

Role of Titanium Dioxide Foliar Spraying in Enhancing Phosphorus Utilization Efficiency and Increasing the Growth and Productivity of Green Beans

Ghufran Amer Munshid^{1*} and Ammar Sami Al-Bayati²

^{1,2}Department of Horticulture and Landscape Design, Faculty of Agriculture, University of Kufa, Najaf, Iraq.

*Corresponding author's email: ammar.albayati@uokufa.edu.iq

Email addresses of coauthors: ghufranaa.almayali@student.uokufa.edu.iq

Abstract

This research was carried out at the research station of the University of Kufa during the growing season of 2025. This study aimed to investigate the response of the Spanish faba bean to high-phosphorus DAP fertilizer (P) and titanium dioxide (Ti). A factorial experiment with three replicates following a completely randomized block design was carried out, where the first factor comprised three levels of P fertilizer—soil incorporated (0, 90, 180) kg.ha⁻¹, while the second factor included three doses of foliar spray of Ti (0, 300, 600) mg.L⁻¹. Our findings indicated that the treatment of P fertilizer (P2) provided a significant superiority in the studied indicators (plant height 50.40 cm, leaf count 313 leaf.plant⁻¹, leaf area 4239 cm².plant⁻¹, root dry weight 5.48 g.plant⁻¹, leaf N 3.81%, leaf P 0.41%, leaf K 2.53%, and total yield 79.98 ton.ha⁻¹). Conversely, the control treatment (P0) recorded the lowest values for the same indicators (42.87 cm, 211.22 leaf.plant⁻¹, 2469 cm².plant⁻¹, 2.53 g.plant⁻¹, 3.31%, 0.25%, 1.88%, and 40.28 ton.ha⁻¹) respectively. Moreover, foliar spraying with Ti improved most plant indicators of growth, yield, and chemical indicators. The treatment (Ti2) recorded the highest values of the traits (plant height 49.13 cm, number of leaves 313.87 leaf.plant⁻¹, leaf area 4325 cm².plant⁻¹, root dry weight 4.80 g.plant⁻¹, leaf N 3.73%, leaf P 0.38%, leaf K 2.47%, and total yield 73.92 ton.ha⁻¹). In contrast, the control treatment (Ti0) recorded the lowest values for the same indicators, reaching (43.44 cm, 224.76 leaf.plant⁻¹, 2739 cm².plant⁻¹, 3.52 g.plant⁻¹, 3.43%, 0.27%, 1.94%, and 49.57 ton.ha⁻¹), consecutively. The interaction between the experiment factors also had a significant impact on some indicators, as the interaction treatment (P2Ti2) achieved the highest values compared to the control treatment (P0Ti0), which gave the lowest values. These results suggest that phosphorus combined with titanium represents an effective strategy for improving faba bean growth and productivity.

Keywords: Broad Bean, Growth, Leaf Nutrients, Phosphorus Fertilizer, Titanium, Yield

Introduction

Faba bean *Vicia faba* L. is an important crop that falls within the leguminous family that is grown in the winter season to obtain green pods and their fresh and dry seeds, which are rich in proteins and vitamins such as vitamin B [36]. Faba bean seeds are consumed as fresh, dry, frozen and canned foods, high-protein flour, and the manufacture of concentrated fodder for

animals [37]. China, Ethiopia and Australia also lead a large proportion of global production, with global production of about 6–7 million tons per year of dry faba beans and cultivated area of about 2.3–2.8 million hectares and average productivity 2.5–3.0 tons/ha, [16]. It is also grown as a soil enhancer due to its ability to stabilize atmospheric nitrogen, which

leads to increased soil fertility and improved productivity of subsequent crops when utilized in crop rotations, and thus reduces the use of synthetic fertilizers that cause soil degradation [21]. Faba bean can impact some soil organisms and increase their activity, such as the Rhizobia bacteria, and has a positive role in sustainable farming systems [14]. Legumes are particularly important for their essential role in root development, energy transfer, and root nodule formation [34].

Phosphorus (P) is considered the second most significant nutrient required for plant life after nitrogen. It is one of the macro elements essential in the nutrition of legumes in particular, as it plays a key role in root development, energy transfer, and root nodule formation [34]. The availability of phosphorus in adequate amounts helps biological nitrogen fixation, thereby improving the biomass of the shoot system and the formation of pods, hence increasing plant yield [31]. Phosphorus also plays a necessary function in most physiological processes in plants, especially photosynthesis, respiration, enzyme cofactors, phospholipid formation, energy compounds (ADP and ATP), as well as growth and differentiation. P also contributed to the formation of nucleotides, which are the building blocks for amino acids, as well as cell division and the process of transport of nutrients in plants [13]. Several studies on broad beans reported that phosphorus (P), which is essential for energy transfer via (ATP), root development, and photosynthesis, is a crucial macronutrient for the growth of broad beans. Their findings confirmed that sufficient phosphorus application improves nitrogen fixation, root nodulation, and seedling vigor—all of which are critical for the best potential growth and productivity. While phosphorus deficiency causes nitrogen fixation deterioration, stunted growth, decreased pod and seed formation,

feeble stature, and poorer seed quality [30,32].

Titanium (Ti) is found in several mineral forms, including Anatase, Rutile, and Brookite, and the most stable oxidized form of titanium is TiO_2 [39]. Although titanium is neither a macronutrient nor a micronutrient needed by plants, it is considered a beneficial element [17] as it has attracted attention for its role in stimulating plant growth. Several studies have shown that foliar spraying of titanium-containing fertilizers has significant benefits and increases the efficiency of photosynthesis, enhances total chlorophyll in the leaves, stimulates certain enzymes, and enhances crop yield and quality [25]. In particular, applying titanium dioxide (TiO_2) at adequate doses improves root function and nitrogen metabolism, which in turn increases nutrient uptake and vegetative growth in faba beans. [15] found that seed soaking and foliar spraying of TiO_2 optimize plant height, dry weight, and leaf nitrogen content through stimulating nitrogen fixation and assimilation. Phosphorus and potassium uptake is simultaneously supported by TiO_2 -induced root architecture modifications [11]. Superior vegetative biomass accumulation and yield are driven by this synergistic NPK increase [1,23].

This current research sought to investigate the optimum rate of phosphate fertilizer for boosting the vegetative growth, leaf nutrient status, and yield of faba bean plants. Also, the research aimed to determine the most effective concentration of titanium dioxide as a foliar application on the growth, yield, and nutritional traits. Moreover, evaluating the synergistic impact of both factors on improving growth and production of faba bean plants via integrated nutrient management strategies.

Material and Methods

Experimental site:

The field trial was performed at the research station of the University of Kufa located at 32.0196° N latitude and 44.3761° E longitude, during the growing season of 2025 in sandy soil under open field conditions. A Spanish faba bean variety, “Luz de otono” produced by

Semillas Fitó, certified by the Ministry of Agriculture/Directorate of Agriculture of Najaf/Iraq, was cultivated under a drip irrigation system. Five random samples of the experiment soil were taken from different locations before planting at different depths (0-30) cm for soil test, which was carried out in the laboratories affiliated to the University of Kufa, Faculty of Agriculture, in the Department of Soil and Water Resources (Table 1).

Table 1. Some chemical and physical properties of the field soil before planting.

Value	Unit	Properties	Value	Unit	Properties
4.73	dS.m ⁻¹	Soil Ec	58	g.kg ⁻¹	Clay
0.607	ppm	Available N	10	g.kg ⁻¹	Silt
0.171	ppm	Available P	932	g.kg ⁻¹	Sand
0.043	ppm	Available K	Sandy		Soil texture
2.52	g.kg ⁻¹	Organic matter (O.M.)	7.04	---	Soil pH

Field preparation, plant, and studied factors:

Field operations were carried out by plowing, smoothing, and leveling the research soil, and then the soil was sterilized by Beltanol fungicide (Agronova Biotech-Spanish origin) at a concentration of 1 ml.L⁻¹ added during watering, as well as Dimethoate 40% EC insecticide (Super Janta-China origin) at a concentration of 2 ml.L⁻¹. Further, a decomposed manure fertilizer was added to the experimental field at 24 ton.ha⁻¹ on 15/9/2025, a month before planting [4]. Faba bean seeds were water-soaked for 12 hours prior to planting, and then the seeds were directly planted on 15/10/2025 in rows per experimental unit, placing three seeds per hole with a depth of 5 cm. Each experimental plot comprised 14 plants planted in two rows with 1.80 m length and 0.60 m width, and leaving a distance of 0.30 m between plants, and 0.75 m between the experimental units.

The experiment included two factors: the soil application of high-phosphorus DAP fertilizer was directly added at planting at

three levels (0, 90, 180) kg.ha⁻¹ and denoted by (P0, P1, P2), respectively. The second factor included foliar application of titanium in the form of TiO₂ with three concentrations (0, 300, 600) mg.L⁻¹ and denoted by (Ti0, Ti1, Ti2), respectively. A 2-liter hand pump was used to spray the canopy of faba bean plants in the early morning until the foliage was completely wet. Three spray applications were performed, with a 3-week interval between each spray. The control treatment was sprayed with distilled water, taking into account the separation among the treatments using polyethylene as a barrier to avoid splashing of the spray between adjacent plots. Spraying was conducted one day after the irrigation process to increase the plants' efficiency in absorbing the sprayed TiO₂ [5]. All experimental units were also fertilized with nitrogen at a dose of 100 kg.ha⁻¹ in the form of urea (46% N) as a booster batch, and potassium sulfate fertilizer (42% K₂O) at a dose of 40 kg.ha⁻¹ was added in two batches, the first 21 days after germination and the second 40 days after planting [27].

Experimental treatments and statistical analysis:

A factorial experiment of two factors (3 levels of P $\times$ 3 con. of Ti) was implemented using a randomized complete block design with three replicates. Each replicate comprised nine treatments, for a total number of 378 faba bean plants distributed across 27 randomly arranged experimental units, in addition to the guard lines planted alongside the plots. Two-way ANOVA procedure was employed to analyze the data, and then treatment comparisons were tested through the least significant difference (L.S.D) test at a probability level of 0.05 using the statistical software Statistix 10 [6].

Studied indicators:

The measurements were performed on five plants randomly selected from each experimental unit, and included plant height (cm) estimated using a measuring tape, leaf count per plant (leaf.plant⁻¹), leaf area of the whole plant (cm².plant⁻¹) according to [29], dry weight of the root system (g.plant⁻¹) according to the method [18], percentage of nitrogen in leaves (%) by Kjeldahl, percentage of phosphorus in leaves (%) by [22], percentage of potassium in leaves (%) using flame photometer following the method described by [5]. Total yield per unit area of faba bean (ton.ha⁻¹) was measured collectively during the entire growing season.

Results and Discussion

Vegetative growth indicators:

Plant height

The results presented in Table 2 showed that phosphorus fertilization significantly affected plant height. The highest phosphorus level (P2) @ 180 kg ha⁻¹ produced the tallest plants, reaching 50.40 cm, followed by P1, whereas the control treatment (P0) recorded the lowest plant

height (42.87 cm). Foliar application of titanium dioxide also significantly influenced plant height. Spraying plants with 600 mg L⁻¹ TiO₂ (Ti2) resulted in the greatest plant height (49.13 cm), whereas untreated plants (Ti0) produced the shortest plants (43.44 cm). The interaction between phosphorus and titanium dioxide significantly affected plant height. The P2Ti2 treatment recorded the highest value (53.47 cm), while the control interaction (P0Ti0) produced the lowest plant height (40.67 cm).

The increase in plant height under the highest phosphorus level can be attributed to the essential role of phosphorus in ATP formation, cell division, and cell elongation, which collectively enhance vegetative growth. Moreover, phosphorus promotes root development and nutrient uptake, thereby improving overall plant vigor [2,3]. The stimulatory effect of TiO₂ is likely associated with enhanced chlorophyll synthesis, improved photosynthetic efficiency, and increased metabolic activity, resulting in greater stem elongation [10,12,19].

Number of leaves per plant

Table 2 revealed significant differences in leaf number among phosphorus treatments. Plants fertilized with 180 kg ha⁻¹ phosphorus (P2) produced the highest number of leaves (313.00 leaves plant⁻¹), followed by P1, whereas the control (P0) recorded the lowest value (211.22 leaves plant⁻¹). Titanium dioxide application significantly increased leaf production. The highest concentration (Ti2) produced 313.87 leaves plant⁻¹, while untreated plants (Ti0) produced only 224.76 leaves plant⁻¹. The interaction between phosphorus and titanium dioxide significantly affected leaf production, with P2Ti2 producing the highest number of leaves, whereas P0Ti0 recorded the lowest value.

Phosphorus enhances leaf formation by stimulating meristematic activity, energy metabolism, and nutrient translocation, leading to greater vegetative development [3,28]. The positive response to TiO_2 may result from enhanced photosynthesis, increased chlorophyll content, and activation of growth-related enzymes, which promote continuous leaf initiation and expansion [19,33].

Leaf area

Significant differences in leaf area were observed among phosphorus treatments (Table 2). Plants supplied with 180 kg ha^{-1} phosphorus (P2) developed the maximum leaf area ($4239 \text{ cm}^2 \text{ plant}^{-1}$), whereas the unfertilized control (P0) produced the minimum leaf area ($2469 \text{ cm}^2 \text{ plant}^{-1}$). Titanium dioxide foliar spray also significantly increased leaf area. The $600 \text{ mg L}^{-1} \text{ TiO}_2$ (Ti2) treatment recorded the highest leaf area ($4235 \text{ cm}^2 \text{ plant}^{-1}$), while unsprayed plants (Ti0) had the lowest value ($2739 \text{ cm}^2 \text{ plant}^{-1}$). The interaction between phosphorus and titanium dioxide significantly affected leaf area. The combination P2Ti2 produced the maximum leaf area ($5598 \text{ cm}^2 \text{ plant}^{-1}$), whereas P0Ti0 recorded the minimum value ($2159 \text{ cm}^2 \text{ plant}^{-1}$).

The expansion of leaf area under phosphorus fertilization is mainly associated with increased cell division, ATP production, and enhanced photosynthetic metabolism, all of which promote leaf expansion [2,28]. Likewise,

TiO_2 improves chlorophyll accumulation and photosynthetic performance, increasing carbohydrate production required for leaf growth. These findings agree with those of [15,20].

Dry weight of the root system

Root dry weight was significantly influenced by phosphorus fertilization (Table 2). The highest phosphorus application (P2) produced the greatest root dry weight ($5.48 \text{ g plant}^{-1}$), whereas the control treatment (P0) produced the lowest value ($2.53 \text{ g plant}^{-1}$). Titanium dioxide significantly increased root dry weight. Plants sprayed with $600 \text{ mg L}^{-1} \text{ TiO}_2$ (Ti2) produced the highest root dry weight ($5.80 \text{ g plant}^{-1}$), while untreated plants (Ti0) recorded $3.52 \text{ g plant}^{-1}$. The interaction between phosphorus and titanium dioxide significantly affected root dry weight. The P2Ti1 treatment produced the greatest root dry weight ($6.50 \text{ g plant}^{-1}$), whereas P0Ti0 recorded the lowest value ($1.40 \text{ g plant}^{-1}$).

Phosphorus boosts root growth through its involvement in energy transfer, root meristem development, and improved nutrient acquisition, leading to greater dry matter accumulation in roots [2,3,28]. Titanium dioxide further enhances root biomass by improving nutrient absorption, particularly N, P, and Ca, stimulating enzyme activity, and increasing photosynthetic assimilate transport to the root system [12,15,26].

Table 2. Effect of high-phosphorus DAP fertilizer and foliar spray of titanium, with their interaction on the vegetative growth indicators of broad bean plants.

Treatments	Plant Height (cm)	Leaf No. (leaf.plant ⁻¹)	Leaf Area (cm ² .plant ⁻¹)	Root Dry Weight (g)
Effect of DAP Fertilizer Levels				
P0	42.87	211.22	2469	2.53
P1	47.04	271.91	3579	5.04
P2	50.40	313.00	4239	5.48

	LSD 0.05	2.05	43.89	637	0.64
Effect of Titanium Concentrations					
Ti 0		43.44	224.76	2739	3.52
Ti 1		47.73	257.51	3223	4.73
Ti 2		49.13	313.87	4325	4.80
LSD 0.05		2.05	43.89	637	0.64
Effect of the Interaction					
P0	Ti 0	40.67	199.67	2159	1.40
	Ti 1	43.73	197.40	2378	2.53
	Ti 2	44.20	236.60	2870	3.67
P1	Ti 0	41.53	234.47	3299	4.25
	Ti 1	49.87	255.73	2932	5.17
	Ti 2	49.73	325.53	4507	5.70
P2	Ti 0	48.13	240.13	2759	4.90
	Ti 1	49.60	319.40	4359	6.50
	Ti 2	53.47	379.47	5598	5.03
LSD 0.05		3.54	N.S.	1104	1.11

N.S. indicates a non-significant effect at $p > 0.05$.

Leaf content of nutrients and yield indicators:

Percentage of nitrogen in leaves

The results in Table 3 showed that phosphorus fertilization significantly affected leaf nitrogen concentration. The highest phosphorus level (P2; 180 kg ha⁻¹) recorded the greatest leaf nitrogen content (3.81%), significantly exceeding both P1 (90 kg ha⁻¹) and the control (P0). In contrast, plants that received no phosphorus fertilizer (P0) recorded the lowest nitrogen concentration (3.31%). Foliar application of titanium dioxide also significantly increased leaf nitrogen concentration. Spraying with 600 mg L⁻¹ TiO₂ (Ti2) produced the highest nitrogen percentage (3.73%), whereas untreated plants (Ti0) recorded the lowest value (3.43%). The interaction between phosphorus and titanium had no significant effect on leaf nitrogen concentration.

The increase in leaf nitrogen concentration with phosphorus fertilization may be attributed to the essential role of phosphorus in enzymatic regulation, ATP formation, and energy transfer, which

improve nutrient absorption and assimilation within plant tissues [35]. Likewise, titanium dioxide has been reported to stimulate photosynthesis and nitrogen metabolism while enhancing nitrogen uptake and amino acid synthesis, thereby increasing leaf nitrogen content [12,38].

Percentage of phosphorus in leaves

Phosphorus fertilization significantly influenced leaf phosphorus concentration (Table 3). The highest phosphorus application (P2) produced the maximum phosphorus content (0.41%), significantly surpassing P1 and the unfertilized control (P0), which recorded the lowest value (0.25%). Similarly, foliar spraying with titanium dioxide significantly affected leaf phosphorus concentration. The highest concentration (Ti2; 600 mg L⁻¹) recorded the greatest phosphorus percentage (0.38%), whereas untreated plants (Ti0) showed the lowest concentration (0.27%). No significant interaction was observed between phosphorus fertilization and titanium dioxide for leaf phosphorus concentration.

Higher phosphorus availability directly increased phosphorus accumulation in leaves owing to enhanced nutrient uptake and improved energy metabolism within plant cells [35]. Titanium dioxide further enhanced phosphorus accumulation by improving root water uptake and nutrient absorption efficiency through stimulation of physiological processes [7,10].

Percentage of potassium in leaves

The data in Table 3 demonstrated significant differences among phosphorus treatments in leaf potassium concentration. Plants supplied with 180 kg ha⁻¹ phosphorus (P2) recorded the highest potassium concentration (2.53%), significantly exceeding P1 and P0, while the control treatment produced the lowest value (1.88%).

Titanium dioxide spraying also significantly increased leaf potassium concentration. Plants treated with 600 mg L⁻¹ TiO₂ produced the highest potassium concentration (2.47%), whereas untreated plants recorded only 1.94%. The interaction between phosphorus and titanium significantly affected leaf potassium concentration. The P2Ti2 combination recorded the highest potassium concentration (2.88%), whereas P0Ti0 recorded the lowest value (1.62%).

The increased potassium concentration following phosphorus fertilization may result from improved metabolic activity and enhanced nutrient transport within plants [40]. Titanium dioxide has also been reported to increase potassium uptake by improving nutrient absorption, root

activity, and water transport, leading to greater potassium accumulation in leaves [9,19].

Total yield of green pod

The results presented in Table 3 revealed that phosphorus fertilization significantly improved total green pod yield. The application of 180 kg.ha⁻¹ phosphorus (P2) produced the highest yield (79.98 ton.ha⁻¹), significantly exceeding P1 and the unfertilized control (P0). The control treatment recorded the lowest yield (40.28 ton.ha⁻¹). Titanium dioxide significantly enhanced total green pod yield. Plants sprayed with 600 mg.L⁻¹ TiO₂ produced the highest yield (73.92 ton.ha⁻¹), whereas untreated plants yielded only 49.57 ton.ha⁻¹. The interaction between phosphorus and titanium significantly affected green pod yield. The P2Ti2 treatment recorded the highest yield (98.25 ton.ha⁻¹), whereas the P0Ti0 treatment produced the lowest yield (32.27 ton.ha⁻¹).

The increase in green pod yield with phosphorus fertilization can be attributed to enhanced enzymatic activity, improved energy transfer, and greater accumulation of assimilates that are subsequently translocated to developing pods, thereby improving productivity [35]. Titanium dioxide further increased yield by enhancing chlorophyll content, photosynthetic efficiency, nutrient uptake, and water absorption, resulting in improved plant growth and greater assimilate production for pod development [7,10,38]. Similar responses have been reported by [8,24] in tomato.

Table 3. Effect of high-phosphorus DAP fertilizer and foliar spray of titanium, with their interaction on the leaf nutrients and yield indicators of broad bean plants.

Treatments	Nitrogen (%)	Phosphorus (%)	Potassium (%)	Total Yield (ton.ha ⁻¹)
Effect of DAP Fertilizer Levels				

P0	3.31	0.25	1.88	40.28	
P1	3.54	0.33	2.34	64.88	
P2	3.81	0.41	2.53	79.98	
LSD 0.05	0.16	0.04	0.13	6.12	
Effect of Titanium Concentrations					
Ti 0	3.43	0.27	1.94	49.57	
Ti 1	3.51	0.33	2.34	61.65	
Ti 2	3.73	0.38	2.47	73.92	
LSD 0.05	0.16	0.04	0.13	6.12	
Effect of the Interaction					
P0	Ti 0	3.09	0.21	1.62	32.27
	Ti 1	3.35	0.25	2.07	38.05
	Ti 2	3.50	0.27	1.96	50.51
P1	Ti 0	3.52	0.27	1.97	48.98
	Ti 1	3.51	0.35	2.48	72.66
	Ti 2	3.60	0.37	2.57	73.00
P2	Ti 0	3.67	0.34	2.22	67.46
	Ti 1	3.68	0.39	2.47	74.24
	Ti 2	4.08	0.50	2.88	98.25
LSD 0.05	N.S	N.S	0.23	10.60	

N.S. indicates a non-significant effect at $p > 0.05$.

Conclusion

Based on the research findings, the application of high-phosphorus DAP fertilizer @ 180 kg.ha⁻¹ is recommended for the Spanish fava bean crop as it significantly improved most vegetative growth indicators, which positively affected the leaf nutrient status and crop production, yielding the best results. Titanium foliar application @ 600 mg.L⁻¹ outperformed the other concentrations in most of the studied traits of Spanish fava beans, including vegetative growth indicators, leaf nutrient compositions, and yield. Subsequently, the combination treatment of 180 kg.ha⁻¹ DAP fertilizer and 600 mg.L⁻¹ titanium foliar spray (P2Ti2) is the optimum treatment, since it consistently enhanced most of the growth, nutritional, and yield traits compared to the

other interaction treatments, especially the control. These results suggest that the integration of phosphorus fertilization with titanium foliar application represents an effective agronomic strategy for improving the growth, nutrient status of leaves, and productivity of faba beans. Further research is recommended to assess the physiological and biochemical mechanisms of phosphorus and titanium applications on other vegetable and legume crops grown under various ecological conditions in Iraq, in order to optimize crop performance and fertilizer use efficiency.

Acknowledgment: The authors would like to thank the Faculty of Agriculture at the University of Kufa for lab work and technical assistance.

References

- [1] Abdelmagid, S. Y., Gharib, F. A. E. L., & Ahmed, E. Z. 2025. Impact of titanium nanoparticles on germination and early growth of faba bean (*Vicia faba* L.). Scientific Reports, 15(1), 32450. <https://doi.org/10.1038/s41598-025-18071-1>

- [2] Abdul Hussain, A. H. A. 2022. Study of some genetic parameters of some genotypes of the faba bean (*Vicia faba* L.) and evaluate its phenotypic performance under different levels of phosphorus. Thesis, College of Agricultural Engineering Sciences, University of Baghdad.
- [3] AL-Azee, A. J., Raheem, A. H., & AL-Obaidy, K. S. A. 2023. Broad bean (*Vicia faba* L.) crop growth and yield response to humic acid and phosphorus fertilizer. *Nativa*, Sinop, 11(3): 408-421.
- [4] Al-Jubory, A. A. W., & Jerry, A. N. 2020. Effect of Antioxidant (Tocopherol- α and Acetylsalicylic acid) and addition method on the growth and components of the green yield for broad bean plants cultivated in the south of Iraq. *Euphrates Journal of Agriculture Science*, 12(2), 324-334.
- [5] Al-Sahaf, F. H. 1989. *Applied Plant Nutrition*. University of Baghdad - Ministry of Higher Education and Scientific Research. Iraq. pp. 260.
- [6] Analytical Software. Statistix 10. 2013. User's Manual. Tallahassee, Florida: Analytical Software; <https://www.statistix.com>
- [7] Bacilieri, F. S., Regina, M. Q. L., Roberta, C. O., & José, M. Q. L. 2022. Foliar application of titanium on potato crop. *Comunicata Scientiae*, 13, e3690. doi.org/10.14295/CS.v13.3690
- [8] Carbajal-Vázquez, V. H., Gómez-Merino, F. C., Alcántar-González, E. G., Sánchez-García, P., & Trejo-Téllez, L. I. 2022. Titanium Increases the Antioxidant Activity and Macronutrient Concentration in Tomato Seedlings Exposed to Salinity in Hydroponics. *Plants*, 11(8),1036. <https://doi.org/10.3390/plants11081036>
- [9] Carvajal, M., Frutos, M. J., Giménez, J. L., Alcaraz, C. F., & Martínez, S. F. 1992. Foliar effect of titanium on paprika pepper plants. Influence on nutrition balance in fruit pericarp. *Suelo y Planta*, 12, 551-562.
- [10] Carvajal, M., Martínez-Sánchez, F., & Alcaraz, C. F. 1994. Effect of Ti (IV) on some indicators of physiological activity in *Capsicum annuum* L. *Journal of Horticultural Science*, 69(3), 427-432.
- [11] Castiglione, M. R., Giorgetti, L., Bellani, L., Muccifora, S., Bottega, S., & Spanò, C. 2016. Root responses to different types of TiO₂ nanoparticles and bulk counterpart in plant model system *Vicia faba* L. *Environmental and experimental botany*, 130, 11-21.
- [12] Choi, H. G., Moon, B. Y., Bekhzod, K., Park, K. S., Kwon, J. K., Lee, J. H., Cho, M. W., & Kang, N. J. 2015. Effects of foliar fertilization containing titanium dioxide on growth, yield and quality of strawberries during cultivation. *Horticulture, Environment, and Biotechnology*, 56, 575-581. <https://doi.org/10.1007/s13580-015-0023-3>
- [13] Devau, N., Hinsinger, P., Le Cadre, E., & Gérard, F. 2011. Root-induced processes controlling phosphate availability in soils with contrasted P-fertilized treatments. *Plant and Soil*, 348(1), 203-218.
- [14] Duc, G., Bao, S., Baum, M., Redden, B., Sadiki, M., Suso, M. J., Vishniakova, M., & Zong, X. 2010. Diversity maintenance and use of *Vicia faba* L. genetic resources. *Field Crops Research*, 115(3), 270-278.
- [15] Faiyad, R. M. N., & El-Sherpiny, M. A. 2023. Effect of Titanium as a Stimulant of Atmospheric Nitrogen

- Fixation on Faba Bean Plants. Egypt. J. Soil Sci., 63(4), 465-474.
- [16] **FAOSTAT. 2024.** Crops and livestock products database. Food and Agriculture Organization of the United Nations. Available at: <https://www.fao.org/faostat/en/#data/QCL>
- [17] **Gómez-Merino, F. C., & Trejo-Téllez, L. I. 2018.** The role of beneficial elements in triggering adaptive responses to environmental stressors and improving plant performance. In: Vats S (Ed). Biotic and abiotic stress tolerance in plants. Springer Nature, Singapore, pp 137-172.
- [18] **Hocking, P. J., Randall, P. J., De Marco, D., & Bamforth, I. 1997.** Assessment of the nitrogen status of field-grown canola (*Brassica napus*) by plant analysis. Australian Journal of Experimental Agriculture, 37(1): 83-92.
- [19] **Hrubý, M., Cigler, P., & Kuzel, S. 2002.** Contribution to understanding the mechanism of titanium action in plant. Journal of Plant Nutrition, 25(3), 577-598.
- [20] **Hussein, Q. M., & Al-Bayati, A. S. 2025.** Impact of titanium dioxide on growth, yield and biochemical parameters of three eggplant genotypes under heat stress conditions. Plant Science Today. 12(4): 1-10.
- [21] **Jensen, E. S., Peoples, M. B., & Hauggaard-Nielsen, H. 2020.** Faba bean in cropping systems. Field Crops Research, 250, 107791.
- [22] **John, M. K. 1970.** Colorimetric determination of phosphorus in soil and plant materials with ascorbic acid. Soil Science, 109, 214-220. <https://doi.org/10.1097/00010694-197004000-00002>
- [23] **Khan, M. N., AlSolami, M. A., Basahi, R. A., Siddiqui, M. H., Al-Huqail, A. A., Abbas, Z. K., Siddiqui, Z. H., Ali, H. M. and Khan, F. 2020.** Nitric oxide is involved in nano-titanium dioxide-induced activation of antioxidant defense system and accumulation of osmolytes under water deficit stress in *Vicia faba* L. Ecotoxicology and Environmental Safety, 190, 110152. <https://doi.org/10.1016/j.ecoenv.2019.110152>
- [24] **Kleiber, T., & Markiewicz, B. 2013.** Application of “Tytanit” in greenhouse tomato growing. Acta Scientiarum Polonorum Hortorum Cultus, 12(3), 117-126.
- [25] **Lyu, S., Wei, X., Chen, J., Wang, C., Wang, X., & Pan, D. 2017.** Beneficial effects of titanium on the growth, photosynthetic activity, and antioxidant responses of tomato seedlings. Plant Physiology and Biochemistry, 119, 103-112.
- [26] **Ma, Y. B., Li, W. L., Li, J. H., Li, M. J., Li, X. Y., Wei, C. M., Li, C. X., Wang, Y., Zhao, Y., & Ma, X. R. 2025.** Titanium ions promote tomato growth and increase stress resistance. BMC Plant Biol., 25(1),995. doi: 10.1186/s12870-025-07077-6
- [27] **Muhammad, S. R., Al-Hassoon, S. N., & Dwenee, S. J. 2024.** A comparative study of organic and phosphate fertilizers with irrigation water quality on some soil properties and bean yield. Iraqi Journal of Agricultural Sciences, 55(1), 505-516.
- [28] **Negasa, G., Bedadi, B., & Abera, T. 2019.** Influence of Phosphorus Fertilizer Rates on Yield and Yield Components of Faba Bean (*Vicia faba* L.) Varieties in Lemu Bilbilo District of Arsi Zone, Southeastern Ethiopia. International Journal of Plant & Soil Science, 28(3), 1-11.
- [29] **Nguyen, T. K. L., Cho, K. M., Lee, H. Y., Sim, H. S., Kim, J. H., &**

- Son, K. H. 2022.** Growth, Fruit Yield, and Bioactive Compounds of Cherry Tomato in Response to Specific White-Based Full-Spectrum Supplemental LED Lighting. *Horticulturae*, 8(4), 319.
- [30] **Papakaloudis, P., & Dordas, C. 2023.** Phosphorus fertilization affects morphological, physiological and agronomic characteristics of faba bean cultivars. *Sustainability*, 15(17), 13172.
<https://doi.org/10.3390/su151713172>
- [31] **Rubio, G., Liao, H., & Yan, X. 2018.** Phosphorus efficiency in legume crops: A root perspective. *Plant Physiology*, 176(2), 1106-1116.
- [32] **Sarkar, S., Sarkar, A., & Zaman, A. 2017.** Effect of irrigation and phosphorus fertilization on growth, yield and nodulation of broad bean (*Vicia faba* L.). *Indian Journal of Agricultural Research*, 51(1), 69-73. doi: 10.18805/ijare.v51i1.7065
- [33] **Sarmiento, C., Daood, H., Pais, I., & Biacs, P. A. 1995.** Effect of titanium ascorbate on the lipoxygenase pathway of tomato and red pepper seedlings. *Journal of Plant Nutrition*, 18(6): 1291-1299.
- [34] **Schneider, K. D., Lynch, D. H., Voroney, R. P., & Dunfield, K. E. 2019.** Phosphorus dynamics in legume-based cropping systems: Implications for soil fertility management. *Agronomy Journal*, 111(5), 2347-2360.
- [35] **Schulze, J., Temple, G., Temple, S. J., Beschow, H., & Vance, C. P. 2006.** Nitrogen fixation by white lupin under phosphorus deficiency. *Annals of Botany*, 98(4), 731-740.
- [36] **Singh, J. 2018.** Folate content in legumes. *Biomed. J. Sci. Tech. Res.* 3, 3475–3480.
- [37] **Stone, A. K., Shi, D., Marinangeli, C. P. F., Carlin, J., & Nickerson, M. T. 2024.** Current review of faba bean protein fractionation and its value-added utilization in foods. *Sustainable Food Proteins*, 2(3), 101–124.
<https://doi.org/10.1002/sfp2.1028>
- [38] **Yang, F., Hong, F., You, W., Liu, C., Gao, F., Wu, C., & Yang, P. 2006.** Influences of nano-anatase TiO₂ on the nitrogen metabolism of growing spinach. *Biol Trace Elem Res*, 110(2), 179-190.
- [39] **Zhang, W., Zhu, Z., & Cheng, C. Y. 2011.** A literature review of titanium metallurgical process. *Hydrometallurgy*, 108, 177–188.
- [40] **Zhang, Z., Liao, H., & Lucas, W. J. 2014.** Molecular mechanisms underlying phosphate sensing, signaling, and adaptation in plants. *Journal of integrative plant biology*, 56(3), 192-220.