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Mini Review

Titanium Dioxide Nanoparticles and its Impact on Growth, Biomass and Yield of Agricultural Crops under Environmental Stress: A Review

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Abstract

Anthropogenic activities of developing and developed countries caused environmental pollution. Environmental pollution causes stress to plants and agricultural yield loss and also imbalance the global food security. Titanium dioxide (TiO_2) is considered as a beneficial element for plant growth and development and also one of the most widely used in the consumer products, agriculture and energy sectors. Titanium dioxide (TiO_2) applied via roots or leaves at low concentrations has been documented to improve crop performance through stimulating the activity of certain enzymes, enhancing chlorophyll content and photosynthesis, promoting nutrient uptake, strengthening stress tolerance and improving crop yield and quality. Widespread application of titanium dioxide nanoparticles caused damage to organisms and ecosystems. For a better understanding of TiO_2 nanoparticle toxicity in living organisms may promote risk assessment and safe use practices of these nanomaterials. This review summarizes the beneficial effect of TiO_2 nanoparticle on plant growth and development and its protective role against abiotic and biotic stress.

Key words: Agricultural crops, titanium dioxide nanoparticles, plant growth and development, abiotic and biotic stress tolerances

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INTRODUCTION

Environmental pollution is a burning problem caused biotic and abiotic stresses to plants and yield loss of crops[1]. The exponential increase in the world's population leads to an increased demand for food. Agricultural production and productivity are directly linked with nutrient availability. For sustained high crop yields, the application of fertilizer efficiently required for the farmer for crop production. Therefore, the productivity of agricultural crops depends on the application of fertilizer[2,3]. In this contest for maintenance of crop production and nutrient management is the most important way of sustainable agriculture. Titanium dioxide nanoparticle can be synthesized as a natural way and widely used in commercial products such as sunscreens and toothpaste, industrial products like paints, lacquers and paper and in photocatalytic processes such as water treatment[4-7]. The annual production of titanium dioxide nanoparticles (TiO_2) was more than 10,000 metric t[8]. The mass production, extensive use and uncontrolled disposal of TiO_2nanoparticle will inevitably lead to their release into the environment, where they may exert harm to individual organisms and ecosystems[9,10].

The toxic effects of TiO_2 NPs on plants[11] and animal cells[12] have been demonstrated in multiple studies. Therefore, understanding the TiO_2 nanoparticle-induced effects on individual organisms and the mechanisms of their action is of great importance in assessing environmental risk. The literature on TiO_2 nanoparticle effects in plants is limited. Toxic effects of TiO_2 nanoparticle with a 100-nm diameter have been observed in the higher plants *Allium cepa* and *Nicotiana tabacum*. Nano-size of TiO_2 induced growth inhibition, DNA damage and lipid peroxidation in *Allium cepa* root and also DNA damage in the *Nicotiana tabacum* leaf[13]. Investigations into the toxicity of TiO_2 nanoparticle to plants mainly focused on plant growth and genotoxicity[14,15]. ROS and free radicals directly destroy the chlorophyll molecule, cause membrane lipid peroxidation and degradation of chlorophyll, protein, relative water contents resulting in the aggravation of membrane damage[16]. In addition, ROS can attack the amino acid residues of proteins to form carbonyl derivatives. H_2O_2 can produce more active OH^- through the Haber-Weiss reaction, leading to membrane lipid per-oxidation, base mutation, DNA strand breaks and protein damage. Although, these studies have substantially increased our knowledge about TiO_2 nanoparticles toxicity to plants.

Titanium dioxide (TiO_2) nanoparticles are also used as an essential nutrient for plant growth and development[17,18] and also improves the photosynthetic pigments in plants such as chlorophyll (a and b), carotenoids and anthocyanins contents, therefore, enhanced the crop growth and yield[19]. Various researchers reported that the titanium dioxide nanoparticle caused positive effects on plant growth i.e., canola (*Brassica napus*)[20], *Solanum lycopersicum* (L.) and *Vigna radiata* (L.)[21]. While the study by Da Costa and Sharma[22] found phytotoxicity of titanium dioxide nanoparticle on *Oryza sativa* which was observed through a decrease in seedling growth, photosynthetic activity and biochemical processes at their elevated concentration (1000 ppm). Tripathi *et al*.[23] elaborately reviewed the number of phytotoxicity created by manufactured nanoparticles indifferent plants on the ground of physiological, biochemical, genetic and molecular levels. The effect of titanium dioxide nanoparticle on metabolic processes has been studied and was found to affect processes such as hormone metabolism[24]. However, the effects of titanium dioxide nanoparticles are still unclear. In the present review, discussion was carried out on the current developments in plant science that attention on the role of nanoparticles (NPs) in plant growth and development and also on plant stress tolerance mechanisms.

APPLICATIONS OF TIO_2 NANOPARTICLES IN AGRICULTURAL CROPS

Nanotechnology is not a single technology but it is a mixture of several technological groups, which is working at the nano-level[25]. In the field of agriculture, nanotechnology has huge potential applications, for instance, in modern agricultural systems nanotechnology ease of chemical release and also use of nano-sensors for recording the data of environmental stress, crop setting, resistance against the biotic and abiotic factors via improving the quality of plants[25-27].

According to Parisi *et al*.[28], European commission assessed that, mainly in developed countries, the main use of nanotechnology is pesticide formulations and nanosensors, which are very helpful in applied and sustainable agricultural practices. Nanotechnology also provides the various biotic and abiotic stresses in way of plant life. Various beneficial and harmful influences of nanoparticles were found out by different research workers in the field of agriculture, Fraceto *et al*.[17] observed in some research works that mainly focus on the agriculturally positive side of nanoparticles.

TiO_2 (titanium oxide) nanoparticles by increasing essential metal nutrient uptake reported to enhances plant development[17,18]. In the support of the above statement, Morteza *et al*.[19] suggested that titanium dioxide nanoparticle enhanced crop yield by improving the chlorophyll (a and b), carotenoids and anthocyanins contents with their concentration of 0.01 and 0.03%, respectively. Similar studies were elaborated with positive effects of titanium dioxide nanoparticle in canola (*Brassica napus*)[29], *Solanum lycopersicum* (L.) and *Vigna radiata* (L.)[21]. While a study by Da Costa and Sharma[22] found phytotoxicity of titanium dioxide nanoparticle on *Oryza sativa* which was observed through a decrease in seedling growth, photosynthetic activity and biochemical processes at their elevated concentration (1000 ppm). Tripathi *et al.*[23] decoratively reviewed the number of phytotoxicity created by industrial nanoparticles indiverse plants on the ground of physiological, biochemical, genetic and molecular.

IMPACT OF TITANIUM DIOXIDE NANOPARTICLES ON AGRICULTURAL PLANTS

The efficiency of nanoparticle is basically justified by their chemical composition like, size of particles, surface cover area, reactive abilities with effective doses[30]. Titanium dioxide nanoparticles play an important role in plant growth and development of plants. When nanoparticles link with plant showing several changes in their morphology and physiology that sole depending on nature and properties of nanoparticles. The different research results showed that TDN responds to both positive and negative ways of plant growth and development[31]. The influence of nanoparticle concentration on various species is highly variable. That way, this particular review covers the various aspects of nanoparticle in seed germination, root growth, root and shoot biomass with photosynthesis rate.

Titanium dioxide nanoparticle enhanced seed germination and promoted radicle and growth of canola seedlings[29]. Jaberzadeh *et al.*[32] reported that titanium dioxide nanoparticle augmented wheat plant growth and yield components under water deficit stress conditions. Titanium dioxide nanoparticle regulates enzymes activity involved in nitrogen metabolisms such as nitrate reductase, glutamate dehydrogenase, glutamine synthase and glutamic-pyruvic transaminase that helps the plants to absorb nitrate and also special treatment the conversion of inorganic nitrogen to organic nitrogen in the form of protein and chlorophyll, that could increase the plant biomass[33,34]. It also acts as a photocatalyst and induces an oxidation-reduction reaction[35]. Therefore promote the chlorophyll formation and stimulate Ribulose 1, 5-bisphosphate carboxylase (Rubisco) activity and increases photosynthesis, thereby increasing plant growth and development[33]. Titanium dioxide nanoparticle increases light absorbance, hasten the transport and conversion of the light energy, protect chloroplasts from aging and prolong the photosynthetic time of the chloroplasts[33]. It may be due to titanium dioxide nanoparticle protects the chloroplast from excessive light by augmenting the activity of antioxidant enzymes, such as catalase, peroxidase, superoxide dismutase (Fig. 1). Overall titanium dioxide nanoparticle enhanced growth biomass and yield of crop cultivars by promoting nutrient uptake efficiency and increasing photosynthesis rate of plants.

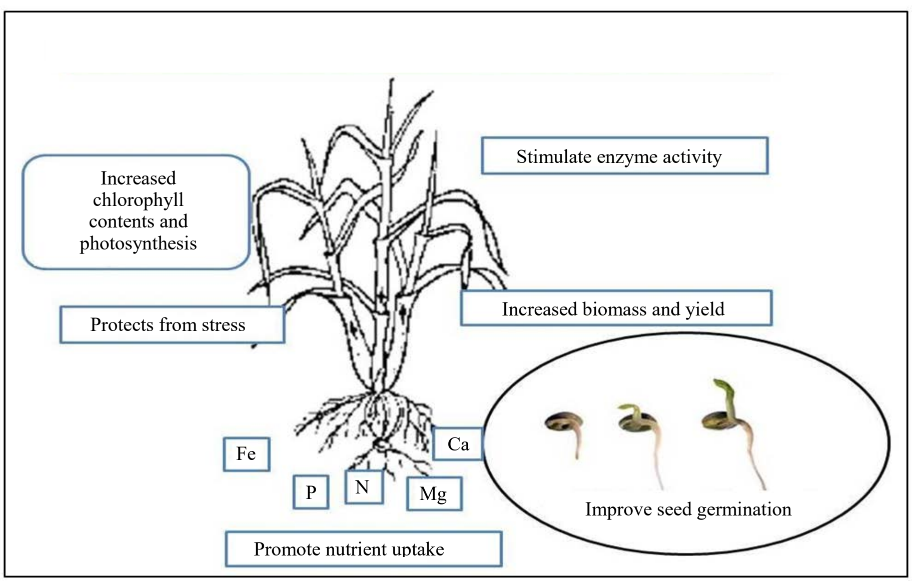

Fig. 1: Effects of titanium dioxide nanoparticles on plants

Table 1: Effect of titanium dioxide nanoparticles (TiO_2 NPs) on plant growth and development

Plant species	Application method	Beneficial effects	References
Allium cepa L. (Onion)	Seeds treated with nanoparticle solutions (0, 100, 200 and 400 mg L^{-1})	Promoted seed germination	Haghighi *et al.*[41]
Allium cepa L.	Seeds treated with nanoparticle solutions (0, 250, 500 and 1,000 µg mL^{-1})	Increased seedling root growth	Andersen *et al.*[43]
Arabidopsis thaliana (L.) Heynh. (Mouse ear cress)	Seeds were immersed in 100, 250, 500 and 1,000 mg L^{-1} nanoparticle solutions	Enhanced root growth	Szymanska *et al.*[8]
Avena sativa L. (Oats)	Seeds treated with nanoparticle solutions (0, 250, 500 and 1,000 µg mL^{-1})	Promoted seed germination and seedling root growth	Andersen *et al.*[43]
Brassica oleracea L. (Cabbage)	Seeds soaked with nanoparticle solutions (0, 250, 500 and 1,000 µg L^{-1})	Promoted seed germination and root growth	Andersen *et al.*[43]
Cucumis sativus L. (Cucumber)	Seeds treated with nanoparticle solutions (0-4,000 mg L^{-1})	Increased root length	Servin *et al.*[38]
Cucumis sativus L.	Seeds treated with nanoparticle solutions (0, 250, 500 and 1,000 µg mL^{-1})	Promoted seed germination and seedling root growth	Andersen *et al.*[43]
Medicago scutellata L. (Snail medic)	Foliar spray of nanoparticle (0, 0.01, 0.02, 0.03, 0.04 and 0.06% g L^{-1})	Increased crop yield	Dolatabadi *et al.*[67]
Solanumly copersicum L. (Tomato)	Soil or foliar application of nanoparticle solutions (0-1,000 mg kg^{-1})	Improved plant growth	Raliya *et al.*[62]
Solanumly copersicum L.	Nanoscale TiO_2 doped applied with zinc (500-800 mg kg^{-1})	Reduced disease	Paret *et al.*[51]
Zea mays L. (Maize)	Foliar spray of nanoparticle solutions (0, 0.01 and 0.03%)	Increased crop yield	Morteza *et al.*[19]

Impact on quantitative and qualitative traits of agricultural plants: Titanium (Ti) is considered a beneficial element for plant growth and development. Application of Ti via roots or leaves at low concentrations has been documented to improve crop performance through stimulating the activity of certain enzymes, enhancing chlorophyll content and photosynthesis, promoting nutrient mobilization, biotic and abiotic stress tolerances and improving crop yield and quality. There has been an increasing amount of attention in the literature regarding the effects of titanium dioxide nanoparticle on plant performance (Table 1). Titanium dioxide nanoparticles suspensions have been used to study the impact on seed germination of various crops. The result showed that titanium dioxide nanoparticles increased the germination rate, root length with improved growth rate of various varieties i.e., *Arabidopsis thaliana* (L.), cabbage, corn, oilseed rape, canola, cucumber, fennel, lettuce, oat, onion, parsley, red clover, soybean, spinach, tomato and wheat[8,36-44].

Effect of titanium dioxide nanoparticle against plant stress: Now, these days environmental pollution is a problem worldwide and caused a negative impact on vegetation and plants. Biotic and abiotic stresses negatively affected the plant growth and biomass also reduced the yield of cultivars[1,45,46]. Titanium dioxide increased plant tolerance to abiotic and biotic stress (Table 2). Various study reported about application of titanium dioxide increased cold stress tolerance in chickpea (*Cicer arietinum* L.)[29,47], heat stress in tomato[48], drought in wheat[32] and flax (*Linum usitatissium* L.)[49], cadmium toxicity in green algae (*Chlamydomonas reinhardtii* P.A. Dang) and soybean[50,21] and bacterial spot disease caused by Xanthomonas perforans in tomato[51]. Foliar spray of titanium dioxide nanoparticle increased chlorophyll content in tomato and oilseeds[52], enhanced the activity of Rubisco (Ribulose-1,5-bisphosphate carboxylase/oxygenase) and promoted net photosynthesis in Arabidopsis[53], spinach[54-57], tomato[48] and basil (*Ocimum basilicum* L.)[58]. Titanium dioxide nanoparticle treatments significantly increased crop yield or biomass of barley[59], corn[60,19], mung bean (*Vigna radiate* L.), snail clover (*Medicago scutellata* Mil.), tomato[61,62] and wheat[63].

Nano-anatase TiO_2 has a photocatalyzed characteristic and improves the light absorbance and the transformation from light energy to electrical and chemical energy and also induces carbon dioxide assimilation and protects chloroplast from aging for long time illumination[33,54,55]. Nano-anatase titanium dioxide nanoparticle enhances the photosynthetic carbon assimilation by activating Rubisco (a complex of Rubisco and Rubisco activase) that could promote Rubisco carboxylation, thereby increasing the growth of plants[64]. Ma *et al.*[65] studied the impact of nano-anatase on the molecular mechanism of carbon reaction and suggested a nano-anatase-induced marker gene for Rubisco activase (RCA) mRNA and enhanced protein levels and activities of Rubisco activase resulted in the improvement of the Rubisco carboxylation and the high rate of photosynthetic carbon reaction. The exogenous application of titanium dioxide nanoparticle improves net photosynthetic rate, conductance to water and transpiration rate in plants[48]. According to Lei *et al.*[57], nano-anatase promoted strongly whole chain electron transport, photoreduction activity of

Table 2: Effect of titanium dioxide nanoparticles (TiO_2 NPs) against stress plants

Plant species	Application method	Beneficial effects	References
Triticum aestivum L. (Bread wheat)	Foliar spray of nanoparticle solutions (0.01, 0.02 and 0.03%)	Increased crop yield under drought stress	Jaberzadeh *et al.*[32]
Cicer arietinum L. (Chickpea)	Foliar spray of nanoparticle (0, 2, 5 and10 mg L^{-1})	Increased cold tolerance	Mohammadi *et al.*[20]
Cucumis sativus L. (Cucumber)	Seeds treated with nanoparticle solutions (0-4,000 mg L^{-1})	Increased root length	Servin *et al.*[38]
Glycine max L. (Soybean)	Soil application of nanoparticle solutions (0-300 mg kg^{-1})	Increased Cd uptake and minimized Cd stress	Singh and Lee[21]
Linum usitatissimum L. (Flax)	Foliar spray of nanoparticle solutions (0, 10, 100 and 500 mg L^{-1})	Increased drought tolerance	Aghdam *et al.*[49]
Ocimum basilicum L. (Basil)	Foliar spray of nanoparticle solution (0, 0.01 and 0.03%)	Increased tolerance of drought stress	Kiapour *et al.*[58]
Solanumly copersicum L. (Tomato)	Foliar spray of nanoparticle solutions (0, 0.05, 0.1 and 0.2 g L^{-1})	Improved photosynthesis under mild heat stress	Qi *et al.*[48]
Spinacia oleracea L. (Spinach)	Seeds soaked with a 0.25% nanoparticle solution and plants sprayed with the same solution	Decreased oxidative stress to chloroplast caused by UV-B radiation	Lei *et al.*[56]

Table 3: Negative effects of titanium dioxide nanoparticles (TiO_2 NPs) on plants

Plant species	Application method	Beneficial effects	References
Allium cepa L. (Onion)	Roots treated with nanoparticle solution (0, 2, 4, 6, 8 and 10 mM)	Caused DNA damages	Ghosh *et al.*[13]
Glycine max L. (Soybean)	Plants grown in a soil mixed with nanoparticle at 0, 100 or 200 mg kg^{-1}	Decreased plant growth	Burke *et al.*[68]
Lemna minor L. (Common duckweed)	Plant growth media treated with nanoparticle (0, 10, 50, 100, 200, 1,000 and 2,000 mg L^{-1})	Inhibited plant growth	Song *et al.*[69]
Lemna paucicostata hegelm. (Duckweed)	Nanoparticles applied to plant growth media (31, 50 and 100 mg L^{-1})	Caused growth inhibition	Kim *et al.*[70]
Linum usitatissimum L. (Flax)	Seeds treated with nanoparticle solutions (0.01-100 mg L^{-1}) and seedling growth	Inhibited seed germination, root lengths	Clement *et al.*[71]
Nicotiana tabacum L. (Tobacco)	Roots treated with nanoparticle solutions (0, 2, 4, 6, 8 and 10 mM)	Caused DNA damages	Ghosh *et al.*[13]
Nicotiana tabacum L.	Seeds treated with nanoparticle solutions (0.1, 1, 2.5 and 5%)	Decreased germination rate, root length and seedling growth	Frazier *et al.*[72]
Solanum esculentum L. (Tomato)	Seeds soaked with nanoparticle solutions (0, 50, 100, 1,000, 2,500 and 5,000 mg L^{-1})	Reduced seed germination and seedling growth	Song *et al.*[73,74]
Triticum aestivum L. (Wheat)	Plants grown in a soil mixed with nanoparticle (10 g nanoparticle mixed with 110 kg soil)	Reduced plant growth	Du *et al.*[75]
Ulmus elongata L.K. Fu and C.S. Ding (Long raceme elm)	Foliar application of 0.1, 0.2 and 0.4% nanoparticle solutions	Reduced photosynthetic rate	Gao *et al.*[76]
Zea mays L. (Maize)	Seeds treated with nanoparticle solutions (0.02, 0.1, 0.2 and 0. 4%)	Reduced seed germination, root lengths and seedling biomass	Castiglione *et al.*[77]
Vicia narbonensis L. (Narbon vetch)	Seeds treated with nanoparticle solutions (0.02, 0.1, 0.2 and 0. 4%)	Reduced seed germination, root lengths and seedling biomass	Castiglione *et al.*[77]

photosystem II, O_2-evolving and photophosphorylation activity of chlorophyll under both visible and ultraviolet light.

DISADVANTAGES OF TITANIUM DIOXIDE NANOPARTICLE

Stresses induce crop loss and create food crises worldwide. The use of titanium dioxide nanoparticles may not show only the right direction impact but also caused a negative impact on plant growth. As shown in Table 3, but some results were a neutral or negative direction. The minimum positive influences of titanium dioxide nanoparticles could be due to various key factors like the variation in species of plant, the physiological position of species at the time being measured, quality of seeds, sizes of titanium dioxide nanoparticles with their consistency, objectives and experimental methods. In some trials titanium dioxide nanoparticles is used at a concentration up to 5000 µg mL^{-1}, normally such type of high volume of concentration may not found naturally in the normal environmental conditions, observations of the result could not provide complete information about the impact of titanium dioxide nanoparticles in the plant body. While serious attention does need to be given to the necessity and outcome of used titanium dioxide nanoparticles within the environment and food chain[66,23], more detailed and specified research in this respect should be followed.

CONCLUSION

Due to the unique properties of titanium dioxide nanoparticles, a handful of research work has been done on toxicological effects on plants, yet research converging on the understanding of the valuable effects of nanoparticle on plant remains incomplete. Some research works revealed that titanium dioxide nanoparticles showed a constructive impact against stress by enhancing the growth and development of plants. Also, more studies are needed to see the sights mode of action of nanoparticle, their interface with biomolecules and their impact on the regulation of gene expressions in plants.

SIGNIFICANCE STATEMENT

This study discovers the impact of titanium dioxide nanoparticles on plants that can be beneficial for protection against stress. This study will help the researcher to uncover the critical areas of agricultural production.

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