement

Public acceptance and trust play a central role in the successful adoption of nanotechnology-based agricultural inputs (Mukherjee et al. 2019). Transparent communication and participatory approaches are needed to align technological development with societal values. The uptake of nano-enabled technologies by farmers depends on perceived benefits, affordability, accessibility, and knowledge dissemination. Surveys conducted in multiple agricultural regions indicate that less than 20% of farmers are aware of nanotechnology and its potential applications. Training programs, demonstrations, and extension services are vital for building familiarity and trust. Acceptance is also influenced by performance consistency, compatibility with existing practices, and absence of visible harm to soil or crops. Effective risk communication requires clear labelling of nano-formulated products, including information on active ingredients, particle size, dosage, and safety instructions (Nagar et al. 2025). Labelling should adhere to international guidelines and be supported by user education materials in local languages. Consumer concerns regarding nanoparticle residues in food can be addressed through traceability systems, residue analysis data, and compliance with Codex Alimentarius standards. Regulatory bodies must ensure that communication strategies are evidence-based, socially inclusive, and responsive to stakeholder feedback.

8. CONCLUSION

Nanotechnology presents transformative potential for sustainable agriculture through precision nutrient delivery, enhanced crop protection, and real-time monitoring. Nano-fertilisers and nano-pesticides offer improved efficacy, reduced input losses, and minimised environmental contamination. Smart nano sensors integrated with IoT enable accurate detection of soil and plant parameters, supporting data-driven decision-making. The uptake and physiological interactions of nanoparticles in plants influence photosynthesis, stress resilience, and nutrient use efficiency. Yet, concerns remain regarding nanoparticle persistence, bioaccumulation, and toxicity, necessitating robust biosafety frameworks. Regulatory bodies such as the OECD and the FAO have initiated guidelines, but long-term field studies are essential to validate environmental safety. Transparent communication, farmer awareness, and ethical governance are critical to fostering stakeholder trust. With responsible deployment, nanotechnology can play a central role in achieving resilient, resource-efficient, and climate-smart agricultural systems for future food security.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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