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Response of Barley (*Hordeum vulgare* L.) Growth, Yield, and Crop Components to Irrigation Frequency and Salicylic Acid Concentrations

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Abstract

The irrigation regime is one of the primary factors limiting barley productivity. This study aimed to investigate the effect of salicylic acid on barley performance under varying irrigation conditions. A field experiment was conducted during the winter season of 2024 to 2025 using a split-plot design arranged in a randomized complete block design (RCBD) with 3 replicates. Irrigation frequency (3, 4, and 5 times during the growing season) was assigned to the main plots, while salicylic acid concentrations (0, 100, 200, and 300 mg l^{-1}) were distributed to the subplots. The studied traits included the number of tillers per plant, plant height, flag leaf area, relative water content of leaf, absolute growth rate, biomass duration, 100-grain weight, number of grains per spike, and grain yield. The results showed that increasing irrigation frequency positively enhanced all studied traits except relative water content, with the 5-irrigation treatment resulting in the highest grain yield (1.383 kg m^{-2}). Spraying salicylic acid at a concentration of 300 mg l^{-1} considerably improved most growth and yield traits, with the highest grain yield (1.370 kg m^{-2}), compared with the control treatment, which recorded the lowest grain yield (0.959 kg m^{-2}). Strong positive correlations were observed among biomass accumulation, yield components, and grain yield. The combined application of 5 irrigations and 300 mg l^{-1} of salicylic acid resulted in the highest grain yield (1.668 kg m^{-2}). These findings suggest that appropriate irrigation management combined with salicylic acid during barley development can be an effective strategy to enhance barley productivity.

Keywords: drought stress; foliar application; grain yield; physiological traits; water deficit

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INTRODUCTION

The barley crop (*Hordeum vulgare* L.), belonging to the Poaceae family, is an essential cereal broadly consumed for food and animal feed. It is widely cultivated due to its adaptability to different environmental conditions. However, its productivity demonstrates considerable variability in yield stability, particularly under suboptimal or stress conditions, which can negatively affect its overall performance (Langridge, 2018; Geng et al., 2022; Tesfaye and Bayih, 2024). Barley exhibits a relatively higher tolerance to abiotic stresses compared with other major cereal crops like rice and wheat, allowing its cultivation under drought, saline, and marginal environments (Zinati et al., 2021; Akbari et al., 2022).

Globally, barley production has shown fluctuations in recent years, reaching approximately 145.21 million metric tons in the 2024/2025 season (Statista, 2024). It is mostly cultivated in cold and temperate climates, making it a potential alternative crop to wheat in stress-

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prone environments (FAO, 2023; USDA, 2025). In Iraq, barley is considered a strategic crop due to its adaptability to semi-arid conditions. However, its productivity and cultivated area have been declining due to drought, salinity, and climate variability, which severely limit yield potential (ASGIS, 2025; USDA, 2025).

Global agricultural productivity is severely constrained by abiotic stresses. In addition to natural climatic variability, human activities have hastened the degradation of agricultural systems, leading to adverse effects from factors such as heavy metal contamination, salinity, ozone, ultraviolet radiation, temperature, nutrient imbalances, and drought (Keshavarz et al., 2019; 2020; dos Santos et al., 2022; Kopecká et al., 2023). These factors negatively impact virtually all physiological, biochemical, and molecular processes in plants, from seed germination to grain filling, ultimately leading to significant crop yield losses (Kathwal et al., 2022; Alsamadany et al., 2024). Drought is among the most damaging abiotic stresses to crop growth owing to its association with water scarcity. Drought-induced stress reduces photosynthetic activity and the rate of carbon synthesis, increases oxidative damage, and impairs pigment synthesis, thereby leading to stunted plant growth and reduced yield (Oguz et al., 2022; Aktas et al., 2025).

These environmental issues highlight the urgent need to develop strategies that enhance crop resilience. The use of natural and synthetic plant growth regulators is one such strategy, such as the use of salicylic acid (SA), which has the potential to improve crop tolerance to abiotic stresses (Farouk et al., 2018; Keshavarz et al., 2019; Abdelaal et al., 2020). Previous studies have demonstrated that foliar application of SA stimulates both enzymatic and non-enzymatic antioxidant systems, involving the AsA-GSH cycle and the glyoxalase pathway (Sharma et al., 2023), thereby mitigating oxidative stress, particularly under drought conditions (Liu et al., 2022; Chen et al., 2023).

Exogenous foliar application of SA (100 mg l^{-1}) at 60% and 80% of field capacity to 2 rice genotypes increased plant height, fresh and dry biomass, and pigments of chlorophyll a and b production under water scarcity conditions (Asma et al., 2023). Furthermore, the photosynthetic rate, chlorophyll content, stomatal control, and grain yield were affected significantly by SA application (Moustakas et al., 2022). Similar positive effects were observed in wheat, maize, and barley, where SA treatments led to increased plant height, biomass, relative water content, fresh weight, and antioxidant activity under water scarcity and abiotic stress (Alsahli et al., 2019; Keshavarz et al., 2019; Abdelaal et al., 2020; Ignatenko et al., 2023). The number of tillers and 1,000-grain weight of barley cultivars (Sultan and Jua-17) were significantly increased at SA concentrations of 0.5 and 1 mg l^{-1} (Hanif et al., 2024).

Several studies have indicated a correlation between frequent irrigation and SA spraying, leading to enhanced crop performance. For instance, Ahmad et al. (2018) reported that 4 irrigations during the growing season, combined with a SA concentration of 300 mg l^{-1}, resulted in the highest grain yield in maize compared to 5 irrigations with a SA concentration of 450 mg l^{-1}. This result confirms that maximizing productivity under water-scarce conditions hinges on using appropriate irrigation with effective SA concentrations. Plant growth regulators play an essential role in regulating signaling pathways, mediating stress responses, and improving tolerance to environmental stressors. Among these regulators is the phenolic compound SA, which is crucial for regulating growth, development, and responses to biotic and abiotic stresses.

SA is involved in numerous physiological processes, such as photosynthesis, nitrogen metabolism, proline accumulation, antioxidant defense, and plant-water relations (Abdelaal et al., 2020). Exogenous application of SA via seed soaking, root drenching, or foliar spraying activates and enhances plant defense mechanisms against abiotic stress conditions (Farouk et al., 2018; Wassie et al., 2020; Ganj-Abadi et al., 2021). Regarding antioxidant enzymes and the photosynthetic pathway, foliar SA at different concentrations under different water-deficient levels increased the antioxidant enzyme activity, proline productivity, photosynthetic rate, controlling osmotic potential, and grain yield and yield components in wheat crop (Ahmad et al., 2021; Khalvandi et al., 2021; Shemi et al., 2021; Khan et al., 2022).

Likewise, previous results have shown that SA application improved leaf morphology, plant height, biomass accumulation, chlorophyll levels, and photosynthetic performance in plants grown under heat stress. It also induces stomatal closure, enhances nutrient uptake, motivates protein synthesis, and inhibits ethylene production in wheat seedlings (Wassie et al., 2020). Abdelaal et al. (2020) demonstrated significant increases in plant height, number of leaves, dry and fresh weight, relative water content, spike length, grain per spike, grain yield, biological yield, and 1,000-grain weight of barley plants under well-watered conditions compared to drought. These traits were further improved with SA under the water deficiency condition.

Despite numerous studies investigating SA application under drought stress, limited information is available on the combined effects of irrigation frequency and SA application on the physiological and yield-related traits of barley under semi-arid Iraqi conditions. Therefore, this study aimed to determine the optimal irrigation frequency under water scarcity conditions and identify the most effective SA concentration to enhance barley drought tolerance and maximize its growth and yield.

MATERIALS AND METHOD

Study site and soil characterization

A field experiment was carried out during the 2024-2025 growing season at the College of Agriculture and Marshes, University of Thi-Qar (46°15’26.28” E and 31°03’28.44” N) under semi-arid climatic conditions characterized by low annual rainfall (96 to 128 mm), high summer temperatures exceeding 40 °C, and winter temperatures ranging from 10 to 25 °C. Soil samples (0 to 30 cm depth) were collected before planting to determine soil physical and chemical properties. Soil pH and electrical conductivity (EC) were measured in a 1:1 soil-to-distilled water extract using digital pH and EC meters. Available nitrogen (N) was determined using the Kjeldahl method, available phosphorus (P) using the Olsen method, available potassium (K) using a flame photometer, and organic matter was determined using the Walkley and Black wet oxidation method following standard procedures reported by Black (1965) and Page et al. (1982), as shown in Table 1.

Experimental design and treatments

The treatments were arranged in a split-plot design within a randomized complete block design (RCBD) with 3 replicates. Irrigation frequency treatments (3, 4, and 5 irrigations during the growing season) were distributed to the main plots, while SA concentrations (0, 100, 200, and 300 mg l^{-1}) were assigned to the subplots. Each plot measured 3.5 m × 1.5 m, with a 0.25 m spacing between subplots and 1 m between main plots.

Barley cultivar “Samir” was planted on October 24, 2024. Irrigation was applied directly after planting date to ensure uniform seedling emergence, while subsequent irrigation practices were arranged according to the crop’s growth stages (Table 2). Each foliar SA concentration was divided into 2 equal doses and applied at the tillering and flowering stages. NPK fertilizer was applied at a rate of 120 kg ha^{-1} at planting, in accordance with ASGIS (2025).

Measured traits

Ten plants were randomly selected from each subplot to evaluate growth and grain yield. The number of tillers and plant height (cm) were

Table 1. Physical and chemical categories of experimental field soil for the growing season 2024-2025

Physical category of soil		Chemical category of soil	
Description	Values	Description	Values
pH	7.3	Available N (%)	0.0122
EC (dS m^{-1})	8.44	Available P (%)	0.0168
Sand (g kg^{-1} soil)	528.0	Available K (%)	0.1212
Clay (g kg^{-1} soil)	381.1	Organic matter (%)	0.0611
Silt (g kg^{-1} soil)	90.9		
Soil texture	Sandy clay		

Table 2. Schedule of irrigation frequency treatments for the 2024/2025 growing season

Plant growth stages	Irrigation intervals		
	3 times	4 times	5 times
Week after emergence	X	X	X
Tillering stage	X	X	X
Booting stage	-	X	X
50% Flowering stage	X	X	X
Grain filling stage	-	-	X

Note: X = Applied irrigation; - = No irrigation

$$\text{Flag leaf area} = \text{Leaf length} \times \text{maximum width} \times 0.858 \quad (1)$$

$$\text{AGR} = \frac{\text{DW2-DW1}}{\text{T2-T1}} \quad (2)$$

$$\text{BD} = \frac{(\text{DW2-DW1})(\text{T2-T1})}{2} \quad (3)$$

$$\text{RWC} = \frac{\text{FW-DW}}{\text{TW-DW}} \times 100 \quad (4)$$

Where, DW1 and DW2 represent plant dry weight at times (T1 and T2).

measured at physiological maturity. Flag leaf area (cm^2) was evaluated at the flowering stage according to Kalra and Dhiman (1977) using Equation 1. The absolute growth rate (AGR, g day^{-1}) was calculated from plant dry weight at 74 and 88 days after planting using Equation 2. Biomass duration (g day^{-1}) was measured according to Kvent et al. (1969) using Equation 3. Relative water content (RWC, %) was evaluated following the method of Barr and Weatherley (1962) using Equation 4.

Dry shoot weight (g) was obtained from an oven-dried sample of 10 plants at 70 °C for 72 hours until constant weight. The 100-grain weight (g) was determined from 5 spikes per subplot, while grains per spike were recorded from 10 spikes. Grain yield (kg m^{-2}) was determined from the harvested area of 0.25 m^2.

Statistical analysis

Statistical analysis was performed using GenStat software (version 12.1) prior to analysis of variance (ANOVA); data normality was assessed using the Shapiro-Wilk test to verify ANOVA assumptions. Data were then analyzed using a split-plot ANOVA arranged in an RCBD (Yakubu et al., 2020). Mean comparisons among treatments were conducted using the least significant difference (LSD) test at $p \leq 0.05$, and the results were expressed as mean ± standard error (SE). Pearson correlation analysis based on treatment means was conducted to determine the relationships among barley growth, physiological, and yield-related traits. A correlation heatmap was further generated using RStudio software (version 4.4.1) to visualize the strength and direction of the relationships among the studied traits.

RESULTS AND DISCUSSION

Tillers per plant

ANOVA revealed that the number of tillers was significantly influenced by both irrigation frequency and SA concentration, while their interaction was not significant (Tables 3 and 4). Plants irrigated 5 times recorded the highest mean number of tillers (11.83), which did not differ significantly from the 4-irrigation treatment (11.17), while the 3-irrigation treatment recorded the lowest mean (7.83). Similarly, foliar application of 300 mg l^{-1} SA resulted in the highest mean number of tillers (11.78), followed by 200 mg l^{-1} (11.11), compared to the control treatment, which recorded the lowest mean (8.11).

The results of the Pearson correlation analysis (Figure 3) showed a strong positive correlation between the number of tillers and flag leaf area, AGR, biomass duration, and dry weight (r = 0.95**, r = 0.81**, r = 0.89**, and r = 0.89**, respectively), representing that improved vegetative growth contributed to reproductive performance and productivity. The increase in the number of tillers can be attributed to sufficient water availability and its role in regulating critical developmental stages such as germination, elongation, and tillering. The availability of water enhances cell division and expansion, the activity of turgor pressure, and nutrient transport efficiency. Khalvandi et al. (2021) reported that physiological activities in wheat were negatively affected by drought stress.

Additionally, SA plays a key role in enhancing drought tolerance by improving physiological and metabolic processes, particularly photosynthesis and the synthesis of proteins and carbohydrates necessary to sustain plant growth during the tillering stage. SA promotes hormonal signaling pathways by modulating the auxin-cytokinin balance, which is critical for bud activity and tiller formation in plants. Furthermore, previous findings have highlighted the importance of SA in modulating the activity of hormones and enzymes to improve vegetative growth and stress tolerance (Khan et al., 2022; Maqsood et al., 2023). These results are consistent with those reported by

Table 3. *p*-values of two-way ANOVA of barley studies traits as affected by irrigation frequency, SA concentration, and their interaction

Barley studied traits	Experimental studies factors		
	I	SA	Interaction I*S
Tiller numbers	< .001	< .001	0.158
Plant height	0.002	0.479	0.956
Flag leaf area	< .001	< .001	< .001
Absolute growth rate	0.020	0.004	0.341
Biomass duration	< .001	< .001	0.241
Relative water content	0.021	0.925	< .001
Dry weight of shoot	< .001	< .001	0.177
100-grain weight	< .001	< .001	0.011
Grains per spike	< .001	< .001	0.003
Grain production	0.003	0.027	0.857

Note: *p*-values indicate significance at $p \leq 0.05$ and highly significant at $p \leq 0.01$. I = Irrigation intervals, SA = Salicylic acid. Degree of freedom (df) is to: block = 2, I = 2, SA = 3, error a = 4, error b = 6, and I*SA = 18

Table 4. Effect of irrigation frequency, SA concentration, and their interaction on the number of tillers (tiller plant^{-1}) of barley

Irrigation frequency	SA concentration (mg l^{-1})				Irrigation treatment means
	0	100	200	300	
3-time	4.67±0.53	7.67±0.53	9.00±0.53	10.00±0.53	7.83±0.24^{c}
4-time	9.67±0.53	11.33±0.53	11.33±0.53	12.33±0.53	11.17±0.24^{b}
5-time	10.00±0.53	11.33±0.53	13.00±0.53	13.00±0.53	11.83±0.24^{a}
SA treatment means	8.11±0.31^{c}	10.11±0.31^{b}	11.11±0.31^{a}	11.78±0.31^{a}	
LSD at $p \leq 0.05$	Irrigation = 0.945		SA = 0.924		Interaction = ns

Note: Values are presented as mean±SE. Means followed by the same letter within each factor are not significantly different at $p \leq 0.05$ according to the LSD test. ns = Non-significant; SE = Standard error

Abdelaal et al. (2020), Maqsood et al. (2023), and Hanif et al. (2024).

Plant height (cm)

Irrigation frequency had a significant effect on plant height, as shown in Tables 3 and 5, while SA and its interactions with the 2 factors did not. Plants irrigated 5 times showed the greatest plant height (59.41 cm), which was significantly taller than those irrigated 4 (52.60 cm) and 3 times (37.97 cm) during the growing season. The results presented in Figure 3 indicated a highly significant correlation between plant height and flag leaf area (r = 0.95**), AGR (r = 0.81**), biomass duration (r = 0.92**), and dry weight (r = 0.94**), suggesting that the taller plants provided greater assimilate accumulation and biomass production.

Adequate irrigation promotes cell elongation and division as a result of biological activities, including photosynthesis and the formation of energy components necessary for growth, resulting in taller plants. This indicates improved vegetative development and no competition for the amount of water required for cell elongation during the stem elongation stage (Khalvandi et al., 2021; Maqsood et al., 2023). In addition, implementing efficient irrigation policies with appropriate (SA) concentrations to improve productivity under water-limited conditions is essential for crops (Ahmad et al., 2018).

Previous studies have demonstrated that foliar-applied SA promotes enzymatic and non-enzymatic antioxidant defense systems (Sharma et al., 2023), thereby mitigating oxidative stress under drought conditions (Liu et al., 2022; Chen et al., 2023). Such physiological improvements may positively influence bud initiation and plant height. The results of this experiment were consistent with previous studies conducted by Abdelaal et al. (2020) and Maqsood et al. (2023).

Flag leaf area (cm^2)

ANOVA showed that both irrigation frequency and SA concentrations, as well as their interaction, had a significant effect on flag leaf area (Tables 3 and 6). The highest leaf area was recorded under the 5-time irrigation treatment (20.22 cm^2), which differed significantly from the 4 irrigations treatment (17.27 cm^2), while

Table 5. Effect of irrigation frequency, SA concentration, and their interaction on plant height (cm)

Irrigation frequency	SA concentration (mg l^{-1})				Irrigation treatment means
	0	100	200	300	
3-time	35.55±2.24	39.55±2.24	38.55±2.24	37.90±2.24	37.97±1.65^{c}
4-time	50.93±2.24	52.63±2.24	54.55±2.24	52.28±2.24	52.60±1.65^{b}
5-time	59.61±2.24	59.04±2.24	61.00±2.24	58.00±2.24	59.41±1.65^{a}
SA treatment means	48.70±1.29	50.41±1.29	51.48±1.29	49.39±1.29	
LSD at $p \leq 0.05$	Irrigation = 6.505		SA = ns		Interaction = ns

Note: Values are presented as mean±SE. Means followed by the same letter within each factor are not significantly different at $p \leq 0.05$ according to the LSD test. ns = Non-significant; SE = Standard error

Table 6. Effect of irrigation frequency, SA concentration, and their interaction on flag leaf area (cm^2) of barley

Irrigation frequency	SA concentration (mg l^{-1})				Irrigation treatment means
	0	100	200	300	
3-time	10.89±0.4^{h}	12.52±0.4^{g}	13.95±0.4^{f}	15.40±0.4^{e}	13.19±0.20^{c}
4-time	13.14±0.4^{fg}	17.33±0.4^{d}	19.10±0.4^{c}	19.51±0.4^{c}	17.27±0.20^{b}
5-time	14.00±0.4^{f}	19.52±0.4^{c}	22.81±0.4^{b}	24.54±0.4^{a}	20.22±0.20^{a}
SA treatment means	12.68±0.23^{c}	16.46±0.23^{b}	18.62±0.23^{a}	19.81±0.23^{a}	
LSD at $p \leq 0.05$	Irrigation = 0.803		SA = 0.689		Interaction = 1.186

Note: Values are presented as mean±SE. Means followed by the same letter within each factor are not significantly different at $p \leq 0.05$ according to the LSD test. SE = Standard error

3 irrigations produced the lowest average for this trait (13.19 cm^2). Among the SA concentrations, 300 and 200 mg l^{-1} treatments resulted in the highest average leaf areas (19.81 and 18.62 cm^2, respectively), although they did not differ significantly from one another. In contrast, the control treatment produced the lowest averages for this trait. The combination of 5 irrigations with 300 mg l^{-1} of SA resulted in the maximum flag leaf area (24.54 cm^2), whereas the combination of 3 irrigations with no SA application produced the minimum leaf area (10.89 cm^2). This result was supported by the significant correlations shown in Figure 3 between flag leaf area and AGR (r = 0.88**), biomass duration (r = 0.96**), and dry weight (r = 0.97**), demonstrating the importance of leaf area for photosynthesis to enhance productivity.

Furthermore, this improvement in leaf area can be attributed to an adequate supply of growth factors, including abundant irrigation during the periods of elongation and cell division in the plant in general and leaves in particular. The antioxidative role of SA in reducing oxidative damage from some free radicals that are activated under critical environmental conditions, including drought, which allows for increased cell enlargement and photosynthetic capacity (Abdelaal et al., 2020; Khalvandi et al., 2021; Maqsood et al., 2023). These results are consistent with those reported by Abdelaal et al. (2020), Maqsood et al. (2023), and Hanif et al. (2024).

AGR (g day^{-1})

The ANOVA results indicated that both irrigation frequency and SA concentration had significant effects on absolute growth rate, while their interaction was not statistically significant (Tables 3 and 7). The 5 and 4-time irrigation treatments produced the highest AGR values (1.661 and 1.423 g day^{-1}, respectively), compared to the 3 irrigation treatment (0.928 g day^{-1}). Regarding SA concentrations, the 200 mg l^{-1} treatment resulted in the maximum absolute growth rate (1.586 g day^{-1}), which was not significantly different from that of the 300 mg l^{-1} treatment (1.482 g day^{-1}). Conversely, the 100 mg l^{-1} and control treatments yielded the lowest absolute plant growth rates (1.177 and 1.105 g day^{-1}, respectively). Additionally, the results presented in Figure 3 showed a significant correlation of AGR with biomass duration (r = 0.93**) and dry weight (r = 0.95**), indicating the important role of assimilation accumulation to enhance growth and production under drought conditions.

These results confirm that irrigation plays an essential role in providing adequate water, especially when combined with SA, thereby maintaining optimal physiological processes, including the continuation of photosynthesis, under relatively acceptable irrigation conditions. By mitigating water stress, this combined application helps sustain biomass production, contributing to plant sustainability under these conditions. Furthermore, SA enhances plant drought tolerance by activating antioxidant enzymes and regulating stress-responsive signaling pathways at the gene expression level (Alsahli et al., 2019; Keshavarz et al., 2019). This result is consistent with the findings of Abdelaal et al. (2020), Maqsood et al. (2023), and Hanif et al. (2024).

Biomass duration (g day^{-1})

The ANOVA results for biomass duration (Tables 3 and 8) showed that both irrigation frequency and SA concentration had significant effects, while their interaction was not statistically significant. The 5 and 4 irrigation treatments recorded the highest values for this trait (1.42 and 1.13 g day^{-1}, respectively), without any significant differences, compared to the 3 irrigation treatment, which recorded the lowest value (0.625 g day^{-1}). On the other hand, the application of SA at 300 mg l^{-1} produced the highest value (1.339 g day^{-1}), compared to the control group (0.778 g day^{-1}). This trait revealed a highly significant correlation with dry weight (r = 0.99**), validating the importance of sustained biomass accumulation during crop growth, especially under drought conditions (Figure 3). Therefore, adequate irrigation and the use of SA enhanced biomass duration by stabilizing the plant's metabolic activity, which supports sustained growth under environmentally stressful conditions.

In addition, drought is the most damaging abiotic stress to crop growth due to its association with water scarcity; it reduces the photosynthetic activity and the rate of carbon synthesis and increases free radical oxygen damage, which leads to stunted plant growth and reduced accumulated biomass in the plant (Abdelaal et al., 2020; Oguz et al., 2022; Aktas et al., 2025). Furthermore, SA had a positive effect on photosynthetic rate, chlorophyll content, and stomatal control under abiotic stress, which increases biomass productivity (Alsahli et al., 2019; Moustakas et al., 2022). This result is consistent with previous findings reported by Abdelaal et al. (2020).

RWC (%)

Two-way ANOVA showed that the irrigation frequency and its interaction with SA treatments significantly affected RWC, while SA application alone had no statistically significant effect on this trait (Tables 3 and 9). The 3 irrigations treatment resulted in the highest RWC (77.80%), which did not significantly differ from the 5 irrigations treatment, which resulted in an average RWC (76.07%). In contrast, the treatment with 4 irrigations yielded the lowest value for this trait (71.73%). The highest value for this trait was

Table 7. Effect of irrigation frequency, SA concentration, and their interaction on AGR (g day^{-1})

Irrigation frequency	SA concentration (mg l^{-1})				Irrigation treatment means
	0	100	200	300	
3-time	0.63±0.16	0.81±0.16	1.07±0.16	1.21±0.16	0.93±0.11^{b}
4-time	0.99±0.16	1.33±0.16	1.78±0.16	1.58±0.16	1.42±0.11^{a}
5-time	1.69±0.16	1.39±0.16	1.90±0.16	1.66±0.16	1.66±0.11^{a}
SA treatment means	1.11±0.09^{b}	1.18±0.09^{b}	1.59±0.09^{a}	1.48±0.09^{a}	
LSD at $p \leq 0.05$	Irrigation = 0.421		SA = 0.274		Interaction = ns

Note: Values are presented as mean±SE. Means followed by the same letter within each factor are not significantly different at $p \leq 0.05$ according to the LSD test. ns = Non-significant; SE = Standard error

Table 8. Effect of irrigation frequency, SA concentration, and their interaction on biomass duration (g day^{-1})

Irrigation frequency	SA concentration (mg l^{-1})				Irrigation treatment means
	0	100	200	300	
3-time	0.44±0.11	0.44±0.11	0.70±0.11	0.92±0.11	0.63±0.02^{c}
4-time	0.88±0.11	1.07±0.11	1.06±0.11	1.51±0.11	1.13±0.02^{b}
5-time	1.01±0.11	1.40±0.11	1.69±0.11	1.60±0.11	1.42±0.02^{a}
SA treatment means	0.78±0.06^{c}	0.97±0.06^{bc}	1.15±0.06^{ab}	1.34±0.06^{a}	
LSD at $p \leq 0.05$	Irrigation = 0.095		SA = 0.202		Interaction = ns

Note: Values are presented as mean±SE. Means followed by the same letter within each factor are not significantly different at $p \leq 0.05$ according to the LSD test. ns = Non-significant; SE = Standard error obtained with the combination of 5 irrigations and a 100 mg l^{-1} SA concentration (84.17%), while the lowest value was recorded with the combination of 5 irrigations and 0 mg l^{-1} SA concentration (72.78%). The correlation of RWC with all other traits studied was very weak and non-significant (Figure 3), indicating that variation in RWC was not strongly correlated with barley growth and production under the study factors.

These results suggest that under water-scarcity conditions, plants irrigated less frequently conserve water by promoting stomatal closure to reduce transpiration. Drought negatively impacts all physiological, biochemical, and molecular processes in plants. This leads to closure of the stomatal apparatus and a decrease in gas exchange, which affects the water relations in the plant. In addition, drought-induced stress reduces photosynthetic activity and the rate of carbon synthesis (Kathwal et al., 2022; Aktas et al., 2025). Although application of SA exerted a non-significant effect on this trait, it enhances the plant's ability to reduce water loss through transpiration. This effect is particularly evident in treatments lacking SA, where water conservation is less efficient (Alsahli et al., 2019; Abdelaal et al., 2020; Ignatenko et al., 2023). These results are consistent with those reported by Keshavarz et al. (2019) and Abdelaal et al. (2020).

Dry weight of shoot (kg m^{-2})

Two-way ANOVA showed that both study factors had a significant effect on shoot dry weight, while their interaction was not statistically significant (Tables 3 and 10). The 5 irrigations treatment recorded the highest average for this trait (57.64 kg m^{-2}), while the 3 irrigations treatment recorded the lowest rate (34.34 kg m^{-2}). Regarding SA concentrations, a similar trend was observed. The maximum dry weight (50.64 and 48.69 kg m^{-2}) resulted in the highest SA concentrations (300 and 200 mg l^{-1}, respectively), while the minimum dry weight (34.18 kg m^{-2}) resulted in the control treatment. The superiority of the 5 irrigations treatment regarding this trait can be attributed to the significant enhancement of vegetative traits (number of tillers, plant height, and leaf area) as shown in Tables 4, 5, and 6, respectively, as well as the significant improvement in physiological traits (absolute growth rate and biomass duration) under the influence of this treatment (Tables 7 and 8).

It is also expected that this treatment contributed to increased dry matter accumulation in the plant's biomass, leading to improved total dry weight. Therefore, this trait is very important for plant development and was significantly correlated with all studied traits (Figure 3), excluding RWC. On the other hand, the SA

Table 9. Effect of irrigation frequency, SA concentration, and their interaction on RWC

Irrigation frequency	SA concentration (mg l^{-1})				Irrigation treatment means
	0	100	200	300	
3-time	74.73±2.1^{bcd}	78.38±2.1^{abc}	79.85±2.1^{ab}	78.22±2.1^{bc}	77.80±0.9^{a}
4-time	76.09±2.1^{bcd}	64.05±2.1^{e}	71.46±2.1^{d}	75.31±2.1^{bcd}	71.73±0.9^{b}
5-time	72.78±2.1^{cd}	84.17±2.1^{a}	74.15±2.1^{bcd}	73.16±2.1^{cd}	76.07±0.9^{a}
SA treatment means	74.53±1.2	75.53±1.2	75.15±1.2	75.56±1.2	
LSD at $p \leq 0.05$	Irrigation = 3.556		SA = ns		Interaction = 5.963

Note: Values are presented as mean±SE. Means followed by the same letter within each factor are not significantly different at $p \leq 0.05$ according to the LSD test. ns = Non-significant; SE = Standard error

Table 10. Effect of irrigation frequency, SA concentration, and their interaction on dry shoot weight (kg m^{-2})

Irrigation frequency	SA concentration (mg l^{-1})				Irrigation treatment means
	0	100	200	300	
3-time	25.37±3.14	27.82±3.14	42.30±3.14	41.88±3.14	34.34±1.08^{b}
4-time	31.55±3.14	36.25±3.14	40.65±3.14	39.72±3.14	37.04±1.08^{b}
5-time	45.63±3.14	51.47±3.14	63.12±3.14	70.32±3.14	57.64±1.08^{a}
SA treatment means	34.18±1.82^{b}	38.51±1.82^{b}	48.69±1.82^{a}	50.64±1.82^{a}	
LSD at $p \leq 0.05$	Irrigation = 4.246		SA = 5.403		Interaction = ns

Note: Values are presented as mean±SE. Means followed by the same letter within each factor are not significantly different at $p \leq 0.05$ according to the LSD test. ns = Non-significant; SE = Standard error treatment, particularly at higher concentrations, enhanced the plant tolerance to drought conditions (Alsahli et al., 2019; Moustakas et al., 2022). These findings are consistent with the outcomes reported by Abdelaal et al. (2020) and Moustakas et al. (2022).

100-grain weight (g)

Two-way ANOVA revealed that this trait was significantly influenced by irrigation frequency, SA concentration, and their interaction (Tables 3 and 11). The 5 irrigations treatment appeared to have the highest average for this trait (4.168 g), significantly outperforming the others, followed by the 4-time (2.281 g) and 3-time irrigation (2.323 g). The 300 mg l^{-1} SA treatment also produced the highest 100-grain weight (g) trait, achieving the highest average of (3.639 g), with a non-significant difference from the 200 mg l^{-1} treatment, which recorded an average of (3.541 g). The control treatment recorded the lowest value (2.887 g), which did not significantly differ from the 100 mg l^{-1} SA treatment. The combination of 5 irrigations and 200 mg l^{-1} SA resulted in the maximum 100-grain weight (4.75 g), while the combination of 3 irrigations and 100 mg l^{-1} SA resulted in the lowest weight (1.98 g).

Additionally, 100-grain weight exhibited a highly significant correlation with all studied traits (Figure 3), recording coefficients of r = 0.89**, 0.95**, 0.95**, 0.93**, 0.98**, and 0.99** for the number of tillers, plant height, flag leaf area, AGR, biomass duration, and dry weight, respectively. Therefore, the observed increase in 100-grain weight may be attributed to the fact that providing water at appropriate times or during the important growth stages, especially when exporting nutrients from the source to the grain storage sites, affects the increase in grain weight (Aktas et al., 2025).

Furthermore, SA application increased the plant's effectiveness in exporting dry matter from its source to its grain destination, especially at high concentrations, due to the important physiological role of this acid in sustaining plant life and increasing production. SA, as a plant growth regulator, plays important roles in regulating plant growth processes and signaling networks, as it participates directly or indirectly in a corresponding set of responses to biotic and abiotic stress and tolerance in plants (Alsahli et al., 2019; Moustakas et al., 2022). These results are consistent with the findings reported by Moustakas et al. (2022) and Hanif et al. (2024).

Grains per spike

Irrigation frequency, SA concentrations, and the interaction between the 2 factors had a significant effect on the number of grains per spike (Tables 3 and 12). The 5-time irrigation treatment significantly outperformed the other treatments, recording the highest average of 37.67 grains $spike^{-1}$, followed by the 4-time irrigation treatment, which recorded an average of 29.92 grains $spike^{-1}$. The 3-time irrigation treatment recorded the lowest average of 27.42 grains $spike^{-1}$. The 300 mg l^{-1} SA treatment significantly outperformed the other treatments, recording an average of 37.67 grains $spike^{-1}$, followed by the 200 mg l^{-1} SA treatment, which recorded 33.89 grains $spike^{-1}$. Conversely, the SA concentration of 100 mg l^{-1} and control treatments resulted in the lowest average number of grains per spike (29.44 and 25.67 grains $spike^{-1}$, respectively). The interaction treatment between irrigation (5 times) and 300 mg l^{-1} SA recorded the highest average of 47.00 grains $spike^{-1}$, exceeding all other interaction treatments. On the other hand, the interaction between irrigation 3 times and 0 mg l^{-1} SA resulted in the lowest average for grain number, reaching 22.00 grains $spike^{-1}$.

Additionally, trends in both water frequency and SA concentration were clearly associated with increased grain number during the barley growing

Table 11. Effect of irrigation frequency, SA concentration, and their interaction on 100-grain weight (g)

Irrigation frequency	SA concentration (mg l^{-1})				Irrigation treatment means
	0	100	200	300	
3-time	2.38±0.14^{ef}	1.98±0.14^{f}	2.37±0.14^{ef}	2.55±0.14^{de}	2.32±0.13^{c}
4-time	2.85±0.14^{de}	2.94±0.14^{cd}	3.49±0.14^{bc}	3.82±0.14^{b}	3.28±0.13^{b}
5-time	3.42±0.14^{bc}	3.96±0.14^{b}	4.75±0.14^{a}	4.53±0.14^{a}	4.16±0.13^{a}
SA treatment means	2.88±0.08^{b}	2.96±0.08^{b}	3.54±0.08^{a}	3.63±0.08^{a}	
LSD at $p \leq 0.05$	Irrigation = 0.511		SA = 0.257		Interaction = 0.561

Note: Values are presented as mean±SE. Means followed by the same letter within each factor are not significantly different at $p \leq 0.05$ according to the LSD test. SE = Standard error

Table 12. Effect of irrigation frequency, SA concentration, and their interaction on grain number (grain spike^{-1})

Irrigation frequency	SA concentration (mg l^{-1})				Irrigation treatment means
	0	100	200	300	
3-time	22.00±1.05^{f}	25.33±1.05^{e}	29.33±1.05^{d}	33.00±1.05^{c}	27.42±0.53^{c}
4-time	25.33±1.05^{e}	29.67±1.05^{d}	31.97±1.03^{c}	33.00±1.05^{c}	29.92±0.53^{b}
5-time	29.67±1.05^{d}	33.33±1.05^{c}	40.67±1.05^{b}	47.00±1.05^{a}	37.67±0.53^{a}
SA treatment means	25.67±0.61^{d}	29.44±0.61^{c}	33.89±0.61^{b}	37.67±0.61^{a}	
LSD at $p \leq 0.05$	Irrigation = 2.069		SA = 1.806		Interaction = 3.094

Note: Values are presented as mean±SE. Means followed by the same letter within each factor are not significantly different at $p \leq 0.05$ according to the LSD test. SE = Standard error

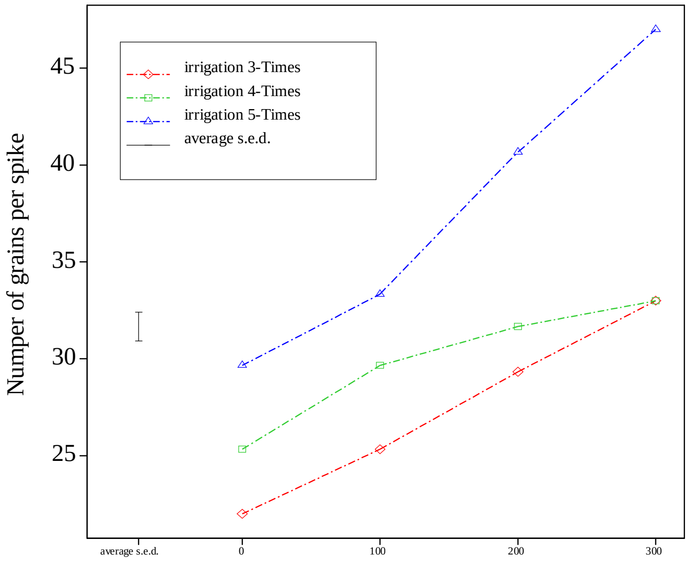

Figure 1. Number of grains per spike as affected by SA concentrations and different levels of irrigation frequency

season (Figure 1). Furthermore, to support these results, the correlation trend of grains per spike was highly related to all vegetative and physiological traits excluding RWC; it was significantly related to the yield component traits (r = 0.95** and 0.96**, respectively) for 100-grain weight and grain yield (Figure 3). Thus, under adequate water and SA availability, these findings suggested that sufficient irrigation during reproductive stages enhanced the physiological activity, promoting successful pollination and fertilization processes, which leads to an increase in the number of grain-bearing spikelets, especially if water is available during the pollination and fertilization stages (Khalvandi et al., 2021; Maqsood et al., 2023; Aktas et al., 2025).

Furthermore, SA likely contributes by supporting genetic and cellular processes within the plant. The success of the pollination and fertilization processes, as well as their role in the division and reproduction of genetic material, may be a reason for the increased number of grains in the spikelet (Farouk et al., 2018; Abdelaal et al., 2020). These results are consistent with earlier findings reported by Abdelaal et al. (2020), Maqsood et al. (2023), and Hanif et al. (2024).

Grain yield (kg m^{-2})

Two-way ANOVA revealed that both irrigation frequency and SA concentration significantly affected grain yield, whereas their interaction was not statistically significant (Tables 3 and 13). The 5 irrigations treatment achieved the highest average yield (1.383 kg m^{-2}), followed by 4 irrigations (1.178 kg m^{-2}), while 3 irrigations recorded the lowest average yield (1.000 kg m^{-2}). On the other hand, SA concentrations of 300 and 200 mg l^{-1} resulted in the highest yields (1.370

and 1.293 kg m^{-2}, respectively). The control not treated with SA produced the lowest yields (0.959 kg m^{-2}). Moreover, the trend of yield enhancement was evident with increasing the number of water frequency and SA concentration (Figure 2).

On the other hand, to understand this trend, the correlation between grain yield and all studied traits was significant, except for RWC (Figure 3). The strong positive correlations were (r = 0.98**, 0.96**, 0.93**, 0.91**, and 0.90**) with flag leaf area, grains per spike, biomass duration, dry weight, and 100-grain weight, respectively. Thus, this increase in grain yield can be attributed to the fact that the total grain yield is the sum of the components of the yield, so increasing any factor leads to an increase in the yield. It was shown during this experiment that irrigation 5 times outperformed the other irrigation treatments in the 2 characteristics of 100-grain weight and grains per spike, which are major contributors to final yield, in addition, the correlations with other growth traits especially flag leaf area, biomass duration, and dry weight, which may increase transportation processing of dry mater from leaves (source) to (sink) grain (Khalvandi et al., 2021; Oguz et al., 2022; Aktas et al., 2025).

Furthermore, SA has well-documented physiological roles in sustaining and extending plant life under unfavorable growth conditions, thereby enhancing plant tolerance to abiotic stress. It also increases photosynthetic rate and carbon assimilation, which optimizes the efficiency of dry matter mobilization into developing grains (Abdelaal et al., 2020; Asma et al., 2023). These results were consistent with those reported by Abdelaal et al. (2020), Maqsood et al. (2023), and Hanif et al. (2024).

Table 13. Effect of irrigation frequency, SA concentration, and their interaction on grain yield (kg m^{-2})

Irrigation frequency	SA concentration (mg l^{-1})				Irrigation treatment means
	0	100	200	300	
3-time	0.89±0.16	0.89±0.16	1.11±0.16	1.11±0.16	1.00±0.03^{c}
4-time	0.96±0.16	1.20±0.16	1.22±0.16	1.33±0.16	1.18±0.03^{b}
5-time	1.03±0.16	1.26±0.16	1.55±0.16	1.67±0.16	1.38±0.03^{a}
SA treatment means	0.96±0.09^{b}	1.13±0.09^{ab}	1.29±0.09^{a}	1.37±0.09^{a}	
LSD at $p \leq 0.05$	Irrigation = 0.128		SA = 0.275		Interaction = ns

Note: Values are presented as mean±SE. Means followed by the same letter within each factor are not significantly different at $p \leq 0.05$ according to the LSD test. ns = Non-significant; SE = Standard error

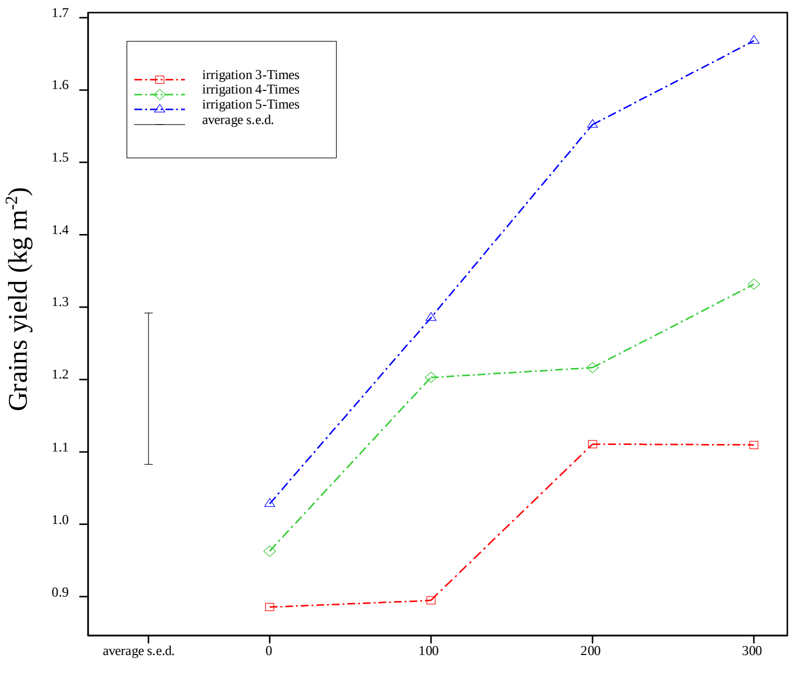

Figure 2. Grain yield (kg m^{-2}) as affected by SA concentrations and different levels of irrigation frequency

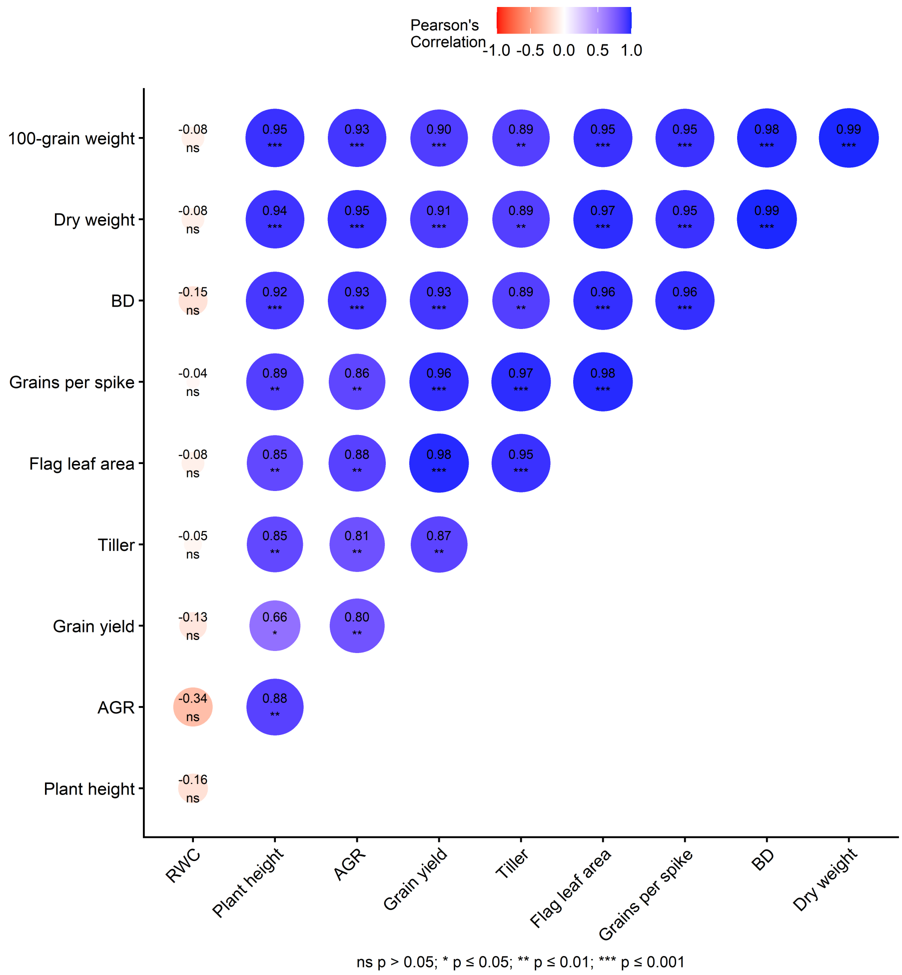

Figure 3. Pearson's correlation bubble heatmap illustrating the relationships among barley growth, physiological, and yield traits under different irrigation frequencies and SA concentrations
Note: * and ** indicate significance at $p \leq 0.05$ and $p \leq 0.01$, respectively; ns = Non-significant

CONCLUSIONS

The present study demonstrated that irrigation frequency and the foliar application of SA significantly enhanced barley growth and grain yield under semi-arid conditions. A 5-time irrigation through the growing season produced the highest growth performance and grain yield compared to the deficit irrigation treatments. In addition, foliar application of SA at 300 mg l^{-1} improved biomass accumulation, yield components, and drought tolerance-related traits. The interaction between the 2 factors positively influenced most of the studied traits, with the highest grain yield recorded under the combination of 5 irrigations with 300 mg l^{-1} SA. Further studies are warranted across diverse environmental conditions and varying barley genotypes to validate these findings.

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