

SOIL MOISTURE AFFECTED THE IMPACT OF TITANIUM NANOPARTICLES ON DIFFERENT BARLEY GENOTYPES AT PARS-ABAD REGION

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Abstract: Climate change, along with decreased and irregular rainfall patterns, has greatly impacted cereal production systems like barley in semi-arid areas. The adoption of climate-resilient management strategies, including effective supplemental irrigation methods and the external application of stimulants of tolerance to abiotic stresses, can prove advantageous. A field study was aimed to assess the effects of foliar application of titanium nanoparticles across three irrigation strategies—rainfed, supplemental irrigation, and full irrigation on the grain yield of seven barley genotypes in a region of northern Ardabil, northwestern Iran. Compared to rainfed conditions, supplementary irrigation and full irrigation enhanced grain yield by 12% and 28%, respectively. The application of titanium nanoparticles via foliar spraying resulted in an average increase of 70 kg ha⁻¹ in grain yield compared to the control group. The highest grain yield (3816 kg ha⁻¹) was observed in the G7 genotype, which sprayed with titanium nanoparticles under optimal moisture levels, while the lowest yield was noted in the G1 genotype without irrigation and nanoparticle application (1386 kg ha⁻¹). The G7 genotype displayed the most significant response to supplemental irrigation. Additionally, the G7, G6, and G4 genotypes demonstrated a marked response to the application of titanium nanoparticles. These genotypes exhibited superior biomass and improved dry matter partitioning in economically important organs. Overall, the findings indicated that foliar application of titanium nanoparticles and the use of supplemental irrigation in conjunction with the high-yielding and tolerant genotypes G7, G6, and G4 can effectively support the barley production systems in semi-arid regions.

Keywords: biomass, genotypic response, nanoparticle spray, supplementary irrigation, water deficit stress, yield components.

INTRODUCTION

Increased greenhouse gas emissions and the expansion of climate change are among the reasons for prolonged drought stress in the semi-arid regions of West Asia and North Africa (WANA), leading to significant yield reductions in rainfed crops (Alotaibi, 2023). Semi-arid regions often experience precipitation below the long-term average, with scattered, unpredictable rainfall and considerable variation between years (Radwan *et al.*, 2025). Cool season cereals are considered key crops in these regions (Spalevic *et al.*, 2025). Barley is an important cereal adapted to water scarcity. In semi-arid regions, when rainfall decreases or drought occurs, farmers often plant barley instead of wheat (Savin *et al.*, 2022). The total global area under barley cultivation is estimated at about 46.2 Mha, with production estimated at 145 Mt. The main barley producers are Russia (23 Mt), Australia (14 Mt), France (11 Mt), Germany (11 Mt), Canada (10 Mt), and Turkey (8.5 Mt). Iran ranks fourteenth, with 3 Mha of cultivated area and 1.65 Mt of barley grain production (FAO, 2023). Although barley is used for malting industries in many countries, its main use in Iran is for animal feed. Given Iran's climate and fodder shortages, barley production is essential for the development of the livestock industry and the production of dairy and meat products. The average grain yield of barley under rainfed conditions is estimated at 1.1 t ha⁻¹ (Houshyar *et*

al., 2017). Meanwhile, the annual demand of Iran's growing livestock industry for barley is about 6 Mt, most of which is met through imports. Therefore, improving barley production is one way to enhance food security. Although barley is relatively resistant to water deficit stress, drought during sensitive reproductive stages reduces yield (Alasti *et al.*, 2022).

In semi-arid WANA climates, most precipitation occurs during the cold seasons, leaving reproductive stages exposed to periods of low rainfall and high temperatures. Water shortages during flowering, pollination, and grain filling stages significantly decrease yield (Janmohammadi *et al.*, 2017a). In these conditions, it is necessary to implement climate-smart agricultural management, such as irrigation during rainless months, to stabilize yield (Janmohammadi & Sabaghnia, 2023). Optimal irrigation scheduling, such as supplementary irrigation, can be effective. Supplementary irrigation provides partial amounts of water under rainfed conditions to plants during critical reproductive stages to maintain yield. These methods increase water efficiency compared to full irrigation (Martelli *et al.*, 2025). However, genotypes may respond differently to supplemental irrigation. Water deficit stress during the reproductive stages may reduce the fertility of late tillers; however, the contribution of these tillers to final yield varies depending on climatic conditions and genotype (Soleimani *et al.*, 2025).

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With the rise of the nanotechnology sector and its integration into diverse agricultural fields, significant progress is being achieved in post-harvest processes and associated industries. Recently, a key advancement has been the use of nanoparticles in foliar applications to enhance plant growth and activate defense mechanisms in response to drought stress (Yang *et al.*, 2025). Titanium dioxide nanoparticles notably boost drought tolerance by improving the plant's capacity to eliminate reactive oxygen species. In arugula (*Eruca sativa*), applying titanium nanoparticles to the leaves enhances the enzymatic antioxidant systems by promoting hydrogen sulfide production, ultimately resulting in improved drought resistance (Khan & Alzuaibr, 2018). Reports indicate that external use of titanium nanoparticles can enhance carbon assimilation during photosynthesis. Foliar application of titanium also improved root absorption efficiency, increased transport, and enhanced water use efficiency in plants. These effects may result from adjustments in intracellular redox state, increased antioxidant activity, reduced production of reactive oxygen species, changes in phytohormone levels, alterations in gene expression, improved fluidity and integrity of biological membranes, and better functioning of the photosynthetic electron transport chain (Tighe-Neira *et al.*, 2020; Rehman *et al.*, 2025; Nwachukwu *et al.*, 2025).

However, the response to external application of nano titanium varies significantly between genotypes. Additionally, the effect of nanoparticles changes under different moisture conditions. The goal of this experiment was to assess the impact of applying titanium dioxide nanoparticles to the leaves on the performance of various barley genotypes under different irrigation conditions in the semi-arid area of Pars Abad.

MATERIALS AND METHODS

Location characteristics

This study was conducted in the semi-arid, elevated area of Pars-Abad, located at latitude 39°36' N and longitude 46°46' E, with an elevation of 35 meters above sea level, during the 2023-2024 crop seasons. Pars-Abad is situated on a flat plain with a temperate to warm climate. As the northernmost city in Iran, it lies along the southern banks of the Aras River and borders the Republic of Azerbaijan. Climatically, the area is classified as semi-arid, with most rainfall occurring in the winter months. Total rainfall during the growing season (September-July) is estimated at 287 mm. The soil texture was loamy clay, its pH was in the neutral range (7.2) and it was slightly saline (EC: 2.2 ds m⁻¹). Fig. 1 shows the temperature and rainfall patterns for the region.

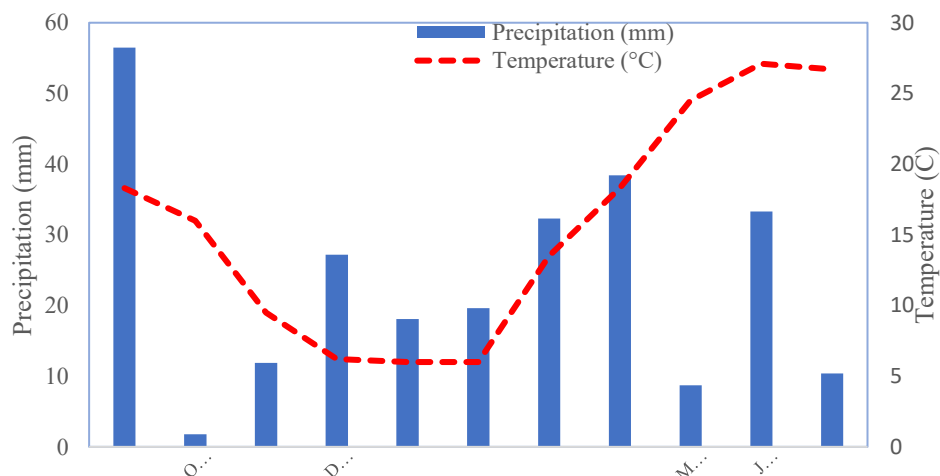


Fig. 1. Precipitation and monthly temperature in Pars-Abad during the growth season of 2023-2024.

Experimental design

The research was conducted using a split-split plot ($3 \times 2 \times 7$) design within a complete block framework, with three replications. Different irrigation strategies were assigned to the main plots: I1, representing rainfed or non-irrigated conditions; I2, involving irrigation applied twice during the flowering and seed setting phases; and I3, which maintained a consistently well-irrigated environment. To avoid moisture transfer between the main plots, a two-meter buffer zone was established. In the sub-plots, two levels of titanium nanoparticles were implemented. The fertilizer treatments were designated as N0: no titanium nanoparticles application (control), and N1: foliar application of titanium nanoparticles at a concentration of 20 ppm (Fig. 2). Foliar application of titanium nanoparticles was performed multiple times during

different growth stages of the barley plant, including stem emergence, early ear formation, and anthesis. Sub-sub plot plots with an area of 15 m² were allocated to 7 different barley lines (Table 1).

Conducting a field experiment

Following soil tillage and seedbed preparation in October, fertilizers containing phosphate and nitrogen were utilized, specifically triple superphosphate and urea, at application rates of 100 kg ha⁻¹ and 130 kg ha⁻¹, respectively. All phosphate was applied in a band during planting, while nitrogen was applied in multiple stages: during planting (band), stem elongation, and booting as a top dressing. Prior to sowing seeds on October 10, 2023, the field underwent plowing using a reversible moldboard plow and a two-way disc. The main plots were divided in the last week of September, with

fertilizer application occurring simultaneously with planting. 20 t ha⁻¹ of rotted farmyard manure, was mixed into the topsoil using a disk and rotary harrow. The manure's chemical composition consisted of 31.1% organic matter, a pH of 7.56, electrical conductivity (EC) of 3.61 ds m⁻¹, and nutrient levels of nitrogen at 1.98%, phosphorus at 0.92%, potassium at 2.03%, and calcium at 1.23%. Each experimental plot measured 5 × 3 meters and included 20 planting rows that were spaced 25 cm apart, with an intra-row distance of 3 cm. Titanium dioxide nanoparticles were obtained from Nanomaterials Pioneers Company, Mashhad, Iran, featuring a particle size of less than 100 nm and a purity exceeding 99%. Foliar application of S 20 occurred at the seven-leaf growth stage, during stem elongation, and

at spike formation, using a motorized hand sprayer. Throughout the spraying process, all sections of the plant were thoroughly wetted until droplets began to form and drip from the leaves. Irrigation for supplementary irrigation or full irrigation plots was provided by well water and distributed over the soil surface by gravity.

Seven barley varieties (G1–G7), bred to enhance grain yield, were sourced from the Grains Division of the Seed and Plant Improvement Institute and assessed in this research. Weeds were manually managed once during the vegetative growth phase in the autumn. Manual weed control was conducted twice more during the stem elongation and tillering stages.

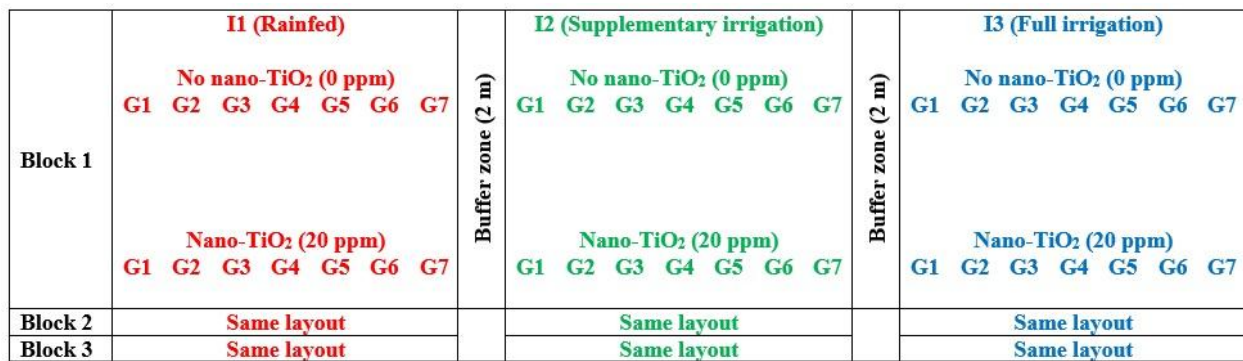


Fig. 2. Diagram of experimental design, three irrigations were applied with nano-TiO₂ (0 and 20 ppm) and seven barley genotypes.

Table 1.
The code and pedigree of barley genotypes

Code	Pedigree
G1	CBSS05M00256S-2M-0Y-0M-0AP-0TR
G2	ICB86-0512-1AP-0TR-4AP-0TR-0AP
G3	ICB95-0204-0AP-16AP-0AP-4AP-0AP-9AP-0AP
G4	LBIRAN/UNA80//LIGNEE640/6/Vmorales
G5	ICB08-0124- OAP - OG-OG-OG- 5G
G6	CBSS05M00680D-K-2M-0M-0AP-0TR
G7	ICB09-1436-0AP-0TR-0AP-0TR-0AP-0TR

Data collection and Statistical analysis

At the stage of physiological maturity, indicated by the browning of the heads, plants were randomly collected using 1 m² quadrats within the experimental plots. Measurements were taken for plant height, spike count, total tillers per plant, and the number of fertile tillers. The plants were then dried in an oven set to 70°C, after which the aboveground biomass was weighed, whereas the moisture content of seeds was 11%. Following the grinding and separation of the seeds, yield per unit area was determined. Data variance analysis for the traits under evaluation was conducted using SAS software. The means were compared using the LSD test at a significance level of 5%. Principal component analysis was carried out with Minitab software. Fig.s and box plots were generated using Excel and SPSS software.

RESULTS

The results of the ANOVA are presented in Table 2. Comparisons of the effects of the evaluated factors on agronomic traits and barley yield components showed that irrigation and genotype had more significant effects than the titanium nanoparticles foliar spray treatment. However, in addition to the main effects, interaction effects between factors were statistically significant for some traits. The assessment of plant height revealed that both the irrigation regime (I) and genotype (G) had significant main effects at the 1% level, while the influence of titanium nanoparticles (N) was significant at the 5% level. Supplementary irrigation (SI) and full irrigation (FI) respectively enhanced plant height by 6% and 12% when compared to rainfed (RF) conditions.

Table 2.

The effect of externally applied titanium nanoparticles on yield components of various barley genotypes under different irrigation regimes in Pars-Abad, Iran

Effects	PH	SL	NS	NFT	TSW	SY	AGB	STY
Irrigation								
RF	87.61c	6.49b	61.59c	2.29b	32.89c	2242.2c	7779.0b	5536.8b
SI	93.24b	6.66b	64.60b	2.30b	34.29b	2506.2b	8142.7b	5636.5 b
FI	98.09a	7.07a	73.91a	2.49a	35.76a	2864.1a	8822.2a	5958.0a
Foliar spay								
N0	91.93b	6.75a	65.46b	2.32a	34.10b	2504.7b	8203.0a	5698.2a
N1	94.02a	6.73a	67.97a	2.36a	34.43a	2570.2a	8292.8a	5722.5a
Genotypes								
G1	86.11d	6.51b	60.11c	2.25b	31.01e	1775.0f	5736.3f	3961.3e
G2	87.75cd	6.45b	62.86bc	2.24b	32.72d	2241.9e	6571.5e	4329.6d
G3	90.42c	6.40b	66.28b	2.55a	34.12c	2587.5c	9070.2c	6482.7b
G4	91.08c	6.63b	64.00bc	2.35b	34.80bc	2441.7d	7782.1d	5340.5c
G5	96.75b	7.17a	64.25bc	2.11c	34.31bc	2581.6c	8962.5c	6380.9b
G6	98.39ab	7.07a	73.11a	2.47a	35.19b	2948.1b	9579b	6631ab
G7	100.38a	6.97a	76.39a	2.56a	38.07a	3186.9a	10033.9a	6847a
statistical levels								
I	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.0004
N	0.0232	0.6931	0.1949	0.7321	0.3617	0.0194	0.37	0.7775
G	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
N×G	0.8082	<.0001	0.5026	0.5124	0.0141	<.0001	<.0001	<.0001
I×N	0.1429	0.1407	0.1236	0.0528	0.1606	0.3774	0.5116	0.5364
I×G	0.0835	<.0001	0.0005	0.0001	0.0001	<.0001	<.0001	<.0001
I×N×G	0.2839	<.0001	0.0242	0.0003	0.0002	<.0001	<.0001	<.0001

RF indicates rainfed, SI denotes supplemental irrigation, FI represents full irrigation, N0 refers to foliar application with distilled water, and N1 signifies the application of titanium nanoparticles. G1-G7 corresponds to the seven lines investigated in the experiment. PH stands for the height of the plant measured in cm, SL indicates the length of the spike, NFT represents the number of fertile tillers, TSW refers to the weight of a thousand seeds in grams, NS signifies the count of seeds per spike, AGB stands for above-ground biomass measured in kg ha⁻¹, STY denotes straw yield in kg ha⁻¹, and SY refers to grain yield in kg ha⁻¹. In each column, means that have the same letter are not statistically significantly different at the 5% level. The bottom rows of the table present F values. Values less than 0.01 and 0.05 indicate statistical significance at the 1% and 5% levels, respectively.

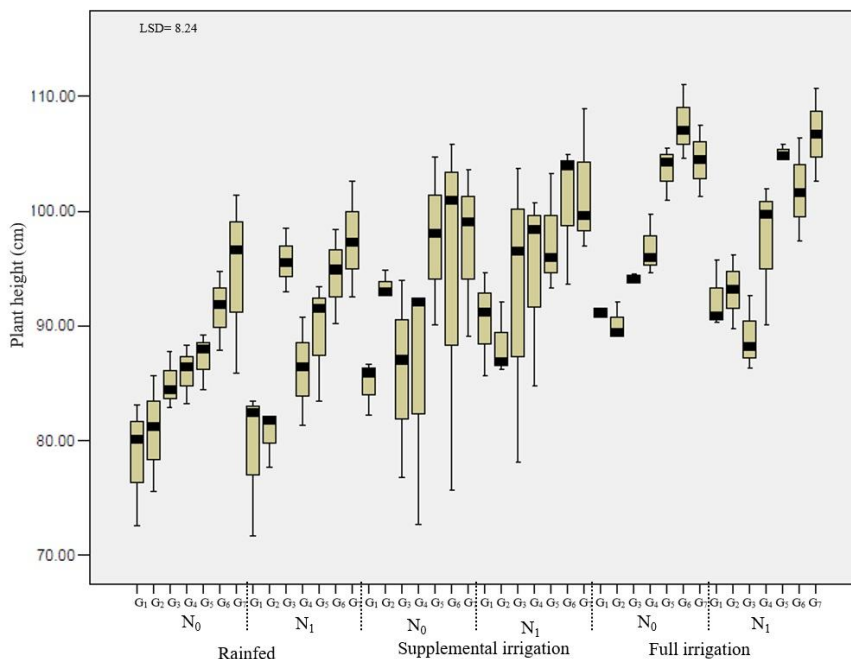


Fig. 3. Mean assessment of barley genotype plant heights under the effects of titanium dioxide nanoparticle foliar spray treatments and different irrigation methods in the Pars Abad area of northwest Iran. G1 to G7 refer to different barley lines. N0: foliar spraying with distilled water without nanoparticles, N1: foliar spraying of plants with a solution containing titanium nanoparticles. Boxes showing differences greater than the least significant difference (LSD) indicate a statistically significant difference at the 5% level.

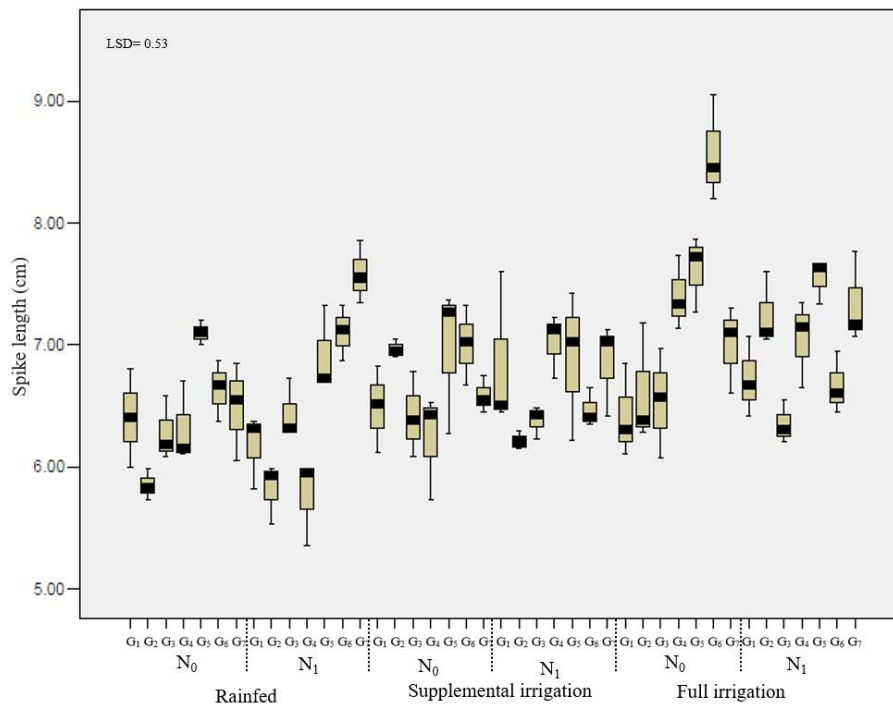


Fig. 4. Evaluation of spike length in various barley genotypes under different irrigation regimes and foliar application of titanium nanoparticles in northwest Iran.

The application of titanium nanoparticles through foliar spray resulted in a 3% increase in plant height. Among the different genotypes, the tallest plants were recorded in G7 (100.3 cm), G6 (98.3 cm), and G5 (96.75 cm) (Fig. 3). The use of titanium foliar spray was found to be more effective in boosting plant height under FI conditions than under other irrigation methods. Spike length evaluation showed that supplementary and full irrigation increased this component by 3% and 9%, respectively, compared to rainfed conditions. However, foliar application of titanium nanoparticles had no

significant effect. The longest spikes were recorded in G5, G6, and G4. The interaction effect of $I \times N \times G$ was significant for spike length. The longest spikes were observed under FI+N0+G7 (8.56 cm) and FI+N0+G6 (7.62 cm). Under RF conditions, foliar application of titanium nanoparticles increased spike length in G7, G6, and G5. However, under FI conditions, foliar application of titanium nanoparticles, especially for G6, decreased spike length. The shortest spikes were observed in RF+N1+G4 (5.75 cm) and RF+N1+G2 (5.81 cm) (Fig. 4).

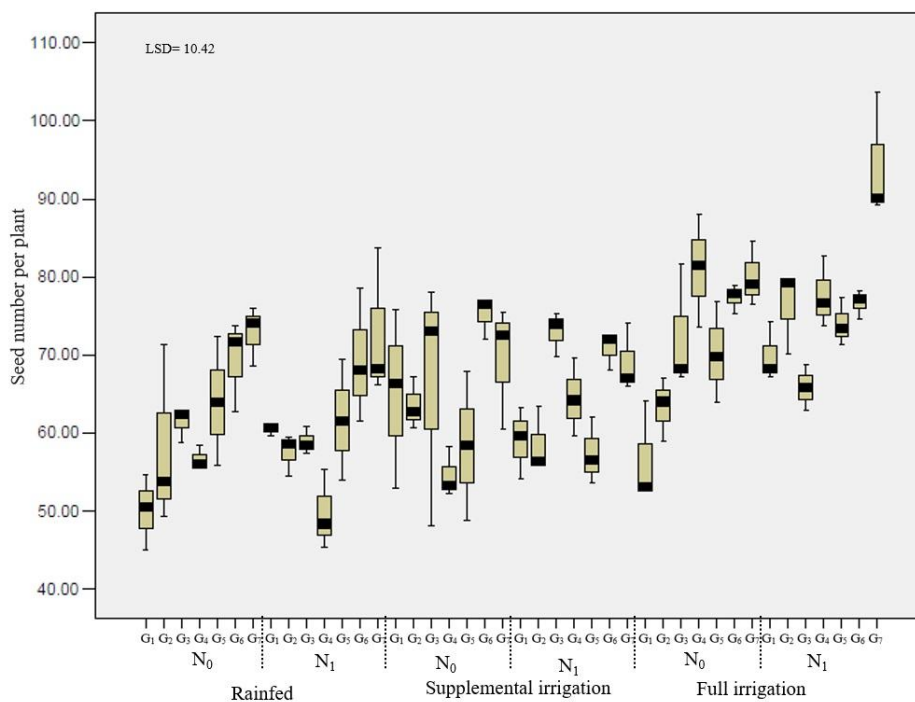


Fig. 5. Foliar application of titanium nanoparticles under different irrigation regimes on the number of seed per plant in different barley lines in the Pars Abad region in northwestern Iran.

Evaluation of the number of fertile tillers per plant (NFT) showed that the interaction effects of $I \times N \times G$ were significant at the 1% level. The highest NFT values were recorded in FI+N1+G7 (2.93), SI+N1+G3 (2.75), and FI+N0+G7 (2.73). The lowest NFT values were observed in RF+N0+G1 (1.90) and SI+N0+G5 (1.98). The grain number analysis showed that the interaction effects of $I \times N \times G$ were significant at the 5% level. Foliar application of nano-titanium under RF conditions reduced grain number, especially in G4. However, under FI conditions, foliar application significantly increased grain number, with this trend more pronounced in G7. The highest grain numbers were recorded in FI+N1+G7 (94.33) and FI+N0+G4 (81), while the lowest were observed in RF+N1+G2 (57.00) and RF+N0+G2 (58.1) (Fig. 5).

Grain yield (SY) increased with greater water supply, with SY rising by 11% and 27% under full irrigation (FI) and supplementary irrigation (SI) conditions, respectively, compared to rainfed (RF) conditions. Foliar application of titanium nanoparticles increased SY by 3%. The highest SY among the genotypes was recorded in G7 (3189 kg ha⁻¹) and G6 (2948 kg ha⁻¹). The lowest SY was observed in G1 (1775 kg ha⁻¹). Comparison of mean SY for the interaction effects of irrigation, nanoparticle application, and genotype ($I \times N \times G$) showed the highest values under FI+N1+G7 (3816 kg ha⁻¹) and FI+N0+G7 (3521 kg ha⁻¹). Foliar application of titanium nanoparticles under RF conditions significantly reduced SY. However, G6

showed a significant increase with foliar application. Water supply through supplementary or full irrigation significantly increased SY in G7 compared to RF conditions. Foliar application of titanium nanoparticles under SI conditions in G6 resulted in a significant increase in SY (Fig. 6).

Improving soil moisture content by increasing irrigation frequency increased the thousand seed weight (TSW). TSW increased by 9% and 4% under FI and SI conditions, respectively, compared to rainfed conditions. Foliar application slightly increased seed weight. Comparison of means for the interaction effects $I \times N \times G$ showed that the highest TSW was recorded in FI+N1+G7 (41.65 g) and SI+N0+G7 (39.17 g). The G1 genotype had the lightest seeds (29.76 g), and TSW in this genotype responded significantly to moisture regimes and remained stable. The highest biomass was recorded in FI+N1+G7 (11,965 kg ha⁻¹) and SI+N0+G7 (11,265 kg ha⁻¹). These results indicate that under supplementary irrigation, genotype G7 without foliar spraying of titanium nanoparticles showed the best biomass production. The lowest biomass response to supplementary irrigation was recorded in G2. The highest share of straw production under RF conditions was observed in G3 and G5. Under supplementary irrigation, the highest share of straw production was recorded in G4 and G3. The lowest amounts of straw were recorded under SI+N1+G4 (3,866 kg ha⁻¹) and SI+N1+G2 (3,883 kg ha⁻¹).

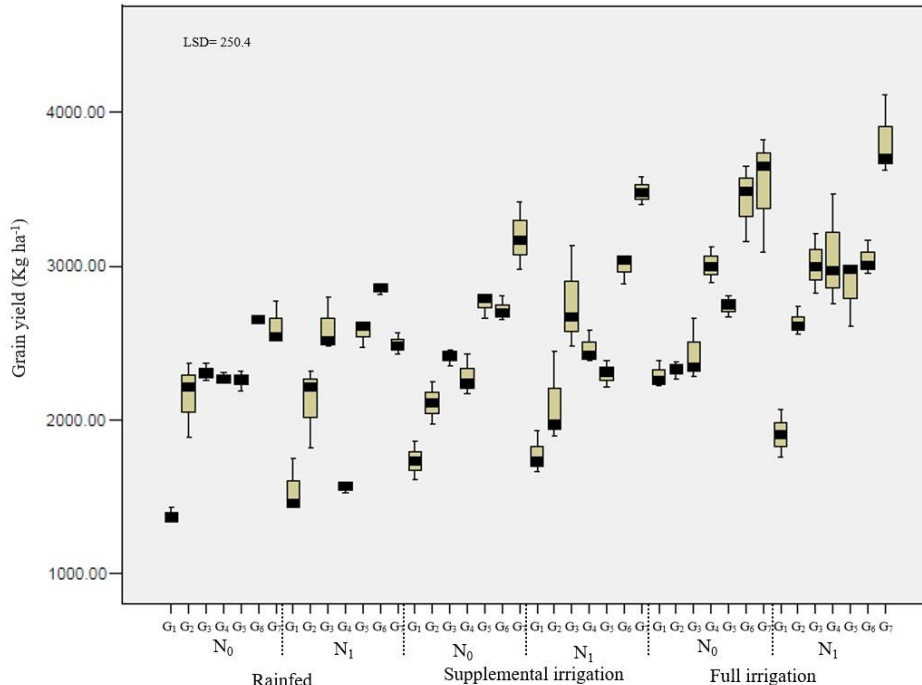


Fig. 6. Grain yield of different barley lines under different irrigation conditions and foliar spraying with titanium nanoparticles in Pars Abad region, northwest Iran. G1 to G7 refer to different barley lines. N0: foliar spraying with distilled water without nanoparticles, N1: foliar spraying of plants with a solution containing titanium nanoparticles. Boxes showing differences greater than the least significant difference (LSD) indicate a statistically significant difference at the 5% level.

The PCA plots are illustrated in Fig. 7. The first component was somewhat able to distinguish between the moisture regimes. The close proximity of the RF treatment combinations in the plot suggests that

differences resulting from foliar application of titanium nanoparticles or genotypic variations due to moisture stress did not manifest. However, within RF conditions, genotypes G7 and G5 were notably distant from the rest.

These genotypes showed the most favorable performance under dryland conditions. Conversely, G3 and G4 typically exhibited the lowest performance under RF conditions when titanium nanoparticles were not sprayed. Nevertheless, the application of foliar spraying under RF conditions did not significantly influence many genotypes. The second component also effectively differentiated the top treatment combinations regarding growth and yield metrics. The highest levels of growth and yield were achieved in G7 and G6 under FI conditions with the application of titanium nanoparticles.

DISCUSSION

The results of the experiment showed that irrigation regimes had a significant effect on all evaluated traits. The studied region has a semi-arid climate with limited rainfall from the beginning of the reproductive stages to the physiological maturity of the crop (May to July). During this period, the highest temperatures in the region occur from June to August. The rate of

evapotranspiration was estimated at about 500 mm during May to July (Fazeli Khiavi *et al.*, 2020). These data highlight the necessity of providing water through irrigation during the final stages of development in rainfed production systems. This explains why barley yield under rainfed conditions was very low in the region. Most precipitation in this region falls in winter, from October to March. Therefore, vegetative growth of the plant was not greatly limited. Even under these conditions, plants can produce many reproductive primordia due to favorable vegetative growth, but as air temperatures rise and rainfall decreases in the following months, low water availability causes many primordia to be lost or the formed yield components to be severely reduced. However, full irrigation during the post-sowing and vegetative stages up to flowering can also result in significant moisture loss. Given the 280 mm of rainfall during barley growth, some irrigations can be eliminated in full irrigation systems, thereby improving water use efficiency. Considering climate change and the reduction of water resources in the region, implementing this approach will be necessary in the near future.

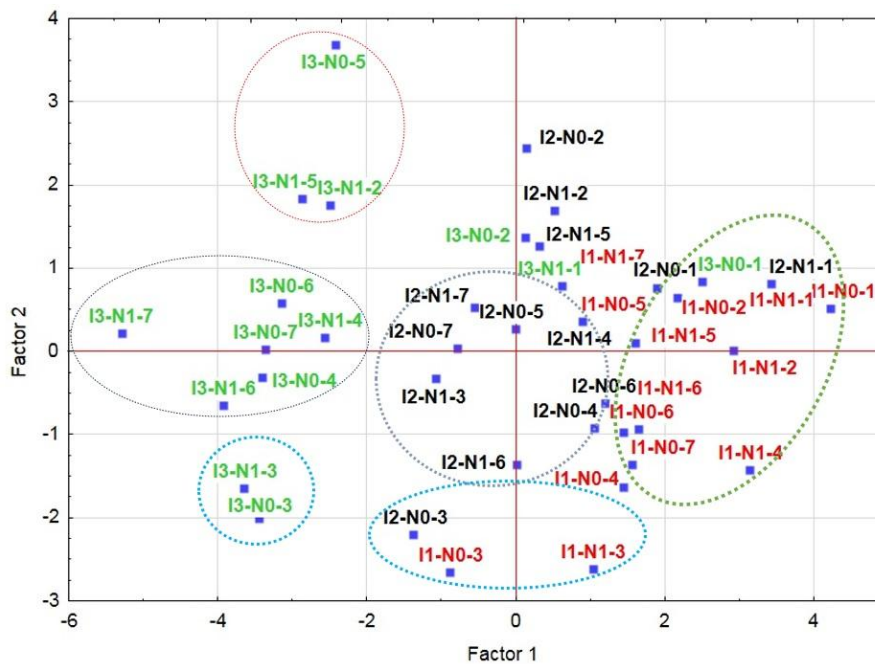


Fig. 7. The scatter plot illustrating the first and second principal coordinates was derived from various combinations of treatments, which included different irrigation methods and varying levels of foliar application of titanium nanoparticles, across seven lines of barley in the Pars Abad area of northwest Iran. I1 denotes conditions without irrigation (red), I2 indicates supplementary irrigation (black), and I3 signifies complete irrigation (green). N0 represents the application of distilled water for foliar treatment, while N1 indicates the use of titanium nanoparticles. 1 through 7 refer to the seven barley lines investigated in the study.

The response of the evaluated traits to foliar application of titanium nanoparticles varied under different moisture conditions. With external application of titanium nanoparticles, spike length increased slightly under rainfed conditions, while this effect was not observed under full irrigation. Titanium nanoparticles can enhance photosynthetic efficiency and light use efficiency by increasing light absorption. External application of these nanoparticles can improve nutrient absorption and increase the activity of light-exposed enzymes. Foliar application of titanium nanoparticles

increases nitrogen assimilation, thereby boosting biomass production (Bhatti *et al.*, 2025). In this study, titanium nanoparticles were applied to the foliage. However, previous findings have shown that titanium nanoparticles deposited on the soil surface can increase the availability of elements such as phosphorus (Rehman *et al.*, 2025). These findings confirm our previous results regarding the application of titanium nanoparticles. Our earlier results in barley showed that titanium nanoparticles increased grain yield and biomass in a semi-arid region by increasing leaf

greenness and altering phenological stages (Janmohammadi *et al.*, 2017). Foliar application of titanium nanoparticles to safflower increased head diameter, harvest index, and grain yield under low soil moisture conditions in a semi-arid region (Aminian *et al.*, 2017; Janmohammadi *et al.*, 2017b). However, the results of this study showed that the effect of titanium nanoparticle application under full irrigation and supplementary irrigation was more prominent than rainfed conditions. It appears that under rainfed conditions, due to water deficiency, intracellular condensation, stomatal closure, cuticle thickening, and increased waxiness of the outer leaf coatings, the effects of foliar application of titanium nanoparticles were not fully expressed (Rehman *et al.*, 2024). Under mild drought stress, however, titanium nanoparticles likely exerted positive effects by stimulating defense systems and increasing antioxidant activity. Genotype also had a significant effect on most of the studied traits. These results are consistent with the findings of Spalevic *et al.* (2022) and Kheyrikhah *et al.* (2018), who reported that the response of rapeseed genotypes to silicon and titanium nanoparticles differed. Genotypic differences in response to foliar spray treatments with titanium nanoparticles or to different irrigation regimes are likely due to variations in defense mechanisms against water deficit stress, such as photosynthesis rate, root water absorption ability, efficiency of water transport and distribution in vascular systems, stomatal function, water use efficiency, growth rate, and tolerance to late-season heat. Differences in response to nanoparticles may also result from variations in stomatal number, stomatal size, leaf area, cuticular wax content, ease of nanoparticle absorption through cuticular coatings, and the transport of nanoparticles to target sites in different cellular parts or plant organs. The results showed that genotypes G7, G6, and G5 performed better under water deficit conditions and with external application of titanium nanoparticles. These lines can be used in advanced breeding programs. Supplementary irrigation with partial water supply significantly prevented yield loss. Additionally, under supplementary irrigation, the effectiveness of titanium nanoparticles in improving plant growth was greater than under rainfed conditions. It has also been reported that partial water supply through supplementary irrigation increases the effectiveness of foliar spray treatments that stimulate defense systems (Janmohammadi *et al.*, 2024).

CONCLUSIONS

Climatic data for the barley growing season indicated that the Pars Abad region does not receive enough annual rainfall for successful rainfed barley cultivation. Additionally, high air temperatures during the spring increase evapotranspiration, worsening soil moisture deficiency. The results showed that supplementary irrigation significantly increased grain yield compared to rainfed conditions. However, there was no significant difference in biomass between supplementary and rainfed treatments. Irrigation during critical reproductive stages improved yield components, but the difference between supplementary and full irrigation was substantial. Genotypes responded

differently to foliar application of titanium nanoparticles. External application of nano titanium to lines 7, 3, and 5 increased yield under rainfed conditions. Lines 7, 6, and 3 performed best under full and supplementary irrigation. The findings indicate that foliar spraying of titanium nanoparticles and supplementary irrigation, combined with compatible lines such as 7, 3, 6, and 5, can reduce yield losses caused by drought and reduced rainfall.

AUTHORS CONTRIBUTIONS

Conceptualization: M.J. and H.G.H.; methodology, H.G.H. and A.E.S.; data collection H.G.H. and A.E.S.; data validation, N.S., A.E.S. and P.N.S.; data processing N.S.; writing—original draft preparation, N.S. and M.J.; writing—review and editing, M.J. and N.S.

FUNDING

This research received no external funding.

CONFLICT OF INTEREST

The authors declared no conflict of interest.

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