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RESEARCH

Combined Application of Zinc and Silicon Improved Growth, Gas Exchange Traits, and Productivity of Maize (*Zea mays* L.) Under Water Stress

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Abstract

Maize (*Zea mays* L.) is an important cereal crop globally and regarded sensitive to water stress. Exogenous application of micronutrients such as zinc (Zn) and silicon (Si) significantly improves abiotic stress tolerance of crop plants. Therefore, the current study assessed the effects of combined Zn and Si application on the growth, gas exchange, and yield-related traits of maize plants subjected to water stress. The plants were grown under either well-watered (75% water holding capacity - WW) or water stress (50% water holding capacity - DS) conditions. Three soil-applied Zn levels [i.e., 0 (Zn_0), 10 (Zn_{10}) and 20 (Zn_{20}) mg kg^{-1}] and two soil-applied Si levels [i.e., 0 (Si_0) and 100 (Si_{100}) mg kg^{-1}] were included in the study. Increased leaf area, root length, number of roots per plant, chlorophyll contents, stomatal conductance, transpiration and photosynthetic rates, plant height, cob length, number of grains per cob, 100-grain weight, and grain and biological yields were recorded for the plants grown under WW conditions supplemented with Zn_{10} and Si_{100}. Conversely, the plants grown without Zn and Si supplementation under DS displayed the lowest values for these traits. The supplementation of Zn_{10} and Si_{100} considerably enhanced growth, gas exchange, and yield-related traits of maize plants cultivated under DS compared to their no application. In conclusion, soil application of Zn_{10} and Si_{100} improved growth, gas exchange, and yield-related characteristics of maize plants under DS; therefore, maize should be supplemented with these nutrients to improve yield and economic returns.

Keywords Drought stress · Zinc · Silicon · Photosynthetic rate · Stomatal conductance

1 Introduction

Maize (*Zea mays* L.) is a prominent cereal crop renowned for its significant grain yield [1, 2]. Maize is grown on 1653 thousand hectares in Pakistan, producing 10.635 million tons grains. It accounts for 0.7% of the country's GDP and 3.2% towards value added in agriculture [3]. Maize grains are composed of starch (72%), protein (10%), fiber (5.8%), vitamins A and B (3–5%), ash (1.7%), and sugar (3%) [4]. Maize fulfils 60% of poultry industry, 28% of wet milling, and 6% of human consumption needs [3]. It is projected that the global population would reach 9.7 billion by the year 2050 [5], which would be a serious threat to food security. Hence, it is essential to increase agricultural productivity twofold by the year 2050 [5, 6]. Nevertheless, detrimental effects of biotic and abiotic stresses on crop yield pose a substantial risk to global food security [7–10].

Plants exhibit several physiological and biochemical changes under water stress, including reductions in leaf water

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status, CO_2 assimilation, and gas exchange rate [11]. Water stress exerts many detrimental effects on crop plants and reduced water absorption by root system is one of these consequences. Reduced water uptake leads to a decreased stomatal conductance and photosynthesis. Additionally, water stress alters the water potential gradient and turgor pressure inside the plant, as well as compromises membrane integrity [12]. Furthermore, it exacerbates other stresses, such as nutrient deficiencies in affected plants [13]. In addition, the production of reactive oxygen species (ROS) is triggered in response water deficiency, resulting in oxidative damage. The detrimental effects of oxidative damage on the production of proteins, carbohydrates, lipids, nucleic acids, and other substances have a severe influence on the growth and quality of crops [14]. Several studies have reported cost-effective biofortification solutions aimed at alleviating the detrimental effects of water stress in agricultural plants [15]. The use of mineral nutrients such as zinc (Zn) and silicon (Si) is a potential strategy employed to promote the sustainable cultivation of field crops under water deficiency [16–18].

Zinc plays a significant role in enhancing the capacity of crop plants to withstand and adapt to various environmental stresses [19]. Zinc is a multi-enzyme activator, plays a crucial role in several biological processes and directly involved in the production of growth regulators, including auxin [20, 21]. Zinc deficiency decreases auxin levels, which may have detrimental effects plant growth. Hence, it is important to apply optimum quantity of Zn to promote plant growth and development. Nevertheless, Zn supplementation has been shown to decrease the generation of ROS and provide cellular protection against ROS-induced damages. Zinc deficiency may result in an increased ROS and generation subsequent cellular damage [22, 23]. Sufficient Zn application has been reported to increase the activities of catalase (CAT), peroxidase (POD), and superoxide dismutase (SOD) enzymes under water deficiency [20].

Silicon increases plant tolerance to various abiotic and biotic stresses such as high or low temperatures, ultraviolet radiation, heavy metal toxicity, nutrient deficiency, water and salinity stresses, and disease infestation [24]. Moreover, Si application under water stress maintained water status of plant leaves and increased photosynthetic activity of maize crop [25]. Silicon plays a pivotal function in enhancing drought tolerance of crop plants. Silicon supplementation mitigates adverse impacts of water stress on plant growth through various mechanisms. These mechanisms include the reduction of transpiration, increased water uptake, enhanced antioxidant defense, preservation of cell structure and function, regulation of stress-related genes, osmotic adjustment, and improvement in photosynthesis. Silicon application improved seed germination and development of wheat plants under water stress. Furthermore, Si supplementation increased the activities of antioxidant enzymes and decreases lipid peroxidation in wheat plants subjected to water stress [26]. Likewise, application of sodium silicate to wheat crop under water stress impressed the activities of antioxidant enzymes [27]. Similarly, sodium silicate application reduced oxidative stress through increased production of antioxidants (specifically glutathione reductase, CAT, POD, and SOD) in wheat, barley, and soybean plants subjected to water stress [28]. Furthermore, both Zn [29] and Si [30] can improve antioxidative defense mechanisms (both enzymatic and non-enzymatic); thus, help to avoid ROS-induced damage under various abiotic stresses. The efficacy of Si in enhancing water stress tolerance might exhibit variability among diverse plant species and environmental circumstances. Nevertheless, Si application improved the ability of different crop species to withstand drought stress.

This study investigated the impact of combined Zn and Si application on physiological, morphological, and yield-related traits of maize under water stress. It was hypothesized that water stress will exert significant negative impacts on physiological, morphological, and yield-related traits of maize, while combined Zn and Si application would significantly improve these traits. The results will help to improve maize productivity under water stress.

2 Materials and Methods

2.1 Experimental Area and Soil Condition

The present research was carried out at Agronomic Research Farm, Bahauddin Zakariya University, Multan, Pakistan (30.26° N, 71.51° E, and 122 m above sea level) during winter season of 2021. Earthen pots with 20 kg soil capacity were used in the experiment. These pots had a height of 50 cm and an interior diameter of 22 cm. The pots were filled with finely ground soil. Three soil samples (0–15 cm depth) were randomly obtained from the experimental soil for analysis. The soil used in the experiment had a loamy texture with a pH value of 8.4, an electrical conductivity (EC) of 1.79 dSm^{-1}, organic matter content of 0.65%, available phosphorus (P) concentration of 6.20 mg kg^{-1}, a potassium (K) concentration of 220 mg kg^{-1}, and a total nitrogen (N) content of 0.023%. Table 1 presents the meteorological data observed at the experimental location during the study.

2.2 Experimental Details and Treatments

The experiment consisted of three different factors, i.e., water stress, Zn levels and Si levels. Water stress was imposed by maintaining water holding capacity (WHC) levels, where 75% WHC was regarded as well-watered (WW), whereas 50% WHC was taken as water stress (DS). Three Zn levels, i.e., Zn_0, Zn_{10} and Zn_{20} corresponding 0, 10 and 20 mg kg^{-1} (using

Table 1 Weather data of experimental site

Months	Average monthly Temperature (°C)	Average monthly RH (%)	Total monthly rainfall (mm)	Average monthly sunshine (hours)
February	19.40	71.30	0.00	7.64
March	24.00	67.20	16.90	7.80
April	28.70	64.00	0.00	7.97
May	32.90	60.90	3.00	11.10

$ZnSO_4$ as source) soil application of Zn were included in the study. Likewise, two Si levels, i.e., Si_0 and Si_{100} denoting 0 and 100 mg kg^{-1} soil application of Si (using Na_2SiO_3 as source) were included in the experiment. The seeds of maize hybrid 'P-1429' obtained from Pioneer Seeds Sahiwal, Pakistan were used as experimental material. Five seeds were sown in each pot on February 12, 2021, under WW conditions for uniform seed germination and water stress was imposed three weeks after germination phase. All Zn and Si doses were applied to the soil at sowing. The experiment was set up using a fully randomized design (CRD) with factorial layouts and four replications. The main plots were water stress, whereas Zn and Si were randomized in sub-plots.

2.3 Crop Husbandry

Each pot was fertilized with 1.30 g N, 0.8 g K and 0.8 g P (equivalent to 200-150-150 kg ha^{-1}) by using urea, diammonium phosphate and sulphate of potash as sources. The whole amount of P and K, and 1/3rd of N was applied at the time of sowing, whereas the remaining N was applied in two splits at crop emergence and tasseling stage. Water stress was imposed by maintaining WHC of WW and DS treatments three weeks after germination. A moisture meter was used to maintain the WHC. Maize borer and shoot fly were controlled by applying 4–5 grains of furadon (Carbofuron, FMC) from the top of each plant. Crop was harvested when cobs were fully matured and threshed after drying.

2.4 Determination of Water Holding Capacity

Gravimetric method was used to determine WHC [31]. Three samples, each weighing 200 g, were randomly collected during pots' filling. The soil samples were oven-dried at of 105 °C for 24 h. Subsequently, the samples were weighed to determine the soil moisture contents. A subsample of 100 g was extracted from each, and saturation percentage was determined by creating a saturated paste. The formula used for calculating field capacity is given in Eq. 1.

$$\text{Water holding capacity} = \frac{\textit{Saturation percentage}}{2} \quad (1)$$

The WHC of each pot was maintained according to the treatments. The soil moisture percentage of each pot was assessed daily using a soil moisture meter. Water was applied on a regular basis to maintain the appropriate levels of WHC according to the treatments throughout the growth phase.

2.5 Data Collection

2.5.1 Root and Allometric Traits

The data regarding root (number and length) and allometric traits (leaf area and plant growth rate) were recorded from 35 days after sowing (DAS) till 80 DAS with 15 days interval. One randomly selected plant from each pot was carefully removed and used for measurements at each data collection. The roots were cleaned, and their length was measured by using a measuring tape. Leaf area was determined by measuring length and width of the leaf using measuring scale. Chlorophyll index was determined from all plants at 50 DAS by inserting maize leaves from three random positions in SPAD meter (Minolta Camera Co. Ltd., Osaka, Japan) and averaged.

2.5.2 Gas Exchange Traits

Five mature and healthy leaves were selected from each pot to record gas exchange traits. All physiological parameters, i.e., photosynthesis rate (A), stomatal conductance (gs) and transpiration rate (E) were recorded by using Infrared Gas Analyzer (LCi-SD, ADC Bioscientific Ltd. Serial No. 34,113). Stomatal conductance, photosynthesis, and transpiration rates were measured between 11:00 and 12:00 a.m. The IRGA chamber was programmed to take readings under the conditions specified by Zekri [32].

2.5.3 Agronomic and yield-related Traits

The data regarding yield and related traits were recorded at maturity. The cob length of all plants within the pot was measure with a measuring tape and averaged. At maturity, the plants from each pot were removed and sun-dried for three days. After drying, the plants were weighed to measure the biological yield. The cobs were threshed manually to calculate the number of grains per cob and grain yield per plant. A sample of 100 seeds were taken from every pot and weighed to compute 100-grain weight. Grain yield was calculated at 10% moisture contents. The harvest index was calculated as the ratio of grain yield to the biological yield.

2.6 Statistical Analysis

The collected data were checked for normality and homogeneity of variance [33]. The data were normally distributed; therefore, statistical analysis was performed on original data. Three-way analysis of variance (ANOVA) was used to infer the significance in the data. The means were compared by least significant difference post-hoc at 99% probability where ANOVA denoted significant differences [34]. The statistical analysis was performed on Statistix 8.1 statistical software. Three-way interaction of water stress, Zn and Si levels was significant for all recorded traits; therefore, interactive effect was presented and interpreted.

3 Results

3.1 Root and Allometric Traits

Root and allometric traits were significantly affected by the individual and interactive effect of Zn and Si under WW and DS conditions at all sampling dates (Figs. 1, 2, 3, 4 and 5). Higher number of roots and root length were recorded for Zn_0 and Si_{100} application under WW conditions, while plants receiving no Si and Zn under DS resulted in the shortest root length at all sampling dates (Figs. 1 and 2).

The highest leaf area was noted in plants receiving Si_{100} under WW environment which was statistically at par with the plants supplemented with Zn_{10} (except at 50 DAS) under WW conditions. The lowest values for leaf area were recorded from the plants which received no Si and Zn under DS (Fig. 3). The highest plant growth rate was noted for the plants supplemented with Zn_{10} and Si_{100} under WW, while plants receiving no Zn and Si under DS resulted in the lowest plant growth rate (Fig. 4). The

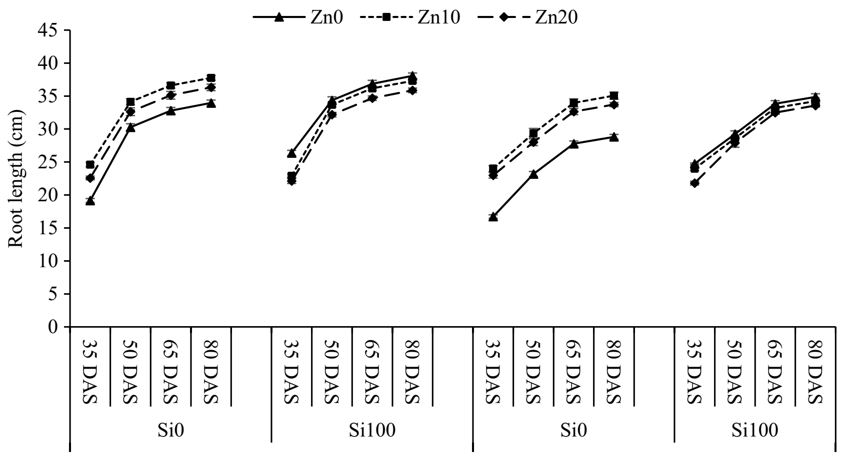

Fig. 1 The influence of different silicon and zinc levels on root length of maize plants grown under well-watered and water-stressed environments. Here, WW = well-watered, DS = water stress, $Si_0 = 0$ mg kg^{-1} Si, $Si_{100} = 100$ mg kg^{-1} Si, $Zn_0 = 0$ mg kg^{-1} Zn, $Zn_{10} = 10$ kg^{-1} Zn, and $Zn_{20} = 20$ kg^{-1} Zn

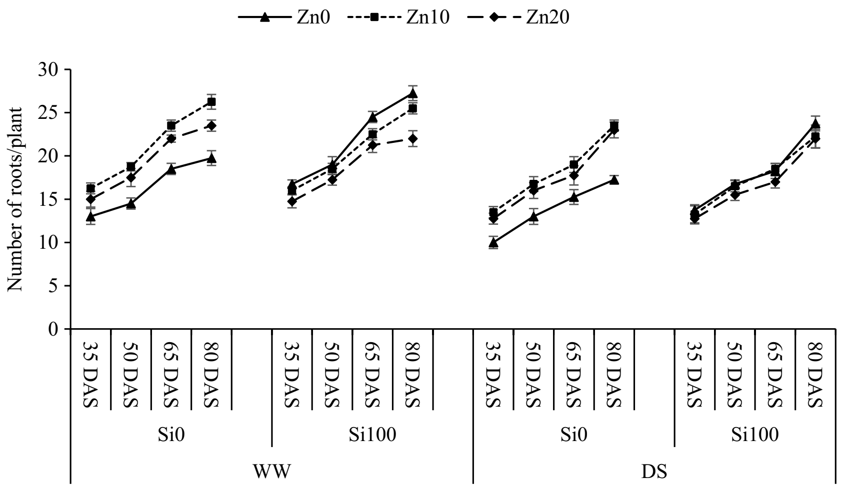

Fig. 2 The influence of different silicon and zinc levels on number of roots of maize plants grown under well-watered and water-stressed environments. Here, WW = well-watered, DS = water stress, $Si_0 = 0$ mg kg^{-1} Si, $Si_{100} = 100$ mg kg^{-1} Si, $Zn_0 = 0$ mg kg^{-1} Zn, $Zn_{10} = 10$ kg^{-1} Zn, and $Zn_{20} = 20$ kg^{-1} Zn

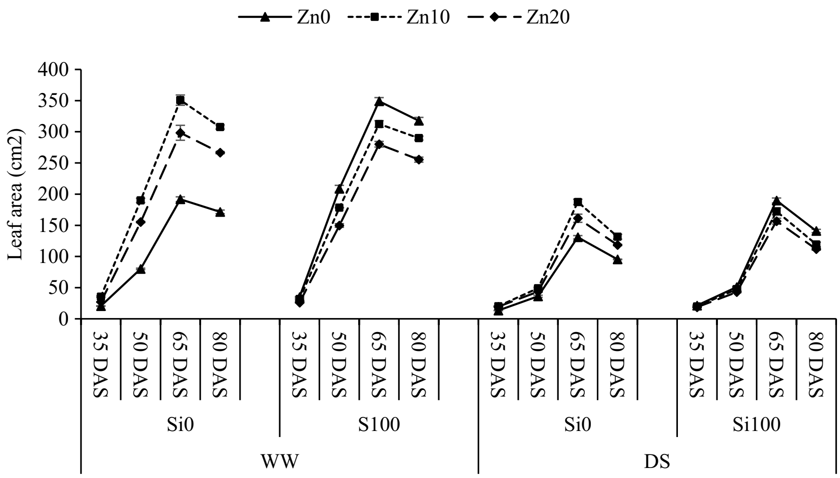

Fig. 3 The influence of different silicon and zinc levels on leaf area of maize plants grown under well-watered and water-stressed environments. Here, WW = well-watered, DS = water stress, $Si_0 = 0$ mg kg^{-1} Si, $Si_{100} = 100$ mg kg^{-1} Si, $Zn_0 = 0$ mg kg^{-1} Zn, $Zn_{10} = 10$ kg^{-1} Zn, and $Zn_{20} = 20$ kg^{-1} Zn

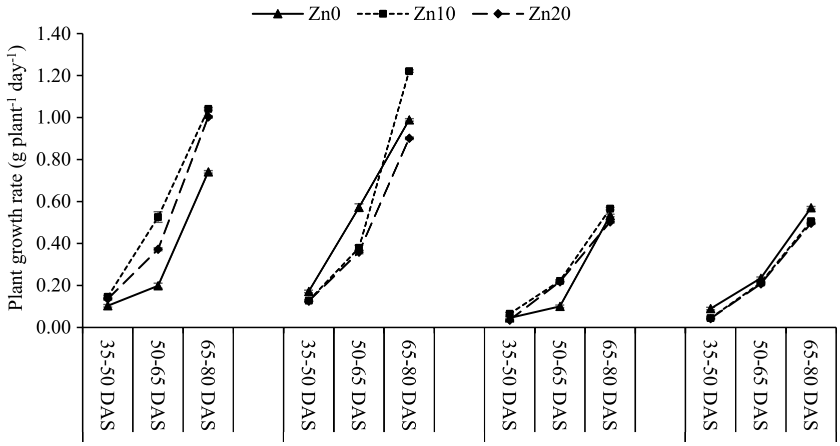

Fig. 4 The impact of different silicon and zinc levels on plant growth rate of maize plants grown under well-watered and water-stressed environments. Here, WW = well-watered, DS = water stress, $Si_0 = 0$ mg kg^{-1} Si, $Si_{100} = 100$ mg kg^{-1} Si, $Zn_0 = 0$ mg kg^{-1} Zn, $Zn_{10} = 10$ kg^{-1} Zn, and $Zn_{20} = 20$ kg^{-1} Zn

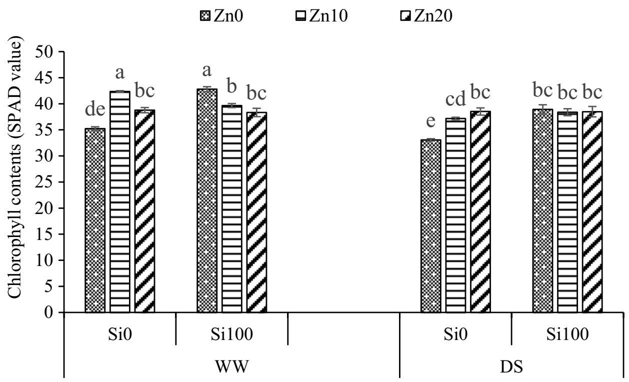

Fig. 5 The impact of different silicon and zinc levels on chlorophyll contents of maize plants grown under well-watered and water-stressed environments. Here, WW = well-watered, DS = water stress, $Si_0 = 0$ mg kg^{-1} Si, $Si_{100} = 100$ mg kg^{-1} Si, $Zn_0 = 0$ mg kg^{-1} Zn, $Zn_{10} = 10$ kg^{-1} Zn, and $Zn_{20} = 20$ kg^{-1} Zn

highest chlorophyll contents were noted in plants which received Si_{100} and Zn_{10} under WW conditions, whereas plants with no supplementation of Si and Zn under DS had the lowest chlorophyll contents (Fig. 5).

3.2 Gas Exchange Traits

The individual and interactive effects of drought, Zn, Si levels significantly affected gas exchange traits, i.e., photosynthetic rate, stomatal conductance, and transpiration rate (Figs. 6, 7 and 8). Maize plants supplemented with Si_{100} and Zn_{10} under WW environment had the highest photosynthetic rate, stomatal conductance, and transpiration rate, while the plants receiving no Si and Zn under DS had the lowest values of these traits (Figs. 6, 7 and 8).

3.3 Agronomic and Yield-Related Traits

The interactive effect of water stress, Zn, and Si levels significantly altered agronomic and yield-related traits, i.e., cob length, 100-grain weight, number of grains per cob, biological yield, grain yield and harvest index (Table 2). The highest values for cob length, 100-grain weight, and grain yield were noted for the plants supplemented with Si under WW conditions, while plant receiving no Zn and Si under DS had the lowest values of these traits (Table 2). Likewise, the highest number of grains and biological yield

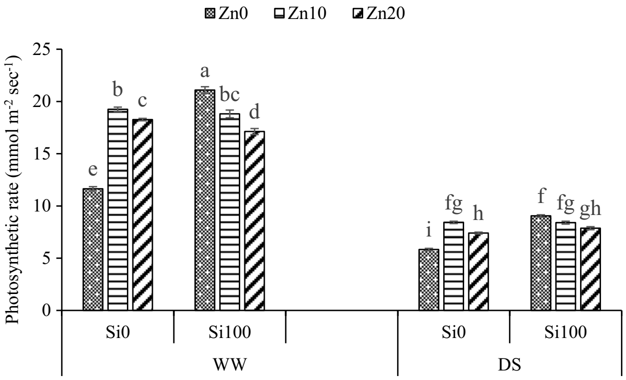

Fig. 6 The impact of different silicon and zinc levels on photosynthetic rate of maize plants grown under well-watered and water-stressed environments. Here, WW = well-watered, DS = water stress, $Si_0 = 0$ mg kg^{-1} Si, $Si_{100} = 100$ mg kg^{-1} Si, $Zn_0 = 0$ mg kg^{-1} Zn, $Zn_{10} = 10$ kg^{-1} Zn, and $Zn_{20} = 20$ kg^{-1} Zn

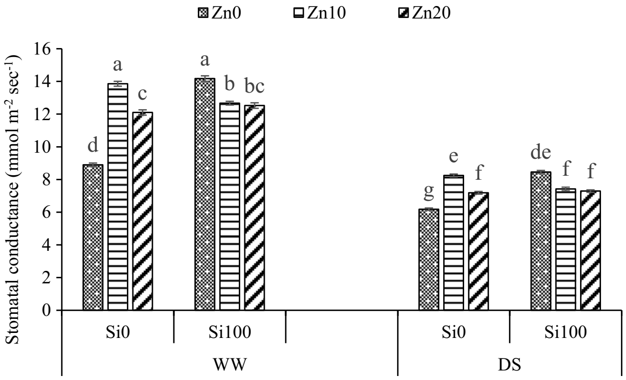

Fig. 7 The influence of different silicon and zinc levels on stomatal conductance of maize plants grown under well-watered and water-stressed environments. Here, WW = well-watered, DS = water stress, $Si_0 = 0$ mg kg^{-1} Si, $Si_{100} = 100$ mg kg^{-1} Si, $Zn_0 = 0$ mg kg^{-1} Zn, $Zn_{10} = 10$ kg^{-1} Zn, and $Zn_{20} = 20$ kg^{-1} Zn

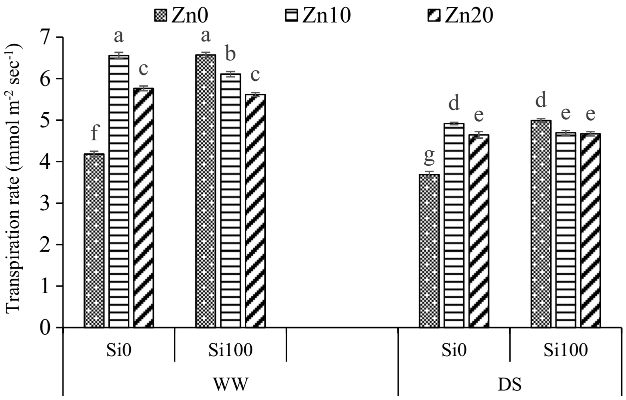

Fig. 8 The impact of different silicon and zinc levels on transpiration rate of maize plants grown under well-watered and water-stressed environments. Here, WW = well-watered, DS = water stress, $Si_0 = 0$ mg kg^{-1} Si, $Si_{100} = 100$ mg kg^{-1} Si, $Zn_0 = 0$ mg kg^{-1} Zn, $Zn_{10} = 10$ kg^{-1} Zn, and $Zn_{20} = 20$ kg^{-1} Zn

was recorded for the plants supplemented with Si_{100} and Zn_{10} under WW conditions (Table 2). However, the lowest number of grains and biological yield were recorded for the plants receiving no Zn and Si under DS. The highest value of harvest index was noted for the plants receiving Si_{100} and Zn_{10} under WW conditions, whereas plants receiving no Zn and Si under DS had the lowest harvest index (Table 2).

4 Discussion

Water stress is a significant constraint that affects several physiological and biochemical pathways in plants. Water stress leads to atypical plant growth and development due to the suppression of cellular proliferation and expansion [35]. The development of maize plants exposed to water stress was significantly inhibited in the current study. Several earlier studies have indicated that water stress exerts negative impacts on growth characteristics of numerous plant species [36–38]. Water stress decreased plant height, number of branches and leaves, and leaf area of fenugreek (*Trigonella foenum-graecum*) [39]. Furthermore, Hanafy [40] reported that water stress significantly suppressed growth of soybean (*Glycine max*) plants. Combined application of Si and Zn significantly improved growth and yield-related traits of maize plants under water stress and well-watered environments in the current study. Silicon and Zn play significant role in chlorophyll biosynthesis, which is crucial for photosynthesis. Silicon facilitates the absorption and translocation of Zn, resulting in higher chlorophyll synthesis. Consequently, plant's ability to absorb light for photosynthetic activities is improved. The improvements in growth and yield-related traits under water stress are owed to improved chlorophyll synthesis and higher photosynthetic activity observed under combined application of Si and Zn.

Leaf area was significantly reduced under water stress in the current study. The observed reduction in leaf area may be attributed to an increased leaf senescence and decreased moisture availability. Water stress has been reported to exert negative effects on leaf area, photosynthetic pigments, photosynthesis rates, which eventually impede plant development [41, 42]. Water stress exerts detrimental impacts on several physiological aspects of plants, including water status, growth patterns, gas exchange traits such as photosynthesis, stomatal conductance, and transpiration rate, chlorophyll levels and photochemical efficiency of PSII [33]. Similar results were observed in the current study (Figs. 6, 7 and 8). Water stress compels plants to close their stomata for conserving water, resulting in a significant reduction in stomatal conductance. Consequently, reduced stomatal conductance imposes limitations on photosynthesis [43]. The primary factor contributing to decreased photosynthesis under

Table 2 Interactive effect of different silicon and zinc levels on yield-related traits of maize plants grown under well-watered, and water-stressed environments

Cob length (cm)					Number of grains per cob			
Treatments	WW		DS		WW		DS	
	Si_0	Si_{100}	Si_0	Si_{100}	Si_0	Si_{100}	Si_0	Si_{100}
Zn_0	12.95 f	16.67 a	11.67 g	13.97 e	212.25 d	237.75 a	197.25 e	217.00 cd
Zn_{10}	15.77 b	15.42 bcd	15.00 cd	15.57 bc	236.50 a	224.75 b	219.25 bcd	218.75 bcd
Zn_{20}	15.11 cd	14.90 d	14.08 e	13.52 ef	222.25 bc	222.00 bc	216.75 cd	214.25 d
LSD at 1%	0.64				7.03			
100-grains weight (g)					Biological yield (g plant^{-1})			
Zn_0	19.40 d	23.80 a	17.67 e	19.17 d	111.30 c	123.74 a	93.20 f	99.95 de
Zn_{10}	22.86 b	22.50 bc	19.84 d	19.52 d	123.44 a	119.82 b	101.80 d	97.95 e
Zn_{20}	21.95 c	21.94 c	19.22 d	19.24 d	119.13 b	118.30 b	98.36 de	98.15 e
LSD at 1%	0.80				3.58			
Grain yield (g plant^{-1})					Harvest index (%)			
Zn_0	41.70 ef	56.28 a	35.61 g	41.14 f	37.49 e	45.49 a	38.22 e	41.15 d
Zn_{10}	53.99 b	51.32 c	43.21 e	42.26 ef	43.74 ab	42.84 bcd	42.44 bcd	43.15 bc
Zn_{20}	49.66 cd	49.09 d	41.31 ef	41.25 ef	41.69 cd	41.50 cd	42.00 bcd	42.03 bcd
LSD at 1%	2.02				1.97			

Means not having common letter for interactive effects significantly vary from each other at $p \le 0.01$. Here, WW = well-watered, DS = water stress, $Si_0 = 0$ mg kg^{-1} Si, $Si_{100} = 100$ mg kg^{-1} Si, $Zn_0 = 0$ mg kg^{-1} Zn, $Zn_{10} = 10$ kg^{-1} Zn, and $Zn_{20} = 20$ kg^{-1} Zn

water stress is a decline in the absorption and internal concentration of CO_2, ultimately resulting in the inhibition of photosynthetic metabolism [44]. In addition, there are other non-stomatal factors that contribute to stomatal closure under water stress. These processes include photophosphorylation and the regeneration of ribulose-1, 5-bisphosphate (RuBP) rubisco activity and ATP synthesis [45]. The findings of our study indicate a significant decrease in photosynthesis and gas exchange parameters of the plants subjected to water stress, mostly because of limitations in stomatal functioning (Figs. 6, 7 and 8).

Chlorophyll plays a pivotal function in photosynthesis by facilitating the absorption of energy from light. It is worth noting that the distribution of chloroplasts inside the leaf is not uniform, resulting in varying concentrations across the leaf structure [46]. The present research observed a reduction in total chlorophyll levels in maize plants under water stress (Fig. 5). The effectiveness photosynthesis is dependent on chlorophyll concentration since it plays a pivotal part in the photochemical process [47]. Water stress significantly hampers the photosynthesis by exerting detrimental effects on photosynthetic organelles and chlorophyll components [48].

Water stress significantly decreased growth rate of maize plants because of significant reduction in the duration between planting and tasseling stages. Singh et al. [49] reported that water stress decreases cell division, cell elongation, and cell broadening, which decrease water potential. Additionally, reduced quantity and size of leaves results in smaller plant canopy, which adversely affects plant height by impeding the oxygen supply due to photosynthetic radiation in maize [50].

Water stress exerted significant negative impact on number of grains per cob, 100-grain weight, cob length, and yield. Similar findings have been reported in recent and previous studies [35, 51, 52]. Reduced grain production under water stress is associated with several factors related to water deficit [53], including soil temperature [54], soil osmotic potential [55], and plant growth and development [56]. The number of grains per cob and 100-grain weight decreased after a water deficit, which led to a decrease in the maize yield [57] (Table 2).

Silicon application enhanced plant height and dry matter production in maize, aligning with the research results of Marques et al. [58]. These results demonstrate the positive impact of Si in enhancing the resilience of maize plants to drought stress, consistent with the findings reported by Amin et al. [59] and Bianchini and Marques [60]. Silicon application improved gas exchange traits, and photosynthetic and transpiration rates under water stress in the current study. These results are in agreement with Bianchini and Marques [60] and Romanatti et al. [61]. Silicon enhances cell metabolism, thereby increasing cell hydration, physiological efficiency, and yield [62]. Silicon uptake by plants is dependent on transpiration [63]. Silica deposition decreases transpiration rate, thereby enhancing the ability of maize plants to withstand water stress [64]. Plants absorb water to meet their physiological needs and supply of nutrients, which are transported along water through mass flow [56]. The findings of our study demonstrate that Si application under water stress greatly enhanced root traits (Figs. 1 and 2). The findings presented in this study are consistent with Wang et al. [65] who demonstrated that Si application increased root length, root biomass, root surface area, and root volume in several horticultural plants under water stress. The Si application in the present investigation led to an increase in grain yield (Table 2). An adequate supply of Si favors photosynthetic process [66], increases dry matter production [59], improve the grain weight [60], and translocation of nutrients, which is influenced by an increase in the application of water to the soil, according to Taiz and Zeiger [56].

Zinc is a crucial micronutrient that plays a significant role in several metabolic processes and serves as a regulator of plant growth and development, especially under challenging environmental conditions [67]. The present study observed that water stress negatively impacted several physiological and biochemical processes. Specifically, water stress decreased photosynthetic and transpiration rates, and these were associated with alterations in stomatal conductance. Nevertheless, Zn application improved these parameters and mitigated the detrimental consequences of water stress in the current study. The observed improvements may be ascribed to the homeostatic regulation of many physiological and metabolic processes by Zn. Sun et al. [67] reported that ZnO application in the form of nanoparticles exerted positive effects on water relations, mitigated the degradation of green pigments, and regulated stomatal opening to enhance the photosynthetic efficiency of maize plants under water stress. Consequently, the growth and development of the plants were significantly enhanced. Barrameda-Medina et al. [68] reported that Zn fertilization leads to the reduction of water stress and better photosynthetic efficiency. These positive effects have been linked to the enhancement of nitrogen metabolism.

Combined application of Si and Zn exerts several beneficial impacts on plant development and stress tolerance. Silicon improves Zn nutrition due to its positive influence on Zn absorption and translocation. Similarly, Zn application also enhances Si uptake. Combined application of Si and Zn regulates water absorption and transpiration, sustaining cellular turgor, and safeguarding against oxidative stress. These mechanisms collectively contribute to a plant's ability to withstand water stress. Combined application of Si and Zn has been shown to effectively mitigate terminal water stress by stimulating morpho-physiological and antioxidant defense mechanisms of plants [69, 70]. The improvements in the morphological and yield-related traits of maize under water stress in the current study are owed to these improvements under combined application of Si and Zn.

Our results indicated that combined Zn and Si application has a positive impact on the morphological and yield-related characteristics of maize plants subjected to water stress (Table 2). The enhancement in morphological and yield-related characteristics may be linked to the improvement in physiological and biochemical parameters resulting from combined Zn and Si application. Enhanced photosynthetic efficiency, increased assimilate production, and enhanced grain storage capacity contributed to the improved grain size, grain yield, and harvest index. These results are supported by Sattar et al. [71].

5 Conclusion

Combined application of Si and Zn through soil significantly improved maize growth and productivity under well-watered conditions and water stress. The highest values for morphological and yield-related traits were noted from the plants supplemented with Si_{100} and Zn_{10} under well-watered conditions. Similarly, soil application of Si_{100} and Zn_{10} under water stress conditions significantly improved for morphological and yield-related traits of maize compared to their no supplementation indicating that combined supplementation of Zn and Si mitigated the adverse impacts of water stress. Therefore, application of 100 mg kg^{-1} Si and 10 mg kg^{-1} Zn through soil is a viable approach to improve maize growth and yield under water stress. However, field studies with more Zn and Si levels and water stress levels are required to reach concrete conclusions and recommendations.

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Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

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Competing Interests The authors declare no competing interests.

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