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EFFECTS OF NANO-FOLIAR NUTRITION ON GROWTH AND YIELD OF BARLEY CULTIVARS IN SOUTHERN IRAQ

Ali R. Alhasany [1], Ali H. Noaema [1], Dunya S. Mohammed [2], Mustafa A. Manshood [3], Ayda Swadi Fatnan [1], Dhurgham S. K. Altai [4], Alexandra Hanász [5], Nóra Mendler-Drienyovszki [5], Waleed A. E. Abido [6]

Department of Field Crops, College of Agriculture, Al-Muthanna University, Al-Muthanna, 66001 Al-Samawah, Iraq 1
University of Misan, College of Pharmacy, Pharmacognosy and Medicinal plants branch, Iraq 2
Department of Soil and Water Resources, College of Agriculture, Al-Muthanna University, Al-Muthanna, 66001 Al-Samawah, Iraq 3
Department of Plant Protection, College of Agriculture, University of Misan, Amarah 62001, Iraq 4
Research Institute of Nyíregyháza, Institutes for Agricultural Research and Educational Farm (IAREF), University of Debrecen, P.O. Box 12, 4400 Nyiregyhaza, Hungary 5
Department of Agronomy, Faculty of Agriculture, Mansoura University, Mansoura 35516, Egypt 6

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Correspondence Email:
hanasz.alexandra@agr.unideb.hu

ABSTRACT

The study aims to determine the optimal concentration of nano-microelements in a two-year (2021–2023) field experiment that maximizes crop yield and quality, as well as to understand the interactions between individual barley varieties (‘Buraq’, ‘Aba 99’, and ‘Aba 265’) and the applied concentrations of nano-microelements. This study also aims to develop variety-specific nano-fertilization protocols for sustainable barley production. A randomized complete block design with three replications was implemented as a split-plot design. Treatments consisted of foliar application of nano-micronutrient fertilizers containing B, Cu, Fe, Mn, Zn, and Mo at 0 (control), 1 g L^{-1}, and 2 g L^{-1}. Results showed that the number of spikes m^{-2}, the number of grains per spike, and the grain yield of each cultivar increased significantly with treatments. The 2 g L^{-1} treatment produced the largest increase in yield (from 3.7 to 4.2 t ha^{-1} for ‘Buraq’; from 4.2 to 4.9 t ha^{-1} for ‘Aba 99’; and from 4.7 to 5.6 t ha^{-1} for ‘Aba 265’). Genotypic differences were also observed; ‘Aba 265’ consistently produced the greatest number of spikes per unit area and the highest final yield. These findings demonstrate how the use of both application rates of the foliar nano-micronutrients significantly improves nutrient use efficiency and overall productivity of barley grown under low soil micronutrient supply.

College of Agriculture and Forestry, University of Mosul.

INTRODUCTION

Meeting the nutritional requirements of a rapidly growing global population is one of the greatest challenges of the 21st century. Since climate change will affect nutrition by altering the environment we grow food in through changes in temperature (increased range and occurrence) as well as heat waves, drought stress, and soil degradation all causing issues with agricultural production, and thereby food security and quality (Christian *et al.*, 2023; Altai *et al.*, 2024). With arable land becoming more limited, and land use pressures increases, improving the productivity and resilience, while ensuring the stability of agricultural land is essential for sustaining global food security (Wang *et al*., 2019). New approaches to modern agriculture are being explored that not only improve yield but also increase the efficiency of using resources and are sustainable for the environment (Tilman *et al*., 2022; Afonso *et al*., 2022). Of the various methods employed, the nanotechnology-based delivery methods have gained relevance, as they can provide a more effective and sustainable means of delivering nutrients (Quintarelli *et al*., 2024).

Iraq, historically known as one of the centers of early agriculture, is impacted by saline soil, drought, and micronutrient deficiencies (especially zinc and manganese) in the high pH and calcareous soil of the central and northern governorates. Within the Nineveh and Salahuddin provinces—major barley-growing areas—average barley yields have decreased by 25-40% since 2015, due in part, to land degradation, erratic rainfall patterns, and the low efficiency of fertilizer (Howell *et al*., 2015; Zahra *et al*., 2022). Such conventional (soil-applied) sources of micronutrients are subject to significant fixation (>80%), resulting in only <15% of the micronutrients being available to crops at the end of the growing cycle, making it increasingly costly for resource-limited farmers to purchase these inputs (Ernst *et al*., 2023). These issues create an immediate need for new fertilization approaches specifically designed for degraded/semi-arid agroecosystems in these regions.

Nano-fertilizers represent an innovative alternative to conventional fertilizers by using small sized particles which can improve the efficiency of nutrient uptake by the plant and decrease the amount of fertilizers lost to the environment (Kah *et al*., 2013). Recent literature reviews and research have shown that nano or nano-enabled nutrients can enhance nutrient use efficiency (NUE), decrease nutrient leaching, synchronize nutrient release with crop demand, and reduce the environmental impact of using fertilizers (Kah *et al*., 2019; Bouhadi *et al*., 2025). Nanotechnology may also provide crops with greater tolerance to drought, salinity, and other non-biological stressors (i.e., abiotic) that are increasing in prominence in Iraq's cereal production regions (Azameti and Imoro, 2023). Nevertheless, sustainability assessments must account for potential ecological risks, as high doses or prolonged exposure to certain nanomaterials can affect soil microbial communities and ecosystem functioning (Chen *et al*., 2014). Responsible, field-based evaluation under real agro-ecosystem conditions is therefore essential before large-scale adoption.

Barley (*Hordeum vulgare* L.) is one of the oldest and most important winter cereal crops worldwide (Newton *et al*., 2011). Its grains contain up to 9.9% protein, as well as dietary fibres, vitamins, and amino acids. The crop's significance stems from its nutritional applications in various industries and starch production (Zainab *et al*., 2022). In Iraq, barley is strategically important to rural farmers and national food and feed security, especially in semi-arid, rain-fed areas of the country where barley is adaptable, providing farmers with a more reliable crop than other cereal grains. The growth and yield of barley are closely affected by the amounts of macro- and micronutrients present in the soil. As for other plants, deficiencies of micronutrients in barley can lead to several physiological disorders including decreased photosynthesis, inhibition of chlorophyll synthesis, inhibition of root growth, and decreased tolerance to biotic and abiotic stress (Hajiboland, 2012).

Foliar fertilization is widely used to supply micronutrients during critical growth stages when nutrient availability from the soil may be limited. Recent advances in nanotechnology have led to the development of nano-micronutrient fertilizers, which may enhance nutrient delivery and improve plant performance under challenging environmental conditions (Kah *et al.*, 2019; Quintarelli *et al.*, 2024). Several studies have reported positive effects of nano-fertilizers on crop growth, productivity, and tolerance to abiotic stress, although responses often vary depending on crop species, cultivar, environmental conditions, and application rate (Azameti & Imoro, 2023; Bouhadi *et al.*, 2025). Despite global interest in nano-micronutrient fertilizers, research on their field-scale application in barley remains limited, and some studies to date have evaluated nano-micronutrient foliar sprays on barley under Iraq's semi-arid, saline-soil conditions. Similarly, while micronutrient and foliar fertilization trials exist for barley elsewhere, there is a lack of genotype-specific assessments involving locally cultivated Iraqi barley cultivars. This knowledge gap is particularly important because cultivar × environment × nutrient interactions strongly determine yield stability in stress-prone agro-ecosystems.

Although research on nano-micronutrients in barley is advancing, field-scale datasets from micronutrient-deficient regions remain limited. Therefore, the aim of this study is to assess the effect of spraying with different concentrations of nano-microelements on the growth and yield of three barley varieties (cv. 'Buraq', cv. 'Aba 99', cv. 'Aba 265'). The study aims to determine the optimal concentration of nano-microelements that maximizes yield and quality of crops, as well as to understand the interactions between individual barley varieties and the applied concentrations of nano-microelements. This study also aims to develop variety-specific nano-fertilization protocols for sustainable barley production. By addressing critical knowledge gaps, this research contributes to the development of environmentally responsible fertilization strategies, advances understanding of plant nutritional responses to nano-micronutrients and supports the improvement of barley productivity in Iraq's climate-vulnerable agricultural systems.

MATERIALS AND METHODS

Description of study Site and the main climate and soil characters

Field experiments were conducted during 2021-2022 (Season 1) and 2022-2023 (Season 2), over two barley growing seasons on a farm field in the Rumaitha district, 25 km north of Al-Muthanna Province. The field's location geo-coordinates were latitude 31.586142° N and longitude 45.169756° E (Fig 1). The main meteorological characteristics of the experimental site are summarized in Table 1. Weather data was taken from the General Authority of Meteorology / Muthanna weather station.

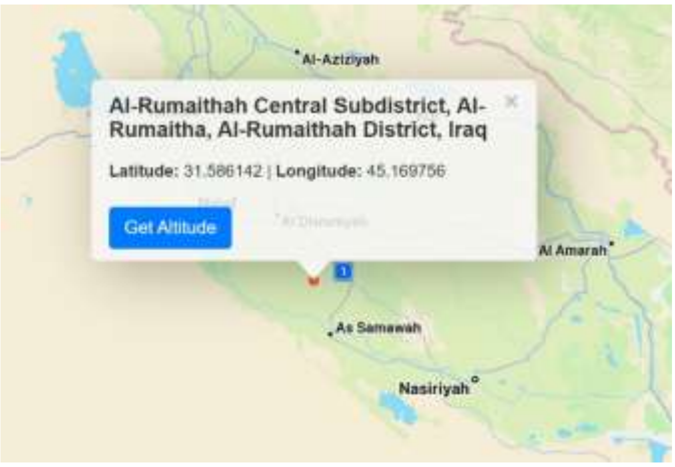

Figure 1. Study site map location (https://www.google.com/maps)

Table 1. A summary of annual total precipitation (mm), average temperature (^{0}C), and average total monthly solar radiation (Mj m^{-2}) through the barley growing season (2021/2022 and 2022/2023).

	Barley Growing Season						
Growing seasons	November	December	January	February	March	April	
	Precipitation (mm)						Average
Season 1	109.3	89.0	56.0	15.4	0.9	1.0	271.6
Season 2	111.3	90.0	49.0	12.1	1.0	1.3	264.7
	Average Temperature (°C)						Average
Season 1	17.8	14.3	12.5	16.2	22.8	24.7	18.0
Season 2	17.3	14.8	11.5	13.7	16.9	22.2	16.0
	Total monthly solar radiation (Mj m^{-2})						Average
Season 1	11.3	11.0	13.9	14.1	22.1	23.0	15.9
Season 2	11.3	11.0	10.7	15.4	20.2	24.3	15.5

The soil type of the experimental plots was silty clay loam, and samples were collected from the experimental field before planting at the depth of 0 to 30 cm and then analysed in the laboratory of College of Agriculture, Al-Muthanna University for chemical and physical properties as shown in Table 2 (see Appendix A). Plant residues were removed prior to soil sample collection after which air drying the soil allowed for grinding to produce particles smaller than 2 mm. The sieved dried ground soil has been thoroughly mixed to produce representative samples for further physical and chemical analyses.

Plant material

The barley varieties used for the study were obtained from the General Authority of Seed Testing and Certification-Muthanna Governorate. These varieties are certified in Iraq and are characterized by the following. ‘Buraq’ barley variety is known for its good yield and grain quality. It has good resistance to diseases and drought, and has very good adaptability, so it is suitable for cultivation in various regions. ‘Aba 99’ has high yield, and the seed has good quality. It is tolerant to different diseases and extreme weather conditions, so it is suitable for cultivation in various environments. ‘Aba 265’ is a high-yielding, disease tolerant barley variety. It has good grain quality and is suitable for various uses. It is suitable for cultivation in regions with different environmental conditions. These barley varieties are characterized by their unique characteristics and can be adapted to various agricultural needs.

Table 2. Main physical and chemical characteristics of the soil collected from the experimental field (0–30 cm depth) in averages of both growing winter seasons.

Soil characters	**Measured values**
pH	7.65
Electrical Conductivity (ds m^{-1})	4.85
Cation Exchange Capacity (cm (+) kg $^{-1}$)	20.8
Available Nitrogen (mg kg^{-1})	24.95
Available Phosphorous (mg kg^{-1})	8.8
Available Potassium (mg kg^{-1})	141.5
Organic Matter (%)	0.65
Clay (g kg^{-1})	383.5
Sand (g kg^{-1})	424
Silt (g kg^{-1})	192.5

Experimental and Treatment Design

The experiment was conducted as a split-plot arrangement within a randomized complete block design (RCBD) with three replications. Barley cultivars (‘Buraq’, ‘Aba 99’, and ‘Aba 265’) were assigned to the main plots, while nano-micronutrient foliar application treatments (0, 1, and 2 g L^{-1}) were assigned to subplots within each replication. Each block was divided into nine experimental units, resulting in a total of 27 plots (Fig 2). Each plot measured 2 × 2 m², with 1 m spacing between plots. Each experimental unit consisted of 10 rows spaced 20 cm apart.

Figure 2. Study site experimental plots of barley crop near Al-Rumaitha District (Al-Muthanna Province, Iraq), during crop growth for Season 1 (2021-2022) and Season 2 (2022-2023).

Agricultural Practices

Before planting, phosphorus and potassium were applied in the form of high-phosphorus (21% phosphorus) triple superphosphate fertilizer and high-potassium (42% potassium) potassium sulfate fertilizer, respectively. Nitrogen was applied as urea fertilizer (46%) at 120 kg ha^{-1} in two doses, the first dose 15 days after planting and the second dose one month later, at constant rates in each experimental unit. Barley was sown on 11/02/2021 for the first season and on 11/03/2022 for the second season. Agricultural practices were performed as needed throughout the growing period. The experimental field was irrigated six times during the growing season from the Euphrates River. Spraying was carried out at the seedling stage using a nano-nutrient fertilizer containing a mixture of nanoelements including boron (0.2%), copper (0.5%), iron (6%), manganese (6%), zinc (6%) and molybdenum (0.2%). Spraying was carried out in the evening (following the manufacturer's recommendations for dosage and application time and for the use of pesticides to minimize environmental and human health risks) with a knapsack sprayer, at two different concentrations (1 g L^{-1} (T1) and 2 g L^{-1} (T2)), and a dispersant was added to increase the efficiency of the spray solution, ensure complete wetting of the leaves and reduce the surface tension of the water. Fertilization, spraying and other mechanical work carried out in the experiment generally comply with the principles of good agricultural practice. All varieties were harvested at full maturity stage, following the comprehensive guidelines of the improved agricultural practices package for barley production.

Growth Characteristics Studied

Several agronomic parameters were assessed to evaluate the growth and productivity of the barley cultivars. Plant height was measured – using a metric measuring tool – by randomly selected ten plants from each experimental plot at the pre-harvest stage, measuring from the soil surface to the end of the spike, and then the average was calculated (Azameti and Imoro, 2023). Spike length was calculated as the average of ten randomly selected spikes at full maturity for each experimental plot, recorded from the base of the basal terminal spikelet to the apex of the upper terminal spikelet. The number of spikes (spikes m^{-2}) was estimated by counting spikes randomly from ten plants harvested from the two central rows of each plot and then converted to basis of square meters. The number of grains per spike was calculated as the average number of grains from ten randomly selected spikes taken from the middle rows of each plot. The weight of a thousand grains was determined by randomly selected samples from the harvested plants and weighing them using a precision electronic balance. Grain yield (tons ha^{-1}) was calculated based on samples from the two middle rows after the threshing. The grains were separated from the straw adjusted to 13.5% moisture content, then weighed with a sensitive electronic balance, and then converted into tons per hectare. Similarly, the biological yield (tons ha^{-1}), representing the total above-ground biomass (grain yield plus straw) was also calculated from the same sampled rows by weighing the harvested plants and converting it to tons per hectare. Finally, the Harvest index was calculated according to the following equation (Howell *et al.*, 2015):

$$Harvest\ index\ (\%) = (grain\ yield \div biological\ yield) \times by\ 100$$

Statistical Analysis

Data were analyzed using analysis of variance (ANOVA) appropriate for a split-plot design, with cultivar as the main-plot factor and nano-micronutrient treatment as the subplot factor. When significant differences were detected, means were compared using Tukey's Honestly Significant Difference (HSD) test at the 5% probability level. Results are presented as mean values with significance groupings indicated using lowercase letters in tables and figures.

RESULTS AND DISCUSSION

Comparative results of varieties from control plots

Averages of the examined parameters of the three barley varieties are summarized in Table 3. In the case of the 'Buraq' variety, we measured higher values in 4 out of the 8 parameters (plant height, spike length, number of grains, and thousand seed weight), however, we obtained significantly higher average values only in spike length (6.1a cm) and thousand seed weight (54.9a g) in Season 1. Regarding the number of spikes (216.3 number m^{-2}) and the harvested yield (ton ha^{-1}), the 'Buraq' variety had the significantly lowest values among the varieties. In the second growing year (Season 2), a similar trend was observed: we obtained significantly higher values for plant height (92.2a cm), spike length (6.1a cm), and thousand seed weight (54a g) for the 'Buraq' variety. Again, considering the number of spikes (227.3 number m^{-2}) and the harvested yield (3.8c ton ha^{-1}), the 'Buraq' variety showed the significantly lowest values among the varieties.

In the case of the 'Aba 99' variety, the number of spikes was significantly higher compared to the 'Buraq' variety in both Season 1 (216.3c and 265.3b number m^{-2}) and Season 2 (227.3b and 324.7a number m^{-2}); however, regarding yield, we obtained significantly higher value only in Season 2 (4.4b ton ha^{-1}). The significantly lowest value for spike length was measured (3.7b cm) in Season 1, while in Season 2, we obtained significantly lower values for plant height (77.0b cm) and spike length (3.9b cm), as well as a lower thousand grain weight (54a and 47.2b g) compared to the 'Buraq' variety.

In the case of the 'Aba 265' variety, in both the first and second the Season, the number of spikes (307.7a and 346a number m^{-2}) and the yield (4.5a and 4.9a ton ha^{-1}) were significantly outstanding compared to the results of the other two barley varieties. However, in terms of spike length (4.2b and 4.2b cm) and thousand seed weight (46.9b and 46.9b g), it was significantly lower in both seasons compared to the 'Buraq' variety (6.1a, 6.1a cm and 54.9a, 54a g).

The effect of the growing season was not significant for most of the examined parameters in the studied barley varieties, with the exception of number of spikes, for which the results were analyzed separately by season. Therefore, data from the two growing seasons were pooled for the analysis of the following parameters: plant height, spike length, number of grains, thousand seed weight, yield, and harvest index (Table 4).

Table 3. Summary of average morphological and yield data of three barley varieties under control conditions

Season 1 (2021/2022)								
Variety	**PH[1]**	**SL[2]**	**NS[3]**	**NG[4]**	**TSW[5]**	**Y[6]**	**BY[7]**	**HI[8]**
“Buraq”	94.4a ±3.5	6.1a ±1.0	216.3c ±22.5	37.2a ±4.3	54.9a ±1.6	3.63b ±0.2	12.8a ±0.6	28.4a±0.23
“Aba 99”	77.9a ±8.6	3.7b ±0.9	265.3b ±11.3	34.3a ±3.3	48.0b ±1.2	4.0b ±0.2	12.4a ±1.1	32.7a ±4.8
“Aba 265”	80.6a ±10.5	4.2b ±0.1	307.7a ±15.7	35.0a ±2.5	46.9b ±4.3	4.5a ±0.2	13.3a ±1.4	34.0a ±4.3
Unit	cm	cm	number m^{-2}	number $grain^{-1}$	g	ton ha^{-1}	ton ha^{-1}	-
Season 2 (2022/2023)								
Variety	**PH[1]**	**SL[2]**	**NS[3]**	**NG[4]**	**TGW[5]**	**Y[6]**	**BY[7]**	**HI[8]**
“Buraq”	92.2a ±2.3	6.1a ±0.57	227.3b ±8.7	37.9a ±1.9	54a ±1.0	3.8c ±0.2	12.5a ±1.2	32.3a ±2.9
“Aba 99”	77.0b ±4.0	3.9b ±0.53	324.7a ±13.5	34.1a ±0.9	47.2b ±1.0	4.4b ±0.3	11.7a ±2.0	38.3a ±4.6
“Aba 265”	80.3b ±1.53	4.2b ±0.2	346a ±21.0	35.3a ±2.5	46.7b ±2.1	4.9a ±0.2	14.0a ±1.9	37.6a ±0.5
Unit	cm	cm	number m^{-2}	number $grain^{-1}$	g	ton ha^{-1}	ton ha^{-1}	-

[1]plant height, [2]spike length, [3]number of spikes, [4]number of grains, [5] thousand seed weight, [6]yield, [7]biological yield, [8]harvest index; The yellow and green shades indicate the variations between the varieties. The more intense the green in a cell, the higher the corresponding value. The lowercase letters indicate significantly different groups between the varieties according to the Tukey's HSD test ($p < 0.05$); ±Std. Deviation.

Table 4. Average morphological and yield data of the three barley varieties under Control, T1 and T2 treatment (0, 1 and 2 g L^{-1})

Control treatment					
Variety	**PH[1]**	**SL[2]**	**NG[3]**	**TSW[4]**	**HI[6]**
Buraq	93.3 aA±2.9	6.1 aA±3	37.5 aA±3	54.4 aA±1.3	30.3 bA±2.8
Aba 99	77.4 bA±6	3.8 bB±2.1	34.2 aB±2.1	47.6 bA±1.1	35.5 aA±5.2
Aba 265	80.4 bA±6.7	4.2 bB±2.2	35.2 aB±2.2	46.8 bA±3	35.8 aA±3.4
Unit	cm	cm	number $grain^{-1}$	g	-
T1 treatment					
Variety	**PH[1]**	**SL[2]**	**NG[3]**	**TSW[4]**	**HI[6]**
Buraq	93.8 aA±4	6.7 aA±2	37.2 aA±2	53.6 aA±2.4	28.9 bA±2.5
Aba 99	77.4 bA±7.1	3.7 cB±2.4	38.3 aA±2.4	47.8 bA±2	38.5 aA±1.9
Aba 265	84.2 bA±4.6	4.3 bAB±2.4	39.6 aA±2.4	45.7 bA±1.8	41 aA±3
Unit	cm	cm	number $grain^{-1}$	g	-
T2 treatment					
Variety	**PH[1]**	**SL[2]**	**NG[3]**	**TSW[4]**	**HI[6]**
Buraq	93.9 aA±1.7	6.7 aA±4.3	38.7 aA±4.3	54.7 aA±2.2	31.7 aA±2
Aba 99	78.9 bA±6.4	4.3 bA±2.4	38.6 aA±2.4	48.6 bA±2	36.8 aA±2
Aba 265	83.3 bA±3	4.6 bA±3.6	38.9 aAB±3.6	48.7 bA±1.9	40 aA±3.8
Unit	cm	cm	number $grain^{-1}$	g	-

[1]plant height, [2]spike length, [3]number of grains, [4]thousand seed weight, [5]biological yield, [6]harvest index; The yellow and green shades indicate the variations between the varieties. The more intense the green in a cell, the higher the corresponding value. The upper (between treatments) and lowercase (between varieties) letters indicate significantly different groups according to the Tukey's HSD test ($p < 0.05$); ±Std. Deviation

Plant height

Regarding plant height (Table 4, Table S1-S2), the effect of genotype was the most pronounced. The highest values were recorded for the 'Buraq' variety (93.3–93.9 cm), while the 'Aba 99' (77.4–78.9 cm) and 'Aba 265' (80.4–84.2 cm) varieties showed lower values. The treatments did not result in significant differences within the varieties examined.

T1 resulted in an increase in plant height (an average of 5.1%) only for the 'Aba 265' variety in Season 1, although no significant difference was observed. In Season 2, the measured parameter values generally increased for all three varieties (2.7%, 1.2%, and 4.1% increase, respectively), although no significant differences were found. A similar trend was observed in 2. treatment. In Season 1, the 'Buraq' variety showed a 3.7% increase, while in Season 2, a slight increase in plant height was observed for all three varieties, although the differences were not significant (2.7%, 4.8%, and 4.2%, respectively).

Spike length

Regarding the spike lengths of the varieties (Table 4), we observed the highest values for the 'Buraq' variety (6.1–6.7 cm), and for this variety, the treatments did not result in significant differences. For the 'Aba 99' variety, T1 did not result in a significant difference compared to the control results (3.8 and 3.7 B cm). However, in T2 treatment, significantly higher values were measured compared to both the control and T1 values (4.3 A cm). Based on the data evaluation, the 'Aba 99' variety generally has a smaller spike length (3.7-4.3 cm) compared to the other two varieties ('Buraq': 6.1–6.7 cm and 'Aba 265': 4.2–4.6 cm).

The T1 (Table S1) resulted in an increase in spike length for both the 'Buraq' (9.6% and 10.4%) and 'Aba 265' (2.1% and 5.1%) varieties in Season 1 and Season 2, although the increase was not significant. The second treatment (T2) (Table S2) positively influenced the results for all three varieties, both in Season 1 (8.7%, 13.5%, and 7.6% increase, respectively) and in Season 2 (11.5%, 14.0%, and 12.0% increase, respectively), although no significant differences were observed.

Spike number

The effect of the treatments on the number of spikes per unit area was noticeable for all three varieties in Season 1 (Fig 3A). However, for the 'Buraq' variety, the higher dose treatment (T2) (216.3 B and 292.3 A number m^{-2}) resulted in significantly higher values compared to the control plots, while for the 'Aba 99' and 'Aba 265' varieties (T1: 378.7 and 410.7 A number m^{-2}, respectively; T2: 379.3 and 410.7 A number m^{-2}, respectively), both treatments produced significantly higher values than the control plots (265.3 B and 307.7 B number m^{-2}, respectively). As a result of the treatments, the genotypes were classified into two significantly different groups based on the data evaluation when the lower dose (T1) treatment was applied. The 'Buraq' variety had lower values (258.3 b number m^{-2}), while the 'Aba 99' and 'Aba 265' varieties had higher values (387.7 a and 410.7 a number m^{-2}).

In Season 2 (Fig 3B), for the 'Aba 265' variety, both treatments resulted in significantly higher values (397.7 and 414.3 A number m^{-2}) for the number of spikes per unit area compared to the control plot data (346.0 B number m^{-2}). In the case of the other two varieties, there was no significant difference in the number of spikes per unit area between the treatments. The performance of the varieties in terms of the parameter studied was similar to that of the control plots following the treatments, although the interpretation of the data from the treated plots resulted in the categorization into three distinct groups instead of the originally planned two significantly different groups. Among the three varieties, the highest values were measured for the 'Aba 265' variety (346.0–414.3 number m^{-2}), followed by the 'Aba 99' variety (324.7–359.0 number m^{-2}), and finally the 'Buraq' variety (227.3–252.3 number m^{-2}) in descending order.

T1 (Table S1) resulted in an increase for the varieties in both seasons, although in Season 1, the percentage deviation compared to the control data was significantly higher ('Buraq' variety: 21.2% and 1.9%; 'Aba 99' variety: 42.9 % and 10.6%; and 'Aba 265' variety: 33.6% and 15.3%). A similar trend was observed in T2 (Table S2) as well ('Buraq' variety: 36.3% and 10.9%; 'Aba 99' variety: 43.1% and 10.9%; and 'Aba 265' variety: 33.5% and 20.2%).

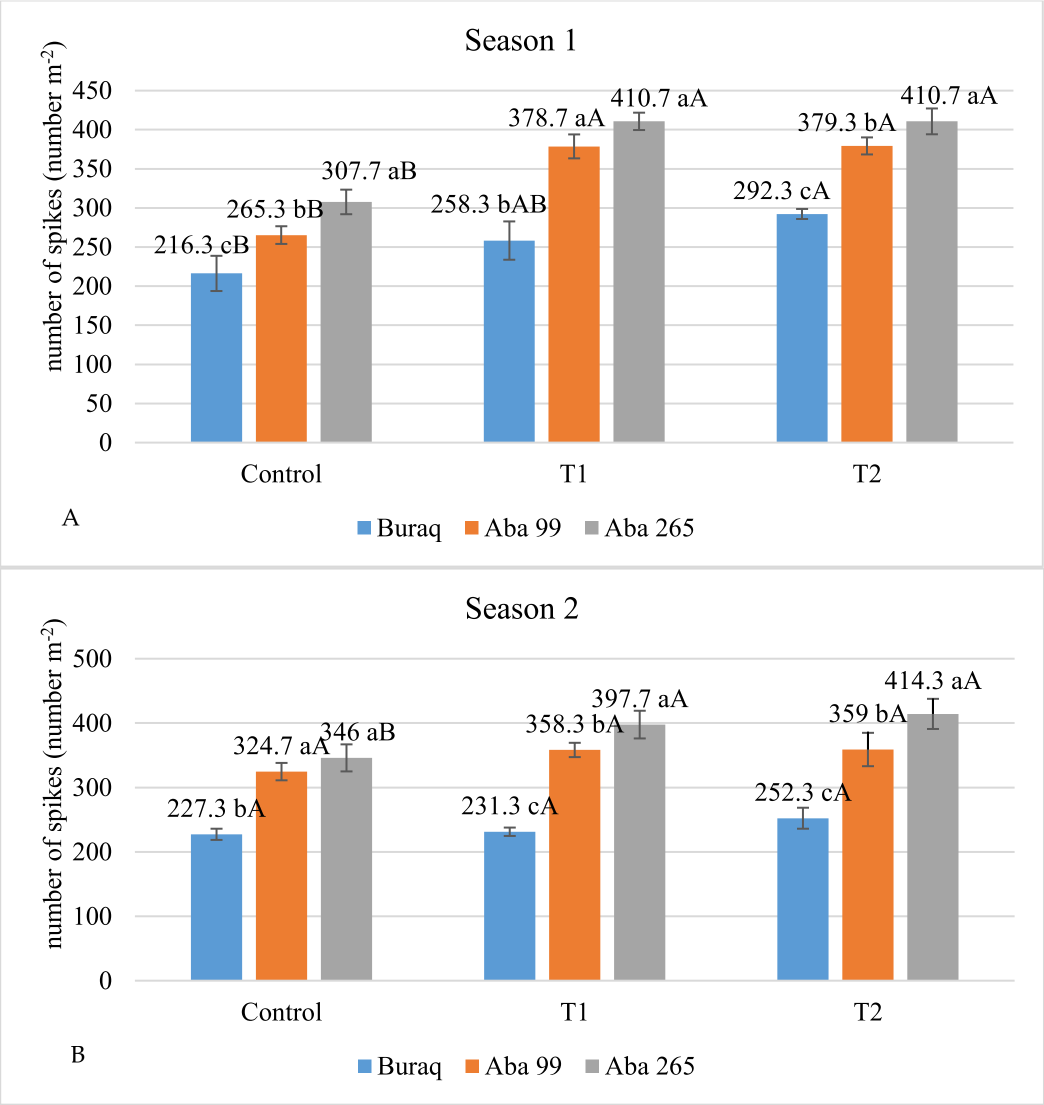

Figure 3. Effect of genotype and treatment on the number of spikes of three barley varieties in two growing seasons (2021/22 and 2022/23), the uppercase and lowercase letters represent the significant groups based on the Tukey-B test ($p < 0.05$) for the varieties and treatments. (A) Season 1 (2021/22), (B) Season 2 (2022/23).

Number of grains

In terms of the average number of grains (Table 4) per 10 plants, as a result of the treatments, we observed a significant increase only in the 'Aba 99' (38.3 A, 38.6 A number grain-1) and 'Aba 265' (39.6 A number grain-1) varieties compared to the control data (34.2 and 35.2 B number grain-1), although in the case of the 'Aba 265' variety, the results were significantly higher in a positive direction only in the T1 treatment.

There was no significant difference between the varieties in terms of number of grains values. The 'Buraq' variety had values ranging from 37.2 to 38.7, the 'Aba 99' variety ranged from 34.2 to 38.6, and the 'Aba 265' variety had values between 35.2 and 39.6.

In T1 (Table S1), although we observed an overall increase, significantly different results were only obtained between the varieties in Season 1. In Season 2, we only measured increasing values for the 'Aba 99' and 'Aba 265' varieties compared to the control areas ('Buraq' variety: 0.8 b %; 'Aba 99' variety: 12.0 a and 12.0 %; 'Aba 265' variety: 12.9 a and 12.0 %).

T2 (Table S2) resulted in growth for the number of grains in both years for all three genotypes, although significant differences between them were only observed in Season 2 regarding the parameter ('Buraq' variety: 3.8 and 2.3 b %; 'Aba 99' variety: 12.7 and 13.5 a %; 'Aba 265' variety: 9.1 and 11.9 a %).

Thousand seed weight

In terms of thousand seed weight (Table 4), significant differences were observed between the varieties regardless of the treatment, with the 'Buraq' variety outperforming the other two. For the 'Buraq' variety, values ranged from 53.6 to 54.7 g, for the 'Aba 99' variety from 47.6 to 48.6 g, and for the 'Aba 265' variety from 45.7 to 48.7 g, where no significant differences were found between certain treatments.

As a result of the first treatment (T1) (Table S1), only the 'Aba 99' variety showed a slight increase (2.7 %) in Season 2. Following the second treatment (T2) (Table S2), in Season 1, a slight increase was observed for the 'Aba 265' variety (2.2 %), while in Season 2, all three varieties showed an increase due to the treatment (2.5%, 4.1%, and 6.0%, respectively). However, the change was not significantly different between the genotypes.

Yield

In terms of yield (Fig 4) results, significantly higher yields were harvested from the treated plots for all three varieties ('Buraq' variety: 3.8 and 4.2 tons per hectare; 'Aba 99' variety: 4.7 and 4.9 tons per hectare; 'Aba 265' variety: 5.6 and 5.6 tons per hectare) compared to the control group ('Buraq' variety: 3.7 tons per hectare; 'Aba 99' variety: 4.2 tons per hectare; 'Aba 265' variety: 4.7 tons per hectare). There were significant differences between the genotypes, and this trend did not change as a result of the treatments. However, in terms of the results, the 'Aba 265' variety stood out as the most outstanding (5.6 tons per hectare).

The effect of T1 (Table S1) in Season 1 caused significant differences in yield increase among the varieties ('Buraq' variety: 4.5 b %; 'Aba 99' variety: 16.4 ab %; 'Aba 265' variety: 29.0 a %). T2 (Table S2) did not cause significant differences among the varieties, but an increase was observed in both seasons (‘Buraq’ variety: 19.2 and 6.8 %; ‘Aba 99’ variety: 24.0 and 12.7 %; ‘Aba 265’ variety: 26.4 and 11.8 % increase).

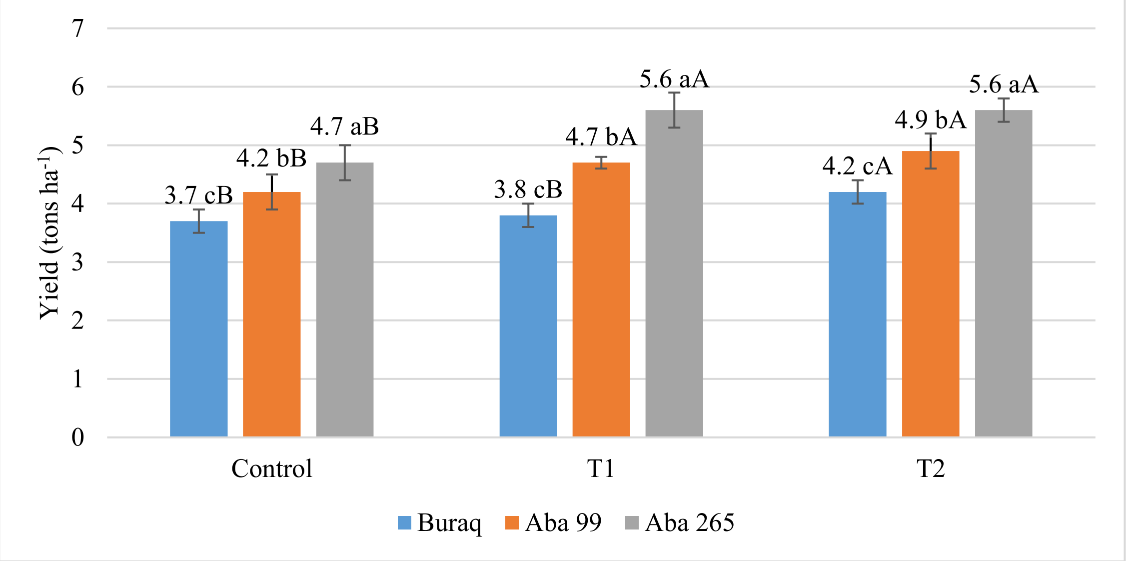

Figure 4. Effect of genotype and treatment on yield of three barley varieties based on the average of two growing seasons (2021/22 and 2022/23), the uppercase and lowercase letters represent the significant groups based on Tukey-B test ($p < 0.05$) for the varieties and treatments.

Harvest index

No significant differences were observed among the treatments regarding the harvest index values of the varieties (Table 4), although the highest values were recorded in the treated plots of ‘Aba 99’ (38.5 and 36.8) and ‘Aba 265’ (41.0 and 40.0).

T1 (Table S1) caused an increase in the harvest index in both seasons, with the highest increase observed in the ‘Aba 99’ (18.3 and 2.1 %) and ‘Aba 265’ (28.7 and 2.3 %) varieties, although these differences were not significant. T2 (Table S2) induced a trend of increase in Season 1 across all three varieties (‘Buraq’: 17.2%, ‘Aba 99’: 14.8%, and ‘Aba 265’: 21.6%). In Season 2, however, this increase was only evident in the ‘Aba 265’ variety (3.2%).

In nanofertilizers the nutrients or their carriers are nano-sized (usually <100 nanometers), and this size difference brings special advantages compared to traditional fertilizers. Their use can increase the nutrient use efficiency, the nanoparticles result in a high surface area/mass ratio, which helps in better utilization towards plant roots and leaves (Zahra *et al.*, 2022). There are nano-phosphate fertilizers that have provided better yields and better nutrient uptake (Ernst *et al.*, 2023; Dhiman *et al.*, 2025). Nanohybrid or nanostructured fertilizers are capable of slower, controlled nutrient release, thus reducing losses (leaching, volatilization) (Zahra *et al.*, 2022). Less loss results in less groundwater pollution, and by using lower doses, nano-form fertilizers are also environmentally friendly. Studies have shown that nanofertilizer application increases the tolerance of plants to abiotic stresses (e.g. salt, drought). In a maize experiment, nano Si treatment gave the largest increase in nutrient use efficiency, even under salt stress (nearly 105% compared to the control) (Shoukat *et al*., 2025).

In our experiment, the application of nano-microelements at different concentrations did not result in a significant difference in plant height for any of the tested genotypes. The ‘‘Buraq’’ genotype showed a stable higher plant height in all three treatments, while ‘‘Aba 99’’ consistently produced lower values. This indicates that plant height was predominantly determined by the genotype, and the nano-microelement treatments had no measurable effect on this morphological trait. Previous studies have reported in several cases that the application of microelements in nanoform can affect plant growth and development (Pszczółkowski *et al*., 2023). In experiments with barley - in which the application of nano-micronutrient (Zn, Fe) fertilizer + $nTiO_2$ (nano titanium dioxide) spraying influenced the extension of flowering time, as well as on yield-influencing traits such as spike length and number of grains per spike. Both parameters improved in nano-fertilized plants, especially with the application of zinc nano (ZnO), and grain yield increased, and the harvest index improved (Janmohammadi *et al*., 2016). No effect on plant height was demonstrated. These results are consistent with the present study, in which nano-microelements also did not significantly affect plant height. This suggests that plant height is less sensitive to this type of application, and the effect of nano-microelements may be more evident in other parameters – such as photosynthetic activity, nutrient uptake or crop yield. However, in an experiment with wheat, an effect was found between the application of nano-fertilizers and plant height: in particular, the SMP (Super Micro Plus) nano-treatment significantly increased the height, which was better than the control and conventional fertilizer treatments (Al-Juthery *et al*., 2018). Furthermore, it was shown that nano-NPK, micronutrients and yeast extract, when used together (and partly separately), increased the plant height of wheat. The strongest effect was when all three treatments were applied together, when the plant height increased by almost 20% compared to the control (Al-Juthery *et al*., 2020).

In the case of spike length, the results show that this character was primarily determined by genotype, and nano-/microelement treatments had only a moderate, genotype-dependent effect. The ‘‘Buraq’’ variety outperforms other varieties in spike length and even responds positively to treatments, which can be promising from a cultivation point of view. The results indicate that the treatments were only able to modify spike length to a small extent, especially in genotypes that already had high potential. For instance, some studies have shown that specific nano- and microelement treatments, such as zinc and magnesium doped hydroxyapatite, can significantly enhance spike length and weight, suggesting a role in improving overall spike development. This enhancement is attributed to improved nutrient uptake and utilization, which supports cellular elongation and division within the spike (Sharma *et al*., 2022). Furthermore, the specific concentration and type of nano-fertilizer, such as zinc oxide nanoparticles, have been demonstrated to differentially affect spike length, with optimal dosages leading to significant increases (Nazir *et al*., 2024). This emphasizes the importance of genotype-specific fertilization strategies to maximize agricultural productivity (Shoormij *et al*., 2022). However, other research indicates that even with mineral and nano-fertilizer applications, the increase in spike length may be limited, especially in cultivars that already possess inherent genetic potential for longer spikes (Gomaa *et al*., 2018). This observation is further supported by findings where certain wheat varieties exhibit statistically significant differences in plant height and spike length in response to varied treatments, suggesting a strong genotypic component (Simarjot *et al*., 2024). For example, dry seeding techniques have been shown to produce longer spikes compared to soaked seeding, irrespective of nutrient treatments, indicating that environmental factors and cultivation practices also play a role in phenotypic expression (Ranazai *et al*., 2024).

The present findings demonstrate that the number of grains per spike was influenced by both genotype and treatment, but with genotype had the primary effect. In control conditions, ‘‘Buraq’’ showed the highest number of grains per spike, whereas ‘‘Aba 99’’ produced the lowest, confirming the role of genetic potential in determining this trait. These results are consistent with other reports highlighting the predominance of genotypic effects on reproductive traits in barley (Noaema *et al*., 2024; Stadnik *et al*., 2024; Ishaq *et al*., 2018). Application of treatments (T1 and T2) improved the number of grains in ‘‘Aba 99’’ and ‘‘Aba 265’’, while ‘‘Buraq’’ showed only a slight increase compared with the control. This indicates that genotypes with low or moderate potential respond more strongly to external treatments, while high-potential genotypes show little additional improvement, having nearly reached their maximum capacity. Similar genotype-dependent responses to microelement or biostimulant treatments have been reported in barley and wheat, where increases in grain number were more pronounced in less productive cultivars (Ali *et al*., 2022). The T2 treatment notably minimized differences among cultivars, resulting in a more uniform grain number across all genotypes. It was observed (Stadnik *et al*., 2024) that foliar micronutrient applications can reduce differences among genotypes by enhancing the performance of weaker varieties. From a breeding and agronomic perspective, such treatments may therefore be particularly useful for stabilizing yield components among varieties with different genetic backgrounds. The results confirm that while spikelet fertility and grain set are largely under genetic control, foliar or nano-/microelement treatments can enhance these traits, especially in genotypes with initially lower potential. This highlights the importance of genotype × treatment interactions and suggests that optimized nutrient applications could complement genetic improvement strategies in barley production. Our results indicate that the weight of 1000 grains were primarily determined by genotype, with ‘‘Buraq’’ consistently showing the highest value across all treatments, confirming its high genetic potential. While the T1 treatment had minor and genotype-dependent effects, the T2 treatment significantly improved the grain weight in lower-performing genotypes, ‘‘Aba 99’’ and ‘‘Aba 265’’, leading to a convergence of values among the cultivars. This suggests that genotypes with high potential, such as ‘‘Buraq’’, may result in minimal gains from additional higher-dose treatments, while genotypes with low and medium performance benefit more significantly from external treatments. Moreover, the reason for this result may be due to the important role of microelements in accelerating the transport of photosynthetic products from the source to the downstream, which contributed to the increase in grain weight and these results agreed with (Imtiaz *et al*., 2010). Our findings are consistent with previous reports showing genotype-dependent responses to nutrient or biostimulant applications, where genotypes with lower inherent productivity respond more strongly to supplemental inputs (Ali *et al.*, 2022).

The results show that the combination of treatment type and variety significantly influences the barely yield. For the ‘‘Aba 265’’ variety, both T1 and T2 treatments resulted in significant yield increases compared to the control, indicating the variety's high responsiveness to treatments. The higher grain yield may be caused by the increase in photosynthetic products and their redistribution, which also contributed to an increase in the number of spikelets per square meter. This was positively reflected in the increase in grain yield and this result agreed with other findings (Aljaberi *et al.*, 2023). In contrast, the ‘‘Buraq’’ variety produced lower yields, but T2 treatment resulted in significant improvements, suggesting that this variety is sensitive to treatment intensity. For ‘‘Aba 99’’, the increase was moderate but consistently represented the middle level among the three varieties. Statistical comparisons showed significant differences between varieties, confirming that genetic background plays a key role in yield variation. Our results are consistent with previous studies that treatments (e.g., nutrient or water supplementation) can have different effects on variety-specific yield. This highlights the importance of variety- and treatment-specific management strategies to maximize yield. Combined studies comparing conventional urea and foliar nano-urea applications have shown improved nitrogen utilization and significant yield increases, especially when nano-urea was combined with conventional N applications in field trials under conservation tillage. This is a practical approach that has shown good results under different agro-environmental conditions (Kumar *et al.*, 2023). Zinc oxide and other metal oxide nanoparticles (TiO_2, FeOx, etc.) have been shown to improve growth parameters, such as plant height, ear length, grain yield and nutrient content in wheat. Results vary by field, but ZnO-NPs have been shown to be particularly effective in several trials conducted on semi-arid soils (Sheoran *et al.*, 2021). Recent experiments with special nanoparticles (e.g. $MnFe_2O_4$ nanocomplexes, chitosan-based nano-carriers) indicate not only yield increases, but also improvements in grain micronutrient composition and changes in local soil biological indicators. These studies are promising in improving crop quality; however, few studies have yet mapped the long-term effects on the soil and microbiome (Huang *et al.*, 2024).

Concerning the harvest index genotypic effect could be observed. In all treatments, the genotypes ‘‘Aba 265’’ and ‘‘Aba 99’’ consistently exhibited significantly higher HI values (35–41%) than ‘‘Buraq’’ (28–32%), indicating a greater efficiency in partitioning biomass towards grain yield. These results suggest that genetic background exerts a stronger influence on HI than exogenous nano-microelement applications, a conclusion consistent with earlier reports that HI is a relatively stable genotype-dependent trait under field conditions (Aljaberi *et al.*, 2023; Kumar *et al.*, 2023. The foliar nano-microelement treatments (T1 and T2) did not elicit statistically significant improvements in HI for most genotypes; however, ‘‘Aba 265’’ responded positively under T1, where HI reached 41%. Similar genotype-specific responses to nano-fertilizers have been reported in wheat and maize, where zinc- and silicon-based nanoparticles improved reproductive growth traits under nutrient-deficient or salt stress conditions (Shoukat *et al.*, 2025; Hussain *et al.*, 2018). The consistently lower HI observed in all treatments for ‘‘Buraq’’ may reflect a weaker responsiveness to external nutrient supplementation. Such genotypic differences emphasize the importance of tailoring nanofertilizer applications to varieties with inherently higher harvest index potential, thereby maximizing yield benefits (Seadh *et al*., 2017).

The observed genotype-dependent yield responses to nano-micronutrient sprays highlight the potential of tailored agri-nanotechnology for optimizing cereal production in micronutrient-deficient regions. By achieving up to 1.9 t ha^{-1} yield gain with only 2 g L^{-1} foliar input, this approach demonstrates nano-enabled nutrient delivery as a low-dose, high-impact strategy for sustainable agriculture, reducing reliance on conventional fertilizers and minimizing environmental risks in semi-arid agroecosystems.

CONCLUSIONS

Nanofertilizers are of a great importance for the future of agriculture, especially in terms of efficient nutrient management, reducing negative environmental impacts and increasing plant resistance/tolerance to different biotic and abiotic stress. However, it is important that safety and cost-effectiveness are also priorities during development, and that more practical data are available for different crops, genotypes, soil and environmental conditions. We can conclude from our research that the use of nanomaterials as foliar spray can contribute to increasing barley yield and improving some plant traits, and that there is an interaction between barley cultivars and nano-microelements concentrations in some traits. At the same time, the effectiveness of nanofertilizers strongly depends on the applied dose, the timing, and the method of application. These factors require further systematic study in order to define optimal combinations for practical use. The uniqueness of nanofertilizers lies in their potential to provide nutrients more efficiently, with reduced losses and lower environmental impact compared to conventional fertilizers. This highlights their importance as a promising tool for sustainable crop production. Future research should therefore not only validate yield benefits across different genotypes and environments but also address the long-term ecological implications of their use. Nanofertilizer technology represents an innovative and valuable approach that could enhance productivity while supporting sustainable and environmentally responsible agricultural development. However, its broad adoption will rely on establishing clear guidelines for dosage, timing, and safe integration into existing farming systems.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest in the publication.

تأثيرات التغذية النانوية الورقية على نمو وإنتاجية أصناف الشعير في جنوب العراق

علي رحيم الحسني [1]، علي حليل نعيمة [1]، دنيا صبيح محمد [2]، مصطفى عابد منشود [3]، عايدة سوادي [1]، ضرغام صبيح كريم [4]، ألكسندرا هاناس[5]، نورا ميندلر[5]، وليد أحمد المداوي[6]
قسم المحاصيل الحقلية / كلية الزراعة / جامعة المثنى / المثنى / العراق [1]
فرع علم العقاقير والنباتات الطبية / كلية الصيدلة / جامعة ميسان / العراق [2]
قسم موارد التربة والمياه / كلية الزراعة / جامعة المثنى / المثنى / العراق [3]
قسم وقاية النبات / كلية الزراعة / جامعة ميسان / العمارة / العراق [4]
معهد بحوث نيرغيهازا / معاهد البحوث الزراعية والمزرعة التعليمية (IAREF) / جامعة ديبريسين / نيرغيهازا / المجر [5]
قسم المحاصيل / كلية الزراعة / جامعة المنصورة / المنصورة / مصر [6]

الخلاصة

تهدف هذه الدراسة إلى تقييم تأثير تراكيز مختلفة من العناصر الصغرى النانوية في نمو ومحصول ثلاثة أصناف من الشعير (براق، إباء 99، إباء 265)، بهدف تحديد أفضل ظروف التطبيق لتعظيم إنتاجية الحبوب وتحسين جودتها. نُفذت تجربة حقلية لمدة عامين في مدينة الرميثة – المثنى - العراق خلال الفترة 2021–2023، تم توزيع المعاملات في تجربة عملية في تصميم القطاعات الكاملة العشوائية (RCBD) بثلاث مكررات، مع اختبار ثلاثة تراكيز من العناصر الصغرى النانوية (0، 1، 2 جم لتر$^{-1}$) وكذلك ثلاثة أصناف من الشعير (براق، إباء 99، إباء 265). أظهر التركيب الوراثي التأثير الأكثر معنوية في ارتفاع النبات، حيث سجل صنف براق أطول النباتات (93.3–93.9 سم)، في حين لم يكن لمعاملات الرش تأثير معنوي في هذه الصفة. أدت معاملة الرش بمعدل (2 جم لتر$^{-1}$) إلى زيادة معنوية في طول السنبلة لصنفي إباء 99 (4.3 سم) وإباء 265 (4.6 سم)، بينما سجل صنف براق أعلى طول للسنبلة (6.7 سم). لوحظت فروق معنوية بين الموسمين في عدد السنابل في وحدة المساحة، حيث سجلت معاملة الرش بمعدل (2 جم لتر$^{-1}$) لصنف براق (292.3 سنبلة م$^{-2}$)، كما سجل كل من صنفي إباء 99 وإباء 265 قيمًا مرتفعة عند المعاملتين (378.7 و379.3 سنبلة م$^{-2}$) في الموسم الأول، و(358.3 و359 سنبلة م$^{-2}$) في الموسم الثاني. كما أسهمت المعاملات النانوية في زيادة عدد الحبوب في السنبلة لصنف إباء 99 (38.3 و38.6 حبة سنبلة$^{-1}$) وصنف إباء 265 عند معاملة T1 (39.6 حبة سنبلة$^{-1}$). وسجل صنف براق أعلى وزن لألف حبة حيث بلغ 54.7 جم. تشير نتائج الدراسة إلى أن الرش الورقي بالمواد النانوية يمكن أن يكون وسيلة فعّالة لتحسين إنتاجية الشعير وتحسين صفاته المورفولوجية.

الكلمات المفتاحية: التكنولوجيا النانوية الزراعية، الأسمدة النانوية، الرش الورقي، الشعير، التفاعل بين النمط الوراثي والإدارة.

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