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Research article

Revitalizing maize growth and yield in water-limited environments through silicon and zinc foliar applications

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ABSTRACT

Maize is an economically vital cereal crop. However, water deficiency can severely impact its productivity. Thus, it is necessary to implement an essential approach to increase maize yield while navigating the limitations imposed by scarce water supplies. The present study aimed to investigate whether foliar applications of silicon (Si) and zinc (Zn) could mitigate the adverse effects of water deficiency and improve maize growth and yield. Field experiments were conducted in Egypt during two growing seasons (2021–2022) under three irrigation regimes: full irrigation (ET0), moderate stress (ET1), and severe stress (ET2). The treatments comprised foliar sprays of Si, Zn, Si + Zn, and water control. Phenological, growth, physiological, chemical, and yield-related traits were assessed. Results showed that adequate irrigation (ET0) enhanced most parameters compared to water stress treatments. Under ET0, the combined silicon and zinc treatment resulted in the highest values for plant height, leaf area, chlorophyll content, grains per ear, kernel weight, ear size, and yield compared to other foliar treatments. Under drought stress (ET1, ET2), Si + Zn applications maintained superiority in mitigating yield losses. Proline accumulation was highest under severe stress (ET2) in the absence of foliar sprays, indicating greater drought impacts. Correlation analysis revealed positive associations of grain yield with ear size, leaf area, kernel weight, and biological yield. Cluster analysis separated irrigation regimes and visualized the consistently beneficial effects of Si + Zn across all water levels. Overall, the results demonstrate the synergistic potential of Si and Zn supplementation to sustain maize performance and yields under varying water availability.

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1. Introduction

Maize (*Zea mays* L.) is a highly significant cereal crop globally due to its versatility and high yield. It is cultivated on 193.7 million hectares, producing approximately 1147.7 million metric tons annually, with an average yield of 5.75 tons per hectare [1,2]. Maize plays a crucial role in various sectors: it is predominantly used as animal feed (61 %), a staple in human diets (17 %), and an industrial raw material (22 %), supporting industries such as starch, biofuels, and biogas [3]. This multifaceted utility underscores maize's importance in both agricultural and industrial contexts, making it a cornerstone of global food and energy systems.

Drought stress is a significant threat to maize production, leading to yield losses ranging from 30 % to 90 %, depending on the severity and duration of the stress. It impacts maize at various stages, from seedling emergence to grain filling, and is particularly detrimental during flowering, where water deficits can delay ear growth and increase the anthesis-silking interval, inhibiting fertilization and leading to yield losses [4–9]. Maize responds to and mitigates the impact of water deficit using three primary strategies: drought escape, avoidance, and tolerance [10,11]. Drought escape is a strategy to prevent the coincidence of water deficit with key developmental stages, and it is primarily achieved by early flowering and maturation. Also, drought avoidance maintains a relatively high tissue water content despite reduced soil water availability [7]. Despite low water potential, drought tolerance maintains cellular homeostasis through adaptive traits [10,12]. Maize seedlings growing under water stress conditions exhibit several important physiological responses, including decreased cell turgor. Additionally, carbohydrate metabolism is one of the most important plant processes for absorbing the energy generated during photosynthesis, and its substrates have been reported to be involved in drought stress responses in addition to acting as energy sources [13–15]. The impact of drought on maize yield loss is influenced by the severity of the drought, duration of exposure, and the plant's growth stage [16]. Drought stress can occur unpredictably at any plant's life cycle stage, making it challenging to forecast. However, extensive research suggests that the flowering stage of maize is particularly susceptible to drought stress [17]. As a result, previous breeding efforts have primarily focused on developing drought-resistant varieties for the flowering and grain-filling stages, with less emphasis on the ability of seedlings to tolerate drought stress [18,19].

Water scarcity can profoundly impact crop growth and agricultural productivity, leading to water stress with various adverse effects [12,20]. Insufficient irrigation hinders growth and affects water productivity, defined as the yield per unit of water used [11]. Effective management of limited water resources is crucial for maintaining crop performance and maximizing water use efficiency. Precise irrigation timing and sustainable practices are vital to optimize yields and enhance profitability in water-limited conditions [21]. Water stress can disturb crop growth, development, and various physiological processes, ultimately decreasing biomass and yield [21–23]. Therefore, adopting innovative strategies and initiatives to improve water use efficiency in crop production systems becomes imperative. Implementing such measures can mitigate the negative impacts of water scarcity and enhance agricultural practices' overall productivity and sustainability [12,20,24]. Over time, various water-saving technologies and management practices have been developed; among them is deficit irrigation (DI), a strategy where crops are deliberately supplied with less water than their full water requirements, known as crop evapotranspiration (Etc.) [12,21,25]. DI is widely accepted to optimize water usage while enabling crops to tolerate mild water stress with minimal or negligible reductions in yield and quality [26,27].

Silicon (Si) is soil's second most abundant element after oxygen. Nonetheless, Si is a beneficial nutrient that plays a vital role in plants, especially under stress conditions [28,29]. Si's beneficial effects on plant growth extend beyond its role as a physical, mechanical barrier, as it actively participates in diverse physiological and metabolic processes while being deposited on cell walls [30,31]. The application of silicon has been established as an effective strategy for reducing and mitigating the detrimental impacts of several abiotic stresses on plants, such as drought, salinity, heavy metals, and high temperature [30]. In drought-stress conditions, silicon helps maintain adequate water status in plant leaves and enhances photosynthetic activity in maize crops [32,33]. Furthermore, exogenous silicon application can form a silica-cuticle layer on the leaf epidermal tissue, improving tissue water status in wheat crops. This demonstrates the potential of silicon to serve as a valuable tool in enhancing plant resilience and productivity under various stress conditions [28,32].

Zinc (Zn) is a vital micronutrient that plays a crucial role in enzymatic processes related to photosynthesis [34,35]. Functionally, Zn serves as a cofactor or structural component for multiple enzymes involved in various metabolic processes, playing a crucial role in photosynthesis, glucose and protein metabolism, pollen generation, auxin metabolism, membrane integrity, and stress tolerance induction, highlighting its significance as a micronutrient for overall plant health and growth in diverse environmental conditions [36–38]. Additionally, it promotes germination rates, enhances product quality, and improves crop productivity per unit area. Zinc acts as a catalyst to facilitate growth and development during critical stages of plant growth [39]. Moreover, zinc supplementation is crucial for enhancing water use efficiency. Proper nutrition practices have increased water utilization efficiency by 20–25 % [40]. It also significantly improves seed yield and quality [41,42]. Zn treatment positively impacts chlorophyll production and carbonic anhydrase activity, leading to enhanced transfer of CO_2 from the cell's liquid phase to the chloroplast, thereby improving the photosynthetic rate [43]. The current study aimed to explore whether foliar application of Si and Zn could alleviate the negative impacts of water scarcity and enhance maize growth and yield. While the individual effects of Si and Zn on plant stress tolerance have been previously reported, this study uniquely investigates the combined application of these two elements and their impact on photosynthesis, transpiration, and overall plant performance under drought conditions. The findings of this study demonstrate that the enhanced water stress resistance achieved through Si and Zn application is mediated by improvements in the photosynthetic rate and reductions in transpiration in drought-stressed maize plants. This information contributes to a better understanding of the physiological and biochemical mechanisms underlying the drought-mitigating effects of these essential nutrients in maize, a globally important cereal crop.

2. Materials and methods

2.1. Experimental site description

Open-field experiments were conducted in Hosh Isa district, El-Behira governorate, Egypt, (27°12′16.7″ N 31°09′36.9″ E) during the 2021 and 2022 seasons. The experimental field's climate was arid with infrequent precipitation. From May to September, the average maximum and minimum air temperatures were 36.4 °C and 22.35 °C, respectively, during both growing seasons. The relative humidity ranged from 35 % to 42 % during this period. The soil's initial physicochemical parameters were assessed in both seasons, as shown in Table 1. Soil samples were obtained from each plot at two specific depths, namely 0–25 cm and 25–40 cm, using a spiral auger with a diameter of 2.5 cm. A composite sample per plot was created by taking three sub-samples from each plot. The samples were brought to the laboratory, dehydrated at 40 °C, and pulverized to pass through a 2 mm sieve. They were then further reduced to a particle size of less than 60 μm to estimate the soil's organic carbon content (%), nitrogen (N) levels, accessible phosphorus (P) in milligrams per kilogram ($mg\cdot kg^{-1}$), and exchangeable potassium (K) in centimoles per kilogram ($cmol\ kg^{-1}$). In addition, the electrical conductivity (E.C.) and soil pH were determined using established protocols [44].

2.2. Experimental design and silicon and zinc foliar treatments

The experiments were carried out using a split-plot design with three replications. The main plots were assigned to three different irrigation depths: ET2 (50 % of crop evapotranspiration - ETc), ET1 (75 % of ETc), and ET0 (100 % of ETc). Within each main plot, the subplots were further divided based on the foliar spraying application, comprising four treatments: Control (water spraying), Si (at 150 mg/l by using potassium silicate (K_2O_3Si; MW = 154.3 g/M; pH = 12.7), Zn (at 5 g/l from zinc sulphate heptahydrate ($ZnSO_4\cdot 7H_2O$; MW = 287.5 g/M), and Si + Zn. Maize (Zea mays L.) cv. Giza 168 was sown on May 5 during both growing seasons (2021 and 2022). At a depth of 25 cm, two kernels were manually planted on each hill. Before the initial irrigation, the plants were shaved down to a single plant per hill. All other agronomic practices were maintained consistently and normally in accordance with the recommendations made by the Egyptian Ministry of Agriculture and Land Reclamation.

2.3. Irrigation management and application

The study utilized drip irrigation with a spacing of 0.3 m, providing one emitter per plant. Emitters with flow rates of 4, 6, and 8 L/h were employed to ensure consistent and standardized irrigation, resulting in water regimes equivalent to 50 %, 75 %, and 100 % of crop evapotranspiration (ETc). Uniformity tests were conducted, showing a distribution coefficient of 92 %, indicating a good level of uniformity in water application. The irrigation management was determined daily based on the reference evapotranspiration data from a Class A evaporimeter pan. The crop evapotranspiration, measured in millimeters per day (mm/day), was calculated using the evaporation data obtained from the Class A pan, following standard methods equation (Eq. (1)):

$$ETc = ECA \times Kp \times Kc \tag{1}$$

where ETc is the crop evapotranspiration, in mm day^{-1}, ECA is the evaporation measured in the class A pan, in mm/day^{-1}; Kp is the class A pan coefficient, dimensionless and Kc is the crop coefficient, dimensionless.

The crop coefficients (Kc) employed in this research were 0.86 for the period up to 40 days after sowing (DAS), 1.23 from 41 to 53 DAS, 0.97 from 54 to 73 DAS, and 0.52 from 74 DAS until the end of the crop cycle [45]. A leaching fraction of 15 % was applied by adding it to the irrigation depth [46]. The irrigation time was determined using equation (Eq. (2)):

$$\mathbf{It} = \frac{\mathbf{ETc\ x\ Sd}}{\mathbf{AF\ x\ q}} \times \mathbf{60} \tag{2}$$

where It; is the irrigation time (min), ETc; is the crop evapotranspiration for the period (mm), Sd; is the pacing between emitters, Af; is

Table 1

Physical and chemical characteristics of the representative composite soil sample from the surface layer (0–25 cm).

Chemical properties

pH (1: 1)	E.C. (dS/m) (1:2)	Soluble cations (1:2) (cmol/kg soil)				Soluble anions (1: 2) (cmol/kg soil)		Available phosphorus (mg/kg)	Total nitrogen (%)
		Ca^{++}	Mg^{++}	Na^{+}	K^{+}	CO_3^{-} + HCO_3^{-}	Cl^{-}		
8.31	3.00	8.40	12.03	11.50	0.52	2.99	18.00	1.70	1.00

Physical properties

Particle size distribution (%)			Soil texture class	Volumetric water content (%)<			OM (%)<	$CaCO_3$ (%)	Bulk density g/cm^3
Sand	Silt	Clay		SP	FC	WP			
60.00	11.10	28.90	sandy loam	23.0	10.9	4.5	0.42	6.60	1.60

FC, field capacity; WP, wilting point; OM, organic matter and EC electrical conductivity.

the application efficiency (0.92) and q; is the flow rate (L h^{-1})

2.4. Data collection

2.4.1. Measurements of plant growth indicators

At the harvest stage (120 days after sowing), five plants were selected randomly from each subplot and the plant height was measured from the soil surface to the top of the highest silk using a meter tape. The leaf area index (LAI, cm^2) was determined according to the method using the standard method [47] as illustrated in the following equation (Eq. (3)):

$$\mathrm{LAI} = \frac{\textbf{leaf area/plant}}{\textbf{plant ground area}} \tag{3}$$

The leaf area is calculated as the length x width x 0.75 of leaves of five plants within each experimental subplot.

2.4.2. Determination of plant phenological characteristics

Days to 50 % tasseling (DTT): The DTT was determined as the number of days extended from the time of planting until 50 % of the maize plants in each experimental subplot had visible tassels. Tasseling is the stage when the male flowers emerge from the top of the plant.

Days to 50 % silking (DTS): The DTS was expressed as the number of days from planting until 50 % of the plants in each subplot reached the silking stage. Silking refers to the emergence of silk threads from the female flowers that will be pollinated to develop into corn kernels.

2.4.3. Determination of plant phenological traits

The chlorophyll content of the plant leaf was measured using the SPAD502 chlorophyll meter. The SPAD502 m estimated chlorophyll content by measuring light absorbance at two wavelengths (650 and 940 nm) passing through intact leaves. All plants were assessed for chlorophyll content, and readings were taken on the highest ear's ear leaf at three different positions on the leaf [48]. Each plant's readings were repeated three times to ensure accuracy, and the average value was recorded.

Leaf proline content (PC, mg/g) in fresh leaf samples which were plunged into a freezing 3 % aqueous sulfosalicylic acid solution for proline extraction [49]. The proline content was then determined using a spectrophotometer, and the measurements were repeated twice to ensure the accuracy of the results.

2.4.4. Determination of yield and yield components

At harvest, samples from the three inner ridges of each sub-plot were collected. Measurements were taken for various components, including ear length (EL, cm), number of grains per ear (NGE), and 100-grain weight (HGW, g). These measurements were obtained from ten randomly selected plants within each subplot. Additionally, the biological yield (BY, t/ha) was calculated by weighing all plants (grain and straw) in each sub-plot, while the grain yield (GY, t/ha) was determined by considering all grains from the plants within each sub-plot and converting it to grain yield per hectare. The straw yield (SY, t/ha) was recorded by subtracting the grain yield from the biological yield. Finally, the harvest index (HI, %) was calculated using appropriate formulas according to equation (Eq. (4)):

$$\text{Harvest index } (\%) = \frac{\textbf{Grain yield}}{\textbf{Biological yield}} \times \mathbf{100} \tag{4}$$

2.4.5. Chemical analysis

At the harvest stage, chemical analysis was conducted on maize grain. The crude grain protein content was calculated using the formula (Eq. (5)):

$$\text{Crude protein } (\%) = \text{Nitrogen (N)} \times 6.25 \tag{5}$$

The N content (%) of maize grain was determined using the standard Micro-Kjeldahl method.

2.5. Statistical analysis

The analysis of variance (ANOVA) was conducted for all studied traits using the general linear model (GLM) procedure in SAS 9.4 software for Windows. Fisher's least significant difference (LSD) test was applied to the data at a 5 % significance level for statistical analysis. Boxplots were created to visually represent the variation in foliar spraying and biofertilizer. Pearson correlation coefficients were computed to examine the associations among growth, yield, and seed biochemical composition parameters. Additionally, hierarchical clustering analysis was performed to uncover the interrelationships among the studied traits and fertilization treatments. The ggplot2 package in the R project (version 3.4.5) was utilized to clearly visualize the data distribution and variability among different treatments for generating the boxplots.

3. Results

3.1. Response of maize to studied different treatments

3.1.1. Effect of water regimes on growth, yield, and yield-related traits

The results in Figs. 1 and 2 show the effect of water regimes on the growth, physiological, phenological, chemical, and yield traits during the 2021 and 2022 seasons. Concerning the significant impact of irrigation intervals on the studied attributes, the results revealed that irrigation treatment ET0 recorded the highest mean plant height (186.9 and 187.3 cm), leaf area index (4.1 and 4.2 cm^2), chlorophyll content (47.3 and 48.1 SPAD unit), tasseling (57, and 58 days) silking (53.8, and 47.8 days), protein content (Fig. 1). Similarly, as shown in Fig. 2, ET0 recorded the highest mean values for the yield and its components, including 100-grain weight (39.9

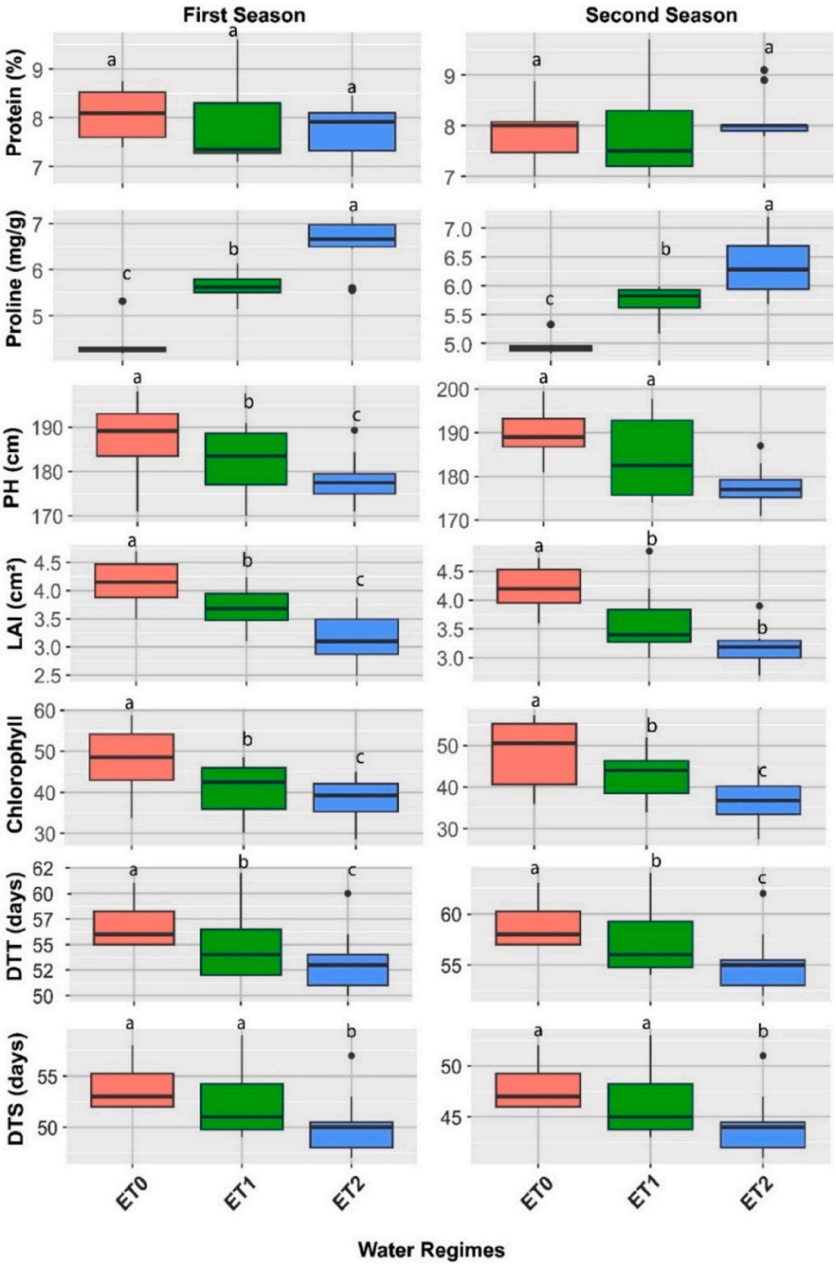

Fig. 1. Effects of different water regimes (ET0, ET1, and ET2) on growth, phenological, physiological, and biochemical traits for maize determined at field experiments during the 2021 and 2022 seasons. Different lowercase letters on boxes indicate statistically significant differences between treatments ($p \leq 0.05$), as performed by the least significant difference (Fisher's LSD) test.

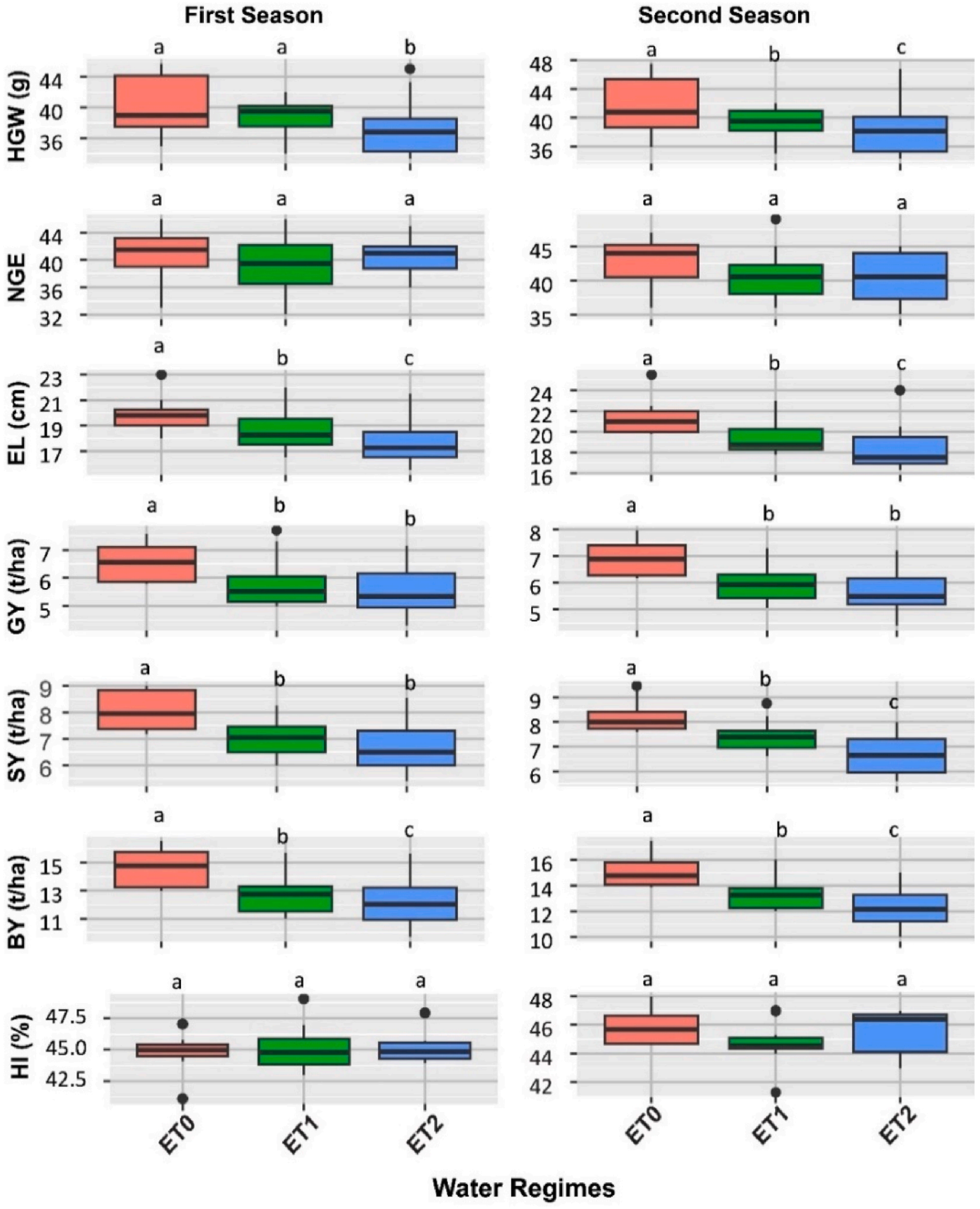

Fig. 2. Effects of different water regimes (ET0, ET1, and ET2) on yield and yield-related traits for maize determined at field experiments during the 2021 and 2022 seasons. Different lowercase letters on boxes indicate statistically significant differences between treatments ($p \leq 0.05$), as performed by the least significant difference (Fisher's LSD) test.

and 41.58 g), ear length (19.9 and 21.2 cm), grain yield (6.5 and 6.9 t/ha), straw yield (8.1 and 8.2 t/ha), and biological yield (14.6 and 15. 1 t/ha), in the first and the second seasons, respectively (Fig. 2). The results also showed no significant difference between the water regimes in the harvest index (Fig. 2) and protein content in both seasons (Fig. 1). On the other hand, the lowest values of growth, yield, and its components were obtained with water regime ET2, while ET2, in contrast, recorded the highest values of leaf proline content (6.6 and 6.4 μmol/g plant) in both growing seasons, respectively (Fig. 1).

3.1.2. Effect of water regimes on growth, yield, and yield-related parameters

The results in Figs. 3 and 4 show the effect of foliar spray treatments on the growth, physiological, phenological, chemical, and

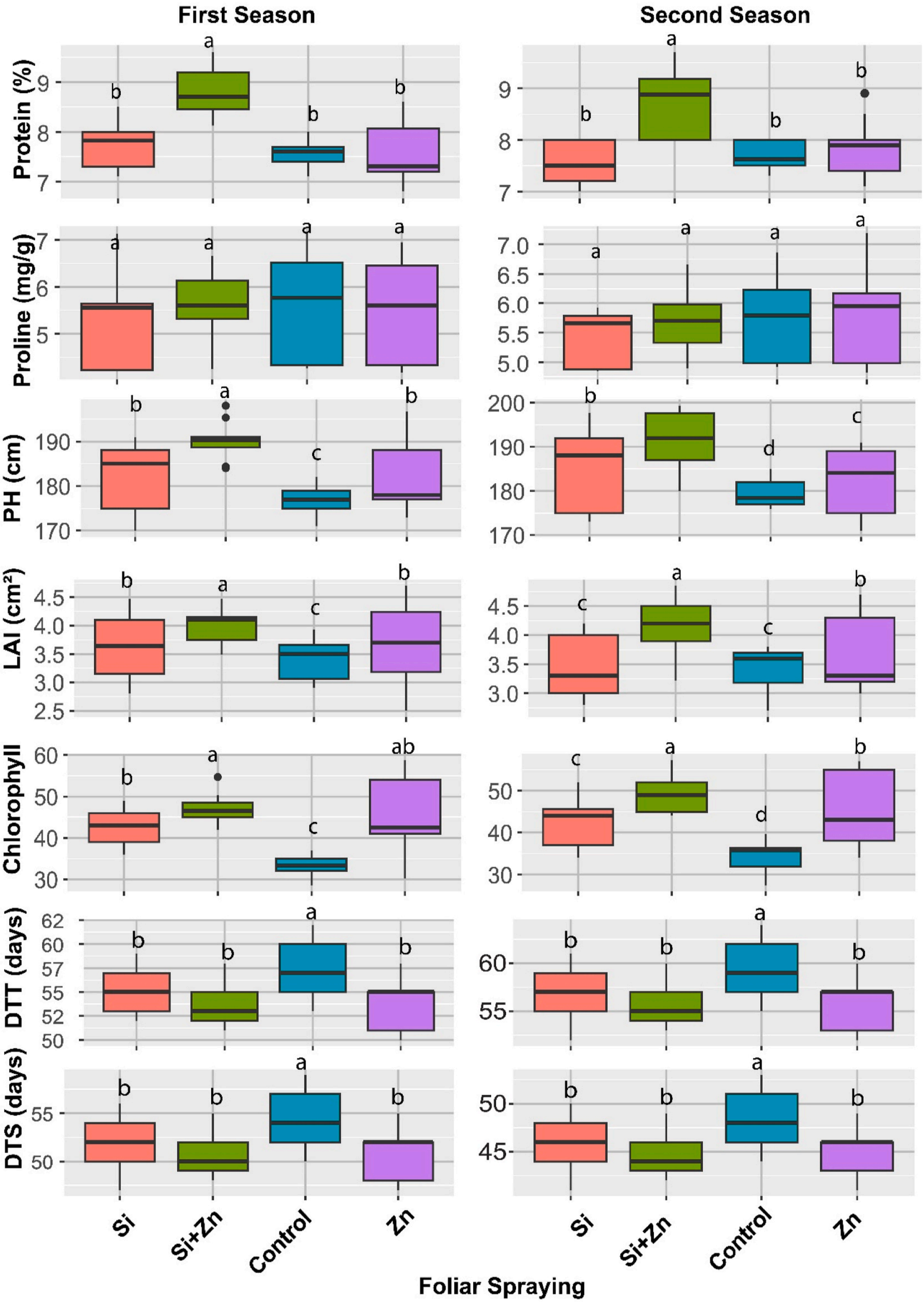

Fig. 3. Effects of different foliar spraying (control, SI, Zn, and Si + Zn) on the growth, phenological, physiological, and chemical traits of maize determined at field experiments during the 2021 and 2022 seasons. Different lowercase letters on boxes indicate statistically significant differences between treatments (*$p \leq 0.05$*), as performed by the least significant difference (Fisher's LSD) test.

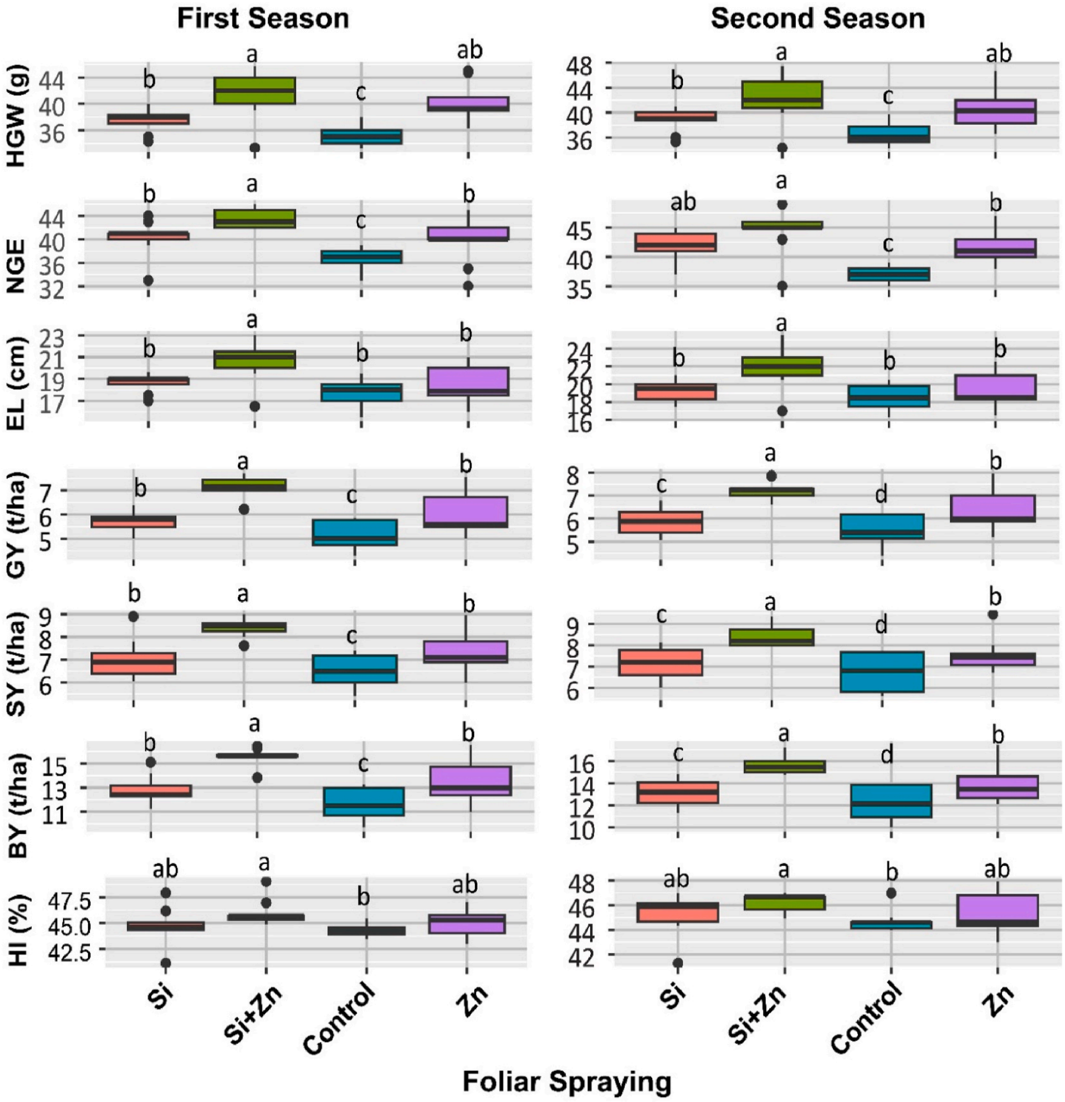

Fig. 4. Effects of different foliar spraying (control, SI, Zn, and Si + Zn) on yield and yield-related parameters of maize determined at field experiments during the 2021 and 2022 seasons. Different lowercase letters on boxes indicate statistically significant differences between treatments ($p \leq 0.05$), as performed by the least significant difference (Fisher's LSD) test.

yield traits during the 2021 and 2022 seasons. Concerning the significant impact of foliar spray treatments on the studied attributes, the results revealed that the Si + Zn treatment recorded the highest mean of plant height (189.8 and 191.4 cm), leaf area index (3.9 and 4.1 cm^2) chlorophyll content (47 and 49.2 SPAD unit), and protein content (8.7 and 8.8 %) (Fig. 3). In contrast, the control treatment recorded the late tasseling and silking date in the two growing seasons, respectively, as shown in Fig. 3. However, a non-significant difference was revealed among four foliar spray treatments in proline content, which showed its highest mean of 6.04 and 6.01 μmol/g plant in the two growing seasons, respectively, (Fig. 3). Similarly, applying both Si + Zn resulted in the highest means grains numbers per ear (43.5 and 44.33 grain/ear), ear length (20.11 and 21.0 cm), 100-grains weight (40.2 and 41.16 g), grain yield (7.2 and 7.3 ton/ha), straw yield (8.4 and 8.40), biological yield (15.6 and 15.6 ton/ha), and harvest index (45.9 and 46.25 %) in both seasons, respectively (Fig. 4).

3.1.3. Response of maize to the interaction between water regimes and foliar treatments

The significant interaction effects between irrigation regimes and foliar spraying treatments on the studied characters are shown in Table 2. The results showed that irrigation treatment ET0 with foliar spraying of Si + Zn exhibited the highest mean values for plant height at (194.3 and 198.0 cm), and the highest values of number of grains/row (44 and 45.6 grains/row), while irrigation treatment ET0 + Zn showed the highest leaf area index (4.50 and 4.54 cm^2), chlorophyll content (56.83 and 56.0 SPAD unit). Also, the irrigation treatment ET0 combined with control recorded the late tasseling and silking date in both seasons, as shown in Table 2. Additionally,

Table 2
Growth attributes of maize as affected by the interaction between irrigation regimes and foliar application during the 2021 and 2022 seasons.

Growth Trait	Water Regime	Foliar Spraying							
		First season (2021)				Second season (2022)			
		Control	Si	Zn	Si + Zn	Control	Si	Zn	Si + Zn
Plant height	ET0	175.3cd	188.0abc	190.0 ab	194.3a	172.0cd	189.33 ab	189.6 ab	198.0a
	ET1	171.3d	181.3abcd	178.3bcd	189.6 ab	172.3cd	189.0 ab	175.0cd	193.0 ab
	ET2	168.3d	174.3cd	177.3bcd	185.6abc	166.3d	174.6cd	175.6cd	183.3bc
Leaf area Index	ET0	3.63bcde	4.2 ab	4.5a	4.10abc	3.6bc	4.1 ab	4.54a	4.47a
	ET1	3.30def	3.42cdef	3.73bcd	4.16abc	3.62bc	3.30cd	3.20cd	4.3a
	ET2	2.96ef	3.19def	2.82f	3.62bcde	2.96d	2.93d	3.26cd	3.483bcd
Chlorophyll content	ET0	34.56de	47.36abc	56.83a	50.56 ab	35.76gh	47.00bcd	56.0a	53.43 ab
	ET1	34.03de	43.66bcd	38.60cde	47.10abc	36.73fgh	44.53cde	40.67defg	50.0abc
	ET2	30.53e	37.66cde	41.00bcd	43.33bcd	29.23h	35.33gh	37.87efg	44.33cdef
Days to tasseling	ET0	60.3a	57.0 ab	55.00 ab	56.0 ab	61.66a	59.0 ab	57.00 ab	58.0 ab
	ET1	57.66 ab	54.33 ab	55.33 ab	52.33b	60.0 ab	56.66 ab	57.33 ab	54.33 ab
	ET2	55.6 ab	54.3 ab	50.33b	52.33b	58.00 ab	55.00 ab	52.6b	54.33 ab
Days to silking	ET0	56.33a	54.00 ab	52.0 ab	53.00b	50.33a	48.0 ab	46.0 ab	47.00 ab
	ET1	55.0 ab	51.6 ab	52.3 ab	49.33 ab	49.0 ab	45.6 ab	46.3 ab	43.3 ab
	ET2	53.00 ab	50.0 ab	47.6b	49.3 ab	47.0 ab	44.00 ab	42.00 b	43.3 ab
Protein content	ET0	7.53cde	8.00bcde	8.26bcd	8.52b	7.40bc	7.50bc	8.16bc	8.39 ab
	ET1	7.70bde	7.20e	7.26e	9.43a	7.70bc	7.23c	7.23c	9.46a
	ET2	7.40de	7.941bcde	7.23e	8.43bc	7.93bc	7.93bc	8.22bc	8.36 ab
Proline content	ET0	4.30de	4.21e	4.24e	4.62cde	4.95de	4.86e	4.89de	5.06cde
	ET1	5.6abcd	5.45bcde	5.58bcd	5.85abc	5.62bd	5.58bcde	5.93 ab	5.72bc
	ET2	6.90a	6.44 ab	6.72 ab	6.29 ab	6.62a	5.78bc	6.67a	6.31 ab
No. grains per ear	ET0	34.3c	41.6abc	35.66bc	44a	37.33bc	42.66abc	45.0a	45.6a
	ET1	38.00abc	39.0abc	35.66bc	43.66 ab	37.6bc	40.0abc	39.6abc	45.6a
	ET2	37.00abc	40.33abc	41.33abc	43.00 ab	36.0c	43.6 ab	40.33abc	41.66abc
100-grain weight	ET0	36.5bcd	37.3abcd	42.91a	42.91a	38.25bc	38.58abc	44.41 ab	45.08a
	ET1	35.58bcd	38.33abcd	40.abc	41 ab	36.66c	39.58abc	39.53abc	41.0abc
	ET2	33.8cd	36.96abcd	37.63abcd	33.6d	35.20c	38.46bc	38.8abc	35.10c
Ear length	ET0	18.83abc	19.2abc	20.3 ab	21.33a	20.03abc	20.26abc	21.83 ab	22.8a
	ET1	17.83bc	18.63abc	17.33c	21.0a	18.43bc	18.76bc	18.6bc	22.0 ab
	ET2	16.33c	18.0bc	17.13c	18.0bc	16.93c	18.83bc	17.26	18.83bc
Grain yield	ET0	5.79cd	6.16bc	7.07 ab	7.29a	6.19cde	6.56bcd	7.36 ab	7.64a
	ET1	5.01de	5.49cde	5.68cde	7.07 ab	5.39ef	5.71de	5.95de	7.05 abc
	ET2	4.58e	5.463cde	5.2de	7.097a	4.68f	5.43ef	5.55e	7.06abc
Seed yield	ET0	7.29bc	7.98 ab	8.29 ab	8.8a	7.69bcd	7.96abc	8.35 ab	8.85a
	ET1	6.3cd	6.71cd	7.16bc	7.95 ab	6.73de	7.19cde	7.43bcd	8.36 ab
	ET2	5.70d	6.53cd	6.49cd	8.3a	5.7f	6.30ef	6.89de	8.00abc
Dry Matter yield	ET0	13.09cd	14.14bc	15.3 ab	16.1a	13.89cdef	14.5bcde	15.7 ab	16.4a
	ET1	11.34de	12.20d	12.85cd	15.02 ab	12.12gh	12.90efgh	13.3defg	15.41abc
	ET2	10.28e	11.99de	11.716de	15.6 ab	10.38i	11.73hi	12.45fgh	15.00abcd

Different lowercase letters indicate statistically significant differences between treatments ($p \leq 0.05$).

there was no significant difference between ET0 and ET1 when interacting with Si + Zn foliar spraying. The irrigation treatment ET0 with spraying of Si + Zn gave the highest values of 100-grain weight (42.41 and 45.08 grains/row), ear length (21.33 and 22.8 cm), grain yield (7.29 and 7.64 t/ha), straw yield (8.80 and 8.85 t/ha), and biological yield (16.10 and 16.40 t/ha) in both seasons, respectively. The findings also showed that irrigation treatment ET1 with Si + Zn gave the highest protein content (9.43 and 9.46 %). In contrast, the highest values of proline content (6.90 and 6.62) were presented with irrigation interval treatment ET2 + control in the first and the second seasons, respectively, followed by Zn, which had no significant difference between Si + Zn in most of the studied characters. On the other hand, there were no significant differences between ET0 and ET1 days with foliar spraying of Si + Zn in most of the studied characters in the two seasons (Table 2).

3.2. Pearson's correlation coefficient between all studied parameters

The combined analysis of data from the 2021 and 2022 seasons revealed several noteworthy correlations among the studied traits of corn plants grown under different water regimes and foliar spraying treatments (Fig. 5). Grain yield (GY) was found to correlate positively with biological yield (BY), harvest index (HI), ear length (EL), leaf area index (LAI), and 100-seed weight (HGW). These positive correlations indicate that higher values for these traits tend to be associated with increased grain yield. In contrast, GY exhibited negative correlations with days to 50 % tasseling (DTT) and days to 50 % silking (DTS). The negative relationships suggest faster growth and development timelines for tasseling and silking stages, which correspond to higher grain yields. An additional finding was that plant height (PH) positively correlated with BY but negatively correlated with harvest index. This suggests that taller corn plants tend to have higher biological yield, but increased height does not necessarily translate to a higher proportion of grain yield relative to overall biological yield (Fig. 5).

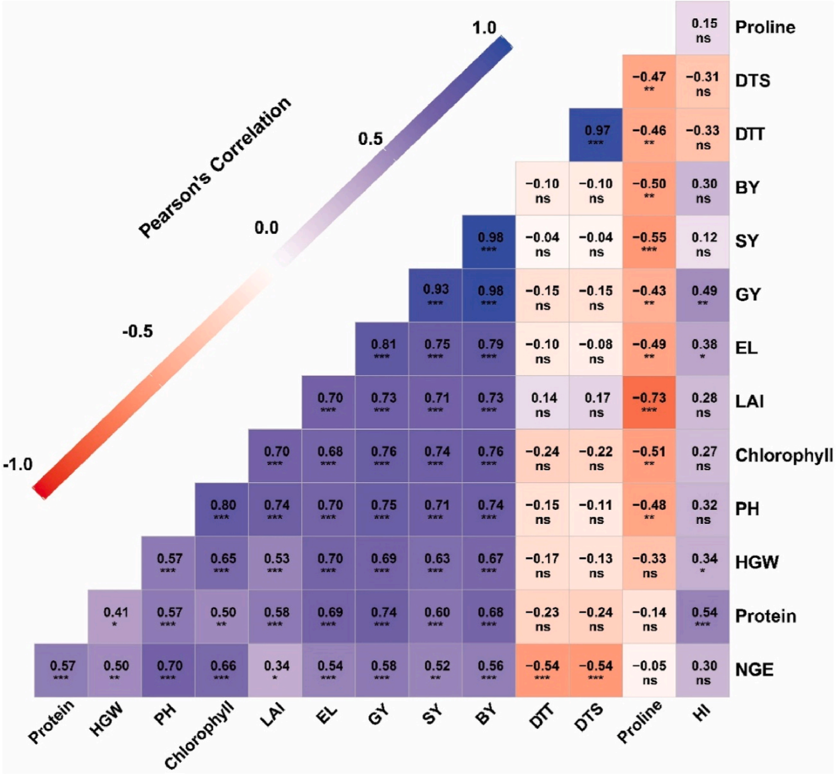

Fig. 5. Pearson's correlation coefficients among studied traits under water regimes and foliar spraying treatments (Combined analysis of 2 successive seasons of 2021 and 2022). HI, harvest index; BY, biological yield; GY, grain yield; SY, straw yield; EL, ear length; LAI, leaf area index; DTT, days to 50 % tasseling; DTS, days to 50 % silking; pH, plant height; NGE, number of grains per ear; HGW, 100-seed weight. Blue indicates a positive correlation, while orange indicates a negative correlation. Asterisks indicate the statistical significance of correlations with *_ for $p < 0.05$, ** for $p < 0.01$,*** for $p < 0.001$, and **** for $p < 0.0001$.

3.3. Heat map analysis for providing an overall picture of the response of different parameters of maize to various water regimes and foliar spraying treatment

The heat map clustering analysis visualized the relationships between the 12 treatment combinations and 14 studied traits (Fig. 6). The hierarchical clustering revealed clear separations between the treatments and traits. The analysis grouped the treatments into two main clusters based on water regime, with the full irrigation (ET0) treatments in one cluster and the drought stress (ET1, ET2) treatments in another. This highlights the major influence of water availability on maize performance.

Within the ET0 cluster, the ET0+Si + Zn treatment formed a distinct sub-group, reflecting its superior enhancement of almost all traits under full irrigation compared to the other ET0 treatments. Specifically, ET0+Si + Zn resulted in the tallest plants, the highest number of grains per ear, heaviest seeds, longest ears, and greatest yields compared to the other fully irrigated treatments. Under drought stress, the ET1+Si + Zn and ET2+Si + Zn treatments clustered together, showing their similar ability to maintain higher trait values despite limited water. The combined foliar sprays of Si + Zn were most effective at improving maize grain yield and yield components under all water regimes, including drought. Additionally, ET0+Zn was linked to the highest chlorophyll, leaf area, and 100-seed weight under full irrigation. Under moderate drought (ET1), Si + Zn sprays (ET1+Si + Zn) conferred the highest protein content and harvest index. The control treatments for both water regimes (ET0+control, ET2+control) were associated with later tasseling and silking dates. The ET2+ control maintained the highest proline levels under severe drought, indicating greater stress. Overall, the Si + Zn sprays had consistently positive impacts under all water levels. The clustering analysis visualized the key relationships between the treatments, traits, and water regimes (Fig. 6).

4. Discussion

Water deficiency is a significant environmental factor that profoundly influences plant development, physiological attributes, yield, and quality. Generally, crops exhibit slower growth and decreased yield when facing reduced available water. The growth and development of maize plants were notably hindered under water stress, leading to reduced growth, leaf area, and yield [50]. Drought stress negatively impacted various growth parameters, including morphological traits, physiological characteristics, and biochemical properties, ultimately affecting the quality and quantity of the maize yield [51]. This study aimed to examine the effects of different

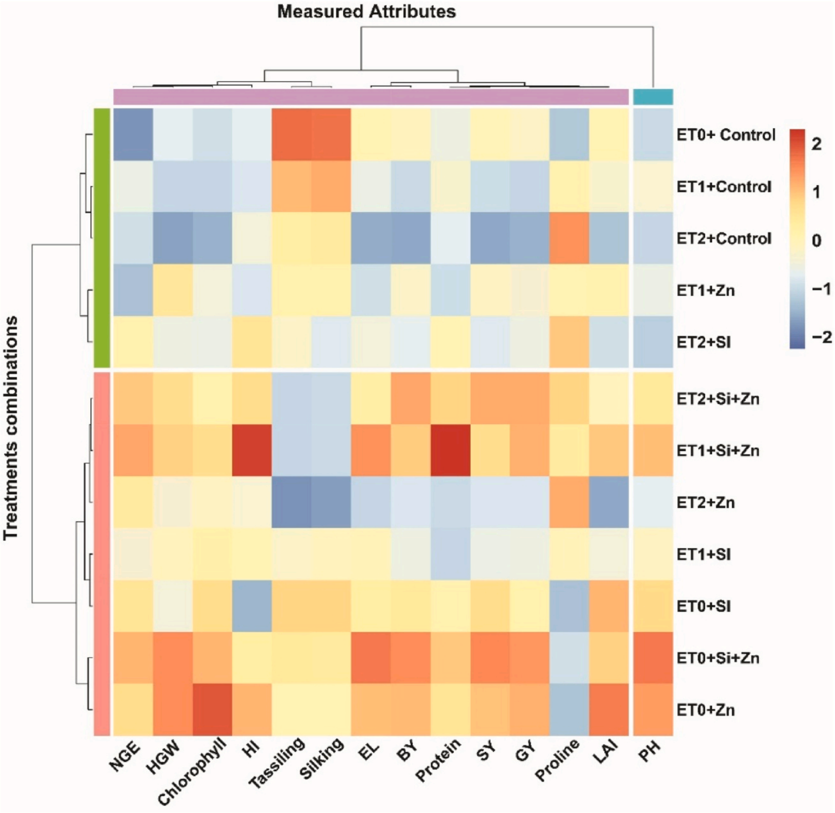

Fig. 6. Clustering analysis presents the relationships between treatment and studied traits. Hierarchical clustering analysis with the Euclidean distance using the principal component scores and Ward's technique as the linkage process was used. HI, harvest index; BY, biological yield; GY, grain yield; SY, straw yield; EL, ear length; LAI, leaf area index; PH, plant height; NGE, number of grains per ear; HGW, 100-seed weight.

irrigation regimes on maize growth, yield, and quality. Additionally, foliar treatments involving Silicon, Zinc, and their combination were employed to mitigate the detrimental effects of water stress. The results indicated that reducing the irrigation interval to ET2 caused a significant reduction in all the studied parameters compared to the two intervals with the highest recorded values for all the characteristics analyzed.

The study's results also revealed that diverse foliar applications substantially impacted plant growth, crop quality, and yield quantity while mitigating the adverse consequences of various abiotic stresses [52]. In line with the present investigation, it was deduced that all growth parameters in maize plants experienced a decline under drought-stress conditions. Conversely, applying Si + Zn significantly increased these growth attributes, positively influencing maize plants facing water stress. The analysis of the results has shown a remarkable improvement in all growth parameters. This enhancement can be attributed to the crucial role of Si + Zn in regulating the concentration of kinetin within plants [53]. Applying Si + Zn leads to increased cell proliferation, cell elongation, and promotion of apical meristems and embryogenesis. Moreover, it triggers callus differentiation, contributing to the significant growth improvements observed in the maize plants [54], and consequently improves plant height, leaf area, root length, number of leaves, and number of pods.

Furthermore, it enhances yield quantity and quality [55] by regulating the work of different enzymes that transport soluble carbohydrates and reduce the contents of nitrates [29]. Numerous studies consistently highlight the influential role of zinc in plant growth and development. In our current investigation, we identified that kinetin zinc oxide may also play a pivotal role in enhancing mung bean growth, especially when subjected to different levels of drought stress. The research data demonstrated that Zn has a significant impact on leaf chlorophyll contents, leading to improved sugar and protein contents, consequently resulting in enhanced overall plant growth and development [56]. Researchers have proposed several pathways for the association and absorption of Si + Zn. According to reports, the foliar spray application of Si + Zn is primarily absorbed through the stomatal openings of leaves. However, the foliar spray method significantly influences the uptake of Si + Zn through this route.

The above results align with the findings of Yuan et al. [57], which indicated a significant reduction in maize grain yield under water stress conditions. This decline was attributed to decreased ear rows and grain weight. Consistently, it was observed that a higher grain yield was directly associated with shorter irrigation intervals in both seasons, as reported by Wang et al. [58]. The combined application of Zn + Si positively impacted the biometric and physiological characteristics of the maize hybrid. Si and Zn played essential roles in various plant physiological processes, such as stomatal regulation, enzyme activation, chlorophyll synthesis, cell osmosis, and enhanced water absorption, ultimately promoting plant growth and development [33,59–61].

The increased levels of studied attributes observed in the maize crop can be attributed to the combined application of Si and Zn. Zn is vital in various metabolic processes, including carbohydrate transformation, enzymatic activation, and protein synthesis [62]. Additionally, Zn application leads to a noticeable increase in leaf area, chlorophyll content, and other photosynthetic pigments, resulting in improved growth and yield. Moreover, it was found that Zn effectively counteracted the adverse impacts of drought stress and significantly increased wheat productivity [63]. Similarly, the Zn application improved maize yield and harvest index under drought stress conditions [64]. Hera et al. [65] also reported that foliar-applied Zn mitigated the adverse effects of water deficit, leading to increased growth and yield in wheat. Under drought stress, Zn application substantially enhances chlorophyll content, Fv/Fm (maximum quantum yield of photosystem II), and other photosynthetic characteristics [11]. Zn's role in chlorophyll synthesis is attributed to its function as a structural component of various proteins and enzymes, serving as a co-factor in the normal biosynthesis of pigments [66].

Additionally, foliar-applied Zn significantly increases the starch content, grain yield, and Zn content in maize crops, which are often prone to deficiency in this essential micronutrient, according to Ref. [67]. These combined effects of Si and Zn application contribute to the enhanced growth and yield observed in the maize crop. Regarding Si application, it may cause the greater mobilization of nutrients in plants and soil, which ultimately increases the green and dry matter yield by improving the photosynthesis process and enzymatic activities. Silicon Application to maize has been displayed to improve salt tolerance and mitigate salinity's harmful impacts on crop growth, yield, nutrient absorption, and photosynthetic activity [68].

The response of maize to the interaction between water regimes and foliar spraying treatments is a critical aspect of understanding the effects of water scarcity on crop growth and productivity. Maize plants exhibit slower growth and decreased yield when facing reduced available water, with drought stress negatively impacting various growth parameters, including morphological traits, physiological characteristics, and biochemical properties [6,69–71]. The results showed that reducing the irrigation interval to ET2 caused a significant reduction in all the studied parameters compared to the two intervals with the highest recorded values for all the characteristics analyzed. The study's results also revealed that diverse foliar applications substantially impacted plant growth, crop quality, and yield quantity while mitigating the adverse consequences of various abiotic stresses. The combined application of Si + Zn positively impacted the biometric and physiological characteristics of the maize hybrid, playing essential roles in various plant physiological processes, such as stomatal regulation, enzyme activation, chlorophyll synthesis, cell osmosis, and enhanced water absorption, ultimately promoting plant growth and development [11,72–74]. The study emphasized the genomic differences among crop plants as valuable tools for selecting hybrids with desirable traits. The increased levels of studied attributes observed in the maize crop can be attributed to the combined application of Si and Zn, vital in various metabolic processes, including carbohydrate transformation, enzymatic activation, and protein synthesis [9,10,23]. Applying Si + Zn leads to increased cell proliferation, cell elongation, and promotion of apical meristems and embryogenesis, triggering callus differentiation, all collectively contributing to the significant growth improvements observed in the maize plants. Furthermore, it enhances yield quantity and quality by regulating the work of different enzymes that transport soluble carbohydrates and reduce the contents of nitrates [21,22,73].

Pearson's correlation analysis results in this study offer important insights into the complex interaction of factors influencing maize growth and yield under different water regimes and foliar application treatments. The non-significant correlations between the harvest index and most studied parameters indicate that these specific factors may not significantly impact the variations in growth and yield-related traits under experimental conditions. This suggests that other factors might be more dominant in determining maize productivity in response to the treatments applied. On the other hand, the strong and positive correlations observed between all yield parameters and grain yield and biological yield are of particular significance. These findings highlight the critical role of grain yield and biological yield as key determinants of overall maize productivity. An increase in grain and biological yield is associated with improvements in various components, indicating that successful strategies targeting grain yield enhancement can improve maize production performance. The positive correlations between chlorophyll content and almost all growth and yield parameters underscore the importance of photosynthetic efficiency in maize plants. Chlorophyll is vital for capturing sunlight and converting it into energy through photosynthesis. Therefore, higher levels of chlorophyll pigments are likely to promote better photosynthetic activity, resulting in improved growth and higher yields in maize. These findings emphasize the significance of optimizing photosynthetic performance through appropriate foliar application treatments to boost maize productivity. Understanding these relationships among corn traits will help guide agronomic practices and hybrid breeding efforts to maximize grain productivity.

The heat map clustering served as a valuable visualization tool to validate and reinforce the results from the other statistical analyses conducted in this study [75]. Specifically, the clear grouping of treatments by irrigation regime in the heat map confirmed the significance of water availability as the primary determinant of maize performance, as was found in the ANOVA results. Additionally, the consistent clustering of Si + Zn treatments away from the water control within each moisture regime corroborated the superiority of combined Si and Zn applications over standard practices across all water levels, aligning with the findings from the mean separation tests. The positive associations between grain yield and related traits like ear size and leaf area visualized in the heat map further verified the correlation analysis. Thus, the unsupervised learning of the clustering technique independently reaffirmed the significance and relationships between treatments and parameters identified through supervised statistical analyses. By confirming these key findings through an alternative approach, the heat map added confidence to the conclusions regarding the synergistic benefits of foliar Si and Zn for optimizing maize productivity across varied irrigation conditions.

5. Conclusions

The combined foliar application of silicon (Si) and zinc (Zn) to improve maize growth and yield under water-limited conditions has significant practical implications for agricultural practices and future research. This study reveals that Si + Zn applications can enhance key growth parameters such as plant height, leaf area, chlorophyll content, and grain yield under drought stress, suggesting a viable strategy for boosting maize productivity in water-scarce environments. For agricultural practice, this means farmers can potentially maintain stable yields and improve water use efficiency by integrating Si + Zn foliar sprays into their cultivation routines, particularly in regions prone to drought. Recommendations for practical application include timely and precise foliar treatments during critical growth stages and regular monitoring to optimize nutrient management. Future research should focus on refining application protocols, conducting longitudinal field trials across diverse climates, and exploring the underlying biochemical mechanisms through advanced analytical techniques. Integrating Si + Zn with other water management strategies and evaluating the economic and environmental impacts of such interventions will further enhance sustainable agriculture practices and support the development of more resilient maize varieties. This integrated approach promises to mitigate the adverse effects of water scarcity on maize cultivation, ensuring improved crop performance and contributing to agricultural sustainability.

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CRediT authorship contribution statement

Sobhi F. Lamlom: Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ahmed M. Abdelghany:** Writing – review & editing, Writing – original draft, Software, Formal analysis, Data curation, Conceptualization. **Honglei Ren:** Writing – review & editing, Validation, Software, Resources, Methodology. **Hayssam M. Ali:** Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Data curation. **Muhammad Usman:** Software, Resources, Methodology, Investigation, Formal analysis. **Hiba Shaghaleh:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Conceptualization. **Yousef Alhaj Hamoud:** Writing – review & editing, Visualization, Validation, Supervision, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Gawhara A. El-Sorady:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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