Gesunde Pflanzen (2023) 75:1601–1613
https://doi.org/10.1007/s10343-023-00836-1

ORIGINAL ARTICLE / ORIGINALBEITRAG

Interaction Effects of Sowing Date, Irrigation Levels, Chitosan, and Potassium Silicate On Yield and Water Use Efficiency for Maize Grown Under Arid Climate

Ayman M. S. Elshamly[1]

Received: 5 June 2022 / Accepted: 18 January 2023 / Published online: 8 February 2023

Abstract

Adopting foliar antiperspirants reduces the negative effects of water stress on crop production. In this study effects of chitosan (Ch) and potassium silicate (PS) on maize sowing at two sowing dates under irrigation water levels (100% of irrigation water applied –Ir_{00} and 70% of irrigation water applied –Ir_{70}) were investigated. Thus, during the spring and fall seasons of 2020–2021, a field experiment of two similar experiments was conducted at the experimental farm of Water Studies and Research Complex (WSRC) station, National Water Research Center, Toshka—Abu Simbel City, Egypt, which the sowing dates were allocated in the main plot, then a strip-plot design with five replicates was used. It was found that sowing maize seeds in the fall season led to attaining a higher maize yield than in the spring. Moreover, the adoption of Ir_{70} provides better maize yield and water use efficiency than Ir_{100}, particularly at the fall season sowing date. In addition, the adoption of the higher Ch concentrations in the spring, led to better improvements in maize yield particularly under Ir_{70}, while the adoption of the higher concentrations of PS in the fall seasons, led to better maize yield. It was concluded based on present findings that applying chitosan as foliar applications with concentrations at 500 (mg l^{-1}) under Ir_{70} in the fall had significant effects to maintain the higher maize yield, water use efficiency and irrigation water use efficiency in the arid regions as Toshka district and other similar areas.

Keywords Maize · Chitosan · Potassium silicate · Sowing date · Irrigation water levels

Introduction

One of the world's biggest challenges to food security today is the pressure on natural resources, for instance over 70% of the fresh water is used for irrigation. The irrigation requirements over the next few years will not be able to be implemented as a result of reduced water supplies and increased competition for clean water. There are wide variations in the duration and severity of environmental stress, which can be aggravated more as a result of climate change that will have a significant impact on the severity and frequency of future droughts (Manabe et al. 2004; Harte et al. 2006). Meanwhile, water stress can drastically reduce the optimum plant products that can be achieved and it has negative influences on the plants such as delaying plant growth, decreasing photosynthesis, and leading to a major inhibition of important biochemical processes in plants (Aimar et al. 2011). The plant's response to stress is complex due it is determined by the characteristics of the constituents that connect and contrast in their individual reactions according to the intensity and duration of the water deficits and temperature. Since water stress continues, plants take certain protection strategies against these stress conditions include: A) a cascade of signs ranging from essential reactions to auxiliary reactions (Haggag Wafaa et al. 2017), B) at the cellular level biochemical restrictions can prevent the photosynthetic CO_2 fixation (Ennahli and Earl 2005; Galmés et al. 2007). These responses enable plants to adapt to the temporary water stress in the short term, nonetheless, the effects of antioxidants and enzymatic activities cannot cope with severe or prolonged water stress (Tan et al. 2006).

Under these circumstances, despite there were reductions in yield as temperatures and evapotranspiration increased, the adoption of certain management practices (i.e., proper irrigation, optimum sowing date, compost, and tillage), capable to alleviate these negative impacts, improve yield

---

✉ Ayman M. S. Elshamly
ayman_saleh@nwrc.gov.eg

[1] Water Studies and Research Complex, National Water Research Center, Cairo, Egypt

and decrease ET (Attia et al. 2022). One of management practice is applying chitosan, which has been proposed to help reduce oxidative damage caused by stress caused by drought in crops (Yang et al. 2009; Mohammadi et al. 2021). The scavenging mechanism of chitosan can be linked to its structure, which has many available hydroxyl and amino groups interacting with reactive oxygen species (ROS) such as superoxide radicals, hydrogen peroxide, hydroxyl, and singlet oxygen that are toxic to plants (Li et al. 2002; Sun et al. 2004). Generally, chitosan is an N-polysaccharide formed by the deacetylation reaction of chitin, it is a naturally degradable substance and derived from the crustacean shield (Bautista-Baños et al. 2006; Duan et al. 2019). Chitosan is divided into three reactive groups, and it should be noted that the amino group is generally preferred because it is more reactive than the other two hydroxyl groups (Jayakumar et al. 2008; Badawy and Rabea 2011). Recently it has attracted much attention owing to its unique biological and physiological properties, for example, it can increase the growth and development of plants under normal conditions and water deficiency which positively changes several characteristics (dos Reis et al. 2019). In addition, chitosan caused an increase in plant height, the number of shoot branches and leaves, leaf area, biomass characteristics, and cereal yield for several plant species, such as maize (Guan et al. 2009). Also, the recent results have shown that chitosan has the potential to work and acts as an antitranspirant agent and an efficient elicitor under agricultural stress conditions which allows fulfilling an important role in stimulating defense mechanisms (Hadwiger 2013).

On the other side, foliar potassium silicate application has some advantages for instance, increases growth and yield production improves strength, minimizes climate stress, and provides impedance to mineral stress (Shedeed 2018; Gomaa et al. 2020). Silicon (Si) is available in large quantities in the soil and on the earth's surface, its concentrations in the plant vegetative parts (shoot) ranging from 0.1 to 10.0% of dry weight (Liang et al. 2006). Its importance has not been proven to be an essential element for the higher plants yet, although some recent studies indicated that Si amendments have some beneficial effects on the growth of crops, including enhancing the crop tolerance to either biotic or abiotic stress (Mustafa et al. 2021; Souri et al. 2021). In addition, Si applications increase the photosynthetic activity, the stomatal conductance, and nutrients uptake (Shaaban and Abou El-Nour 2014; Rao et al. 2018), which through the foregoing ultimately leads in turn to increasing the crop growth parameters, yield and yield quality (Ahmed et al. 2007; Laane 2018; Ali et al. 2019). Therefore, applying potassium silicate as foliar spraying on plants and as a cofactor has become a pioneering approach and it has a prominent effect in the agricultural uses to enhance the growth and ameliorate the deleterious effect of water stress (Gomaa et al. 2021).

Therefore, based on the foregoing, I assume that Ch or PS application has the potential for decreasing transpiration and enhancing corn yield.

Agricultural production is also affected by climate change, in this concern Ramírez and Thornton (2015) reported that maize production is expected to decline by 12–40% due to climate change in Africa. Among several influences of climate change, its effect on sowing date, which requires an urgent need to adjust and determine the better sowing date for each crop under current circumstances. Sowing date depends not only on the environment, but also on the extent to which insects, pests and diseases are prevalent, and selection should focus on allowing critical stages of growth to escape these conditions (Anjum and Arif 2022). Initial work indicated that for each location, there is an optimal planting date for corn to improve crop yield (Hassaan 2018; Maresma et al. 2019). In Egypt, the most appropriate sowing date is between May 10 and May 20 in the Gemmiza (Lower Egypt) and Sids areas (Middle Egypt) and through July in the Mallawy area (Middle Egypt) (El-Marsafawy et al. 2012), in the same context (Hassaan 2018; Abaza 2021) mentions that sown yellow maize hybrids in the second week of August successfully improved production of maize yield and its components under Toshka conditions which are located in the south of Egypt.

The efficiency of water use has been defined as the obtained grain yield per unit of water consumed or transpired by the crop (Hatfield and Dold 2019). In order to improve crop yield, it is essential to identify evapotranspiration to proper manage irrigation water and avoid the adverse effects of water stress on plants, where proper irrigation management may prevent nutrient and yield losses caused by inadequate irrigation (Kheir et al. 2021). In arid regions the adoption of the determination of irrigation amounts based on actual evapotranspiration has attracted less attention (Srivastava et al. 2018). In this concern, Attia et al. (2022) indicated that in arid regions, adoption combination of crop models and machine learning algorithms is a powerful tool for predicting yield and water use efficiency, that are especially susceptible to climate change and water scarcity. On the other side, Kheir (2013) revealed that the seasonal water consumptive use values were ranged between 2936.3 to 3295.0 m^3 fed^{-1} when maize plants were irrigated at 20% depletion of soil water. Moreover, the maximum value of water productivity 1.43 kg m^{-3} was achieved by adding 120 kg N fed^{-1}(fed = 4200 m^2) to the North Delta soils (clay soil). While Abaza et al. (2016) investigated the impact of different irrigation systems, pulse technique and silicon on maize yield and water use efficiency under the same climatic conditions of the current study, they mentioned that the average maize water use efficiency values were (0.56, 0.52 and 0.52 kg m^{-3}) for pulse technique, irrigation system and silicon application, respectively. In addition, Abaza (2021) studied the effects of irrigation water levels and applied the filter mud cake at different sowing dates on water use efficiency indicated that the seasonal values of the actual ETa of under toshka climatic conditions were ranged between 930 and 793 mm.

Maize hybrid (*Zea mays L.*) is one of Egypt's most important cereal crops, and as all C_4 type plants maize has a higher capability to use CO_2, solar radiation, water, and N in photosynthesis than C_3 crops which leads to increase the effectiveness of water use efficiency (Abideen 2014). The yellow maize variety is rich in vitamin A (carotenoid), whereas blue, purple, and red are rich in antioxidants and phenolic compounds (Flint-Garcia et al. 2009; Chaudhary et al. 2014).

However, there have been little studies that have examined the effects of Ch &PS applications to maize with a view toward assessing the effects of these applications on enhance plant tolerance to water stress under different sowing dates. Thus, I used maize plants to test the hypothesis that Ch &PS applications would enhance yield traits and grain yield and thereby ameliorate the deleterious influences of water stress and improve the efficiency of water use and irrigation water use efficiency of maize under a drip irrigation system in Toshka—Egypt.

Materials and Methods

Experimental Site

In the south of Egypt, field experiments were conducted during the spring (March) and fall (September) seasons of 2020 and 2021 at the experimental farm of Water Studies and Research Complex station, National Water Research Center, Toshka—City of Abu Simbel which is located at the latitude of 22°, 24′.11′ N longitude of 31°, 35′.43′ E and altitude 188 m. The texture of the experimental soil is sand, and the other main physical and chemical properties are given in Table 1. The main source of irrigation water is groundwater through a well that has been dug into the area under investigation, depending on the quality of the water it has been classified as C_2S_1, and the chemical properties of the irrigation water are given in Table 2.

Table 1 The physicochemical properties of soil at the experimental site, Egypt

Parameter	Unit	Value	
		0–30	30–60
Mechanical analysis			
Sand	%	92.34	92.87
Silt	%	3.59	4.06
Clay	%	3.07	2.06
Texture	Sand		
Chemical analysis (soil extract (1:1))			
pH		7.94	7.75
Electrical conductivity (ECe)	Ds m^{-1}	1.52	1.27
$CaCO_3$	%	8.33	6.25
Calcium cations (Ca^{+2})	Meq l^{-1}	1.6	1.4
Magnesium cations (Mg^{+2})	Meq l^{-1}	0.6	0.9
Sodium cations (Na^{+})	Meq l^{-1}	1.0	1.1
Potassium cations (K^{+})	Meq l^{-1}	0.2	0.2
Chloride anions (Cl^{-})	Meq l^{-1}	1.2	1.2
Bicarbonate anions (HCO_3^{-})	Meq l^{-1}	0.3	0.2
Sulfate anions (SO_4^{-2})	Meq l^{-1}	1.8	1.9
Nitrogen available	mg l^{-1}	12.6	19.6
Organic matter	%	0.01	0.07
Saturation percent	%	21.7	26.8

Each value represents the mean of three replications

Table 2 Water chemical properties at the experimental site during the spring and fall seasons of 2020 and 2021

Parameter		Unit	Value
Spring seasons	pH		6.32
	TDS	mg l^{-1}	448.0
	HCO_3	mg l^{-1}	89.5
	Calcium cations (Ca^{+2})	mg l^{-1}	68.1
	Magnesium cations (Mg^{+2})	mg l^{-1}	20.3
	Sodium cations (Na^{+})	mg l^{-1}	112.6
	Potassium cations (K^{+})	mg l^{-1}	0.2
	Chloride anions (Cl^{-})	mg l^{-1}	117.0
	Sulfate anions (SO_4^{-2})	mg l^{-1}	237.0
Fall seasons	pH		6.73
	TDS	mg l^{-1}	512.3
	HCO_3	mg l^{-1}	78.3
	Calcium cations (Ca^{+2})	mg l^{-1}	57.1
	Magnesium cations (Mg^{+2})	mg l^{-1}	16.8
	Sodium cations (Na^{+})	mg l^{-1}	101.0
	Potassium cations (K^{+})	mg l^{-1}	0.1
	Chloride anions (Cl^{-})	mg l^{-1}	104.0
	Sulfate anions (SO_4^{-2})	mg l^{-1}	194.7

Meteorological Data

The experimental site has an arid climate with a daily average temperature ranging from 40 to 45. The meteorological data from March to September in both growing seasons were obtained from the agrometeorological station at Toshka, approximately 100 m from the experimental site. The weather data of the monthly relative humidity (%), T maximum, and minimum temperature (°C) during the 2020–2021 growing season are given in Fig. 1 in the spring and fall. The T max during spring 2020 & 2021 ranged from

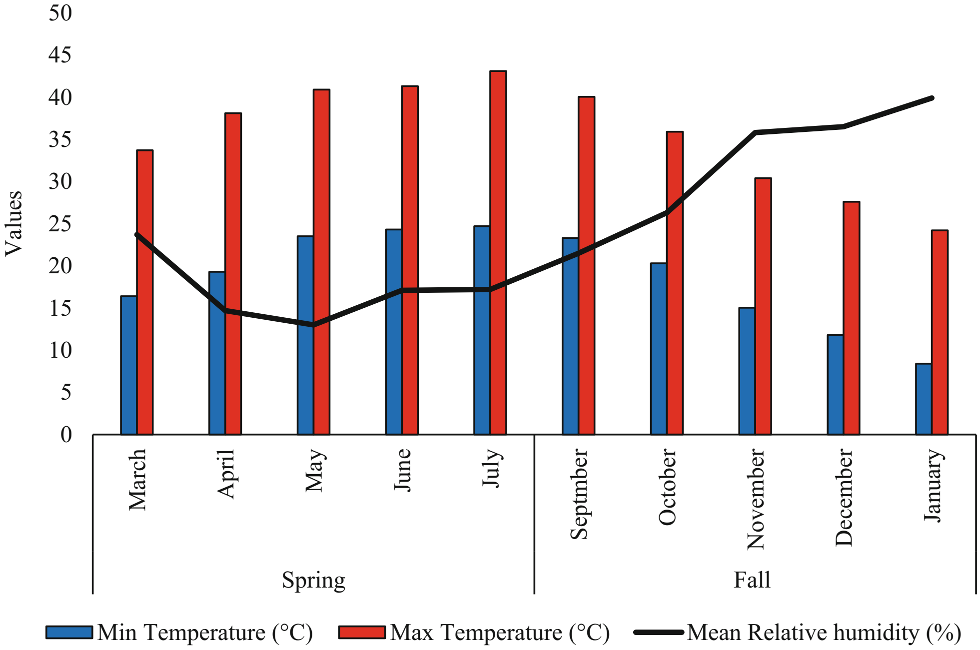

Fig. 1 The weather data of the monthly relative humidity (%), T maximum, and minimum temperature (°C) during the 2020–2021 growing season

33.7 to 43.1 °C (39.4 °C as mean) and T min was ranged from 16.4 to 24.7 °C (21.6 °C as mean). While, the T Max for fall 2020 & 2021 ranges from 24.2 to 40.0 °C (31.6 °C as mean), the T Min was ranged from 8.4–23.3 °C (15.8 °C as mean).

Experimental Details

In order to accomplish the purpose of this study two similar experiments were chosen, and the sowing dates (spring sowing date—**Sd1** and fall sowing date—**Sd2**) were allocated in the main plot, then a strip-plot design with five replicates was used. The vertical plots were allocated to the two irrigation water levels, i.e., 100 and 70%, whereas the horizontal plots were devoted to the four foliar application rates, namely, 0 (control—spray with pure water), 250 (mg l^{-1}) chitosan, 500 (mg l^{-1}) chitosan, 1000 (mg l^{-1}) potassium silicate, 2000 (mg l^{-1}) potassium silicate. The foliar chitosan was sprayed four times every 15-day initiated after 4 weeks of emergence, while potassium silicate (K_2SiO_3) (10% K_2O, 25% SiO_2) as foliar spraying has been applicated three times at 40, 60, and 80, days after sowing. The experimental area of each plot was 5 × 3 m (15 m^2) with five lines, the experimental site was irrigated by drip irrigation.

Management Practices

The fertilization recommendations and field practices of the Ministry of Agriculture in Egypt for the newly reclaimed soils were implemented as follows: with the preparation of the soil before sowing phosphorous fertilizer has been added at the rate of 710 Kg ha^{-1} with calcium super phosphate (15% P_2O_5), while at a rate of 235 Kg ha^{-1} potassium sulfate (48% K_2O) has applied in three equal portions, at 60, 75, and 90 days of cultivation. Nitrogen as ammonium nitrate (33.5% N) was applied in equal portions on a basis of 950 kg ha^{-1}, it started after 15 days of sowing and was repeated every 3–4 days at a rate of 50 kg per portion until it reached the flowering stage. The cultivar of maize (*Zea mays L.*) was Triple Hybrid Giza 352, which is resistant hybrid to late wilt, the most appropriate date for planting is during the month of May and lasts until August, and the harvesting takes place 110–120 days after planting. In the **Sd1** and **Sd2** seasons of 2020 and 2021 maize seeds were sown in hills at a rate of 35 kg ha^{-1} on the 15th of March and 15th of September, respectively. The maize seeds were sown on one side of the dripper's jet. The spacing between the plants was 20 cm, the spacing between the rows was 50 cm, and the depth was 5 cm. Two seeds were drilled, and about 2 weeks after emergence, it was thinned to ensure a plant per hill to maintain the population density at 10 plants m^{-2} (100,000 plants ha^{-1}).

Calculations Related to Irrigation

Crop Evapotranspiration (ETc)

The reference evapotranspiration of maize (**ETo**) was calculated using the weather data obtained from Toshka agrometeorological station by using Fao Penman-Monteith (Allen et al. 1998). While **ETc** was determined as the following equation:

$$ETc = (ETo \times kc\,stage) \quad (1)$$

Where

ETc = the crop evapotranspiration (mm day^{-1}).
ETo = the reference evapotranspiration (mm day^{-1}).
kc = the crop coefficient.

The irrigation water applied (100% Ir) was calculated according to the equation of James (1988) as follows

$$Ir = \frac{ETc + Lf}{ER} \quad (2)$$

Where

Ir = the irrigation water applied (mm).
Etc = the crop evapotranspiration (mm).
Lf = the leaching factor 10% (since electrical conductivity of soil solution is low, LR was neglected).
ER = the irrigation system efficiency% (the efficiency for drip irrigation = 85%).

The irrigation amounts for the other treatments were proportionally obtained from the (100% Ir) treatment. The ETc and Ir which are applied to maize crops at the different growth stages during the growing seasons 2020 and 2021 are presented in Table 3**.**

Water Use Efficiency (Wue)

Mathematically the water use efficiency (Wue) can be represented as:

$$Wue = \left(\frac{Y}{ETc}\right) \quad (3)$$

Where

Wue = water use efficiency (kg m^{-3})
Y = yield (kg ha^{-1}) and
ETc = equals seasonal actual evapotranspiration (mm).

Irrigation Water Use Efficiency (Iwue)

The irrigation water use efficiency (Iwue) can be represented as:

$$Iwue = \left(\frac{Y}{Ir}\right) \quad (4)$$

Table 3 The crop evapotranspiration and irrigation water applied for maize at different growth stages during the spring and fall seasons of 2020 and 2021

First sowing date (March)/spring seasons		Growth stages				Total
		Seedling	Vegetative	Flowering	Maturation	
ET_o (mm)		183.1	458.0	322.0	112.7	1075.6
Crop coefficient		0.60	0.90	1.20	0.90	
ET_C (mm)		109.9	412.0	386.0	101.4	1009.6
Irrigation system efficiency%		0.85				
Ir (mm)		129.2	485.0	454.0	119.3	1187.8
Leaching requirements		12.9	49.0	45.0	11.9	118.8
The total Ir (m^3 ha $^{-1}$)	**100%** Ir (c)	**1421.7**	**5336.0**	**4996.0**	**1312.6**	**13,065.7**
	70% Ir	**1421.7**	**3735.0**	**3497.0**	**918.8**	**9572.5**
Second sowing date (September)/ fall seasons						
ET_o (mm)		187.8	271.0	249.0	53.6	761.3
Crop coefficient		0.60	0.90	1.20	0.90	
ET_C (mm)		112.7	244.0	299.0	48.2	703.5
Irrigation system efficiency%		0.85				
Ir (mm)		132.6	287.0	351.0	119.3	827.6
Leaching requirements		13.3	29.0	35.0	11.9	82.8
The total Ir (m^3 ha $^{-1}$)	**100%** Ir (c)	**1458.2**	**3158.0**	**3864.0**	**1312.6**	**9103.7**
	70% Ir	**1458.2**	**2210.0**	**2705.0**	**918.8**	**6810.1**

ET_o reference evapotranspiration, *ET_C* crop evapotranspiration, *mm* millimeter, *$m^3 h^{-1}$* cubic meter per hectare, 100% Ir (applying 100% of irrigation water applied—represent full irrigation level), 70% Ir (applying 70% of irrigation water applied—represent limited irrigation scheme)

Table 4 Summary of combined F significance from analysis of variance

S.O.V.	Df	MS			
		Average Plant height (cm)	Average ear length (cm)	Average No. of Ear/plant	Average No. of Row/Ear
Sd	**1**	*	*	NS	*
Ir	**1**	*	*	NS	*
Fa	**4**	*	*	NS	*
Sd * Ir	**1**	*	*	NS	*
Sd * Fa	**4**	*	*	NS	NS
Fa * Ir	**4**	*	*	NS	NS
Sd * Ir * Fa	**4**	*	NS	NS	*
CV (%)		2.56	4.59	23.66	4.47

Table 5 Continue

S.O.V.	Df	MS		
		Average Ear Weight (g)	Average Grain Index Weight (g)	Average Grain Yield (kg h^{-1}
Sd	**1**	*	*	*
Ir	**1**	*	*	*
Fa	**4**	*	*	*
Sd * Ir	**1**	*	*	NS
Sd * Fa	**4**	*	*	*
Fa * Ir	**4**	NS	*	*
Sd * Ir * Fa	**4**	NS	*	*
CV (%)		11.09	2.62	8.32

S.O.V. Sources of variation, *Sd* Sowing date, *Ir* irrigation levels, *Fa* Foliar applications, *CV* Coefficient of variability, *Df* Degrees of freedom, *MS* Mean squares, *NS* non-significant

* Significant at 0.05 probability level

Where

Iwue = irrigation water use efficiency (kg m^{-3})
Y = yield (kg ha^{-1}) and
Ir = irrigation water applied (m^3 ha^{-1}).

Measurements

After 60 days of planting, composite plant samples were taken from each experimental unit to record the plant height, each consisting of five plants. To measure the growing parameters of maize, the three middle rows were harvested. After the border rows were excluded, the plants were harvested to determine the grain yield and yield components: number of ears $plant^{-1}$, (thousand) grain weight, number of row/ears, ear length, and weight (g).

Statistical Analysis

Differences between treatments were analyzed through analysis of variance (ANOVA) and the significance of differences between the experimental treatment data means were analyzed and tested using the least significant difference (LSD) multiple range tests (at the $p \leq 0.05$ level) with SAS version 9.1 (SAS Institute, Cary, NC, USA) using a factorial arrangement to assess individual effects and interaction.

Results

Maize Growth Yield Characteristics as Affected by Sowing Date, Water Levels and the Application of Ch and PS

The individual effect of the treatments for sowing dates, irrigation levels and foliar application rates of **Ch** and **PS** ($p < 0.05$), as well as the interaction effects of sowing dates × irrigation regimes × foliar application rates of Ch and PS ($p < 0.05$) on maize growth yield characteristics are given in (Table 4 and 5). Regarding the individual effect of the irrigation levels in $\mathbf{Sd_1}$, the results refer to a negative significant effect on most growth characteristics (comparison between $\mathbf{C_{100}}$ with $\mathbf{C_{70}}$) except for (ear weight and grain index). In the contrast, the results mention that in $\mathbf{Sd_2}$ there were fluctuated influences, the adoption of $\mathbf{Ir_{70}}$ has positive

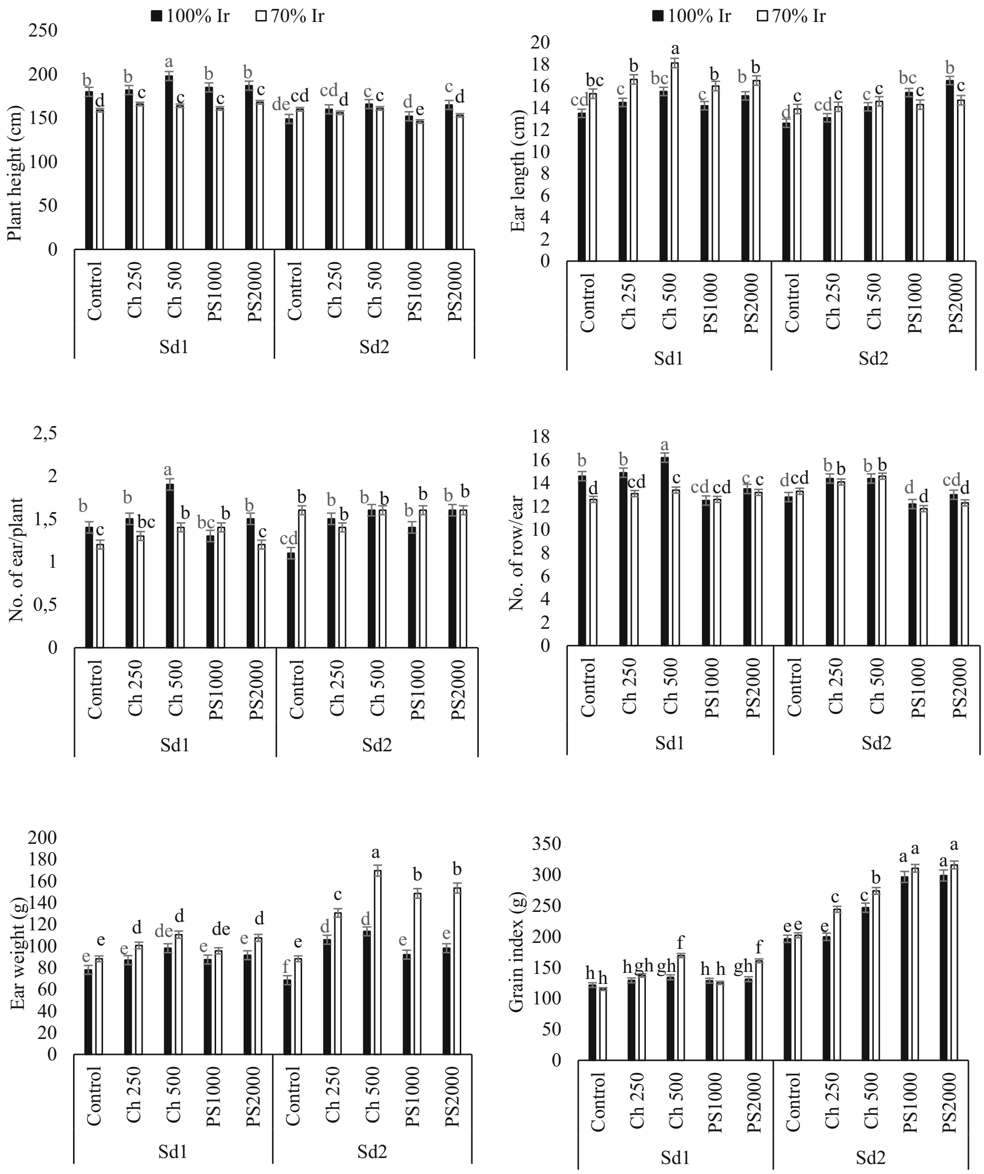

Fig. 2 Average plant height, ear length, number of ears per plant, number of rows per ear, ear weight and grain index of maize as affected by sowing date, irrigation levels, chitosan, and potassium silicate, during the spring and fall growing seasons of 2020/2021. Vertical bars represent ± standard error (SE) of the means. Bars with different letters are statistically significant at $p \leq 0.05$. Abbreviations: Control (spray with pure water); Ch 250 (spray with 250 mg l^{-1} chitosan); Ch 500 (spray with 500 mg l^{-1} chitosan); PS 1000 (spray with 1000 mg l^{-1} potassium silicate); PS 2000 (spray with 2000 mg l^{-1} potassium silicate);100% Ir (applying 100% of irrigation water applied—represent full irrigation level); 70% Ir (applying 70% of irrigation water applied—represent limited irrigation scheme); Sd1(spring sowing date); and Sd2 (fall sowing date)

significant impacts on (ear length, number of ears/plant and number of rows/ear), as seen in (Fig. 2).

By comparing the adoption of the same applications of **Ch** and **PS** treatment, it was found that under $\mathbf{Ir_{100}}$ in $\mathbf{Sd_1}$, the adoption of the higher concentration rates of **Ch** caused in significant improvements differences in (plant height, number of ears/plant and number of rows/ear), while under $\mathbf{Ir_{70}}$ there had no significant differences. Likewise, in the $\mathbf{Sd_2}$ season, it was found that under $\mathbf{Ir_{100}}$ the adoption of the higher concentration rates of **Ch** caused significant improvements in (ear length and grain index), while under $\mathbf{Ir_{70}}$ there had no significant differences in growth yield characteristics.

Maize Grain Yield, WUE, and IWUE as Affected by Sowing Date, Water Regimes, and the Application of Ch and PS

Based on the results illustrated in (Fig. 3a), by comparing the control treatment, the gained results mention that under $\mathbf{Ir_{100}}$ planting maize seeds in the $\mathbf{Sd_2}$ caused an increase in grain yield than spring $\mathbf{Sd_1}$ by 29.7%, also it was increased with using $\mathbf{Ir_{70}}$ by 33.0% under the same circumstances.

On the other side, the foliar application of **Ch** and **PS** leads to obtaining more enhancement on grain yield than the control treatment under each irrigation level, for instance, in the $\mathbf{Sd_1}$ under $\mathbf{Ir_{100}}$ it was raised by 37.2, 80.5, 6.9, and 59.0% for $\mathbf{Ch_{250}}$, $\mathbf{Ch_{500}}$ $\mathbf{PS_{1000}}$ and $\mathbf{PS_{2000}}$ treatments, respectively. In the same context, in the $\mathbf{Sd_2}$ under $\mathbf{Ir_{100}}$ it

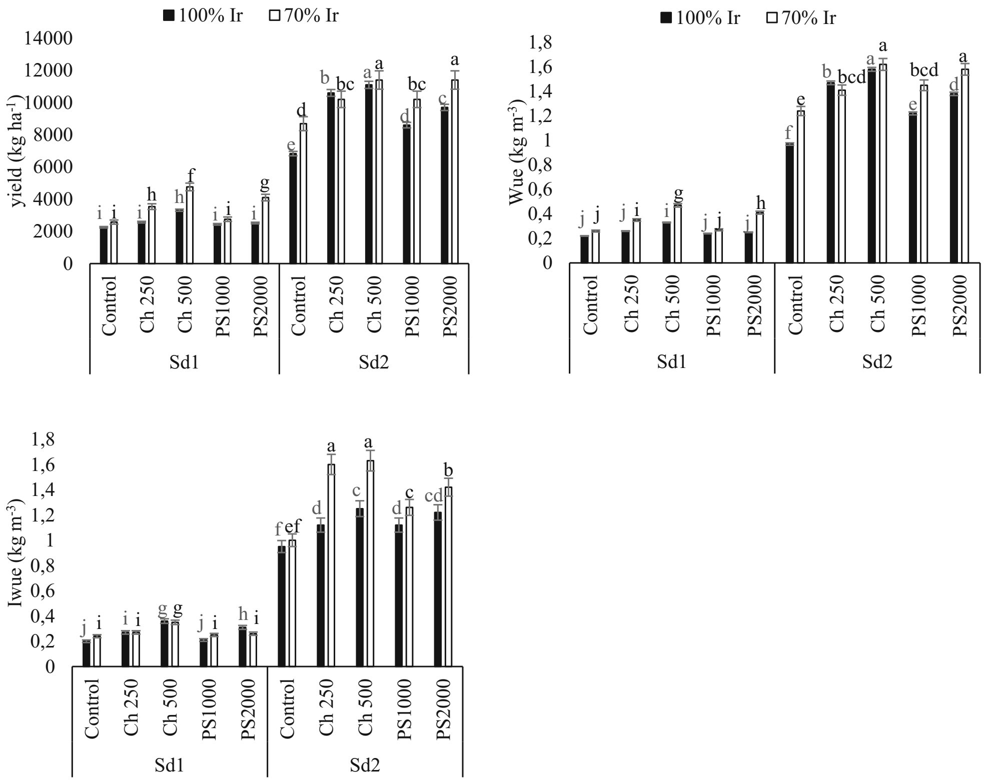

Fig. 3 Average maize yield, water use efficiency, and irrigation water use efficiency as affected by sowing date, irrigation levels, chitosan, and potassium silicate, during the spring and fall, growing seasons of 2020/2021. Vertical bars represent ± standard error (SE) of the means. Bars with different letters are statistically significant at $p \leq 0.05$. Abbreviations: Control (spray with pure water); Ch 250 (spray with 250 mg l^{-1} chitosan); Ch 500 (spray with 500 mg l^{-1} chitosan); PS 1000 (spray with 1000 mg l^{-1} potassium silicate); PS 2000 (spray with 2000 mg l^{-1} potassium silicate);100% Ir (applying 100% of irrigation water applied—represent full irrigation level); 70% Ir (applying 70% of irrigation water applied—represent limited irrigation scheme); Sd1(spring sowing date); Sd2 (fall sowing date); Wue (water use efficiency); and Iwue (irrigation water use efficiency)

was raised by 17.4, 31.2, 17.4, and 27.7% for $\mathbf{Ch_{250}}$, $\mathbf{Ch_{500}}$ $\mathbf{PS_{1000}}$, and $\mathbf{PS_{2000}}$ treatments, respectively.

By comparing the control treatment, a lower maize yield was obtained with sowing maize seeds in the $\mathbf{Sd_1}$ season, as can be seen in (Fig. 3a). Furthermore, by comparing the application of **Ch** and **PS** treatment in $\mathbf{Sd_1}$ under $\mathbf{Ir_{100}}$, a higher maize yield was obtained with adopting $\mathbf{Ch_{500}}$ in contrast to adopting the other applications. Likewise, in the $\mathbf{Sd_2}$ season, it was found that under $\mathbf{Ir_{100}}$ or $\mathbf{Ir_{70}}$, a higher maize yield was obtained with adopting $\mathbf{Ch_{500}}$ which was significantly equaled adopting $\mathbf{Ir_{70}}$ × foliar applications of $\mathbf{PS_{2000}}$. In the same context, the superiority of the adoption of the higher concentration rates of **Ch** and **PS** under $\mathbf{Ir_{100}}$ or $\mathbf{Ir_{70}}$ irrigation level is still pronounced in attaining the highest maize yield in the $\mathbf{Sd_1}$ and $\mathbf{Sd_2}$ except with adopting higher concentration rates of **PS** in the $\mathbf{Sd_1}$ × the adoption of $\mathbf{Ir_{100}}$.

On those grounds, by comparing the control treatment, a lower maize **Wue** was obtained with sowing maize seeds in the $\mathbf{Sd_1}$ season, as can be seen in (Fig. 3b). Furthermore, the obtained results showed that the highest **Wue** values were attained by applying $\mathbf{Ch_{500}}$ or $\mathbf{PS_{2000}}$ as a foliar application and irrigating maize plants at $\mathbf{Ir_{100}}$ in the $\mathbf{Sd_2}$ which caused increases in **Wue** reach to 30.6% than the control treatment which were significantly equaled applying foliar applications of $\mathbf{PS_{2000}}$ × adopting $\mathbf{Ir_{70}}$ irrigation level for attaining the highest **Wue** in the second season—$\mathbf{Sd_2}$.

By sowing maize seeds in the $\mathbf{Sd_2}$ and applied $\mathbf{Ch_{500}}$ × the adoption of $\mathbf{Ir_{70}}$ irrigation level, caused in increases of **Iwue** by 63.0% than the control ($\mathbf{C_{70}}$), which allowed to confer irrigation water at par with attained the highest **Iwue**.

In this respect, adopting $\mathbf{Ir_{70}}$ × foliar applications of $\mathbf{Ch_{250}}$, $\mathbf{PS_{2000}}$ **and** $\mathbf{PS_{1000}}$ were significantly equaled control treatment under $\mathbf{Ir_{70}}$ for attaining the lowest **Iwue** in the $\mathbf{Sd_1}$. Likewise, in the $\mathbf{Ir_{100}}$, the adoption of $\mathbf{PS_{1000}}$ applications were significantly equaled the control treatment for attaining the lowest **Iwue**. In the same context, the results in (Fig. 3c) indicated that the highest **Iwue** values in the first season were obtained with adopting $\mathbf{Ir_{100}}$ or $\mathbf{Ir_{70}}$ irrigation level and applying $\mathbf{Ch_{500}}$ applications. While in the $\mathbf{Sd_2}$, it was obtained by adopting the limited irrigation level- $\mathbf{Ir_{70}}$ × foliar applications of $\mathbf{Ch_{250}}$ or $\mathbf{Ch_{500}}$.

Discussion

Agricultural policies that use less water must be adopted to improve the efficiency of water use in irrigation by focusing on agronomic management (Ghazy 2021). Maize is generally known to be heavily irrigated and sensitive to water stress, while having the ability to cope with a short period of water stress, however, water stress caused numerous influences on the morphological and the photosynthesis process which ultimately caused decreased dry matter accumulation (Rekaby et al. 2017; Gheysari et al. 2017). Thus, this study sought to find the equilibrium between maize water requirements and the current changes in the climatic situation and available irrigation issues.

The Effect of Sowing Date

Sowing date constitutes one of the prominent factors that limit maize crop yield and is also a fundamental factor in determining yield. Accordingly, determining the optimum sowing date is considered essential to crop production, as the planting date depends on the temperature since an increase in temperature affects crop yield due a shorter duration of different growing seasons (Harrison et al. 2011; Ahmad et al. 2018). The obtained results indicated that **Sd_2** leads to attaining a higher maize yield than the **Sd_1**, this due to the suitable climatic condition in the fall which allows for maize plants to growing better such as (suitable temperature, humidity, less transpiration, etc), these results are closed to those obtained by (Hassaan 2018; Abaza 2021). In this concern, as the other crops maize plants are susceptible to climate change (high temperature, precipitation, and CO_2), however, the temperature showed more negative impacts on crop yield than other variables (Ottman et al. 2012; Wheeler and Von Braun 2013). Moreover, increased mean temperatures have been shown to reduce the actual growth period between planting date and crop maturity due to accelerated crop development, and although that enhancing filling, the fill rate cannot compensate for these temporal constraints which leads to a decrease in biomass accumulation and yields (Dias and Lidon 2009; Wang et al. 2009; Asseng et al. 2011). Hence, it's worth noting that the average climatic data which has been recorded in the spring and fall seasons of 2020 and 2021 indicated that the mean maximum and minimum temperatures were (40.0–23.3) in September, (35.9–20.3) in October, (30.4–15.0) in November, and (27.6–11.8) in December, respectively, while it was (33.7–16.4) in March, (38.1–19.3) in April, (40.9–23.5) in May, (41.3–24.3) in June, and (43.1–24.7) in July, respectively, as seen in (Fig. 1). Through the obtained results herein, it's interesting to point out that at higher temperatures than 32 °C most significant effects occur on starch production and grain weight, resulting in lower fill rate and causing deterioration of the quality of maize cereals (Wilhelm et al. 1999; Siebers et al. 2017), furthermore according to (Waqas et al. 2021) they mention that stress caused by high temperatures limits pollen viability and silk receptivity, resulting in significant reductions in grain yield. In addition, referring to the obtained data that has been recorded for the mean maximum and minimum temperatures in the period from 2005 to 2007 reached (39.4–23.4) in September, (36.8–21.1) in October, (29.2–13.8) in November, and (34.2–18.6) in December, respectively, while it was (31.5–13.2) in March, (36.1–17.8) in April, (39.8–22.7) in May, (41.7–24.3) in June, and (42.3–24.5) in July, respectively. As such it is important to note that simply increasing the average seasonal temperature by 1 °C can reduce the economic production of the maize crop by 3% to 13% (Izaurralde et al. 2011). Thus, through the forgoing clarified the prominent impact of climate change which involves the importance of rearrangement of the common recommendations that related to the optimum sowing dates in south of Egypt and other similar areas.

The Effect of Water Levels

The obtained data indicated that the adoption of **Ir_{70}** provides better maize yield and wue than **Ir_{100}**, particularly in the **Sd_2** sowing dates. I assumed that attribute to improvements in the yield characteristics, which were in agreement with those obtained by (Atta 2007; Rekaby et al. 2017; Wang et al. 2022). Furthermore, I concluded that with exposing maize plants to water stress in the fall season there were several interrelated factors that could partly ameliorate the impact of these circumstances among them the short span of time which plants have exposed to water stress, viz when the sowing date was shifted from the middle of March to the middle of September this status allowed plants to exceed the negative impact of water shortage by escaping strategy which based on the ability to complete its life cycle after exposure to water shortage as long as that didn't exceed the critical point at par with availability of suitable climatic conditions for growth in the studying area, in this case, plants do not suffer from water deficiency due they are capable of modulating their vegetative and reproductive phenology according to the most favorable period, which is consistent with (De Micco and Aronne 2012). Moreover, planting maize seeds in the fall works in decreasing the growing period which reaches to 100–110 days approximately, conversely planting maize seeds in the spring the growing season reaches 135–140 days. These reasons are accompanied by the self-ability of maize to cope with short periods of water stress resulting in maintaining the yield profitability at acceptable values in the fall, these findings are in harmony with the study of (Kulczycki et al. 2022).

The Effect of Chitosan and Potassium Silicate

The current results showed that at **Sd_1 & Sd_2** applying **Ch** and **PS** as a foliar application on maize plants fulfills pronounced improvements in yield, **Wue**, and **Iwue** under full irrigation (**Ir_{100}**) or stress treatment (**Ir_{70}**). The previous findings attributed to the numerous benefits that **Ch** and **PS** confer, this effect has been widely studied among them that **Ch** has an important effect on plant growth by catalyzing cell growth and development, increasing the activity of key enzymes in nitrogen metabolism, and enhancing nitrogen transfer, leading to increased yield (Guan et al. 2009; Mondal et al. 2013; dos Reis et al. 2019; Mohammadi et al. 2021). On other hand, applying **PS** not only improved physiological and agronomic features affecting crop growth and yield through optimum treatment of the water supply but has also mitigated the negative impacts of water stress. Generally, the application of **PS** enhances growth, seed yield, and WUE, thus it is an appropriate management strategy (Eyni-Nargeseh et al. 2022). In this regard, Artyszak (2018) hypothesized that such increases in yield, yield components, and WUE attributed to the promotion of photosynthetic activities and optimal growth conditions in **PS**-treated plants, moreover Li et al. (2018) indicated that plants treated with silicon produce respectively 35% more biomass and 24% more grain yield than untreated treatment.

Furthermore, the gained results clarified that the favorable impacts were rising steadily by using the higher concentrations of **Ch** and **PS**, such findings are in parallel with those obtained by (Chibu and Shibayama 1999; Mondal et al. 2013; Shedeed 2018) they demonstrated that the morphological and the physiological traits, and yield was improved by using the higher rates of foliar **Ch** and **PS**. In this regard, (Kamenidou 2005; Wang et al. 2022) recommended that a number of horticultural plants have been improved through supplementation in Si according to the source, the rate, the Si content, and its deposit in plant tissues which varied from one species to another. On the other side, the results point out to the immense improvements in yield by the adoption of $\mathbf{Ch_{500}}$ which were superior than the $\mathbf{PS_{2000}}$ under $\mathbf{Ir_{100}}$ and $\mathbf{Ir_{70}}$, these findings attribute to the butter solubility of **Ch** than **PS** particularly after adjustment pH of **Ch** by diluting acetic acid, this finding is corroborated by (Almeida et al. 2020).

On the other hand, the obtained results demonstrated that adoption of the higher **Ch** concentrations in $\mathbf{Sd_1}$, lead to better improving maize yield particularly under $\mathbf{Ir_{70}}$, while the adoption of the higher concentrations of **PS** in $\mathbf{Sd_2}$, lead to better improving maize yield particularly under $\mathbf{Ir_{70}}$ (Fig. 3a). In this concern, I conclude that in $\mathbf{Sd_1}$ due to the increments of the weather conditions, confer the educated amounts of water within the plant tissues are considered a crucial factor, while in $\mathbf{Sd_2}$ the main crucial factor is the reduction of the growing season (90–100 day). Therefore, with the adoption of the higher **Ch** concentrations under $\mathbf{Ir_{70}}$ although plants have severed of increasing climate conditions, it appears that Ch applications form a transparent layer reducing perspiration, which in turn worked on the maintenance of water within the tissues of plants that was useful for the mitigation of harmful effects of the reduction in soil moisture (Roychoudhury et al. 2022). Therefore, the multiple features of $\mathbf{Ch_{500}}$ work on ameliorating unfavorable effects of water stress in growth and yield, these findings are parallel to those obtained by (Malerba and Cerana 2015; Hidangmayum et al. 2019). Whilst, it appears that the adoption of higher **PS** applications in $\mathbf{Ir_{70}}$ treatment at ($\mathbf{Sd_2}$) attained better yield. In this context, I hypothesized that in $\mathbf{Sd_2}$ the higher humidity rates seems it worked on in more improvements in **PS** solubility, which perform some features such as improving the nutrients transportation and accumulation, which has led to the enhancements of yield.

From the foregoing, the impacts of Ch &PS applications on maize plants sowing in spring or in fall sowing dates and exposure to water stress were clear. It's quite important noted that the obtained results indicated the positive impact of identify the optimum sowing dates and irrigation level. However, there are some obstacles facing that such as (the competition between crops, insects and diseases). The obtained results recommended sowing maize during the fall season, which will lead to the inability to sow an important crop (i.e., wheat, barley, faba bean etc.). Therefore, the competition between crops on the available cultivation area remains the main limitation, thus I suggest that the better crop for sowing will be identified, in accordance with the highest wue. Furthermore, by sowing maize during the fall season, as humidity increased, more insects and diseases arose, particularly fall armyworm insect. Where maize is the preferred host for fall armyworm insect in the countries (Rashed et al. 2022). It can decrease annual maize yield from 21% to 53% without control methods (Huang et al. 2020). However, in the current study noticed that it's appearance and damage was more detected in the spring season. On the other side, regarding the enhancing of the diseases during the fall season, the current study noticed that the Ch &PS applications enhance maize tolerance. In this concern, Kocięcka and Liberacki (2021) demonstrates that this Ch is very effective against diseases and pathogens that are most dangerous to cereals, which have been broadly emerging at the $\mathbf{Sd_1}$ than $\mathbf{Sd_2}$.

Conclusion

As a consequence of water scarcity and severe changes in climate, the irrigation water conservation has become an urgent priority. This research provides new information about the impact of the separate foliar application of chitosan and potassium silicate on stressed plants and studies their reflection on the efficiency of water use. The main conclusions of this study include: (1) irrigate maize plant of 70% of irrigation water applied, provides better maize yield and water use efficiency than the adoption of the full irrigation level, particularly in the fall sowing date; (2) maize yield could be increased by applying foliar applications of chitosan at the rate of 500 mg l^{-1}, or potassium silicate at the rate of 2000 mg l^{-1} particularly with the adoption of 70% of irrigation water applied. Nonetheless, sowing the seeds in the fall season showed a more positive increase; (3) the tested applications were similar in their influences on maize yield although the adoption of the higher Ch concentrations in the spring, lead to better improving maize yield particularly under 70% of irrigation water applied, while the adoption of the higher concentrations of potassium silicate in in the fall, lead to better improving maize yield particularly under 70% of irrigation water applied; (4) Also, the findings of this study indicated that there are some obstacles facing the identification of the optimum sowing dates and irrigation level such as (the competition between crops, insects and diseases), further studies are required to observe the obstacles on other similar areas. Overall, as a consequence that water is considered the crucial factor in arid regions, thus it seems to be logical for recommended sowing maize in the fall and applying chitosan four times as foliar applications with concentrations at 500 (mg l^{-1}), which mitigates water stress impacts in the arid regions as this study and other similar areas and rises water use efficiency of the maize crop.

Acknowledgements The author would like to thank the Water Studies and Research Complex (WSRC) Station and National Water Research Center (NWRC) for their financial support to conduct this work.

Funding Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB).

Declarations

Conflict of interest A. M. S. Elshamly declares that he has no competing interests.

Ethical standards This manuscript is an original paper and has not been published in other journals. The author agreed to keep the copyright rule.

References

Abaza A S D (2021). Effect of irrigation water levels, filter mud cake application and sowing dates on maize Production under tushka conditions. Ph.D. Thesis. Fac. Agric, Assiut University.

Abaza ASD, Ragheb HMA, Rushdi MK, Wahpalla OHA (2016) Effect of different irrigation systems, pulse irrigation technique and silicon application on maize growth, yield and water relations under toshka climatic conditions. Assiut J Agric Sci 47:191–202

Abideen ZU (2014) Comparison of crop water requirements of maize varieties under irrigated condition in semi-arid environment. J Environ Earth Sci 4:1–3

Ahmad I, Wajid SA, Ahmad A, Cheema MJM, Judge J (2018) Assessing the impact of thermo-temporal changes on the productivity of spring maize under semi-arid environment. Int J Agric Biol 20:2203–2210

Ahmed FF, Mohamed Y, Abdalla BM (2007) The relation between using some antioxidants and productivity of Sewy date palms. Minia J Agric Res Dev 27:753–770

Aimar D, Calafat M, Andrade AM, Carassay L, Abdala GI, Molas ML (2011) Drought tolerance and stress hormones: from model organisms to forage crops. Plants Environ 10:137–164

Ali A, Ibrahim S, Abou-Amer I (2019) Water deficit stress mitigation by foliar application of potassium silicate for sugar beet grown in a saline calcareous soil. Egypt J Soil Sci 59:15–23. https://doi.org/10.21608/ejss.2019.7086.1236

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and drainage paper no 56. Food and agriculture Organization of the United Nations (FAO), Rome

Almeida LG, Magalhães PC, Karam D, Silva EMD, Alvarenga AA (2020) Chitosan application in the induction of water deficit tolerance in maize plants. Acta Scientiarum. Agron. https://doi.org/10.4025/actasciagron.v42i1.42463

Anjum MM, Arif M (2022) Perspectives of wheat hybrid yield and quality under limited irrigation supply and sowing windows. Gesunde Pflanz. https://doi.org/10.1007/s10343-022-00649-8

Artyszak A (2018) Effect of silicon fertilization on crop yield quantity and quality—A literature review in Europe. Plants 7:54. https://doi.org/10.3390/plants7030054

Asseng S, Foster IAN, Turner NC (2011) The impact of temperature variability on wheat yields. Glob Change Biol 17:997–1012. https://doi.org/10.1111/j.1365-2486.2010.02262.x

Atta YI (2007) Improving growth, yield and water productivity of some maize cultivars by new planting method. Egypt J App Sci 22:1–16

Attia A, Govind A, Qureshi AS, Feike T, Rizk MS, Shabana MM, Kheir AM (2022) Coupling process-based models and machine learning algorithms for predicting yield and evapotranspiration of Maize in Arid Environments. Water 14:3647. https://doi.org/10.3390/w14223647

Badawy ME, Rabea EI (2011) A biopolymer chitosan and its derivatives as promising antimicrobial agents against plant pathogens and their applications in crop protection. Int J Carbohydr Chem. https://doi.org/10.1155/2011/460381

Bautista-Baños S, Hernandez-Lauzardo AN, Velazquez-Del Valle MG, Hernández-López M, Barka EA, Bosquez-Molina E, Wilson CL (2006) Chitosan as a potential natural compound to control pre and postharvest diseases of horticultural commodities. Crop Prot 25:108–118. https://doi.org/10.1016/j.cropro.2005.03.010

Chaudhary DP, Jat SL, Kumar R, Kumar A, Kumar B (2014) In: Chaudhary DP, Kumar S, Singh S (eds) Maize: nutrition dynamics and novel uses. Springer, Berlin, Heidelberg, pp 153–156 https://doi.org/10.1007/978-81-322-1623-0

Chibu H, Shibayama H (1999) Effects of chitosan applications on the early growth of several crops. Rep Kyushu Branch Crop Sci Soc Jpn 65:83–87

De Micco V, Aronne GR (2012) Morpho-anatomical traits for plant adaptation to drought. In: Aroca R (ed) Plant responses to drought stress. Springer, Berlin, Heidelberg https://doi.org/10.1007/978-3-642-32653-0_2

Dias AS, Lidon FC (2009) Evaluation of grain filling rate and duration in bread and durum wheat, under heat stress after anthesis. J Agron Crop Sci 195:137–147

Duan C, Meng X, Meng J, Khan MIH, Dai L, al Khan Aet (2019) Chitosan as a preservative for fruits and vegetables: a review on chemistry and antimicrobial properties. Antimicrob Prop 4:11–21. https://doi.org/10.21967/jbb.v4i1.189

El-Marsafawy SM, Hassanein MK, Abdel-Salam AA (2012) Studies on vulnerability of Egyptian maize varieties to future climatic changes. Am J Agric Environ Sci 12:1153–1161

Ennahli S, Earl HJ (2005) Physiological limitations to photosynthetic carbon assimilation in cotton under water stress. Crop Sci 45:2374–2382. https://doi.org/10.2135/cropsci2005.0147

Eyni-Nargeseh H, Shirani Rad AH, Shiranirad S (2022) Does potassium silicateimprove physiological and agronomic traits and oil compositions of rapeseed genotypes under well-watered and water-limited conditions? Gesunde Pflanz. https://doi.org/10.1007/s10343-022-00652-z

Flint-Garcia SA, Bodnar AL, Scott MP (2009) Wide variability in kernel composition, seed characteristics, and zein profiles among diverse maize inbreds, landraces, and teosinte. Theor Appl Genet 119:1129–1142. https://doi.org/10.1007/s00122-009-1115-1

Galmés J, Medrano H, Flexas J (2007) Photosynthetic limitations in response to water stress and recovery in Mediterranean plants with different growth forms. New Phytol 175:81–93. https://doi.org/10.1111/j.1469-8137.2007.02087.x

Ghazy HA (2021) Influence of potassium silicate on water deficit tolerance for some rice genotype. J Plant Produc 12:1101–1110

Gheysari M, Sadeghi SH, Loescher HW, Amiri S, Zareian MJ, Majidi MM, Asgarinia P, Payero JO (2017) Comparison of deficit irrigation management strategies on root, plant growth and biomass productivity of silage maize. Agric Water Manag 182:126–138. https://doi.org/10.1016/j.agwat.2016.12.014

Gomaa MA, Kandi EE, Zen El-Dein AAM, Abou-Donia MEM (2020) Effect of irrigation intervals and foliar application of potassium silicate on growth of maize. Egypt Acad J Biol Sci H Bot 11:103–109

Gomaa MA, Kandil EE, El-Dein AA, Abou-Donia ME, Ali HM, Abdelsalam NR (2021) Increase maize productivity and water use efficiency through application of potassium silicate under water stress. Sci Rep 11:1–8. https://doi.org/10.1038/s41598-020-80656-9

Guan YJ, Hu J, Wang XJ, Shao CX (2009) Seed priming with chitosan improves maize germination and seedling growth in relation to physiological changes under low temperature stress. J Zhejiang Univ Sci B 10:427–433. https://doi.org/10.1631/jzus.B0820373

Hadwiger LA (2013) Multiple effects of chitosan on plant systems: solid science or hype. Plant Sci 208:42–49. https://doi.org/10.1016/j.plantsci.2013.03.007

Haggag WM, Tawfik MM, Abouziena HF, El Wahed AMSA, Ali RR (2017) Enhancing wheat production under arid climate stresses using bio-elicitors. Gesunde Pflanz 69:149–158. https://doi.org/10.1007/s10343-017-0399-3

Harrison L, Michaelsen J, Funk C, Husak G (2011) Effects of temperature changes on maize production in Mozambique. Clim Res 46:211–222

Harte J, Saleska S, Shih T (2006) Shifts in plant dominance control carbon-cycle responses to experimental warming and widespread drought. Environ Res Lett 1:14001. https://doi.org/10.1088/1748-9326/1/1/014001

Hassaan MA (2018) Response of some yellow maize hybrids (Zea mays L.) to sowing date under Toshka conditions. J Plant Produc 9:509–514

Hatfield JL, Dold C (2019) Water-use efficiency: advances and challenges in a changing climate. Front Plant Sci 10:103. https://doi.org/10.3389/fpls.2019.00103

Hidangmayum A, Dwivedi P, Katiyar D, Hemantaranjan A (2019) Application of chitosan on plant responses with special reference to abiotic stress. Physiol Mol Biol Plants 25:313–326. https://doi.org/10.1007/s12298-018-0633-1

Huang Y, Dong Y, Huang W, Ren B, Deng Q, Shi Y, Bai J, Ren Y, Geng Y, Ma H (2020) Overwintering distribution of fall armyworm (Spodoptera frugiperda) in Yunnan, China, and influencing environmental factors. Insects 11:805

Izaurralde RC, Thomson AM, Morgan JA, Fay PA, Polley HW, Hatfield JL (2011) Climate impacts on agriculture: implications for forage and rangeland production. Agron J. https://doi.org/10.2134/agronj2010.0304

James LG (1988) Principles of farm irrigation systems design. State University, Washington, p 543

Jayakumar R, Selvamurugan N, Nair SKV, Tokura S, Tamura H (2008) Preparative methods of phosphorylated chitin and chitosan—An overview. Int J Biol Macromol 43:221–225. https://doi.org/10.1016/j.ijbiomac.2008.07.004

Kamenidou S (2005) Silicon supplementation affects greenhouse produced cut flowers. MSc, Oklahoma State University

Kheir A M S (2013) Modeling for crop water productivity at North Delta soils, Egypt. Ph.D. Thesis Fac, Agric, Mansoura. Univ.

Kheir AMS, Alrajhi AA, Ghoneim AM, Ali EF, Magrashi A, Zoghdan MG, Abdelkhalik SAM, Fahmy AE, Elnashar A (2021) Modeling deficit irrigation-based evapotranspiration optimizes wheat yield and water productivity in arid regions. Agric Water Manag 256:107122. https://doi.org/10.1016/j.agwat.2021.107122

Kocięcka J, Liberacki D (2021) The potential of using chitosan on cereal crops in the face of climate change. Plants 10:1160. https://doi.org/10.3390/plants10061160

Kulczycki G, Sacała E, Chohura P, Załuska J (2022) Maize and wheat response to drought stress under varied sulphur fertilisation. Agronomy 12:1076. https://doi.org/10.3390/agronomy12051076

Laane HM (2018) The effects of foliar sprays with different silicon compounds. Plants 7:45. https://doi.org/10.3390/plants7020045

Li W, Jiang X, Xue P, Chen S (2002) Inhibitory effects of chitosan on superoxide anion radicals and lipid free radicals. Chin Sci Bull 47:887–889. https://doi.org/10.1360/02tb9198

Li Z, Song Z, Yan Z, Hao Q, Song A, Liu L et al (2018) Silicon enhancement of estimated plant biomass carbon accumulation under abiotic and biotic stresses. A meta-analysis. Agron Sustain Dev 38:1–19. https://doi.org/10.1007/s13593-018-0496-4

Liang YC, Hua HX, Zhu YG, Zhang J, Cheng CM, Romheld V (2006) Importance of plant species and external silicon concentration to active silicon uptake and transport. New Phytol 172:63–72. https://doi.org/10.1111/j.1469-8137.2006.01797.x

Malerba M, Cerana R (2015) Reactive oxygen and nitrogen species in defense/stress responses activated by chitosan in sycamore cultured cells. Int J Mol Sci 16:3019–3034

Manabe S, Wetherald RT, Milly PCD, Delworth TL, Stouffer RJ (2004) Century-scale change in water availability: CO2-quadrupling experiment. Clim Change 64:59–76. https://doi.org/10.1023/B:CLIM.0000024674.37725.ca

Maresma A, Ballesta A, Santiveri F, Lloveras J (2019) Sowing date affects maize development and yield in irrigated Mediterranean Environments. Agriculture 9:67. https://doi.org/10.3390/agriculture9030067

Mohammadi H, Aghaee Dizaj L, Aghaee A, Ghorbanpour M (2021) Chitosan-mediated changes in dry matter, total phenol content and essential oil constituents of two origanum species under water deficit stress. Gesunde Pflanz 73:181–191. https://doi.org/10.1007/s10343-020-00536-0

Mondal MMA, Puteh AB, Dafader NC, Rafii MY, Malek MA (2013) Foliar application of chitosan improves growth and yield in maize. J Food Agric Environ 11:520–523

Mustafa T, Sattar A, Sher A, Ul-Allah S, Ijaz M, Irfan M, Butt M, Cheema M (2021) Exogenous application of silicon improves the performance of wheat under terminal heat stress by triggering physio-biochemical mechanisms. Sci Rep 11:23170. https://doi.org/10.1038/s41598-021-02594-4

Ottman MJ, Kimball BA, White JW, Wall GW (2012) Wheat growth response to increased temperature from varied planting dates and supplemental infrared heating. Agron J 104:7–16. https://doi.org/10.2134/agronj2011.0212

Ramírez Villegas J, Thornton PK (2015) Climate change impacts on African crop production. In: CCAFS working paper no. 119. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen

Rao GB, Pi PY, Syriac EK (2018) Effect of various silicon sources on nutrient uptake by rice and available nutrient status in soil. J Pharmacogn Phytochem 7:1449–1452

Rashed HS, Khalil MS, Khalwy KM, El-Ghbawy IA (2022) Appearance of fall armyworm, Spodoptera frugiperda as a new invasive insect pest on maize plants in the Nile Delta, Egypt. J Plant Protec Path 13:231–234

dos Reis CO, Magalhães PC, Avila RG, Almeida LG, Rabelo VM, Carvalho DT et al (2019) Action of N-Succinyl and N, O-Dicarboxymethyl chitosan derivatives on chlorophyll photosynthesis and fluorescence in drought-sensitive maize. J Plant Growth Regul 38:619–630. https://doi.org/10.1007/s00344-018-9877-9

Rekaby SA, Eissa MA, Hegab SA, Ragheb HM (2017) Effect of water stress on maize grown under drip irrigation system. Assiut J Agric Sci 48:1110–486

Roychoudhury A, Datta K, Tagore R (2022) Influence of chitosan and chitosan-based nanoparticles against abiotic stress in plants. In: Kumar S, Madihally SV (eds) Role of Chitosan and Chitosan-based nanomaterials in plant sciences, pp 297–320 https://doi.org/10.1016/B978-0-323-85391-0.00001-0

Shaaban MM, Abou El-Nour EZAA (2014) Macro and micro-nutrients concentrations and uptake by maize seedlings irrigated with fresh or saline water as affected by K-Silicate foliar fertilization. Am J Plant Physiol 9:95–102. https://doi.org/10.3923/ajpp.2014.95.102

Shedeed SI (2018) Assessing effect of potassium silicate consecutive application on forage maize plants (Zea mays L.). J Innov Pharm Biol Sci 5:119–127

Siebers MH, Slattery RA, Yendrek CR, Locke AM, Drag D, Ainsworth EA et al (2017) Simulated heat waves during maize reproductive stages alter reproductive growth but have no lasting effect when applied during vegetative stages. Agric Ecosyst Environ 240:162–170. https://doi.org/10.1016/j.agee.2016.11.008

Souri Z, Khanna K, Karimi N, Ahmad P (2021) Silicon and plants: current knowledge and future prospects. J Plant Growth Regul 40:906–925. https://doi.org/10.1007/s00344-020-10172-7

Srivastava A, Sahoo B, Raghuwanshi NS, Chatterjee C (2018) Modelling the dynamics of evapotranspiration using Variable Infiltration Capacity model and regionally calibrated Hargreaves approach. Irrig Sci 36:289–300. https://doi.org/10.1007/s00271-018-0583-y

Sun T, Xie W, Xu P (2004) Superoxide anion scavenging activity of graft chitosan derivatives. Carbohydr Polym 58:379–382. https://doi.org/10.1016/j.carbpol.2004.06.042

Tan Y, Liang Z, Shao H, Du F (2006) Effect of water deficits on the activity of anti-oxidative enzymes and osmoregulation among three different genotypes of Radix Astragali at seeding stage. Colloids Surf B Biointerfaces 49:60–65. https://doi.org/10.1016/j.colsurfb.2006.02.014

Wang F, Xue J, Xie R, Ming B, Wang K, Hou P et al (2022) Assessing growth and water productivity for drip-irrigated maize under high plant density in arid to semi-humid climates. Agriculture 12:97. https://doi.org/10.3390/agriculture12010097

Wang J, Wang E, Luo Q, Kirby M (2009) Modelling the sensitivity of wheat growth and water balance to climate change in Southeast Australia. Clim Change 96:79–96

Waqas MA, Wang X, Zafar SA, Noor MA, Hussain HA, Azher Nawaz M, Farooq M (2021) Thermal stresses in maize: effects and management strategies. Plants 10:293. https://doi.org/10.3390/plants10020293

Wheeler T, Von Braun J (2013) Climate change impacts on global food security. Science 341:508–513. https://doi.org/10.1126/science.1239402

Wilhelm E, Mullen R, Keeling P, Singletary G (1999) Heat stress during grain filling in maize: effects on kernel growth and metabolism. Crop Sci 39(6):1733–1741

Yang F, Hu J, Li J, Wu X, Qian Y (2009) Chitosan enhances leaf membrane stability and antioxidant enzyme activities in apple seedlings under drought stress. Plant Growth Regul 58:131–136. https://doi.org/10.1007/s10725-009-9361-4

Ayman M.S. Elshamly works as Research at the Water Studies and Research Complex. National Water Research Center, Cairo, Egypt. my fields of interest are irrigation systems, water management and evapotranspiration, for improving yield and tolerance of crops to abiotic constraints.