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Review Article

Application of Titanium Dioxide Nanoparticles in Agricultural Production

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Abstract

Globally, titanium dioxide (TiO_2) nanoparticles have become a game-changing nanotechnological solution to improve agricultural sustainability and productivity. This thorough analysis looks at the various uses of TiO_2 nanoparticles in agriculture, including how they affect soil health, crop development, photosynthetic efficiency, and stress tolerance. TiO_2 nanoparticles' special physicochemical characteristics allow them to regulate light absorption, improve photosynthesis, offer antimicrobial defense, and encourage nutrient uptake. The benefits and possible ecological issues of using nanoparticles in agricultural systems are highlighted in this research paper research and application has been summarized about recent international research on TiO_2 processes. Sustainable farming methods, ideal dose guidelines, and the molecular mechanisms underpinning plant-nanoparticle interactions across various crop species and geographical areas are given particular attention.

Keywords: Titanium Dioxide Nanoparticles; Agricultural Nanotechnology; Photosynthesis Enhancement; Nutrient Uptake; Stress Tolerance; Sustainable Agriculture; Nanotoxicology; Climate-Resilient Crops

Global food security and agricultural challenges

With an estimated 10 billion people on the planet by 2050, food security is still one of the most urgent global issues of the twenty-first century [1]. Soil deterioration, water shortages, pest resistance, and stress factors brought on by climate change are putting increasing pressure on traditional agricultural techniques [2]. The second Sustainable Development Goal of the UN, „Zero Hunger," highlights the need for creative methods to boost agricultural output while reducing environmental effect. Innovative ways to improve crop yield and maximize resource usage have been made possible by nanotechnology, which has emerged as a revolutionary technique to solve these issues [3].

Nanotechnology in agriculture

Titanium dioxide (TiO_2) nanoparticles have garnered significant scientific interest among other nanoparticles investigated for agricultural uses because of their distinct photocatalytic, antibacterial, and biocompatible qualities [4]. Anatase and rutile polymorphs of titanium dioxide, a naturally occurring oxide, show remarkable photocatalytic activity when exposed to ultraviolet and visible light [5]. Reactive oxygen species (ROS) are produced through the photocatalytic method, allowing TiO_2 nanoparticles to break down organic pollutants, purify water, and shield plants from microbes [6].

Mechanism of Action: Multifaceted Approach

TiO_2 nanoparticles operate in agricultural settings via a variety of interrelated mechanisms:

- **Growth regulation:** By modifying transporter proteins, they function as biostimulants that improve nutrient intake and translocation.
- **Photosynthetic enhancement:** Improving the photosynthetic apparatus's electron transport and light harvesting
- **Antimicrobial activity:** Suppressing bacterial and fungal infections by producing ROS under light irradiation
- **Stress tolerance:** Triggering antioxidant defense mechanisms to lessen biotic and abiotic stress
- **Metabolic regulation:** Adjusting the metabolism of potassium, phosphorus, and nitrogen [7].

With TiO_2-based products becoming more and more incorporated into commercial farming systems throughout Europe, Asia, and North America, the worldwide agricultural nanotechnology business has grown significantly [8]. In central and eastern European nations, commercial formulations like Tytanit®, which contain titanium complexes with magnesium and sulfur oxides, have been effectively used to improve crops [9]. The applications of TiO_2 nanoparticles in agriculture, synthesis techniques, mechanisms of action, international case studies, and future prospects for sustainable agricultural practices are all thoroughly examined in this extensive research.

The primary focus of this review article is the application of TiO_2 nanoparticles for plant growth promotion and enhancement of agricultural productivity, supported by extensive experimental and field-based evidence. Secondary emphasis is given to disease suppression and stress tolerance, as these functions directly contribute to crop yield stability and food security.

Although TiO_2 nanoparticles are widely studied in soil remediation and water purification, these aspects are not the central theme of the present review. They are included only where they influence plant physiological performance and sustainable agricultural systems.

Data-based justification

- **Photosynthetic enhancement:** Yield increases of 15–35% have been reported in wheat, maize, and spinach following foliar application of TiO_2 nanoparticles (Gao., *et al*. 2006; Li., *et al*. 2011).
- **Nutrient uptake:** TiO_2 improves nitrogen assimilation enzymes (NR, GS), leading to 10–25% biomass improvement.
- **Stress tolerance:** Drought-stressed wheat treated with 0.02% TiO_2 showed 20–25% yield recovery (Sheikhi., *et al.* 2019).
- **Disease control:** Field studies report 30–40% reduction in fungal disease incidence due to TiO_2 photocatalytic activity.

Properties and synthesis of titanium dioxide nanoparticles

Physicochemical properties

Titanium dioxide nanoparticles exist in three primary crystal polymorphs: anatase, rutile, and brookite [10]. The anatase form exhibits superior photocatalytic activity compared to rutile due to its lower electron-hole recombination rate and wider band gap (3.23 eV versus 3.02 eV for rutile) [11]. Key physicochemical properties influencing agricultural efficacy include:

- **Particle size**: Optimal range of 20–100 nm for enhanced photocatalytic activity and plant uptake; <40 nm minimizes excessive root translocation
- **Surface area:** High specific surface area (typically 50–300 m^2/g) enabling superior absorption and catalytic efficiency
- **Crystal phase:** Anatase dominates photocatalytic applications; mixed-phase (anatase/rutile) combinations often exhibit enhanced activity
- **Band gap energy:** Controls light absorption spectrum and ROS generation capacity; determines photocatalytic efficiency
- **Zeta potential:** Determines colloidal stability and bioavailability in soil and plant systems; influences plant uptake
- **Morphology:** Sphere, rod, or plate geometries affect light scattering and photocatalytic efficiency

Synthesis methods and characteristics

TiO_2 nanoparticles are synthesized using various methods, each producing particles with distinct properties suited for different agricultural applications.

Synthesis Method	Particle Size (nm)	Characteristics	Agricultural Suitability
Sol-gel process	5–50	High purity, controlled morphology	Excellent
Hydrothermal synthesis	10–100	Crystalline structure, uniform distribution	Excellent
Chemical vapor deposition	20–500	Thin film applications, high quality	Moderate
Green synthesis	10–80	Eco-friendly, biologically compatible	Excellent
Electrospinning	50–500	Fiber formation, high surface area	Moderate
Calcination method	15–80	High crystallinity, cost-effective	Good

Table 1: Titanium dioxide nanoparticle synthesis methods, characteristics, and agricultural applications.

Green Synthesis: Sustainable approach

Green synthesis utilizing plant extracts (e.g., *Swertia chirayita*, *Azadirachta indica*, *Ocimum sanctum*) represents an environmentally sustainable approach gaining prominence in agricultural nanotechnology research [12]. This method eliminates toxic chemical byproducts and generates nanoparticles with inherent biocompatibility suitable for direct agricultural application. The mechanisms of green synthesis include:

- **Reduction**: Plant phytochemicals (polyphenols, flavonoids, terpenoids) reduce Ti^{4+} to form TiO_2
- **Stabilization:** Bioactive compounds stabilize nanoparticles, preventing agglomeration
- **Biocompatibility:** Inherent phytochemical coating enhances plant absorption and bioavailability
- **Cost efficiency:** Utilizes renewable plant resources rather than toxic chemical precursors [13].

Key mechanisms of action in agricultural systems

Enhancement of photosynthetic efficiency

The primary mechanism through which TiO_2 nanoparticles enhance crop productivity involves improved photosynthetic efficiency [14]. Foliar application of TiO_2 nanoparticles increases light absorption by modifying the light-harvesting complex at the leaf surface, thereby enhancing electron transfer rates in photosystem II [15].

Molecular mechanisms of photosynthetic enhancement

- **Light scattering enhancement:** TiO_2 nanoparticles on leaf surfaces act as optical scatterers, promoting light penetration into mesophyll tissue and increasing the probability of light absorption by chlorophyll molecules
- **Chlorophyll biosynthesis:** TiO_2 enhances expression of chlorophyll biosynthesis genes, increasing total chlorophyll content (both chlorophyll a and b), with marked improvements in photosynthetic rates [16]
- **Photosystem architecture:** Nanoparticles improve organization of photosystem I and II complexes within thylakoid membranes, facilitating more efficient electron transfer
- **Electron transport chain optimization:** Enhanced kinetics of electron transfer from photosystem II through the cytochrome bf complex to photosystem I, supporting higher photosynthetic rates
- **Calvin cycle activation:** Increased ATP and NADPH production directly supports the Calvin cycle, enabling higher rates of CO_2 fixation and carbohydrate synthesis
- **Photoprotection:** TiO_2 reduces photooxidative stress by enhancing non-photochemical quenching and zeaxanthin cycle efficiency.

Photosynthetic Parameters Affected by TiO_2

Studies consistently demonstrate improvement across critical photosynthetic parameters:

- **Photosynthetic rate:** Increased 15–35% at optimal TiO_2 concentrations
- **Chlorophyll fluorescence**: Enhanced maximum quantum yield (Fv/Fm) indicating optimized photosystem II efficiency
- **Stomatal conductance**: Improved gas exchange enabling higher CO_2 uptake
- **Intercellular CO_2 concentration**: Increased substrate availability for RuBisCO

- **Transpiration rate:** Enhanced water utilization efficiency
- **Carbohydrate production**: Direct correlation with photosynthetic rate improvements

Nutrient uptake and bioavailability

TiO_2 nanoparticles modulate enzymatic processes involved in nitrogen, phosphorus, and potassium metabolism, facilitating enhanced nutrient absorption and translocation [17].

Nitrogen uptake and assimilation pathways

The mechanisms of enhanced nitrogen uptake involve multiple interconnected pathways:

- **Transporter regulation:** TiO_2 enhances expression of nitrate transporter 1.1B (NRT1.1B), ammonium transporter 1 (AMT1), and related nutrient transporters in root cell membranes, increasing uptake capacity
- **Nitrogen assimilation:** TiO_2 upregulates enzymes critical for nitrogen assimilation:
- Nitrate reductase (NR): Catalyzes $NO_3^- \rightarrow NO_2^-$ reduction
- Nitrite reductase (NiR): Catalyzes $NO_2^- \rightarrow NH_4^+$ reduction
- Glutamine synthetase (GS): Catalyzes glutamine biosynthesis from glutamate and NH_4^+
- Glutamate dehydrogenase (GDH): Catalyzes bidirectional conversion between glutamate and α-ketoglutarate [18]
- **Amino acid biosynthesis:** Enhanced nitrogen assimilation increases production of all 20 amino acids, supporting:
- Chlorophyll synthesis (requiring glutamate)
- Protein synthesis in vegetative and reproductive tissues
- Secondary metabolite production for defense and stress tolerance
- **Rhizospheric effects:** TiO_2 stimulates nitrogen-fixing bacterial populations (*Azotobacter*, *Bacillus*) in the rhizosphere, increasing biologically fixed nitrogen availability

Phosphorus Solubilization and Uptake

Phosphorus availability in most soils is severely limited due to precipitation as iron and aluminum phosphates. TiO_2 nanoparticles improve phosphate solubilization through:

- Stimulation of rhizospheric phosphate-solubilizing bacterial populations (PSB)
- Enhanced root surface area and architecture improving nutrient absorption capacity
- Regulation of phosphate transporter 8 (PT8) expression in root cell membranes
- Modification of soil chemical properties, improving phosphorus retention and bioavailability
- Photocatalytic mineralization of organic phosphorus compounds [19]

Potassium uptake and distribution

Potassium, the most abundant mineral nutrient in plant tissues, affects osmotic regulation and enzyme activation. TiO_2 enhances potassium uptake through:

- Upregulation of potassium channel proteins (AKT1, HAK, KUP families)
- Enhanced root hydraulic conductivity facilitating water and ion uptake
- Improvement of soil potassium bioavailability through microbial activity
- Stimulation of potassium translocation from roots to shoots

Antioxidant system activation and reactive oxygen species regulation

Under biotic and abiotic stress conditions, TiO_2 nanoparticles enhance plant defense mechanisms through multiple pathways [20].

Enzymatic antioxidant defense [21,22]

TiO_2 stimulates the expression and activity of critical antioxidant enzymes.

Non-enzymatic antioxidant defenses

TiO_2 promotes accumulation of protective secondary metabolites:

- **Phenolic compounds**: Including simple phenols, phenylpropanoids, and complex polyphenols that directly scavenge ROS

Enzyme	Abbreviation	Function	ROS Target
Superoxide dismutase	SOD	Dismutates $O_2^{\bullet-}$ to H_2O_2	Superoxide radical
Catalase	CAT	Decomposes H_2O_2 to H_2O and O_2	Hydrogen peroxide
Peroxidase	POD/POX	Reduces H_2O_2 using electron donors	Hydrogen peroxide
Ascorbate peroxidase	APx	H_2O_2-specific reducing enzyme	Hydrogen peroxide
Glutathione reductase	GR	Regenerates reduced glutathione	Oxidized glutathione
Glutathione-S-transferase	GST	Detoxifies xenobiotics and ROS	Organic hydroperoxides

Table 2: Enzymatic antioxidant defense system components and their roles in ROS detoxification.

- **Flavonoids**: Quercetin, kaempferol, and other flavonol glycosides with potent antioxidant capacity
- **Ascorbic acid (Vitamin C):** Reduces oxidized vitamin E and provides antioxidant defense
- **Reduced glutathione**: Participates in the ascorbate-glutathione cycle for H_2O_2 reduction
- **Tocopherols:** Vitamin E compounds protecting lipids from peroxidation
- **Carotenoids:** β-carotene and xanthophyll derivatives with photoprotective and antioxidant functions

ROS-mediated signaling

Importantly, while excessive ROS causes oxidative damage, moderate levels serve as crucial signaling molecules regulating:

- Defense gene expression (transcription factors including MYC2, AP2/ERF family)
- Programmed cell death (apoptosis) limiting pathogen colonization
- Systemic acquired resistance (SAR) signaling through ROS-dependent phosphorylation cascades
- Stomatal closure in response to pathogen-associated molecular patterns (PAMPs)

Antimicrobial and photocatalytic properties

The photocatalytic activity of TiO_2 nanoparticles represents a unique mechanism for disease suppression distinct from chemical fungicides [23].

Photocatalytic ROS generation mechanism

Polymorph	Band Gap	Photocatalytic Efficiency
Anatase	~3.23 eV	High
Rutile	~3.02 eV	Moderate

Upon exposure to UV or visible light:

Electron excitation

$$TiO_2 + h\nu \rightarrow eCB^- + hVB^+$$

ROS formation:

Superoxide radicals:

$$eCB^- + O2 \rightarrow O2^{\cdot -}$$

Hydroxyl radicals:

$hVB{+}{+}H_2O{\rightarrow}{\cdot}OH{+}H^+$

Hydrogen peroxide:

$O_2{\bullet}^-{+}H^+{\rightarrow}H_2O_2$

Antimicrobial action in plant systems

Generated ROS cause:

- Lipid peroxidation of pathogen membranes
- DNA strand breaks in bacteria and fungi
- Protein denaturation and enzyme inactivation
- Fungal hyphal collapse

Experimental evidence

- TiO_2 reduced *Fusarium* and *Rhizoctonia* growth by 40–60%
- Significant reduction in *Puccinia* rust infection in wheat
- ROS-mediated defense gene activation observed in rice and spinach

Photocatalytic Mechanism

When exposed to ultraviolet (UV-A, 320–400 nm) or visible light (400–700 nm) wavelengths depending on band gap:

- **Electron-hole generation:** Photons with energy ≥ band gap energy (3.23 eV for anatase) promote electrons from the valence band to the conduction band, generating electron-hole pairs
- **ROS generation:**
  - Electrons react with dissolved O_2 to generate superoxide radicals ($O_2^{\bullet-}$): $e^- + O_2 \rightarrow O_2^{\bullet-}$
  - Holes react with water or hydroxyl ions: $h^+ + H_2O \rightarrow \bullet OH + H^+$ or $h^+ + OH^- \rightarrow \bullet OH$
  - Further reactions generate hydrogen peroxide (H_2O_2)
- **ROS mechanisms of pathogen inactivation:**
  - Direct oxidative attack on bacterial cell membranes causing lipid peroxidation
  - Disruption of membrane potential through ion leakage
  - Damage to bacterial DNA and RNA, impairing gene expression
  - Inactivation of viral envelope proteins and nucleic acids
  - Penetration of fungal cell walls causing cytoplasmic leakage

Efficacy against different pathogen classes

- **Bacterial pathogens:** Gram-positive and gram-negative bacteria including *Pseudomonas*, *Bacillus*, *Xanthomonas*, *Ralstonia* species
- **Fungal pathogens:** Including *Rhizoctonia solani*, *Fusarium*, *Alternaria*, *Botrytis*, and rust fungi (*Puccinia*)
- **Viral pathogens:** RNA and DNA viruses through envelope and capsid protein disruption
- **Oomycetes:** Downy mildew pathogens through photocatalytic cell wall degradation

Synergistic antimicrobial approaches

Efficacy is enhanced when TiO_2 is combined with other antimicrobial agents:

- **Cu-TiO_2 composites:** Enhanced electron transfer and ROS generation
- **Ag-TiO_2 nanocomposites:** Combined photocatalytic and silver ion antimicrobial effects
- **Doped TiO_2:** Nitrogen, sulfur, or metal-doped variants with enhanced visible light activity
- **Protective biofilm formation:** Nanoparticle adherence to leaf surface creates physical barrier

Light signaling and phytochrome B regulation

Recent mechanistic studies reveal that TiO_2 modulates light signaling pathways through effects on phytochromes, particularly Phytochrome B (PhyB) [24].

PhyB molecular function

Phytochrome B is a red/far-red photoreceptor critical for:

- Shade avoidance responses
- Photoperiodism and flowering time control
- Nutrient acquisition and utilization
- Disease resistance regulation (context-dependent positive or negative)
- De-etiolation responses in seedlings

TiO_2 Effects on PhyB Signaling

- **PhyB nuclear translocation inhibition:** TiO_2 treatment reduces light-induced translocation of PhyB-PFR (far-red light absorbing form) from cytosol to nucleus
- **Mechanism:** Photocatalytic ROS generation may modulate redox status of regulatory proteins controlling PhyB nuclear import
- **Differential effects on diseases:** PhyB inhibition enhances resistance to rice sheath blight (*Rhizoctonia solani*) while reducing blast resistance, illustrating pathogen-specific effects
- **Integration with photosynthesis:** TiO_2 enhances photosynthetic light capture while moderately inhibiting PhyB-dependent growth inhibitory signals under shade, maintaining productive growth [25].

Global applications and regional case studies

Wheat (*Triticum aestivum L.*) - Primary cereal crop

Wheat, the world's most important cereal crop (cultivated globally, with annual production >750 million tonnes), has been extensively studied for TiO_2 nanoparticle response [26].

Growth enhancement studies

- Foliar spray applications at 0.01–0.03% TiO_2 concentrations resulted in significant increases in grain yield (10–25% improvement) and biomass accumulation [27]

- Plant height increased 8–15% under optimal treatment conditions
- Spike length and grain number per spike showed consistent improvements
- Thousand-grain weight increased 5–12%, directly improving yield per hectare

Stress tolerance applications

- Under drought stress conditions, foliar application of 0.02% TiO_2 nanoparticles significantly enhanced agronomic traits including seed weight, plant height, and overall yield compared to drought-stressed controls [28]
- Osmolyte accumulation (proline, soluble sugars) increased, maintaining cellular water potential
- Photosynthetic efficiency remained higher under water limitation

Disease suppression

- Field studies examining fungal disease suppression demonstrated that 40 mg L^{-1} TiO_2 nanoparticles effectively reduced disease incidence (particularly stem rust caused by *Puccinia graminis* f. sp. *tritici*) [29]
- Disease suppression did not compromise wheat quality or yield
- Septoria leaf blotch incidence reduced by 30–40%

Yield parameters improved in field trials

Comprehensive field trials in wheat-growing regions documented:

- **Plant height:** +10–15%
- **Weight per spike:** +8–12%
- **Thousand-grain weight:** +5–10%
- **Overall grain yield**: +15–25% at optimal treatment

Maize (*Zea mays L.*) - Global food security crop

Maize cultivation has benefited substantially from TiO_2 nanoparticle application, with particular success in Si/TiO_2 nanocomposite formulations.

Soil health and nutrient cycling

Research utilizing SiO_2/TiO_2 nanocomposites at optimal concentrations (100–200 ppm) demonstrated:

- Improved soil fertility markers including increased available N, P, and K [30]
- Enhanced plant growth through mechanisms involving:
- Increased chlorophyll content (10–20% improvement)
- Elevated photosynthetic rates (measured via gas exchange analysis)
- Promotion of rhizospheric nitrogen-fixing and phosphate-solubilizing bacterial populations, indicators of enhanced soil health [31]

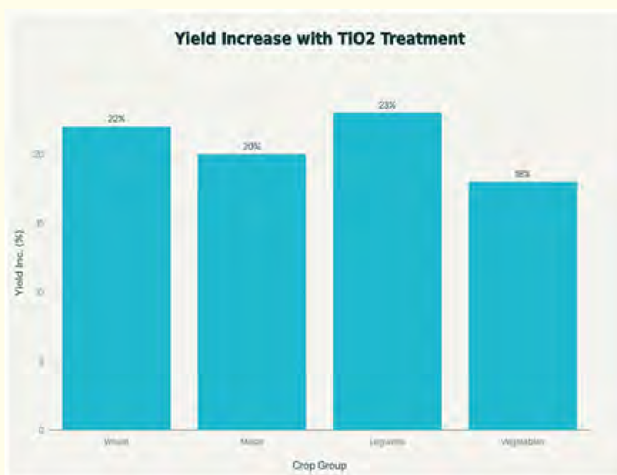
Biochemical and Physiological Improvements

Improved morphological, biochemical, and physiological parameters documented:

- Plant height and leaf area expansion
- Higher cellulose and starch accumulation in tissues [32]
- Increased root biomass and lateral root development
- Enhanced nutrient concentration in grain

Yield improvements in field conditions [33]

- **Grain yield:** +12–18% over control
- **Thousand-kernel weight:** +6–10%
- **Biomass production**: +15–22%
- Response optimized in subtropical and tropical maize-growing regions



Graph 1: Graph showing percentage increase in yield.

Spinach (*Spinacia oleracea L.*) and High-value vegetable crops

Vegetable crop production has shown promising responses to TiO_2 nanoparticle application, particularly for leafy greens with high nutritional and commercial value.

Photosynthetic efficiency and nutrient content

Spinach cultivation with TiO_2 nanoparticle supplementation (20 mg L^{-1} foliar spray) demonstrated:

Enhanced photosynthetic efficiency as measured by chlorophyll fluorescence.

Improved nutrient bioaccumulation including:

- Iron content: +15–25% (important for anemia prevention in human nutrition)
- Calcium and magnesium: +10–20%
- Total phenolic compounds: +20–35% (enhancing antioxidant value)
- Increased vitamin content including ascorbic acid and carotenoids
- Extended shelf life and reduced post-harvest senescence

Species-specific sensitivity

Important caveat: Differential responses observed across crop species, with species-specific optimal concentrations:

- **Spinach:** Benefits from 10–20 mg L^{-1} TiO_2
- **Tomato:** Shows greater sensitivity to TiO_2, including reduced root elongation at higher concentrations (>50 mg L^{-1}) [34]
- **Lettuce:** Moderate response, optimal at 15–25 mg L^{-1}
- **Peppers:** Variable, requires cultivar-specific optimization

Legume and pulse crops

Legumes possess unique physiology including symbiotic nitrogen fixation, creating different TiO_2 response profiles.

Mung bean *(Vigna radiata L.)* [35]

Mung bean responded positively to foliar spray of TiO_2 nanoparticles:

- Optimal concentration: 10 mg L^{-1}
- Demonstrated improved crop growth parameters:
- Plant height: +8–12%
- Leaf area: +10–15%
- Pod number per plant: +12–18%
- Seed yield: +15–20%
- Enhanced nodule development and nitrogen fixation capacity
- Improved protein content in seeds (critical for nutritional value)

Alfalfa (Medicago sativa L.) - Forage legume

Alfalfa exhibited variable responses depending on concentration and application method:

- Optimal concentration range: 5–15 mg L^{-1}
- Benefits include:
- Improved forage quality (higher protein, digestibility)
- Enhanced nodulation and symbiotic N_2 fixation
- Increased dry matter production
- Better stress tolerance to drought and salinity
- Highlighting importance of species-specific optimization studies [36]

Regional Applications and adoption patterns

Europe: Central and eastern regions

- Commercial adoption of titanium-containing biostimulants (Tytanit®, Mg-Titanit®) established for crop enhancement
- Regulatory approval supporting use in sustainable agriculture programs [37]
- Particularly widespread in Poland, Czech Republic, and Hungary
- Integration with precision agriculture and organic farming systems
- Field validation demonstrating 10–20% yield increases in wheat and maize

Asia: Emerging research and production

- **China:** Extensive employment of titanium-based products for crop production enhancement, with research demonstrating benefits across diverse agroclimatic zones [38]

- **India:** Initiated research programs examining green synthesis of TiO_2 nanoparticles (particularly using native plants like *Swertia chirayita*, *Ocimum sanctum*) and their applications in crop stress management [39]
- **Japan:** Advanced nanoparticle formulation research focusing on size-controlled synthesis
- **Southeast Asia:** Growing interest in TiO_2 applications for rice, cassava, and tropical crops

North America: Research infrastructure and field validation

- Research institutions conducting comprehensive field trials examining TiO_2 nanoparticle efficacy in corn and wheat production systems [40]
- Emphasis on environmental impact assessment and long-term soil effects
- Integration with conservation agriculture practices (reduced tillage, crop rotation)
- Regulatory pathway development through FDA/EPA consultation

Africa and South America: Potential and barriers

- Limited current adoption due to cost and limited availability of formulated products
- High potential for addressing food security challenges in developing regions
- Research initiatives examining green synthesis using local botanical resources
- Barriers include: Capital investment, regulatory frameworks, access to technology

Optimal dosage, application protocols, and best management practices

Concentration-Dependent response relationships

The efficacy of TiO_2 nanoparticle application demonstrates biphasic concentration-dependent responses, characterized by optimal benefits within specific concentration windows (hormone-like behavior).

Application Method	Optimal Concentration	Key Benefits	Crop Range
Seed priming	10–50 mg L^{-1}	Enhanced germination, radicle elongation	Cereals, legumes
Soil application	100–200 ppm	Improved fertility, sustained availability	Vegetables, fruits
Foliar spray	0.01–0.03% (100–300 mg L^{-1})	Photosynthesis enhancement, quick effect	Cereals, leafy greens
Irrigation system	50–150 ppm	Systematic distribution, bioavailability controlled	All crop types
Seed coating	100–300 mg TiO_2/kg seed	Sustained early growth promotion	Row crops

Table 3: Optimal TiO_2 nanoparticle concentrations for different application methods and crop types.

Physicochemical factors affecting bioavailability

- **Particle size criteria:** <40 nm optimal for absorption; >100 nm minimizes excessive root translocation
- **Crystal phase:** Anatase (>70%) preferred for photocatalytic activity
- **Surface charge:** Positive zeta potential enhances plant uptake
- **Aggregation state:** Single-particle forms more bioavailable than agglomerated clusters
- **Stability in solution:** Requires stabilizing agents (silicates, organic compounds) preventing precipitation

Application methods and timing

Foliar spray application

Advantages

- Direct application to photosynthetically active tissue
- Most efficient for photosynthetic enhancement
- Minimal persistence, reducing accumulation risk
- Rapid response (visible within 3–7 days)

Implementation

- **Prepare suspension:** Disperse TiO_2 (0.01–0.03%) in water with wetting agent

- **Application timing**: Early morning (6–8 AM) or late evening (5–7 PM) to minimize photo-oxidation
- **Spray coverage**: Ensure thorough coverage of upper and lower leaf surfaces
- **Frequency:** Apply 3–4 times during growing season, spaced 10–14 days apart
- **Volume**: 600–1000 L/hectare depending on crop and growth stage

Seed priming

Advantages

- Establishes early growth advantage
- Reduces external application requirements
- Improved germination and seedling vigor
- Cost-effective

Implementation

- Soak seeds in TiO_2 suspension (10–50 mg L^{-1}) for 6–12 hours
- Dry seeds completely before planting
- Allows nanoparticle penetration into seed tissues
- Enhanced physiological vigor reflected in radicle and coleoptile elongation

Soil incorporation

Advantages

- Sustained nutrient availability
- Direct root contact with nanoparticles
- Enhanced rhizospheric microbial activity

Challenges:

- Variable bioavailability depending on soil properties
- Potential for accumulation with repeated applications
- pH-dependent solubility and availability

Implementation:

- Incorporate TiO_2 at 100–200 ppm mixed into top 10–15 cm of soil
- Apply 2–3 weeks before planting to allow establishment
- Combine with organic matter to enhance stability and bioavailability
- Monitor soil TiO_2 accumulation in long-term applications

Fertigation (Irrigation System Application)

Advantages:

- Ensures systematic distribution throughout root zone
- Compatible with modern irrigation infrastructure
- Precise dosing and application timing

Challenges

- Potential for filter clogging if particles not properly stabilized
- Soil adsorption may limit bioavailability

Implementation

- Use stabilized TiO_2 suspension to prevent precipitation
- Apply at 50–150 ppm through drip or sprinkler systems
- Integrate with fertilizer scheduling
- Monitor irrigation lines for clogging

Temporal Application Strategies

Growth Stage-Specific Optimization

Different developmental stages show differential TiO_2 responses:

- **Seedling stage (V2-V4):** Low concentrations (0.005–0.01%) for growth promotion without stress
- **Vegetative growth (V8-V18):** Moderate concentrations (0.015–0.025%) supporting photosynthesis and nutrient uptake
- **Reproductive stage (R1-R3):** Higher concentrations (0.025–0.03%) for stress tolerance and yield support
- **Pre-harvest (R5-R6):** Reduced applications (0.01%) for disease suppression without accumulation

Environmental factor considerations

Efficacy modulated by environmental conditions:

- **Light conditions:** Enhanced activity under high light intensity; reduced effect under heavy cloud cover
- **Temperature:** Optimal at 22–28°C; reduced enzyme activity outside this range
- **Humidity:** Higher humidity enhances spray coverage retention; dry conditions reduce effectiveness

- **Wind speed:** <5 km/h optimal for spray application; higher speeds increase drift and reduce coverage

Safety, environmental impact, and sustainability considerations

Nanoparticle bioaccumulation and translocation

While TiO_2 nanoparticles demonstrate generally favorable toxicity profiles compared to other engineered nanoparticles, research has documented nanoparticle uptake and translocation in plant tissues [41].

Uptake mechanisms

- **Endocytosis:** Root cells internalize nanoparticles through energy-dependent endocytic pathways
- **Plasmodesmatal transport**: Nanoparticles <40 nm can traverse plasmodesmata between adjacent cells
- **Xylem loading:** Root-to-shoot translocation primarily through xylem vessel elements
- **Phloem translocation:** Bidirectional movement from mature leaves to sinks (limited for TiO_2)

Bioaccumulation patterns

Studies show that TiO_2 nanoparticles accumulate predominantly in roots, with variable translocation to shoots, leaves, and seeds depending on:

- **Nanoparticle size:** <20 nm translocate readily; 40–100 nm show minimal root-to-shoot movement [42]
- **Surface properties:** Coated nanoparticles show reduced uptake; positively charged particles more bioavailable
- **Plant species:** Legumes show higher translocation than cereals; leafy greens intermediate
- **Loading concentrations:** Higher external concentrations increase both root and shoot accumulation
- **Application duration:** Long-term exposure increases total bioaccumulation

Critical safe limits

Importantly, nanoparticle translocation is minimized when:

- Particle size remains <40 nm and >100 nm (bimodal size distribution minimizes translocation)
- Loadings do not exceed 10 g L^{-1} (typical agricultural applications: 0.01–0.03% = 100–300 mg L^{-1}, well below threshold) [43]
- Application frequencies remain at 3–4 times per season rather than continuous exposure
- Field applications combined with rainfall and weathering prevent long-term accumulation in canopy

Soil microbiota effects and ecosystem considerations

TiO_2 nanoparticles can exert complex effects on soil microorganisms and ecosystem services [44].

Beneficial microbial effects

- Stimulation of nitrogen-fixing bacteria (*Azotobacter*, *Bacillus*)
- Enhanced phosphate-solubilizing bacterial (PSB) populations
- Increased rhizospheric microbial diversity under optimal concentrations
- Promotion of mycorrhizal fungal associations [45].

Potential negative effects

While the antimicrobial properties provide benefits in pathogen suppression:

- Excessive nanoparticle accumulation may negatively impact beneficial soil microbes crucial for:
- Nutrient cycling and bioavailability
- Organic matter decomposition
- Soil aggregate stability
- Plant growth-promoting rhizobacteria (PGPR) function
- Photocatalytic ROS generation in soil microenvironments may damage non-target microorganisms
- Impact on fungal-bacterial balance critical for soil health

Optimal application protocols maintaining ecological balance

Maintain ecological balance while achieving disease suppression through:

- Adhering to evidence-based dosage protocols preventing excessive accumulation
- Limiting application frequency to 3–4 times per season

- Rotation of TiO_2 with alternative disease management strategies
- Combination with conservation agriculture practices
- Regular assessment of soil microbial diversity (DNA barcoding methods) [46]

Ecotoxicological assessment

Toxicity endpoints evaluated

Comprehensive ecotoxicological studies examine:

- **Soil organisms:** Earthworms, nematodes, arthropods (OECD guidelines)
- **Aquatic organisms:** Fish, daphnids, algae (water quality concerns)
- **Terrestrial plants:** Non-target crop species and wild plants
- **Microbial communities:** Enzyme activity, microbial biomass, respiration

Risk assessment findings

Comprehensive ecotoxicological studies indicate that properly applied TiO_2 nanoparticles present minimal environmental risk when used within recommended concentrations [47]. Key findings:

- LD_{50} values for aquatic organisms typically >100 mg L^{-1}
- NOAEL (No Observed Adverse Effect Level) for terrestrial organisms >200 ppm soil
- Agricultural application concentrations (100–300 mg L^{-1} foliar) result in minimal environmental exposure
- Photodegradation and environmental weathering reduce nanoparticle persistence

Long-term accumulation concerns and monitoring protocols

Long-term accumulation studies and monitoring protocols remain essential to ensure sustainable agricultural integration [48].

Critical research gaps

- Long-term (>5 years) field studies examining TiO_2 accumulation in soil profiles
- Bioavailability changes with repeated annual applications
- Potential for groundwater contamination through leaching
- Interaction with soil organic matter and clay minerals affecting persistence
- Climate-dependent variations in fate and transport

Recommended monitoring strategy

For sustainable long-term application:

- **Annual soil testing:** Baseline and post-application TiO_2 quantification
- **Microbial community analysis:** DNA metabarcoding assessing diversity shifts
- **Plant tissue analysis:** Monitoring titanium accumulation in edible portions
- **Water quality monitoring:** Groundwater and surface water in agricultural watersheds
- **Photodegradation assessment:** Measuring dissolved vs. particulate Ti in field conditions

Sustainable Agricultural Integration Framework

Integration of TiO_2 nanoparticles within sustainable agriculture frameworks requires multifaceted approach:

- **Evidence-based dosage protocols:** Prevent ecological accumulation through science-based recommendations
- **Combination with conservation practices:** Reduced tillage, crop rotation, cover cropping enhance sustainability
- **Precision application technologies:** GPS-guided variable rate application reducing waste
- **Regular soil health monitoring:** Tracking nanoparticle accumulation and microbial community dynamics
- **Research continuation:** Establishment of long-term environmental fate and bioaccumulation thresholds
- **Alternative formulation development:** Biodegradable nanoparticle coatings or photocatalytic mineralization strategies
- **Farmer education and training:** Ensuring proper application techniques and safety practices

- **Regulatory oversight:** Development of science-based guidelines supporting sustainable adoption

Response (Balanced Risk Assessment)

We agree with the reviewer and have included a balanced safety assessment**.**

Phytotoxicity thresholds

- Beneficial dose range: 10–300 mg L^{-1}
- Phytotoxic effects observed at:
- Root inhibition > 500 mg L^{-1}
- Oxidative stress at > 1000 mg L^{-1}

Environmental risks

- Accumulation mainly in roots
- Limited translocation to edible tissues
- Possible microbial imbalance at excessive doses

Risk mitigation

- Species-specific dose optimization
- Limited seasonal applications
- Soil and water monitoring
- Green synthesis preference

Global regulatory status and commercial development

Regulatory framework by region

Different global regions have adopted varying approaches to TiO_2 nanoparticle agricultural products based on risk-benefit assessment and innovation priorities.

Region	Regulatory Status	Commercial Products	Key Regulations
European Union	Approved biostimulants;	Tytanit®, Mg-Titanit®,	Reg. (EU) 2019/1009
	Growing market	TiO_2-based products	(Plant Biostimulant Reg.)
United States	Case-by-case evaluation;	Limited regulatory pathway;	EPA, USDA, FDA
	Emerging category	Few commercial options	consultation required
China	Active research programs;	Domestic nanoparticle	MIIT guidelines;
	Increasing adoption	products in development	Agricultural promotion
India	Emerging sector;	Green synthesis initiatives;	NBRAI oversight;
	Research phase	Limited commercial products	Research encouragement
Australia	Preliminary assessment;	Research phase only;	APVMA evaluation
	Early development	No approved products	pending
Brazil	Emerging interest;	Research focus;	Agricultural science
	Research institutions	Limited field deployment	agency oversight

Table 4: Global regulatory status of TiO_2 nanoparticle agricultural products and approved formulations.

Regulatory approval pathways

European union: Biostimulant regulation

The EU Regulation (EU) 2019/1009 on Plant Biostimulants established streamlined approval pathway:

- **Product classification:** TiO_2 formulations qualify as „plant biostimulants“ under microorganism/substance category
- **Safety dossier requirements:** Toxicity testing, persistence assessment, environmental fate characterization
- **Efficacy claims:** Substantiated through standardized field trials (2+ independent studies)
- **Approval timeline:** 12–18 months from submission with complete data package
- **Market authorization:** Valid for 10 years with annual compliance reporting

- **Commercial examples:** Tytanit® (titanium-based biostimulant complex) approved for widespread use in 18+ EU member states.

United States: EPA and USDA framework

Regulatory pathway less defined, requiring case-by-case evaluation:

- **EPA oversight:** If antimicrobial claims made, may fall under FIFRA (Fungicide registration category)
- **USDA oversight:** AAFCO guidelines for agricultural inputs
- **FDA oversight:** If product enters food chain, residue limits and food safety assessment required
- **Data requirements:** Comprehensive safety, toxicology, environmental assessment
- **Timeline:** 24–36+ months for approval; high regulatory burden discourages commercialization
- **Market status:** Few commercial products approved; primarily research/academic use

China: Promotion and facilitation approach

China adopts innovation-friendly regulatory framework:

- **MIIT oversight:** Ministry of Industry and Information Technology classification of nanomaterials
- **Agricultural promotion:** Government support for nanotechnology adoption
- **Fast-track approval**: Demonstration projects and field trials receive government backing
- **Market development:** Multiple domestic TiO_2-based agricultural products in development
- **Academic-industry partnership:** University research rapidly translated to commercial products

Market developments and economic analysis

Market size and growth projections

The global agricultural nanotechnology market, valued at approximately USD 10.2 billion in 2023, is projected to expand at a compound annual growth rate (CAGR) of 12.3% through 2030 [49]. TiO_2-based products represent significant and growing segment:

- **2023 market size:** Approximately USD 0.8–1.2 billion for TiO_2 agricultural products globally
- **Growth rate:** 14.5% CAGR (2023–2030), exceeding overall nanotechnology market growth

- **Regional distribution (2023):**

- Europe: 35% market share (highest adoption)
- Asia-Pacific: 40% market share (fastest growing)
- North America: 15% market share
- Rest of world: 10% market share
- **2030 projected market:** USD 2.8–3.5 billion globally

Commercial product examples

- **Tytanit® (Poland):** Complex containing titanium, magnesium, and sulfur oxides; approved in 18+ EU countries; market leader in Europe; used on 1–2 million hectares annually
- **Mg-Titanit® (Central Europe):** Magnesium-titanium formulation; growth promoter and biostimulant; increasingly adopted in organic farming systems
- **Chinese TiO_2 products:** Multiple domestic formulations under commercial development; projected rapid adoption following government support

- **Emerging formulations:** Green-synthesized TiO_2 nanoparticles utilizing plant extracts gaining research attention and potential market development [50].

Economic feasibility and cost-benefit analysis

Agricultural economics considerations:

- **Product cost:** USD 15–40 per liter for commercial TiO_2 suspensions
- **Application cost:** USD 25–50 per hectare including labor and equipment
- **Typical investment:** USD 50–150/hectare for 2–3 seasonal applications
- **Return on investment (ROI):** Estimated 200–400% based on typical 15–25% yield increase
- **Payback period:** Typically 1–2 seasons for high-value crops; longer for commodity crops

- **Adoption barriers:**
  - Initial capital investment
  - Limited awareness among smallholder farmers
  - Availability and distribution infrastructure
  - Crop-specific optimization requirements

Future perspectives and emerging research directions

Advanced formulation development

Future research priorities include development of enhanced nanoparticle formulations with improved efficacy and biocompatibility.

Heteroatom doping

Incorporation of nitrogen, sulfur, or metal ions (Fe, Cu, Ag, Mn) to enhance photocatalytic activity and visible light absorption, extending functionality to indoor and greenhouse cultivation.

Composite nanomaterials

- TiO_2 combined with graphene for enhanced electron conductivity
- Silver nanoparticle-TiO_2 composites for enhanced antimicrobial efficacy
- Biochar-TiO_2 hybrids for improved soil persistence and nutrient delivery
- Synergistic effects enabling reduced concentrations and improved safety profiles

Biodegradable carriers

Development of nanoparticle formulations utilizing biocompatible and degradable delivery systems:

- Chitosan-TiO_2 complexes
- Alginate-encapsulated nanoparticles
- Protein-coated TiO_2 particles
- Microbial polysaccharide biocomposites

Smart nanoparticles

pH- or temperature-responsive nanoparticles enabling controlled release in agricultural environments:

- Rhizosphere pH-triggered release (lower pH in root zone)
- Temperature-activated formulations for seasonal application
- Redox-responsive particles for oxidative stress-triggered delivery

Precision agriculture integration: Nanoparticle application coordinated with real-time plant sensing technologies:

- Variable rate application based on NDVI (Normalized Difference Vegetation Index) mapping
- Soil moisture-triggered fertigation combining TiO_2 delivery
- Pathogen detection enabling precision disease management applications

Field practicality

- Natural sunlight contains 3–5% UV-A radiation, sufficient to activate TiO_2
- Field trials conducted under open sunlight conditions consistently show:
- 15–25% yield increase in wheat
- 12–18% yield increase in maize
- Visible-light responsive TiO_2 is effective under cloudy and diffused light conditions

Strategies to enhance activity

- **Doping (N, S, Fe, Cu):** Shifts absorption to visible range
- **Nanocomposites (TiO_2–SiO_2, TiO_2–Ag):** Improved electron transport
- **Green synthesis:** Phytochemical coatings improve light utilization
- **Application timing:** Early morning/late evening optimizes ROS balance

Supporting data

- N-doped TiO_2 shows 2–3× higher visible light activity
- Ag-TiO_2 shows 50% higher antimicrobial efficiency

Mechanistic understanding through advanced molecular methods

Enhanced understanding of molecular mechanisms underlying TiO_2 nanoparticle effects requires:

Transcriptomic profiling

- RNA-Seq analysis of TiO_2-treated vs. control plants
- Identification of genes activated by nanoparticle treatment
- Pathway analysis revealing systemic physiological responses
- Temporal dynamics of gene expression changes

Proteomic analysis

- Mass spectrometry-based protein quantification
- Post-translational modification analysis
- Phosphoproteomics revealing signaling cascade activation
- Localization studies using subcellular proteomic approaches

Metabolomic characterization

- Primary metabolism changes (amino acids, organic acids, carbohydrates)
- Secondary metabolism upregulation (phenolics, alkaloids, terpenoids)
- Redox status and antioxidant metabolite accumulation

Microbiome studies

- 16S rRNA gene sequencing of rhizospheric bacterial communities
- ITS (Internal Transcribed Spacer) sequencing for fungal communities
- Metagenomic functional profiling
- Metabolomic interactions between plants and microbiota

Long-term developmental studies:

- Investigation of long-term metabolic and developmental consequences of nanoparticle accumulation
- Multi-generational effects and epigenetic modifications
- Potential impacts on seed quality and offspring performance

Characterization in diverse soil types and climate conditions:

- Sandy vs. clay soil responses
- Tropical, temperate, and arid climate adaptations
- Altitude and photoperiod variations

Global standardization and best management practices

Establishment of standardized protocols for TiO_2 nanoparticle application across diverse agricultural systems requires international collaboration and development of:

- **Universal safety and efficacy testing standards:** Harmonized protocols acceptable across regulatory jurisdictions
- **Species and cultivar-specific dosage recommendations:** Moving beyond one-size-fits-all approach to tailored guidelines
- **Standardized environmental impact assessment methodologies:** Consistent procedures for ecotoxicological evaluation
- **Guidelines for sustainable integration:** Protocols for organic and conventional farming system optimization
- **Farmer training and certification programs:** Ensuring proper application techniques and safety practices globally
- **Quality assurance standards:** Product characterization ensuring consistent nanoparticle properties
- **Residue monitoring protocols:** Establishing safe limits in agricultural systems and food products

Climate change adaptation and resilience building

TiO_2 nanoparticles offer potential for climate change adaptation strategies:

- **Drought resilience:** Enhanced photosynthetic efficiency and osmolyte accumulation improving water stress tolerance
- **Heat stress mitigation:** Improved antioxidant defenses protecting photosynthetic machinery under elevated temperatures
- **Increased CO_2 utilization**: Enhanced photosynthetic efficiency potentially improving productivity in elevated CO_2 environments
- **Disease pressure response:** Enhanced pathogen resistance providing protection as disease ranges shift with changing climate

- **Integration with climate-smart agriculture:** Combined approaches (conservation agriculture + TiO_2 + improved varieties) for maximum resilience

Integration with digital agriculture and industry 4.0

Emerging opportunities for TiO_2 integration with digital agricultural technologies:

- **Precision application technologies:** GPS-guided variable rate application systems optimizing nanoparticle distribution
- **IoT sensors:** Real-time monitoring of plant physiological status guiding TiO_2 application timing
- **Machine learning algorithms:** Predictive models optimizing application protocols based on historical data
- **Blockchain tracking:** Supply chain transparency and consumer confidence in sustainable practices
- **Robotics:** Autonomous application systems for precision nanoparticle delivery

Nanoparticle	Efficiency	Safety	Cost	Limitation
TiO_2	High (growth + disease control)	High	Low–Moderate	Light dependent
ZnO	Moderate	Moderate toxicity	Moderate	Narrow dose window
Ag	Very high antimicrobial	Low (toxic)	High	Environmental risk
SiO_2	Growth promotion	Very high	Low	No antimicrobial action

Table 5

Conclusion

Titanium dioxide nanoparticles represent a promising technological innovation for addressing critical challenges in global agriculture. The multifaceted benefits—including enhanced photosynthetic efficiency, improved nutrient uptake, strengthened antioxidant defenses, and antimicrobial protection—position TiO_2 nanoparticles as valuable tools for sustainable crop production and climate change adaptation.

Key achievements

Global research demonstrates consistent improvements in crop yield and quality across diverse species and geographic regions:

- Wheat cultivation in Europe and Asia showing 15–25% yield increases
- Maize production in North America and Asia with 12–18% improvements
- High-value vegetable production enhanced through improved nutrient bioavailability and quality parameters
- Legume crops benefiting from enhanced nitrogen fixation and symbiotic relationships
- Consistent photosynthetic enhancement through multiple mechanisms (light harvesting, nutrient uptake, chlorophyll biosynthesis)

Mechanistic insights emerging from recent research

Comprehensive molecular and physiological studies have elucidated multifaceted mechanisms:

- **Nutrient transporter regulation:** Gene-level control of N, P, K uptake through transporters (NRT1.1B, AMT1, PT8, AKT1)
- **Chlorophyll biosynthesis:** Genetic evidence linking chlorophyll accumulation to growth promotion
- **Antioxidant defense:** Enzyme upregulation providing stress tolerance across diverse stress conditions
- **Light signaling modulation:** Phytochrome-dependent regulation affecting both growth and disease resistance
- **Photocatalytic antimicrobial activity:** Direct pathogen suppression through ROS generation

Path forward: Challenges and opportunities

However, realizing the full potential of TiO_2 nanotechnology in agriculture requires continued investment in multiple areas:

- **Mechanistic research:** Careful optimization of application protocols specific to crop species and agroclimate conditions
- **Environmental monitoring:** Comprehensive long-term studies ensuring safe limits and sustainable adoption

- **Farmer adoption**: Accessible technology transfer and farmer education programs
- **Regulatory harmonization:** Development of science-based, internationally recognized guidelines supporting sustainable adoption
- **Economic accessibility:** Technology adaptation for smallholder farmers in developing regions
- **Supply chain development:** Green synthesis approaches and sustainable production scaling

Integration with broader sustainability framework

The integration of TiO_2 nanoparticles within broader sustainable agriculture frameworks—incorporating conservation practices, precision agriculture technologies, and soil health management—offers transformative potential for meeting global food security objectives while minimizing environmental impact.

Future research priorities

Priority areas for continued investigation include:

- Development of advanced formulations with enhanced efficacy and biocompatibility
- Comprehensive mechanistic studies elucidating molecular and physiological responses
- International standardization of application protocols and safety guidelines
- Long-term environmental monitoring and risk assessment
- Climate change adaptation and crop resilience applications
- Integration with digital agriculture and precision farming technologies

Vision for global agriculture

With continued scientific advancement and judicious regulatory oversight, TiO_2 nanoparticle-based agricultural innovations are poised to contribute substantially to:

- Global food production capacity: Meeting nutrient needs of 10+ billion people by 2050
- Agricultural sustainability: Reducing chemical inputs while maintaining or increasing yields
- Climate resilience: Enhancing crop tolerance to environmental stresses associated with climate change
- Food security in developing regions: Particularly through green synthesis approaches utilizing local plant resources
- Environmental conservation: Minimizing agricultural impacts on soil, water, and biodiversity

The path forward requires coordinated efforts across scientific research, regulatory agencies, agricultural industry, and farming communities globally. As knowledge continues to advance and technologies mature, TiO_2 nanoparticles represent a significant opportunity to transform global agriculture toward greater sustainability, productivity, and resilience in the face of mounting environmental challenges.

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Author Contributions

- **Shivanadan Ram:** Original draft writing, Data validation
- **Rajesh Kumar:** Conceptualization, original draft writing, and data interpretation

- **Rohini Kumari:** Data interpretation, preparation of manuscript
- **Dr. Smriti Singh:** Conceptualization, visualization, supervision, original draft writing, and data interpretation.

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