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Impact of Titanium Dioxide Nanoparticles on Agricultural Crops Performance: A Review of Efficacy and Mechanisms

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ABSTRACT

The rapidly increasing global population has escalated the demand for food production, intensifying the pressure on agricultural systems to meet this rising need. Traditional farming methods often fall short of addressing this challenge due to limitations in crop yield and resistance to environmental stress. In response, nanotechnology has emerged as a promising solution, particularly through the application of titanium dioxide nanoparticles (TiO_2 NPs). TiO_2 NPs, due to their unique physicochemical properties, have gained attention for their potential to enhance agricultural productivity. Their mechanism primarily involves the modulation of light absorption, improving photosynthesis, and offering antimicrobial properties that protect crops from pathogens. Additionally, these nanoparticles can promote nutrient uptake and enhance plant growth, ultimately leading to higher crop yields. The utilization of TiO_2 NPs in agriculture offers a sustainable and efficient approach to boosting food production, making it a valuable tool in addressing global food security concerns. However, further research is essential to assess their long-term safety and scalability for widespread agricultural applications.

INTRODUCTION

Richard Feynman first put forward the idea of nanotechnology in 1959, and it has since developed into a major area of research and invention with potential uses in environment, healthcare, and agriculture. Considering their distinct physical and chemical characteristics, which make them valuable in a variety of industries and research sectors, Nanoparticles (NPs), particularly titanium dioxide nanoparticles (TiO_2 NPs), have drawn attention [1, 2]. TiO_2 NPs have been highlighted among metal oxides due to their advantages in environmental remediation, photocatalysis [3]. More recently, TiO_2 NPs have gained attention in agriculture, especially for enhancing plant growth and crop yield in stressful environments like soil with high salinity. Millions of hectares of agricultural land experience drop in the production as a result of soil salinity's negative effects on plant growth, which include oxidative damage and ionic balance disruption [4]. There are few traditional ways to counteract salinity, such as the application of chemical agents and development of genetically resistant crops. TiO2 NPs present a possible substitute since they promote the plant growth and enhance the nutrient absorption [5]. The capacity of TiO_2 NPs to control Reactive Oxygen Species (ROS), which are molecules that have two roles in stress reactions, is one of their main advantages. TiO_2 NPs shield plants from oxidative damage by regulating ROS levels [5]. Under stressful situations, TiO_2 NPs improve the plant's ability to uptake nutrients [6]. Additionally, TiO_2 NPs improve photosynthetic efficiency, which increases the amount of energy and biomass produced by stressed plants [7]. However, greater doses of TiO_2 NPs can be

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detrimental, resulting in cytotoxicity and genotoxicity, however, low amounts are advantageous. A careful consideration and administration of dosage is required to maximize the advantages and minimize the hazardous effects [8]. This study highlighted significance of safe integration of TiO2 NPs into large-scale farming while examining the effectiveness, processes, and possible uses of these particles in agriculture, specifically for treating soil salinity.

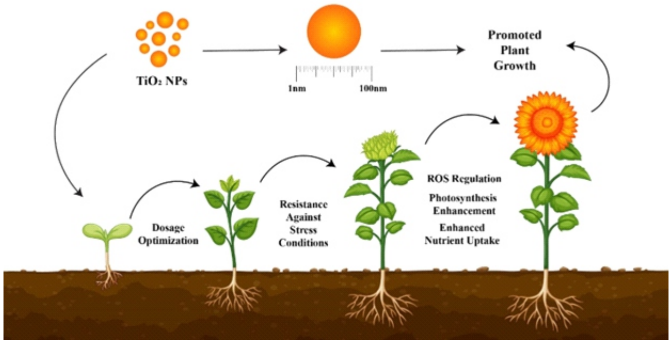

Figure 1: Mechanisms and Benefits of TiO₂ Nanoparticles in Agricultural Crops[9]

Titanium dioxide nanoparticles have been reported enhance photosynthesis. In a study on spinach *(Spinacia oleracea).* Acting as photocatalysts, TiO_2 NPs improve light penetration and energy transfer to photosynthetic pigments, enhancing biomass, moisture content, and root and shoot lengths. The chlorophyll-a and chlorophyll-b levels were found to be increased by 14% and 33%, respectively, in TiO_2 NP-treated plants compared to controls [9]. TiO_2 NPs also enhance metabolic pathways and overall plant health, without causing oxidative stress at low concentrations [10]. These findings highlight the potential of TiO_2 NPs, under optimal dosages, to enhance photosynthesis and plant productivity. TiO_2 NPs improve nutrient absorption in plants. When applied at optimal levels (up to 400 mg/kg), they enhance the uptake of Potassium (K), Iron (Fe), Manganese (Mn), and Phosphorus (P) by increasing root exudation and nutrient bioavailability. However, higher doses (above 600 mg/kg) can lead to toxicity and reduced nutrient absorption. TiO_2 NPs also catalyze antioxidant enzyme activity, lowering oxidative stress and enhancing nutrient metabolism. Wheat plants, in particular, exhibit improved growth parameters and nutrient concentrations when treated with optimal TiO_2 NP dos ages [11]. In a study, P uptake in wheat plants increased significantly when treated with TiO_2 NPs in soil over 60 days. Specifically, a 1.0-fold increase in P uptake was observed with a treatment concentration of 60 mg/kg TiO_2 NPs compared to the control. All tested TiO_2 NP concentrations demonstrated higher P uptake than the control, indicating their effectiveness in enhancing nutrient absorption [12]. Stress Tolerance: TiO_2 NPs enhance plant's resistance against abiotic stress, such as salinity, by enhancing the antioxidant defense system. At low doses (e.g., 0.01%), they increase the activity of antioxidant enzymes like Peroxidase (POD), Catalase (CAT), and Superoxide Dismutase (SOD), reducing oxidative damage caused by Reactive Oxygen Species (ROS) like Hydrogen Peroxide (H2O2). TiO_2 NPs also promote the production of osmo-protectants, such as proline and soluble sugars, which maintain osmotic balance and mitigate stress-induced growth inhibition [7]. In a study, the foliar application of 50 mg/kg TiO_2 NPs significantly increased the leaf Relative Water Content (RWC) by 6% and 12% under deficit irrigation conditions compared to control and full irrigation, respectively. However, applying 100 mg/kg TiO_2 NPs under severe drought conditions reduced leaf RWC below control levels, suggesting a threshold concentration beyond which adverse effects may occur. These findings indicate that optimal concentrations of TiO_2 NPs can improve drought stress tolerance [13].

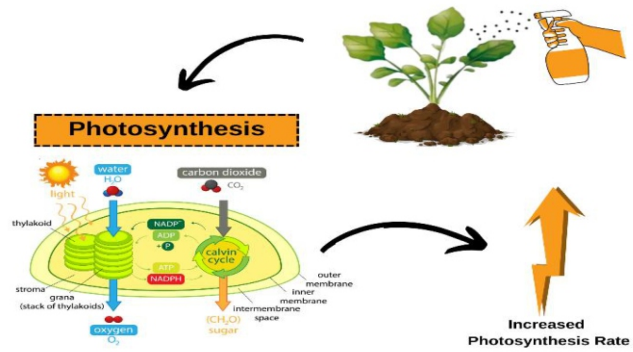

Figure 2: Foliar Application of TiO2 can Increase the Rate of Photosynthesis [14]

Effect of TiO₂ Nanoparticles on Various Crops: Cereal Crops: TiO2 NPs affect the development and yield of barley in both positive and negative ways. In general, they stimulate plant growth by increasing the plant height and leaf area. A study conducted on barley in soil with various concentrations of NPs showed that amongst all the concentrations, a concentration of 1000mg/kg of TiO_2 NPs had significant positive impact on the growth parameters, including taller plants and greater number of tillers compared to untreated barley plants. Additionally, the plants possessed an increased photosynthetic rate, gaseous exchange, stomatal conductance and transpiration during early developmental stages. Moreover, TiO_2 NPs mitigated the negative effects of cerium dioxide nanoparticles which caused a stunt growth. Generally, TiO_2 NPs have the potential to influence growth and yield of barley when administered at an optimal concentration [14]. The application of TiO_2 NPs has been regarded to influence plants' physiological functions by providing the protection to chloroplasts as well as enhancing the growth rate. TiO_2 NPs supply stabilization to the chloroplast's membrane, prevents aging and improve chlorophyll content during reproductive phase. A research conducted on spinach demonstrated that TiO_2 NPs lead to

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increased chlorophyll content as compared to TiO_2 application in bulk. The small size of the particle led to greater cellular absorption. Furthermore, better light absorption, faster energy transfers and protection of chloroplast led to improved photosynthetic rate. In addition, an improvement in anthocyanin content has been observed in various studies when compared to control groups [15]. Another study explored the effects of TiO_2 NPs on Cadmium (Cd) toxicity and migration in the soil-rice system. Results demonstrated that TiO_2 NPs positively influenced the physiological parameters of Oryza sativa such as increasing plant height, biomass, and chlorophyll content while reducing Malondialdehyde (MDA) levels and antioxidant enzyme activities. Such changes suggested that TiO_2 NPs mitigated the stress levels induced by Cd. Although TiO_2 NPs showed positive effects on growth but they demonstrated no effect in reducing the Cd content in rice grains below the maximum legal limits. Therefore, the usage of TiO_2 NPs is not feasible in reducing the toxicity generated by Cd content. Thorough research investigating the interaction between nanoparticles and environment, particularly rhizosphere, is necessary [16]. Leguminous Crops: Several physiological and biochemical responses have been recorded upon the foliar application of TiO2 NPs at various growth stages in pinto beans. These responses contributed to the enhanced stress tolerance. Increased light absorption and improved photosynthetic efficiency has been attributed to the photo-catalytic characteristics and thermal conductivity of TiO_2 NPs. Additionally, TiO_2 NPs treatment reduced ROS accumulation and stimulated antioxidants activity in pinto beans which were exposed to stress. Such treatment led to increased biomarkers such as Malondialdehyde (MDA) and 8-OH-2-DG, demonstrating an improved ROS management in pinto beans. These findings indicate the TiO2 NPs prove to be an effective agent in inducing tolerance against various stress [17]. Horticultural Crops: Foliar application of TiO_2 NPs on tomatoes during the rainy season under varying light conditions revealed mixed effects on yield and growth of plant. Improved photosynthetic rate and electron transfer rate with increased fruit yield was observed at a concentration of 100mg/kg of TiO_2 NPs. However, at a higher concentration such as 200mg/kg, there was no observable improvement in the fruit yield but a decline in photosynthetic rate. Moreover, the weight of fruit decreased with an increase in its hardness, regardless of the TiO_2 NPs concentration. These findings demonstrated that certain factors such as light intensity, nanoparticle concentration and type of crop being treated, influence the efficacy of TiO_2 NPs in both negative and positive manner. Therefore, such variables must be carefully analyzed before applying TiO_2 NPs in agricultural settings to gain the positive outcomes [18]. TiO_2 NPs were applied to coriander, an increase in the absorption of vital nutrients like nitrogen, potassium and phosphorous was observed. Moreover, growth parameters and physiological function were influenced positively due to an increase in total chlorophyll contents, carotenoids, sugar, indoles, amino acids and phenols. Overall, TiO_2 NPs improved the growth properties as well as yield in coriander crop. These studies suggested that TiO_2 NPs have the potential to replace the conventional fertilizers and act as cost-effective nano-fertilizer for raising the overall crop productivity [19].

Table 1: Effect of Nanoparticles on Growth, Photosynthesis, and Stress Tolerance in Different Crops

Crop	Effect on Growth	Photosynthesis Rate	Stress Tolerance	Reported Effective Concentration	References
Barley	Significant increase in plant height and tillers	Enhanced leaf photosynthetic rate and stomatal conductance	Mitigated the negative effects of Cerium Dioxide NPs	1000mg/kg	[20]
Spinach	Increased overall plant growth	Increased Chlorophyll content	Protection of Chloroplast membranes and prevention of aging	20mg/kg	[21]
Rice	Increased plant height and biomass	Improved Chlorophyll content and MDA levels	Alleviated Cadmium toxicity stress though Cd in grains remained high	50-100mg/kg	[22]
Pinto Beans	Enhanced water uptake and light absorption	Increased photosynthetic efficiency through Rubisco activation	Boosted Antioxidants activity and reduced ROS accumulation	16-80mg/kg	[23]
Tomato	Increased fruit yield	Higher photosynthetic rate and electron transfer rate at optimal concentration	Fruit hardness increased but higher concentration led to negative effects	100mg/kg	[24]
Coriander	Improved plant growth	Enhanced Carotenoid and nutrient content	Increased essential nutrients (Nitrogen, Potassium, Phosphorous)	6mg/kg	[25]

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Other Crops: TiO_2 NPs boosted the Rubisco carboxylation that led to higher photosynthetic carbon reactions, enhanced photosynthetic rate, growth parameters, carotenoid and chlorophyll content [26]. Plants which were treated with 24mM and 75mM of TiO_2 NPs had reduced lesions (85-93%) caused by *Xanthomonas axonopodis* [27]. Despite their benefits for pathogen resistance, TiO_2 NPs can negatively affect soil microbes, reducing denitrification enzyme activity and altering bacterial community structure after 90 days [28]. In Moldavian balm, TiO2 NPs reduced oxidative damage, boosted essential oil content, and improved stress tolerance, though higher concentrations (200 mg/kg) caused toxicity through increased ROS levels [29]. Water deficiency stress significantly reduces leaf area in plants due to inhibited cell division and limited leaf enlargement. In sunflower, foliar application of Salicylic Acid (SA) and TiO_2 NPs helped sustain leaf area under water stress, with both treatments showing similar effects [30]. SA promotes mitotic activity in growth apices, aiding leaf maintenance under stress, while TiO_2 NPs protects leaves from salt stress and upregulates stress-related genes [30-32]. However, SA and TiO_2 NPs lessened these effects, with SA improving photo-assimilate translocation to seeds and maintaining cell turgidity [32, 33], while TiO_2 NPs protected chloroplasts and increased leaf phenolic content, mitigating oxidative stress [34]. Water stress decreased sunflower seed oil content and increased oil acid value and free fatty acid content, lowering biodiesel yield. Both SA and TiO_2 NPs improved oil quality by preventing the rise in free fatty acids, which is crucial for higher biodiesel yield [35]. TiO_2 NPs improved the production of biodiesel by stabilizing the TiO_2 nanocatalysts [36]. Severe water stress adversely impacts the biodiesel production and growth of sunflower. A combination of Salicyclic acid and TiO_2 NPs alleviated these impacts when applied at a concentration of 5mg/kg and 50mg/kg respectively. The combined application of these two enhanced the leaf area, biodiesel yield and oil quality. These treatments induced tolerance in the plant against the drought and other stress conditions as well as increased the total phenolic content [37]. Furthermore, a study specified an increase in the essential oil content in rosemary upon the application of TiO_2 NPs, till the concentration of 200mg/kg. This study introduced a novel approach for understanding the metabolic changes, uptake rate and translocation induced by nanoparticles in medicinal plants [38]. TiO_2 NPs improve the light absorption and thus the plant growth, stimulate Rubisco activity, increase the uptake of nitrate, and promote the transformation of inorganic substances to organic materials [39-41]. They positively influence photosystem II, thylakoid membranes, mitosis and plant hormones such as cytokinins and gibberellins [42, 43]. TiO_2 NPs extend the functionality of chloroplast by the increased light absorption, converting light energy into chemical energy [21]. Such photocatalytic characteristics make them significantly effective in decomposing organic contaminants and disinfecting viruses, bacteria and even cancerous cells [44]. TiO_2 NPs also facilitate in stabilizing CO2 [45]. Such findings highlight the significance of TiO_2 NPs in improving plant performance and their potential environmental applications [46]. Figure 3 illustrated the positive impact of TiO_2 nanoparticles (NPs) on photosynthesis, highlighting how their application can enhance chlorophyll content and stimulate better photosynthetic efficiency in plants.

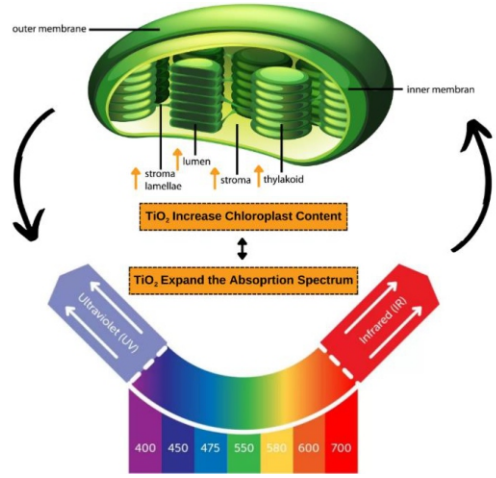

Figure 3: TiO_2 NPs' Positive Impact on Photosynthesis [47]

Efficacy of TiO_2 NPs under Varying Environmental Conditions: Soil Quality and Type: The performance of TiO_2 NPs in agricultural applications is significantly affected by soil characteristics such as pH, structure, organic matter content, etc [47]. Studies have shown that TiO_2 NPs perform optimally in soils with a neutral to slightly alkaline pH value where NPs are more valuable stability and reduced agglomeration, thus enhancing their bioavailability to plants [48]. Soil structure also plays an important role, this is because soil rich in organic matter facilitates the diffusion of TiO_2 NPs, improving their interaction with plant roots and promote nutrient absorption [49]. In addition, the presence of essential nutrients such as nitrogen and phosphorus in together with TiO_2 NPs can enhance photosynthesis and increase stress tolerance in nutrient-deficient soil [38]. Table 2 summarizes the performance of TiO_2 NPs in different types of soil. It emphasizes the effect of pH and organic content on nanoparticle performance.

Table 2: Performance of TiO_2 Nanoparticles across Different Soil Types

Types of Soil	pH Range	Organic Matter Content	TiO_2 NPs Performance	Reference
Sandy Loam	5.5 - 7.0	Low	Medium	[50]
Black Cotton Soil	7.0 - 8.5	Medium	High	[50]

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Fine Sand	6.0 - 8.0	Medium	High	[51]
Chalky Soil	7.5 - 8.5	Low	Medium	[51]
Silty Loam	6.0 - 7.5	Medium	High	[52]
Coarse Sand	6.5 - 8.5	Low	Medium	[53]
Desert Soil	8.0 - 9.0	Very Low	Low	[53]
Alluvial Soil	6.5 - 8.0	High	High	[54]
Peaty Soil	5.0 - 7.0	Very High	Low	[54]

Irrigation and Water Management: Water availability is another important factor affecting the performance of TiO_2 NPs in agriculture. Research showed that adequate irrigation is essential for proper diffusion and mobility of TiO_2 NPs within the matrix of soil in order to reach the root zone where nutrients are absorbed [50]. In drought conditions, the performance of TiO_2 NPs tends to decrease due to limited mobility, restricting their interaction with plant roots. However, in a good irrigation system TiO_2 NPs were found to improve water use efficiency by reducing evaporation and improving column conductivity, especially under stress from heat and salinity [51]. Additionally, studies have shown that TiO_2 NPs can retain essential nutrients in the soil, reducing leaching during heavy irrigation and improve the availability of nutrients to crops [52]. This increased water and nutrient management results in improved growth and yield in many crops especially under conditions of abiotic stress [53]. Climatic Factors: The effectiveness of TiO_2 nanoparticles is also affected by climate, light intensity especially ultraviolet light. It is necessary to start the photocatalytic process that breaks down pollutants. Reduced efficiency of TiO_2 due to limited ROS generation under low light conditions [50]. High temperature increases the reaction rate of TiO_2, although too high temperature can cause nanoparticle agglomeration. As a result, the surface area available for the reaction is reduced [51]. In the same way, moderate humidity levels support the formation of hydroxyl particles. But excessive moisture reduces photocatalytic activity by forming a water film on the nanoparticle surface [51]. Potential Risks and Environmental Concerns: Ecotoxicity and Environmental Persistence: TiO_2 NPs are widely used in various industries, including agriculture, but concerns have emerged about their long-term impact on the environment. In soil ecosystems, studies have shown that concentrations as low as 1 mg/kg of TiO_2 NPs can disrupt microbial activity, leading to reduced nitrogen fixation by bacteria like Rhizobium that are crucial for plant growth [51]. Additionally, TiO_2 NPs have been shown to affect earthworm reproduction, with one study reporting a 27% reduction in the number of cocoons produced at concentrations of 100 mg/kg. When NPs enter water systems, they pose risks to aquatic life. For instance, research has shown that at 10 mg/kg, TiO2 NPs can reduce the growth rate of algae by 30%, which can have cascading effects on the food web [54]. Human Health Considerations: There is growing evidence that TiO2 NPs could pose risks to human health, particularly through bioaccumulation in the food chain. A study demonstrated that plants exposed to TiO2 NPs at concentrations of 500 mg/kg exhibited significant uptake, potentially leading to human consumption. In laboratory studies on mammals, ingestion of TiO2 NPs has been linked to inflammatory responses in the gastrointestinal tract, and at doses as low as 5 mg/kg body weight, they were found to cause oxidative stress in liver cells. While the exact mechanisms of toxicity in humans are still being researched, these findings underscore the potential risks of long-term exposure through contaminated food, particularly given that TiO_2 is classified as a Group 2B carcinogen by the International Agency for Research on Cancer (IARC) [55, 56]. Regulatory and Safety Guidelines: The regulation of TiO2 NPs in agriculture and food systems is inconsistent across different regions. In the European Union, the use of TiO2 NPs in food products has been banned since 2022, following the European Food Safety Authority's conclusion that their safety could not be established. In contrast, the United States has no specific regulations limiting TiO_2 use in food, though the U.S. Food and Drug Administration (FDA) allows it as a food additive, provided it does not exceed 1% by weight of the food's total composition. In agriculture, no global limits have been established for the use of TiO2 NPs in soil or water, despite evidence suggesting that levels above 50 mg/kg can cause significant environmental damage. As the use of nanotechnology grows, there is an urgent need for more comprehensive, standardized guidelines on nanoparticle use to protect human and environmental health [57].

CONCLUSIONS

Titanium dioxide nanoparticles hold tremendous potential in revolutionizing agriculture by enhancing plant growth, improving stress tolerance, and increasing nutrient absorption, particularly in crops exposed to challenging conditions such as soil salinity. Their ability to improve photosynthetic efficiency, regulate ROS levels, and boost antioxidant defense mechanisms makes them a promising tool for modern farming. However, while the benefits of TiO2 NPs are well-documented, their potential risks to the environment and human health cannot be overlooked. Future research must focus on optimizing their concentration, application methods, and safety protocols to harness their full potential while minimizing adverse effects. Comprehensive risk assessments and regulatory frameworks will be critical in ensuring that TiO2 NPs can be safely integrated into large-scale agricultural practices, paving the way for sustainable and resilient food production systems in the face of global challenges like climate change and population growth.

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Authors Contribution

Conceptualization: LZ, AT
Methodology: LZ, AT, EUN, AR, AA, DM, HE
Formal analysis: LZ, AT, EUN, AR, AA, DM, HE
Writing, review and editing: LZ, AT, EUN, AR, AA, DM, HE

All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

All the authors declare no conflict of interest.

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