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EFFECT OF IRON NANOPARTICLES ON THE POTATO'S SUSCEPTIBILITY TO ENHANCE PHYTOREMEDIATION OF TITANIUM-CONTAMINATED SOIL

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SUMMARY

Phytoremediation is an excellent technique that utilizes green plants for the partial degradation of heavy elements found in soil. Plants utilize a diverse range of biological and physical properties to assist in managing pollution. This study proceeded to investigate the effect of iron nanoparticles and titanium for phytoremediation and their impact on the growth and physiological traits of potato (*Solanum tuberosum* L.). A field experiment on potato, carried out in the spring of 2021 at the University of Anbar, Al-Anbar, Iraq, used various combinations of titanium and iron nanoparticles. The results revealed treatment T7 (100 mg kg^{-1} Ti soil + 150 mg kg^{-1} FeNPs) outperformed in plant height, number of stems, leaf area, dry weight, and percentage of nitrogen, phosphorus, and potassium, with rates of 1.92%, 0.58%, and 1.85%, respectively, compared with the control treatment. The study further disclosed treatment 100 mg kg^{-1} Ti soil + 150 mg kg^{-1} FeNPs positively affected the physiological traits of the potato crop.

Keywords: Potato (*S. tuberosum* L.), phytoremediation, iron nanoparticles, titanium, growth and physiological traits

Key findings: Iron nanoparticles and titanium dioxide enhanced vegetative growth, improved element levels, plant vegetative and physiological traits of potato (*S. tuberosum* L.), and treated the soil pollution. Additionally, employing varying concentrations of iron nanoparticles in plant treatment exhibits promise for remediating contaminated soils.

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INTRODUCTION

Researchers in the agriculture field face numerous challenges in accurately diagnosing the specific factors determining plant growth and productivity. Working to overcome them through a safe approach and adopting modern techniques help achieve environmental balance and exclude the pollution of environmental components, especially in the soil, from pesticide residues, and chemicals (Chang *et al*., 2005; Jumaah *et al*., 2021).

The potato (*Solanum tuberosum* L.) crop is one of the vegetable crops belonging to the Solanaceae family, which includes more than 2,000 species and 90 genera. It is a considered most important and widely consumed vegetable crop, with tuber crops taking the lead (Ismail *et al.,* 2022b). The potato crop plays a vital role in the economy and food system by providing suitable food. It contributes, along with other strategic crops, to meeting the increasing requirements of consumers (Hassan, 1999). Nutritionally, it occupies an influential position in human nutrition, being the primary food for Europe, the Americas, and Africa due to its easy digestion and metabolism in the body. It is also an essential source of energy due to the content of beneficial nutrients. Furthermore, it is rich in amino acids, with 18 out of 20 essential amino acids necessary for humans (Górska-Warsewicz *et al.,* 2021).

Titanium is often a beneficial element for agricultural crop production. Research has confirmed titanium (Ti) positively affects the growth of farming crops by enhancing chlorophyll production, increasing the efficiency of photosynthesis, boosting enzyme activity, and enhancing nutrient absorption from the soil. Titanium also makes plants more resistant to environmental stress conditions (Chavan *et al*., 2020).

Titanium is a transition element in the periodic table, and plants contain approximately 1-578 ppm of titanium in dry plant matter, with an average of 33.4 ppm. Therefore, the concentration of titanium in plant tissue is equal to or higher than some essential elements for plant growth (Abdel-Latef *et al*., 2018). With numerous studies confirming positive effects of titanium on improving vegetative growth and physiological traits, many major global companies have produced titanium as organic salts, such as, titanium ascorbates, used for foliar application to enhance growth and increase production. Plants easily absorb titanium, through the foliar or root system. Moreover, a relationship between titanium and iron is evident. Titanium promotes iron absorption from the soil and can replace iron when it is deficient in the plant. Additionally, titanium participates in nitrogen fixation through root nodules in legumes (Ghoto *et al*., 2020).

Iron is an element considered crucial for plant growth, as it influences various biological processes. It directly participates as a structural component in plant compounds and activates enzymatic processes within the plant (Qureshi *et al*., 2018). Iron has physiological importance in chlorophyll formation as it acts as a cofactor and activator for the reactions involved in the synthesis of green pigments, ultimately leading to chlorophyll molecule formation (Singh *et al.*, 2017).

Nanotechnology has become a prominent and innovative approach for the development of agriculture and food production. The diverse methods of preparing nanoscale iron particles have facilitated the use of this technology, which also served in genetically modified plants and the production of agricultural chemicals (Narayanan and Sakthivel, 2011).

Phytoremediation is an innovative and cost-effective plant-based technique. Plants function to clean a wide range of organic and inorganic pollutants (Ismail *et al*., 2022a). Phytoremediation involves several key processes, including phytotransformation, converting organic pollutants into less toxic, less mobile, and more stable forms; phytodegradation, involving the breakdown of organic pollutants by specific plant enzymes; phytoevaporation, which is the release of organic pollutants through plant leaves; and rhizodegradation, occurring in the root zone near the soil surface (Glick, 2010).

Plant-associated microorganisms can influence all these plant-based remediation processes. Microorganisms present in the rhizosphere and plant roots can play a role in remediation by reducing pollutants, thereby enhancing plant growth. Since subjecting plants to lower pressures compared with pollutants, these processes can reduce phytotoxicity, promote plant growth, and increase phytoremediation efficiency (Ismail *et al*., 2022b).

MATERIALS AND METHODS

The potato (*Solanum tuberosum* L.) experiment commenced during the autumn of 2021 in the lath house of the Department of Horticulture and Garden Engineering at the College of Agriculture, University of Anbar, Iraq. Field preparation comprised clearing the weeds and covering the soil with polyethylene material to prevent weed growth. The potato plants of the Burren variety were products of the Dutch company IBM and imports from the newly approved Nahar Al-Awrad Company for Trading Potatoes and Agricultural Supplies. Potato plant sowing occurred on September 20, 2021, in pots with a diameter and height of 30 cm × 50 cm. The treatments, divided into three replicates, had 30 pots per replicate. Titanium element and nano iron addition to all treatments continued according to the required levels. The age of the plant when added is one month. Adding nano-iron particles had the plant at 45 days, on October 25, 2021, and subsequently, nanoscale iron.

The prepared iron nanoparticles came from the VIZDA Industrial Co., Ltd. The nanometers range in size from 8.5 nanometers to 27.72 nanometers. Iron nanoparticles' detection used infrared spectroscopy (FTIR) and scanning electron microscope (SEM). Their addition on November 10, 2021, was according to the concentrations specified in the prepared and approved study from an international company. Agricultural practices, such as, irrigation, fertilization, and weed control proceeded during the growth period of the crop. The experiment followed a randomized complete block design (RCBD), with the means compared using LSD test at a 5% level of significance (Al-Rawi and Khalef Allah, 1980). The following traits underwent measuring: plant height, leaf area, number of branches, dry weight, total nitrogen percentage, total phosphorus percentage, and total potassium percentage in the leaves. The study included the following treatments (Table 1).

RESULTS

Plant height

The results revealed significant differences among the treatment levels (Table 1, Figure 1). Treatment T7 (100 mg kg^{-1} Ti in soil + 150 mg kg^{-1} FeNPs) recorded the highest average plant height of 59.86 cm, followed by treatment T3 (50 mg kg^{-1} Ti in soil + 150 mg kg^{-1} FeNPs) with a plant height of 54.21 cm. Meanwhile, the control treatment showed the shortest plant height of 34.75 cm.

Table 1. Details of treatments used in the study on potato crops.

No.	Treatments	Details
1	T1	Comparison transaction
2	T2	50 mg kg^{-1} Ti in soil
3	T3	50 mg kg^{-1} Ti in soil + 150 mg kg^{-1} FeNPs
4	T4	50 mg kg^{-1} Ti in soil + 300 mg kg^{-1} FeNPs
5	T5	50 mg kg^{-1} Ti in soil + 450 mg kg^{-1} FeNPs
6	T6	100 mg kg^{-1} Ti in soil
7	T7	100 mg kg^{-1} Ti in soil + 150 mg kg^{-1} FeNPs
8	T8	100 mg kg^{-1} Ti in soil + 300 mg kg^{-1} FeNPs
9	T9	100 mg kg^{-1} Ti in soil + 450 mg kg^{-1} FeNPs

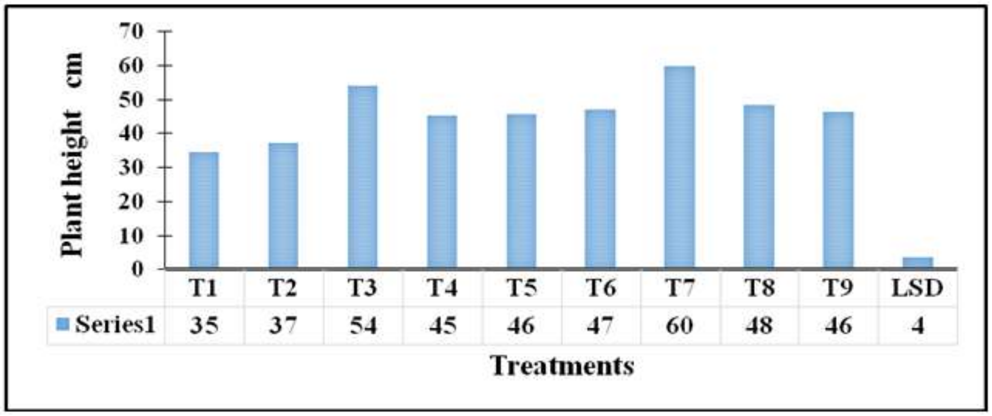


Figure 1. Effect of titanium-treated soil on the plant height of potato crops.

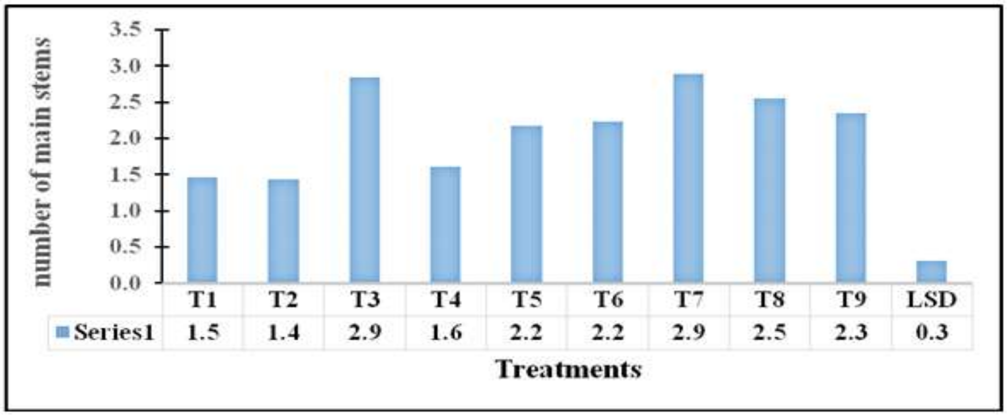


Figure 2. Effect of soil treated with titanium element on the main stems of potato crops.

Number of main stems

The findings indicated a substantial difference between treatment levels (Figure 2). Treatment T7 (100 mg kg^{-1} Ti soil + 150 mg kg^{-1} FeNPs) outperformed with the maximum average number of stems, reaching 2.89. This has treatment T3 following closely, which recorded an average of 2.85 stems, while the control treatment had the lowest average of 1.46 stems.

Leaf area

The outcomes confirm remarkable differences between treatment levels and nano-iron particles (Figure 3). Treatment T7 (100 mg kg^{-1} Ti soil + 150 mg kg^{-1} FeNPs) showed the utmost rate, reaching 114.34 dm², compared with the control treatment, recording the least leaf area rate of 77.28 dm².

Vegetative dry weight

The results gave notable variations between treatments (Figure 4), with treatment T7 (100 mg kg^{-1} soil Ti + 150 mg kg^{-1} FeNPs) as superior with the maximum dry weight of 54.05 g, and the control treatment recording the minimum weight of 31.66 g.

Nitrogen in leaves (%)

Results from Figure 5 show significant differences between treatments, with treatment T7 (100 mg kg^{-1} soil Ti + 150 mg

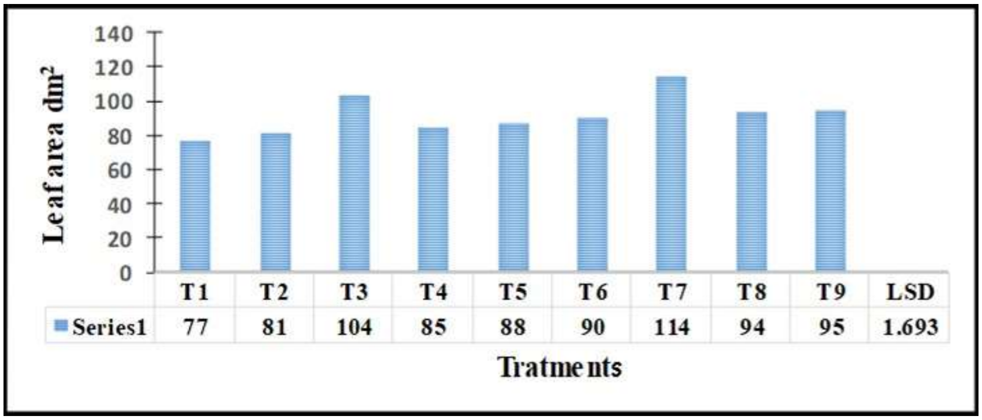


Figure 3. Effect of soil treated with titanium element on the leaf area of potato crops.

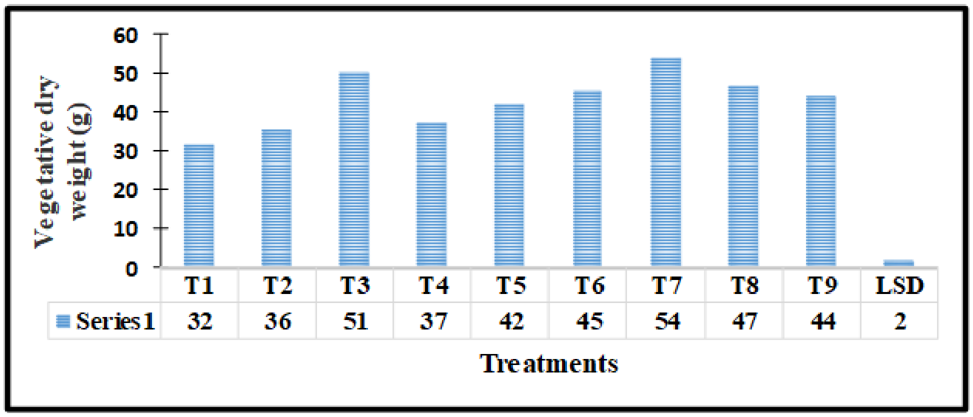


Figure 4. Effect of soil treated with titanium element on the vegetative dry weight of potato crops.

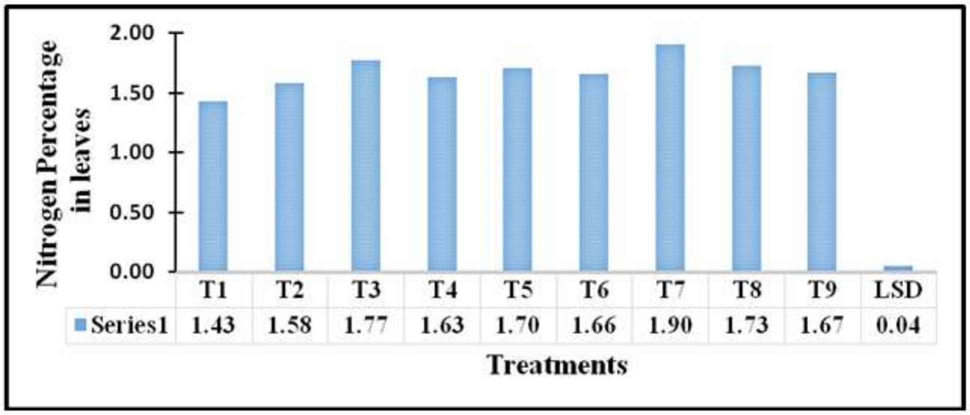


Figure 5. Effect of soil treated with titanium element on nitrogen (%) in leaves of potato crops.

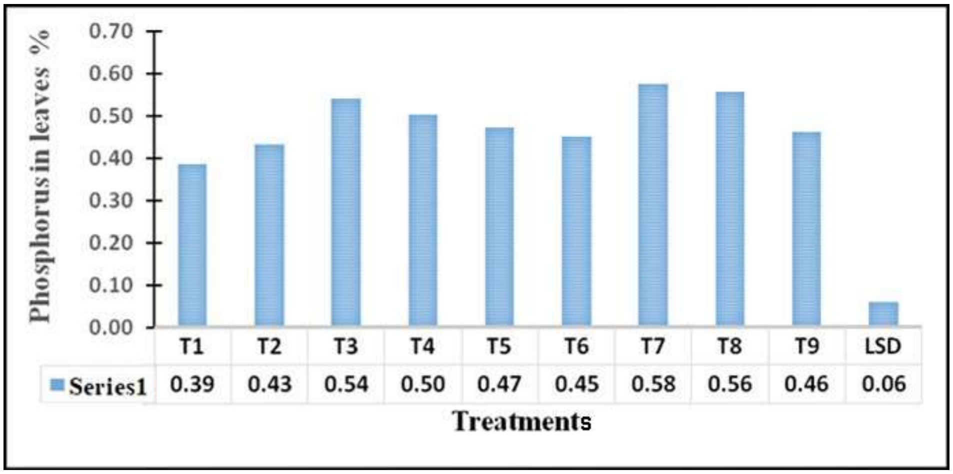
kg^{-1} FeNPs) excelling with the highest percentage of 1.90% compared with the control treatment, recorded at 1.43%.

Phosphorus in leaves (%)

The outcomes provided considerable variations between the levels of treatment with titanium element and iron nanoparticles in the phosphorus content (Figure 6). The treatment level of 100 mg kg^{-1} Ti soil + 150 mg kg^{-1} FeNPs recorded the topmost phosphorus content at 0.57%, followed by treatment T3, which recorded a phosphorus content of 0.54%. The control treatment recorded the lowest level at 0.38%.

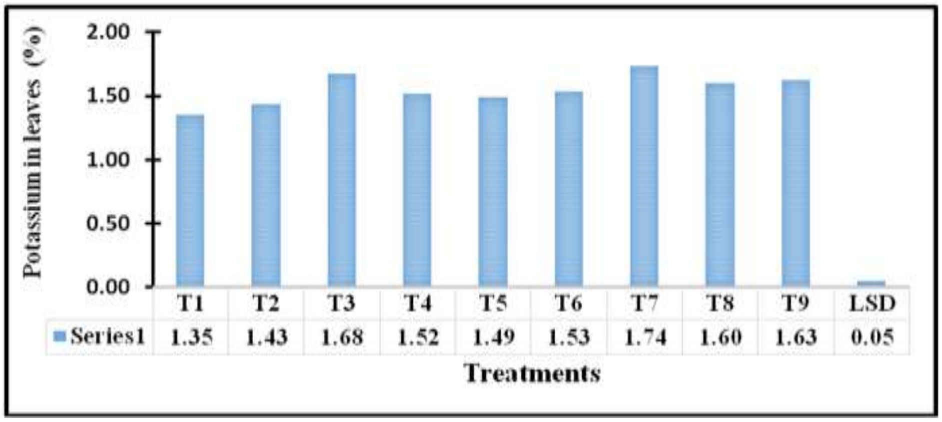
Potassium in leaves (%)

The findings revealed significant differences between the treatments (Figure 7). Treatment T7 outperformed other treatments with the ultimate potassium content at 1.73%, followed by treatment T3, recording a potassium content of 1.68%. The comparison treatment, T1, recorded the lowest percentage at 1.35%.



	T1	T2	T3	T4	T5	T6	T7	T8	T9	LSD
▪ Series1	0.39	0.43	0.54	0.50	0.47	0.45	0.58	0.56	0.46	0.06

Figure 6. Effect of soil treated with titanium element on phosphorus (%) in leaves of potato crops.



	T1	T2	T3	T4	T5	T6	T7	T8	T9	LSD
▪ Series1	1.35	1.43	1.68	1.52	1.49	1.53	1.74	1.60	1.63	0.05

Figure 7. Effect of soil treated with titanium element on potassium (%) in leaves of potato crops.

DISCUSSION

The accumulation of titanium in plant roots may contribute to improving specific growth traits by enhancing soil properties. Titanium affects soil properties as plants easily absorbed and utilized it, resulting in faster growth and development, improved nutrient uptake, and enhanced stress resistance. Titanium also protects plants from environmental stresses, such as, drought, heavy metals, and exposure to ultraviolet radiation. This is because titanium can eliminate free radicals and protect plant cells from oxidative damage (Bacilieri *et al*., 2017). The results showed the coarse particles of the soil increased and the plasticity index, swelling potential shrinkage, and compression index decreased, while significantly improving the strength characteristics of unconfined compressive strength, cohesion, and internal friction angle of the stabilized soil.

Microcosmic experiment results revealed the densification process of the internal structure and reflected the ion exchange, coagulation, and agglomeration of the stabilized soil. This study suggests titanium gypsum has broad application prospects as a stabilizer for expansive soils (Zha *et al*., 2021). It has proven to assist in the germination of spinach seeds (Zheng *et al*., 2005). It may also influence the early growth development of some crops, although at high concentrations, it has no effect. For example, no impact on tomato growth was evident after 48 hours (Andersen *et al*., 2016). The reduction of titanium dioxide nanoparticles can sustain effects from particular active compounds, such as, terpenes, ketones, aldehydes, alkaloids, and phenols. It plays vital roles as reducing, capping, and stabilizing agent in the formation of TiO2, vital in the reduction and stability of titanium dioxide in the soil and root zone (Aslam *et al*., 2021).

Titanium (choosing plain titanium for its ease of availability) also reduces the activity of the enzyme urease and increases peroxidase and nitrate reductase enzymes during potato growth. A positive correlation has emerged between superoxide (SOD) and peroxidase enzymes and the addition of titanium during tuber formation (Bacilieri *et al*., 2017). Titanium affects some physiological parameters and the content of elements, such as, iron, manganese, and magnesium. It has also shown to stimulate or induce gene expression related to iron acquisition, enhancing iron absorption and plant growth (Kužel *et al*., 2003).

Nanoparticles of iron play an influential role in the accumulation of salicylic acid within the plant, which reflects on plant growth and resistance to environmental and biological stresses. Nanoparticles of iron reduce the bioavailability of chromium, improving plant growth, biomass, yield, and carbon metabolism efficiency by increasing chlorophyll content and reducing oxidative stress (Almohammedi *et al*., 2023). The addition of iron nanoparticles has referred to their impact on the interactions between iron and zinc ions within soil aggregates and clay particles. The addition of iron nanoparticles also decreased the activity of the enzymes superoxide dismutase (SOD), ascorbate peroxidase (APX), and catalase (CAT) (Wu *et al*., 2016).

The association between plant treatment and nanomaterials contributes to enhancing bioremediation. The use of iron nanoparticles has proven to be more efficient in treating soils contaminated with various heavy elements, yielding positive results in remediating polluted soils (Srivastav *et al*., 2018). The study's findings align with numerous research studies, indicating the use of iron nanoparticles leads to increased vegetative and chemical traits by stimulating plant nutrient uptake, thus, enhancing plant metabolic processes (Giraldo *et al*., 2014). Furthermore, adding iron nanoparticles through soil amendment has confirmed to facilitate direct entry of nutrients into the plant system by penetrating the root epidermis and absorption by the plant (Mahil and Kumal, 2019).

The increase in plant traits observed in the study may refer to the complete dissolution of nanoparticles, transforming them into mineral forms, thereby, altering their properties and fate in plant species. This transformation occurs outside the roots due to some organic acids secreted by the roots (Alani *et al*., 2021), which, upon entering the plant, take the form of variable nanoscale mineral particles undergoing redox reactions and biological reduction within the plant (López-Moreno, 2010). Additionally, the increase in ions observed in the study could be attributable to the plant's ability to tolerate titanium toxicity, which is in line with findings by Hannink *et al*. (2016).

A reason could also be the plant's secretion, contributing to the transformation of this compound into less toxic compounds through adding nanoparticles, thereby, reducing the toxicity of soil pollutants (Haq *et al*., 2021; Siregar *et al*., 2023). Furthermore, the added nanoparticles have appeared to increase the nitrogen, phosphorus, and potassium elements in the soil by substituting equivalent ions, resulting in the release of essential ions for plant growth (Barrena *et al*., 2009).

CONCLUSIONS

From this study, we can conclude iron nanoparticles and titanium dioxide can synergistically work to enhance specific vegetative growth traits. Additionally, they improve the levels of elements, such as, magnesium, iron, nitrogen, phosphorus, and potassium. Iron nanoparticles can also contribute to improving vegetative and physiological traits. Furthermore, plant treatment using iron nanoparticles at different concentrations could serve to remediate polluted soils, as it improved the visual and chemical characteristics of the studied plants.

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