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Bulletin of the National Research Centre (2022) 46:248
https://doi.org/10.1186/s42269-022-00934-6

Bulletin of the National Research Centre

RESEARCH

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Beneficial effects of antitranspirants on water stress tolerance in maize under different plant densities in newly reclaimed land

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Abstract

Background: The global freshwater shortage is an important issue threatening the sustainable development of agriculture and food security. A field study was conducted in two seasons, i.e., 2019 and 2020, in the newly reclaimed land at Village 8, El-Minia Governorate, Egypt, to evaluate maize crop response to three irrigation levels ($IL_1 = 80$, $IL_2 = 70$, and $IL_3 = 60$% of the crop evapotranspiration "ETc"), three plant densities ($PD_1 = 17.500$, $PD_2 = 23.333$, and $PD_3 = 35.000$ plants fed^{-1}), and three antitranspirants treatments (An_1 = control, An_2 = kaolin at 6%, and An_3 = chitosan at 150 L fed^{-1}). The experiment was designed as a randomized complete block design (RCBD) using a split plot in strips.

Results: Results revealed that the irrigated maize plants with IL_1 (80% of ETc) recorded the maximum values for all traits such as vegetative growth, phenology, and yield and its attributes in both seasons. The heaviest value of grain yield (3.15 and 3.10 tonnes fed^{-1}, where 1 feddan = 0.42 hectare) was realized from IL_1 treatment in the 1st and 2nd seasons, respectively. Plant density of 35.000 plants fed^{-1} (PD_3) produced the greatest values of leaf area index (6.70 and 6.85), more days to 50% for each of tasseling (62.16 and 61.99 days), and silking (63.63 and 63.73 days), heaviest grain yield (3.11 and 3.16 ton fed^{-1}) and greater water use efficiency WUE (1.46 and 1.48 kg m^{-3}) in both seasons, respectively.

Conclusions: Foliar spraying with antitranspirants, i.e., kaolin at 6%, led to a tremendous impact on all studied traits by alleviating the water stress and reducing the rate of transpiration. The effect of second-order interaction among $IL_1 \times PD_3 \times An_3$ indicated a significant increase in grain yield by 69.91% as compared with the interaction of $IL_3 \times PD_1 \times An_1$ in the 2020 season only. CS 10 single-cross maize realized the highest productivity and most efficient use of available resources via using a sowing density of 35.000 plant fed^{-1}, foliar spraying with kaolin at 6%, and irrigation level (80% of ETc) under El-Minia conditions.

Keywords: Maize, Irrigation levels, Plant densities, Antitranspirants, Growth, Penology, Yield, WUE

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Background

Realizing the optimal balance between maize yield and water use efficiency is an important challenge for irrigation maize production in arid areas, to relieve the contradiction between food desire and water availability. Globally, maize (*Zea mays* L.) is the top-ranking cereal crop in high productivity, especially in temperate and subtropical regions due to carbon pathway (C4), and it is a major source for feeding humans and animals, manufacturing industrial products, superior transpiration efficiency, and is widely adapted to climate change. Therefore, maize is responsive to the amount of irrigation water applied, positive when irrigation is enough and negative when not (Usama 2019) because corn is highly sensitive to amendments in irrigation scheduling and water stress during the critical stages, hindering grain production substantially (Halli et al. 2021).

Water resources in Egypt are limited, which delimits crop production in the newly reclaimed lands because of the dense agricultural production in the Nile Delta and valley area. Water stress is a critical problem that severely threatens the growth and productivity of agricultural crops worldwide because of its impact on morphological and physiological processes (inhibits the photosynthesis of plants), which is grave for arable field crops and later for food security (Shemi et al. 2021). Research has revealed that they can mitigate drought stress, resulting in increased grain yield (Mphande et al. 2020). Eissa et al. (2017) indicated that maize irrigated by 75% of water requirements had a higher grain yield by 5 and 10% in the 1st and 2nd seasons, respectively, than that received 100%. Saad-Allah et al. (2022) recorded that water stress significantly reduced leaf area, biomass, and yield characteristics. With irrigation levels decreased, the grain yield of maize decreased, the WUE increased, and a water deficit at the tasseling stage had the greatest effect on the yield and WUE (Huang et al. 2022). Also, Lubajo and Karuku (2022) showed that the increased amount of irrigation water increased the growth and yield of maize, while reduced irrigation increased WUE.

Optimization of plant density is the major strategy for increasing yield till an optimum number of plants per unit area is attained (Djaman et al. 2022), and it is one of the basic techniques to increase maize yield potential (Yang et al. 2022 and Zhai et al. 2022). Low plant density leads to reduced maize grain yield, while high density causes stress on the plants (Ajayo et al. 2021). High-density plants heighten intraspecific competition among the plants. The efficient transformation of intercepted solar radiation to the grain may be limited by apical dominance, exposing the plant to shading, which led to a reduction in leaf development, leaf area index, leaf photosynthesis, and grain yield (Djaman et al. 2022). Numerous studies have shown that the evapotranspiration differences among different densities of plants might return to the leaf area index differences (Mian et al. 2021). Increasing plant density from 47,600 to 71,400, 95,200, and 119,000 plants ha^{-1} caused a significant reduction in 100-kernel weight, stem diameter, and ear leaf area, but caused a significant increase in grain yield ha^{-1}, leaf area index, days to anthesis, and days to silking (AL-Naggar et al. 2021).

The corresponding increase in water use efficiency and availability could be achieved by the introduction of improved irrigation systems, reducing runoff, soil evaporation, and plant transpiration, using antitranspirants, and changes in cropping patterns toward crops that use less water and soil conditions. The addition of antitranspirants by spraying onto the leaves of plants reduces the rate of transpiration through the plant stomata, conserves irrigation water, and also reduces disease and insect pest incidences, consequently resulting in greater food production by realizing more of a crop's potential yield during drought. Although antitranspirants improved the water status of plants by reducing the rate of transpiration, they also reduced the intake of CO_2 and hence the rate of photosynthesis (Kettlewell et al. 2010). Chitosan is the biotic factor derived from chitin, a slightly toxic compound and eco-friendly that can elicit a positive response in crops. Chitosan contributes to improving yield and chlorophyll content, as well as some plant growth parameters, and also induces excellent resistance to drought, salt, and low-temperature stress and reduces their negative impact on cereals (Kocięcka and Liberacki 2021). Kaolin is non-toxic and eco-friendly and is used as a natural antitranspirants. The application of kaolin led to an increase in growth traits, yield, and its components, as well as mitigated the negative influences of water deficiency in wheat (Abdallah et al. 2019), has a reverse impact on leaf temperature if the target plant is not under drought stress (Mphande et al. 2020).

Thus, the present study is an attempt to determine maize productivity under water stress, and optimum plant densities using some antitranspirants to reduce water losses by reducing the extent of transpiration in newly reclaimed soil under El-Minia conditions as well as develop an equation to express maize productivity under the experimental conditions.

Methods

Experimental site description

A field study was conducted for 2019 and 2020 growing seasons in the newly reclaimed land at Village 8, El-Minia Governorate, Egypt, which is located at an altitude of 40 m above mean sea level and is intersected by 28°28 N latitude and 30°58 E longitude. Meteorological data were obtained from the Center Laboratory for Agricultural Climate (CLAC), Agricultural Research Center, Egypt, allocated for the experimental site during the two seasons of growth presented in Table 1. The soil was sandy loam in texture, with pH 8.1, EC 2.03 ds m^{-1}, organic matter 0.20% and available N 1.8, available P 3.0, and available K 33.1 mg kg^{-1} as an average of both seasons.

Table 1 Climate data and reference evapotranspiration (ETo) (as an average 2019 and 2020 seasons under El-Minia conditions)

Months	Temperature °C		WS (m s^{-1})	RH (%)	Sunshine (h)	ETo (mm day^{-1})
	Max	Min				
May	36.29	18.88	3.45	23.88	13.55	9.74
June	38.46	22.21	3.73	26.35	13.91	10.80
July	38.85	23.27	3.65	28.87	13.74	10.66
August	38.82	23.50	3.27	30.23	13.12	9.72
September	37.07	21.97	3.63	36.35	12.32	8.77
October	33.63	19.00	3.02	40.73	11.48	6.43

Experimental details

The treatments were laid in a randomized complete block design (RCBD) using a strip-split plot arrangement with three replicates which were used in this study, as follows:

- Vertical plots: irrigation regime at three levels (I_1: 80, I_2: 70, and I_3: 60% of ETc). The amount of irrigation water applied was 2445, 2139, and 1834 m^3 fed^{-1} for 80, 70, and 60% of the crop evapotranspiration, respectively.
- Horizontal plots: plant densities, *i.e.*, D_1: 17.500, D_2: 23.333, and D_3: 35.000 plants fed^{-1}, could be achieved by planting maize in hills on one side of the ridge, and the distances between hills were 40, 30, and 20 cm, respectively, to the distribution plant densities previously mentioned.
- Subplots: foliar application with antitranspirants {An_1: control (water spray), An_2: kaolin (Al4Si4O10 $(OH)_8$ at 6% (as a reflected agent), and An_3: chitosan 150 mg L^{-1} (as a metabolic agent)} was done sprayed two times at 35 and 70 days from planting.

Each subplot consisted of 5 ridges 3.5 m in length and 60 cm in width. (Plot area was 10.5 m^2.) The experimental unit included five lateral drip lines with a length of 3.5 m and a width of 60 cm between each two dripper lines that had a flow rate of 2.1 L h^{-1} at an operating pressure of 1.2 bar.

Agricultural applications

Maize grains (Single-Cross 10 Hybrid) were manually sown on May 29, 2019, and June 1, 2020. The preceding winter crop in the two seasons was faba bean. Organic manure was added at a rate of 20 m^3 fed^{-1} during the preparation of soil for cultivation. Nitrogen fertilizer was added at a rate of 360 kg fed^{-1} form of ammonium nitrate (NH_4NO_3-33.5% N) with irrigation water at 5 equal doses applied weekly, starting after 15 days of planting. Phosphorus fertilizer was applied directly to the soil in one dose before planting at a rate of 150 kg fed^{-1} as calcium super-phosphate (15.5% P_2O_5), while potassium fertilizer was added at a rate of 50 kg fed^{-1} as potassium sulfate (48% K_2O) with irrigation water in 2 equal doses after 35 and 50 days of sowing. All other agricultural practices, including weed, pest, and disease control and fertilizers applications, were executed uniformly and simultaneously for all treatments, according to the standard recommendations for planting maize in this region.

Parameter assessments

Growth parameters

At 80 days from planting (DFP), ten plants were randomly selected from each plot to measure:

- Number of green leaves $plant^{-1}$.
- The leaf area index (LAI) was estimated as described by Stickler (1964) using the following equation: LAI = Leaf area $plant^{-1}$ ÷ Land area $plant^{-1}$.

  $$\text{Leaf area} = L \times W \times 0.75$$

  where L is the leave length, W is the leave width, and 0.75 is the correction factor.

Phenological parameters

The phenology of maize was observed during the growing period of the crop and estimated from the whole plants in the three center ridges as:

- Days to tasseling were determined as the number of (DFP) to 50% tasseling.
- Days to silking were determined as the number of days (DFP) to 50% silking.

Yield and some traits of the plant

At physiological maturity, 10 plants were taken at random from the middle ridges of each plot to determine ear diameter (cm), 100-grain weight (g), and grain weight ear^{-1}.

Maize hand harvesting was carried out about 120 days after planting by cutting the aboveground biomass and leaving it for further drying before removing the ears from the stems. Then, the ears were shelled and the grains were weighed and adjusted to the water content of 15.5% to obtain the grain yield (GY) in kg fed^{-1}. The drought depression (DD) and relative yield reduction (RYR %) based on grain yield (ton fed^{-1}) for normal (Yn) and drought stress (Ys) conditions were calculated using the equations as follows:

- Relative yield reduction (RYR %) $= 1 - (Y_{stress}/Y_{normal}) \times 100$ (Golestani and Assad 1998).
- Drought depression (DD) $= Y_{normal} - Y_{stress}$ (Hossain et al. 1990).

Calculation of irrigation water applied

Maize plants were given 28 irrigations with 3 days interval; starting after 24 days from planting, each treatment was irrigated according to prescribed irrigation scheduling treatments. In both seasons, the amount of water needed for each irrigation was calculated according to the crop coefficient (Kc) and the daily reference potential evapotranspiration (ET_o) was determined according to the Penman–Monteith modified equation (Allen et al. 1998) depending mainly upon the predicted climatic factors at each irrigation time and the growth stage of a maize plant. The actual evapotranspiration (ET_c) and the irrigation requirements water were calculated according to the equations:

$$ET_o = E_{pan} \times K_{pan}$$

$$ET_c = ET_o \times K_c$$

$$IR = ET_c + LR \times 4.2/E_i$$

where ET_c is the evapotranspiration of crop (mm day^{-1}), ET_o: reference evapotranspiration (mm day^{-1}), E_{pan}: Pan evaporation (mm day^{-1}), and K_{pan}: Pan coefficient.

K_c is the calculated crop coefficient values at the experimental site, IR: irrigation requirement for the crop (m^3 fed^{-1} days^{-1}), LR: leaching requirement (%), and Ei: efficiency of irrigation application of the drip irrigation system.

The application efficiency of drip irrigation system Ea = 85%, and leaching fraction=10% of water requirement.

Water use efficiency (WUE) in kg m^{-3}: It was calculated as:

$$WUE = \text{Grain yield}\left(\text{kg fed}^{-1}\right)/\text{water applied}\left(\text{m}^3\ \text{fed}^{-1}\right) \text{ (Kanber et al.1993)}$$

Statistical analysis

All data were subjected to analysis of variance according to Gomez and Gomez (1984) by the MSTAT-C Computer program. Comparison between treatments means was done by least significant difference (LSD) procedures at 5% level of probability. A statistical model has been developed to express the relationship between the amount of applied water and grain yield under the experimental conditions, and a regression analysis was performed, obtaining the adjusted equation, using Curve Expert.

Results

Number of leaves plant.$^{-1}$ and leaf area index (LAI)

The number of leaves plant^{-1} and LAI are important traits for plant growth and development. The data in Tables 2 and 3 showed that irrigation levels, plant densities, antitranspirants, and their interactions had a significant influence on the number of leaves per plant and LAI of maize in both seasons.

The irrigation of drip-irrigated plants at 80% of ETc (IL_1) was significantly surpassed the IL_2 and IL_3 which recorded the best values of the number of leaves plant^{-1} and LAI in the two growing seasons (16.21 and 17.28 leaves) and (6.96 and 7.01), respectively, followed by IL_2, while 60% of ETc (IL_3) produced the lowest values in both seasons.

Regarding the effect of plant densities (PD), Table 2 shows that the greatest values of the number of leaves plant^{-1} (15.37 and 16.31 leaves in the 1st and 2nd seasons, respectively) were obtained from planting 17.500 maize plants fed^{-1} (PD_1). The lowest values of the number of leaves plant^{-1} were recorded under a high level of plant density of 35.000 plants fed^{-1} (PD_3).

Planting with 35.000 plants fed^{-1} recorded the highest values of LAI of 6.70 and 6.85 in the 1st and 2nd seasons, respectively (Table 3). The lowest values of LAI (5.63 and 5.76) resulted from plant densities of 17.500 plants fed^{-1} in both seasons, respectively. When compared to a low plant density of 17.500 plants fed^{-1} (PD_1), an elevated plant density of 23.333 (PD_2) and 35.000 (PD_3) plants fed^{-1} caused a significant increase in LAI of 9.59 and 19.01% in 2019 and LAI of 9.55 and 18.92% in 2020. Our results were supported by Sibonginkosi et al., (2019); Sidi et al. (2019); Djaman et al. (2022), and Yang et al. (2022). Concerning the impact of antitranspirants (An), data in Tables 2 and 3 revealed that the foliar application of

Table 2 Effects of irrigation levels, plant densities, antitranspirants, and their interaction on number of leaves plant^{-1} of maize during 2019 and 2020 seasons

Treatments		Antitranspirants (An)			Mean of IL × PD	Antitranspirants (An)			Mean of IL × PD
Irrigation levels (IL)	Plant densities (PD)	An_1: control	An_2: chitosan	An_3: kaolin		An_1: control	An_2: chitosan	An_3: kaolin	
		2019 season				2020 season			
IL_1: 80%	PD_1:17.500	15.13	17.07	18.17	16.79	15.66	18.97	19.15	17.93
	PD_2:23.333	14.70	17.00	17.65	16.45	15.24	18.23	18.46	17.31
	PD_3:35.000	14.11	16.00	16.06	15.39	15.04	17.26	17.48	16.60
Mean of IL_1		14.65	16.69	17.29	16.21	15.31	18.15	18.37	17.28
IL_2: 70%	PD_1:17.500	14.31	15.93	16.06	15.43	14.99	17.40	17.40	16.60
	PD_2:23.333	13.46	15.41	16.00	14.96	14.20	16.22	16.45	15.62
	PD_3:35.000	13.13	15.05	15.63	14.60	13.40	16.02	16.10	15.17
Mean of IL_2		13.63	15.46	15.90	15.00	14.19	16.55	16.65	15.80
IL_3: 60%	PD_1:17.500	13.11	14.17	14.35	13.88	13.16	15.00	15.08	14.41
	PD_2:23.333	13.00	13.33	13.77	13.37	13.10	14.55	14.65	14.10
	PD_3:35.000	12.86	13.14	13.38	13.12	12.86	14.03	14.12	13.67
Mean of IL_3		12.99	13.54	13.83	13.45	13.04	14.53	14.62	14.06
Mean of (PD × An)	PD_1:17.500	14.19	15.73	16.19	15.37	14.60	17.13	17.21	16.31
	PD_2:23.333	13.72	15.25	15.81	14.93	14.18	16.33	16.52	15.68
	PD_3:35.000	13.37	14.73	15.02	14.37	13.77	15.77	15.90	15.15
Mean of An		13.76	15.23	15.67	–	14.18	16.41	16.54	–
$LSD_{0.05}$		IL: 0.13		PD: 0.08		IL: 0.04		PD: 0.06	
		An: 0.11		IL × PD: 0.09		An: 0.07		IL × PD: 0.08	
		IL × An: 0.19		PD × An: 0.19		IL × An: 0.12		PD × An: 0.12	
		IL × PD × An: 0.33				IL × PD × An: 0.21			

kaolin and chitosan improved the number of leaves and LAI of maize compared with corresponding untreated plants in both seasons. The data revealed that chitosan (An_2) and kaolin (An_3) increased the number of leaves plant^{-1} by 10.68 and 13.88% and LAI by 10.68 and 13.31% in 2019, and number of leaves plant^{-1} by 15.73 and 16.64% and LAI by 12.26 and 14.34% in 2020, respectively, as compared to the values of control (An_1). The maximum increase in the three traits in order was kaolin ˃ chitosan ˃ untreated plants, in both seasons.

With respect to the effect of the interaction, results in Tables 2 and 3 show that the number of leaves plant^{-1} and LAI are affected significantly by all interactions in both seasons. The obtained results in Tables 2 and 3 revealed that the first-order interaction IL1 × PD1 gave the maximum number of leaves plant^{-1} values (16.79 and 17.93 leaves) in the two seasons, respectively. On the other hand, the greatest LAI values (7.88 and 7.95) were recorded from $IL_1 \times PD_3$, respectively, in both seasons. The interaction of $IL_1 \times An_3$ produced the highest values for the number of leaves plant^{-1} (17.29 and 17.28 leaves) and for LAI (7.14 and 7.21) in the 1st and 2nd seasons, respectively. As for the first-order interaction (PD × An), the data in Tables 2 and 3 clear that the maximum number of leaves plant^{-1} (16.19 and 17.21 leaves) was obtained by $PD_1 \times An_3$ and LAI (6.99 and 7.18) was recorded by $PD_3 \times An_3$ in the 2019 and 2020 seasons, respectively.

The results of second-order interaction (IL × PD × An) revealed that the greatest number of leaves (18.17 and 19.15 leaves) was obtained by $IL_1 \times PD_1 \times An_3$ and the maximum LAI (7.17 and 8.27) was recorded by $IL_1 \times PD_3 \times An_3$ in 1st and 2nd seasons, respectively.

Number of days from planting to 50% tasselling and 50% silking:

The 50% of tasselling and 50% of silking were significantly affected by irrigation levels, plant density, antitranspirants, and their interaction in both seasons, except PD × An and IL × PD × An in the 2nd season only (Tables 4 and 5). The crop took 59.40 and 59.55 days to appear at 50% of tasseling with third irrigation level (IL_3, 60%) to 63.00 and 62.73 days with the first irrigation level (IL_1, 80%) in 2019 and 2020 seasons, respectively. Likewise, days taken to reach 50% of silking under IL_3 irrigation

Table 3 Effects of irrigation levels, plant densities, antitranspirants, and their interaction on LAI of maize during 2019 and 2020 seasons

Treatments		Antitransspirants (An)			Mean of IL × PD	Antitransspirants (An)			Mean of IL × PD
Irrigation levels (IL)	Plant densities (PD)	An_1: control	An_2: chitosan	An_3: kaolin		An_1: control	An_2: chitosan	An_3: kaolin	
		2019 season				2020 season			
IL_1: 80%	PD_1:17.500	6.02	6.10	6.14	6.09	6.03	6.13	6.19	6.12
	PD_2:23.333	6.55	7.06	7.11	6.91	6.60	7.13	7.18	6.97
	PD_3:35.000	7.39	8.07	8.17	7.88	7.47	8.12	8.27	7.95
Mean of IL_1		6.65	7.08	7.14	6.96	6.70	7.13	7.21	7.01
IL_2: 70%	PD_1:17.500	5.72	6.01	6.03	5.92	5.86	6.08	6.12	6.02
	PD_2:23.333	6.12	6.56	6.98	6.56	6.19	7.01	7.05	6.75
	PD_3:35.000	6.16	7.08	7.12	6.79	6.28	7.17	7.23	6.89
Mean of IL_2		6.00	6.55	6.71	6.42	6.11	6.75	6.80	6.56
IL_3: 60%	PD_1:17.500	4.14	5.17	5.36	4.89	4.36	5.44	5.58	5.13
	PD_2:23.333	4.19	5.27	5.66	5.04	4.20	5.50	5.90	5.20
	PD_3:35.000	5.09	5.53	5.68	5.43	5.15	5.88	6.06	5.70
Mean of IL_3		4.47	5.32	5.57	5.12	4.57	5.61	5.85	5.34
Mean of (PD × An)	PD_1:17.500	5.30	5.76	5.84	5.63	5.42	5.89	5.97	5.76
	PD_2:23.333	5.62	6.30	6.58	6.17	5.66	6.54	6.71	6.31
	PD_3:35.000	6.21	6.89	6.99	6.70	6.30	7.06	7.18	6.85
Mean of An		5.71	6.32	6.47	-	5.79	6.50	6.62	–
$LSD_{0.05}$		IL: 0.08		PD: 0.05		IL: 0.05		PD: 0.05	
		An: 0.05		IL × PD: 0.05		An: 0.04		IL × PD: 0.05	
		IL × An: 0.08		PD × An: 0.08		IL × An: 0.07		PD × An: 0.07	
		IL × PD × An: 0.15				IL × PD × An: 0.11			

level were early by 3.30 and 3.31 over IL_1 in both seasons. The increase in the 2019 and 2020 seasons amounted to (6.06 and 5.34%) for 50% tasseling, and (5.35 and 5.36%) for 50% silking, respectively, under irrigation level 80% IL_1 and was high compared to 70% IL_3. Shah et al. (2018) pointed out that optimum irrigation enhanced days to tasseling and silking compared with reduced irrigation.

In respect of plant density (PD), the 35.000 plants fed^{-1} took more days to 50% tasseling (62.16 and 61.99 days) and 50% silking (63.63 and 63.73 days), in the 2019 and 2020 seasons, respectively. Otherwise, the minimum days for both traits were obtained for a lower plant density of 27.500 plants fed^{-1} in both seasons.

Regarding the effect of foliar spraying of antitranspirants, two phenology stages were significantly increased in response to spraying all foliar applications as follows: kaolin > chitosan > untreated plants in both seasons (Tables 4 and 5). When spraying maize plants by kaolin led to delayed days till 50% of tasseling of 61.45 and 61.42 days and delayed days till 50% of silking of 63.43 and 63.47 days, followed by chitosan in 2019 and 2020 seasons, respectively. The untreated plants took fewer days to attain 50% tasseling and 50% silking in both seasons.

Concerning the effect of interaction, Tables 4 and 5 show that the most significant values of the number of days till 50% of tasseling (64.95 and 64.19 days) and 50% of silking (66.10 and 66.26 days) were obtained by $IL_1 \times PD_3$. Moreover, the maximum values of days to 50% of tasseling (63.22 and 62.73 days) and 50% of silking (65.26 and 66.65 days) were recorded with $IL_1 \times An_3$ in the two seasons, respectively. The interaction between ($PD_3 \times An_3$) resulted in a delay in the number of days to take till 50% of tasseling (62.28 days) in the 2nd season only and silking (63.94 and 64.05 days) in the 1st and 2nd seasons, respectively. As for the second-order interaction ($IL_3 \times PD_1 \times An_1$), it produced the earliness of days till 50% of tasseling (58.62 days) in the 2nd season only and also the earliness of days to 50% of silking (61.00 and 61.06 days) in both seasons, respectively.

Ear diameter, 100-grain weight, and grain weight ear^{-1}:

Analysis of variance in both seasons indicated that ear diameter, 100-grain weight, and grain weight ear^{-1} traits were significantly influenced by irrigation levels, as shown in Tables (6, 7, and 8). Applied water with 80% of ETc (IL_1) significantly increased ear diameter (12.00 and 11.63%), 100-grain weight (34.07 and 33.95%), and grain

Table 4 Effects of irrigation levels, plant densities, antitranspirants, and their interaction on days to tasseling of maize during 2019 and 2020 seasons

Treatments		Antitranspirants (An)			Mean of IL × PD	Antitranspirants (An)			Mean of IL × PD
Irrigation levels (IL)	Plant densities (PD)	An_1: control	An_2: chitosan	An_3: kaolin		An_1: control	An_2: chitosan	An_3: kaolin	
		2019 season				2020 season			
IL_1: 80%	PD_1:17.500	60.78	61.40	61.38	61.19	60.80	61.42	61.41	61.21
	PD_2:23.333	62.50	63.48	63.21	63.07	62.53	62.89	62.93	62.78
	PD_3:35.000	64.04	65.07	65.05	64.75	63.42	64.56	64.58	64.19
Mean of IL_1		62.44	63.33	63.22	63.00	62.25	62.95	62.98	62.73
IL_2: 70%	PD_1:17.500	59.62	60.82	60.86	60.43	59.75	60.93	60.92	60.53
	PD_2:23.333	60.26	61.86	61.76	61.29	60.35	61.83	61.83	61.33
	PD_3:35.000	60.76	61.94	61.95	61.55	60.78	61.93	61.94	61.55
Mean of IL_2		60.21	61.54	61.52	61.09	60.29	61.56	61.56	61.14
IL_3: 60%	PD_1:17.500	58.53	58.41	59.04	58.66	58.62	59.12	59.13	58.95
	PD_2:23.333	58.98	59.53	59.52	59.34	59.01	59.66	59.68	59.45
	PD_3:35.000	60.04	60.29	60.26	60.20	60.09	60.32	60.33	60.25
Mean of IL_3		59.18	59.41	59.60	59.40	59.24	59.70	59.71	59.55
Mean of (PD × An)	PD_1:17.500	59.64	60.21	60.43	60.09	59.72	60.49	60.49	60.23
	PD_2:23.333	60.58	61.62	61.50	61.23	60.63	61.46	61.48	61.19
	PD_3:35.000	61.62	62.45	62.43	62.16	61.43	62.27	62.28	61.99
Mean of An		60.61	61.43	61.45	-	60.59	61.40	61.42	-
$LSD_{0.05}$		IL: 0.13		PD: 0.13		IL: 0.04		PD: 0.02	
		An: 0.17		IL × PD: 0.20		An: 0.02		IL × PD: 0.04	
		IL × An: 0.29		PD × An: NS		IL × An: 0.03		PD × An: 0.03	
		IL × PD × An: NS				IL × PD × An: 0.05			

weight ear^{-1} (11.03 and 11.79%) as compared to plots irrigated with 60% of ETc (IL_3) in the 1st and 2nd seasons, respectively.

The data in Tables 6, 7, and 8 revealed that the differences between the studied three plant densities, *i.e.*, 17.500, 23.333, and 35.000 maize plants fed^{-1}, were significant in ear diameter, 100-grain weight, and grain weight ear^{-1} in both seasons. Data revealed that planting 17.500 maize plants fed^{-1} (PD_1) increased ear diameter by 9.36 and 8.76%, 100-grain weight by 11.79 and 11.40%, and grain weight ear^{-1} by 6.16 and 6.01%, compared with planting 35.000 maize plants fed^{-1} (PD_3) in the 2019 and 2020 seasons, respectively. Temesgen (2019) indicated that ear diameter increases as density sowing decreases. This could be because of relatively less competition for water, nutrients, and light in low plant density.

In connection with the effect of foliar spraying of antitranspirants, the results illustrated that ear diameter, 100-grain weight, and grain weight ear^{-1} were significantly increased in response to a foliar application of kaolin and chitosan in both seasons. The maximum increase in the aforementioned traits was recorded by using kaolin at 6% as compared to the control treatment. The ratio of increases was 9.48 and 9.68% in ear diameter, 9.27 and 10.15% for 100-grain weight, and 3.29 and 3.42% for grain weight ear^{-1} as compared with the control treatment (An_1), in 1st and 2nd seasons, respectively. Generally, the sequence of foliar antitranspirants treatments in descending order was An_3 (kaolin 6%) > An_2 (chitosan 150 mg L^{-1}) > An_1 (control).

The effect of 1st and 2nd order interactions on these traits was significant, except the interactions among IL × PD which were not significant on 100-grain weight in the 2nd season, IL × An on 100-grain weight in the 1st season; PD × An on grain weight ear^{-1} in both seasons, and ear diameter in 2019 only, as presented in Tables (6, 7 and 8). The maximum values of ear diameter (4.72 and 4.76 cm), grain weight ear^{-1} (162.72 and 163.49 g) in the two seasons, respectively, and 100-grain weight (34.98 g) in 2019 were gained from $IL_1 \times PD_1$, whereas the lowest values of these traits were obtained from $IL_3 \times PD_3$ in both seasons. The interaction among $IL_1 \times An_3$ on the aforementioned traits produced the highest mean values in both seasons. The interaction ($PD_1 \times An_3$) gave the highest averages of ear diameter (4.62 cm) in the 2nd season and 100-grain weight (32.53 and 34.19 g) for the 1st and 2nd seasons, respectively, whereas the interaction between $PD_3 \times An_1$ produced the lowest averages

Table 5 Effects of irrigation levels, plant densities, antitranspirants, and their interaction on days to silking of maize during 2019 and 2020 seasons

Treatments		Antitranspirants (An)			Mean of IL × PD	Antitranspirants (An)			Mean of IL × PD
Irrigation levels (IL)	Plant densities (PD)	An_1: control	An_2: chitosan	An_3: kaolin		An_1: control	An_2: chitosan	An_3: kaolin	
		2019 season				2020 season			
IL_1: 80%	PD_1:17.500	63.86	63.98	64.11	63.98	63.92	63.97	64.04	63.97
	PD_2:23.333	64.03	65.13	65.19	64.78	64.11	65.18	65.20	64.83
	PD_3:35.000	65.40	66.43	66.46	66.10	65.52	66.61	66.65	66.26
Mean of IL_1		64.43	65.18	65.26	64.95	64.52	65.25	65.29	65.02
IL_2: 70%	PD_1:17.500	61.90	62.94	62.91	62.58	61.94	62.97	62.98	62.63
	PD_2:23.333	62.05	63.49	63.58	63.04	62.06	63.55	63.60	63.07
	PD_3:35.000	62.14	63.01	63.05	62.73	62.15	63.08	63.09	62.78
Mean of IL_2		62.03	63.14	63.18	62.78	62.05	63.20	63.23	62.83
IL_3: 60%	PD_1:17.500	61.00	61.10	61.14	61.08	61.06	61.17	61.15	61.12
	PD_2:23.333	61.33	62.05	62.07	61.82	61.37	62.09	62.10	61.85
	PD_3:35.000	61.56	62.28	62.32	62.05	61.65	62.36	62.40	62.14
Mean of IL_3		61.30	61.81	61.84	61.65	61.36	61.87	61.88	61.71
Mean of (PD × An)	PD_1:17.500	62.25	62.67	62.72	62.55	62.30	62.70	62.72	62.58
	PD_2:23.333	62.47	64.56	63.61	63.21	62.51	63.61	63.63	63.25
	PD_3:35.000	63.03	63.91	63.94	63.63	63.11	64.02	64.05	63.73
Mean of An		62.59	63.38	63.43	–	62.64	63.44	63.47	–
$LSD_{0.05}$		IL: 0.05		PD: 0.04		IL: 0.02		PD: 0.01	
		An: 0.03		IL × PD: 0.05		An: 0.02		IL × PD: 0.04	
		IL × PA: 0.06		PD × An: 06		IL × PA: 0.02		PD × An: 0.02	
		IL × PD × An: 0.11				IL × PD × An: 0.05			

(3.87 cm) for ear diameter in the 2020 season and 100-grain weight (26.40 and 27.88 g) in the two seasons, respectively.

The 2nd interaction effect of $IL_1 \times PD_1 \times An_3$ pointed out the significant increase of ear diameter by 43.35 and 40.68%, 100-grain weight by 66.15 and 71.38%, and grain weight ear^{-1} by 22.21 and 22.94% in the 1st and 2nd seasons, respectively, as compared to $IL_3 \times PD_3 \times An_1$.

Grain yield, drought depression (DD), and relative yield reduction (RYR %)

Grain yield

At harvest, irrigation levels showed a significant effect on grain yield in both seasons (Table 9). Increasing the irrigation level to $IL_1 = 80\%$ ETc resulted in a significant increase in the grain yield by 25.00 and 21.09% in the 1st and 2nd seasons, respectively, compared to $IL_3 = 60\%$ ETc. The irrigation level at 60% ETc (IL_3) resulted in the lowest grain yield due to insufficient soil moisture supply.

In the case of planting densities, data revealed that plant densities had a significant effect on the grain yield of maize in both seasons (Table 9). Plant density of 35,000 plants fed^{-1} (PD_3) produced the highest grain yield (3.11 and 3.16 ton fed^{-1}) as compared to a lower plant density of 17.500 plants fed^{-1} PD_1 for grain yield (2.68 and 2.61 ton fed^{-1}) in the 1st and 2nd seasons, respectively.

Table 9 shows that the foliar application of antitranspirants, *i.e.*, kaolin and chitosan, had a significant increase in grain yield of maize as compared to control (untreated plant) in both seasons. Sprayed maize plants with kaolin at 6% (An_3) produced the heaviest grain yield compared with chitosan 150 mg L^{-1} (An_2) and untreated plants (An_1) in both seasons. Foliar antitranspirants treatments could be arranged in the following descending order: An3 > An2 > An_1.

Significant effects of all interactions were recorded on grain yield in both seasons, while the interaction of IL × PD × An in the 1st season was insignificant. In regard to the interaction between IL × PD on grain yield, Table 9 illustrates that the highest values for grain yield (3.39 and 3.49 ton fed^{-1}) were gained from $IL_1 \times PD_3$ during the 2019 and 2020 seasons, respectively. As for the interaction between IL × An, the data reveal that the plants irrigated with applied water equal to 80% of ETc (IL_1) and sprayed with 6% of kaolin (An_3) recorded the

Table 6 Effects of irrigation levels, plant densities, antitranspirants, and their interaction on ear diameter (cm) of maize during 2019 and 2020 seasons

Treatments		Antitranspirants (An)			Mean of IL × PD	Antitranspirants (An)			Mean of IL × PD
Irrigation levels (IL)	Plant densities (PD)	An_1: control	An_2: chitosan	An_3: kaolin		An_1: control	An_2: chitosan	An_3: kaolin	
		2019 season				2020 season			
IL_1: 80%	PD_1:17.500	4.29	4.92	4.96	4.72	4.34	4.95	4.98	4.76
	PD_2:23.333	4.05	4.62	4.68	4.45	4.09	4.66	4.71	4.49
	PD_3:35.000	4.04	4.35	4.40	4.26	4.05	4.41	4.44	4.30
Mean of IL_1		4.13	4.63	4.68	4.48	4.16	4.67	4.71	4.51
IL_2: 70%	PD_1:17.500	4.17	4.53	4.58	4.43	4.19	4.57	4.60	4.45
	PD_2:23.333	4.11	4.31	4.33	4.25	4.14	4.36	4.39	4.30
	PD_3:35.000	4.01	4.15	4.19	4.12	4.03	4.19	4.21	4.14
Mean of IL_2		4.10	4.33	4.37	4.27	4.12	4.37	4.40	4.30
IL_3: 60%	PD_1:17.500	4.01	4.22	4.27	4.17	4.01	4.26	4.28	4.18
	PD_2:23.333	3.90	4.10	4.10	4.03	3.93	4.13	4.15	4.07
	PD_3:35.000	3.46	3.93	4.00	3.80	3.54	4.04	4.05	3.88
Mean of IL_3		3.79	4.08	4.12	4.00	3.82	4.15	4.16	4.04
Mean of (PD × An)	PD_1:17.500	4.16	4.56	4.60	4.44	4.18	4.59	4.62	4.47
	PD_2:23.333	4.02	4.34	4.37	4.24	4.05	4.38	4.41	4.28
	PD_3:35.000	3.84	4.14	4.20	4.06	3.87	4.21	4.23	4.11
Mean of An		4.01	4.35	4.39	-	4.03	4.40	4.42	-
$LSD_{0.05}$		IL: 0.03		PD: 0.10		IL: 0.02		PD: 0.04	
		An: 0.03		IL × PD: 0.01		An: 0.005		IL × PD: 0.01	
		IL × An: 0.04		PD × An: NS		IL × An: 0.01		PD × An:0. 01	
		IL × PD × An: 0.08				IL × PD × An: 0.02			

highest mean values of grain yield in both seasons. On the other hand, the plants watered with 60% of ETc (IL_3) and unsprayed with antitranspirants (An_1) gave the lowest grain yield values in both seasons. The interaction of $PD_3 \times An_3$ gained an increased grain yield of 34.95 and 41.53% in the 1st and 2nd seasons, respectively, compared to the interaction of $PD_1 \times An_1$ (Table 7). As for the 2nd order interaction effect, i.e., $IL_1 \times PD_3 \times An_3$ indicated a significant increase in grain yield (69.91%) during the second season only as compared with $IL_3 \times PD_1 \times An_1$.

Drought depression (DD) and relative yield reduction (RYR %)

The DD and RYR% increased with decreasing irrigation levels from 70 to 60% of ETc in the average of the two seasons (Table 9). Increasing the irrigation deficit from IL_2 to IL_3 increased the values of DD from 0.15 to 0.59, and RYR% from 4.55 to 18.59% (as an average of both seasons). This means that a high depression in grain yield was recorded when exposed plants to water-deficit levels, i.e., IL_2 and IL_3 than irrigation with 80% of ETc (IL_1) as an average for the two seasons.

Among plant densities, the plant density of 17.500 plants fed^{-1} gave the lowest values of DD (0.22) and RYR% (7.91%) compared to other densities as an average of both seasons. Foliar spray with 6% of kaolin on maize plants results decreasing in DD (0.35) and RYE% (10.19%) under drought stress as an average of both seasons.

Foliar spraying with kaolin at the rate of 6% caused an increase in the seed yield and the lowest RYR% but for other plants such as sunflower in two seasons (El-Mantawy and El-Bialy, 2018). The best or lowest interactions for DD and RYR% were 0.01 and 0.67% of ($IL_2 \times PD_1$), 0.13 and 3.47% of ($IL_2 \times An_3$), 0.13 and 4.28% of ($PD_1 \times An_3$), and − 0.04 and − 1.41% of ($IL_2 \times PD_1 \times An_2$) as an average of both seasons, respectively.

Water Use Efficiency (WUE) of drip-irrigated maize:

Data in Table (10) illustrated that WUE of maize was significantly affected by the IL, PD, An, and their interactions, except for the interaction, i.e., PD × An and IL × PD × An were insignificant in the 1st season only. With reference to irrigation levels (IL), the maximum values of WUE (1.38 and 1.40 kg m^{-3}) were achieved from maize plants irrigated with 70% of ETc (IL_2), while the lowest values (1.29 and 1.27 kg m^{-3}) were obtained from 80% of ETc (IL_1), respectively, in both seasons. WUE under 70% of ETc (IL_2) was increased by 6.98 and 10.24%

Table 7 Effects of irrigation levels, plant densities, antitranspirants, and their interaction on 100-grain weight (g) of maize during 2019 and 2020 seasons

Treatments		Antitranspirants (An)			Mean of IL × PD	Antitranspirants (An)			Mean of IL × PD
Irrigation levels (IL)	Plant densities (PD)	An_1: control	An_2: chitosan	An_3: kaolin		An_1: control	An_2: chitosan	An_3: kaolin	
		2019 season				2020 season			
IL_1: 80%	PD_1:17.500	32.73	35.43	36.77	34.98	34.20	37.20	39.47	36.96
	PD_2:23.333	31.23	33.03	34.40	32.89	32.40	34.67	35.50	34.19
	PD_3:35.000	30.37	31.80	32.07	31.41	31.40	33.50	34.53	33.14
Mean of IL_1		31.44	33.42	34.41	33.09	32.67	35.12	36.50	34.76
IL_2: 70%	PD_1:17.500	31.47	32.67	33.63	32.58	32.47	34.00	34.27	33.58
	PD_2:23.333	29.30	30.37	31.00	30.29	30.70	32.17	32.93	31.93
	PD_3:35.000	26.70	29.47	29.60	28.59	29.20	30.20	31.40	30.27
Mean of IL_2		29.15	30.90	31.41	30.49	30.79	32.12	32.87	31.93
IL_3: 60%	PD_1:17.500	24.33	26.50	27.20	26.01	25.63	27.70	28.83	27.39
	PD_2:23.333	23.30	24.47	25.20	24.32	24.20	26.43	27.30	25.98
	PD_3:35.000	22.13	24.00	25.00	23.71	23.03	24.63	25.77	24.48
Mean of IL_3		23.26	24.99	25.80	24.68	24.29	26.26	27.30	25.95
Mean of (PD × An)	PD_1:17.500	29.51	31.53	32.53	31.19	30.77	32.97	34.19	32.64
	PD_2:23.333	27.94	29.36	30.20	29.17	29.10	31.09	31.91	30.70
	PD_3:35.000	26.40	28.42	28.89	27.90	27.88	29.44	30.57	29.30
Mean of An		27.95	29.77	30.54	–	29.25	31.16	32.22	–
$LSD_{0.05}$		IL: 0.37		PD: 0.27		IL: 0.30		PD: 0.21	
		An: 0.20		IL × PD: 0.46		A: 0.23		IL × PD: NS	
		IL × An: NS		PD × An: 0.35		IL × An: 0.39		PD × An: 0.39	
		IL × PD × An: 0.60				IL × PD × An: 0.68			

in the 2019 and 2020 seasons, respectively, compared with 80% of ETc (IL_1).

As for plant densities, high plant density displayed the highest values of WUE in both seasons (Table 10). Planting maize with 35.000 plant fed^{-1} recorded the highest values of WUE (1.46 and 1.48 kg m^{-3}) in the 2019 and 2020 seasons, respectively, compared to the other treatments. The average WUE values of PD_3 were increased by 15.87 and 9.77% above PD_1 and PD_2 in the 2019 season, respectively, while the corresponding values in the 2020 season were recorded at 20.33 and 9.63% in the same order.

Data in Table 10 revealed that foliar antitranspirants application (An) had a significant effect on WUE in both seasons. Spraying kaolin at 6% (An_3) caused a 15.20 and 15.20% increase in WUE in both seasons, respectively, compared to the control treatment (An_1).

The effect of the first- and second-order interaction on WUE was significant, except the interactions among PD × An and IL × PD × An in the 1st season only which were not significant as presented in Table 10. Results indicated that the interaction among $IL_2 \times PD_3$ produced the greatest values for WUE (1.50 and 1.51 kg m^{-3}) in the 2019 and 2020 seasons, respectively (Table 10). In the same table, results showed that the interaction among IL3 × An3 realized the highest values for WUE (1.48 and 1.50 kg m^{-3}) in both seasons. The highest mean values of WUE (1.57 kg m^{-3}) were obtained from the interaction between $PD_3 \times An_3$ in the 2nd season. Moreover, the highest mean values for WUE (1.61 and 1.61 kg m^{-3}) were gained from the interaction among $IL_3 \times PD_3 \times An_3$ in the 2019 and 2020 seasons, respectively.

Grain yield and applied irrigation water relationships

The relationship between the applied irrigation water (m^3 $fed.^{-1}$) and the grain yield (ton $fed.^{-1}$) has been developed for the 2019 season and 2020 seasons separately, and the two growing seasons together. The relationship between them was linear (Fig. 1) with an accepted regression > 0.85. The highest regression has been gained using the 2019 season data with the least amount of error. The linear equation of the 1st season implies that a grain yield of approximately 0.6 ton fed^{-1} can be gained even without the application of irrigation water. Karasu et al. (2015) mentioned that it is only possible if there is residual moisture in the soil to support such a yield. A linear relationship has been reported between maize yield and the used applied water by Dagdelen et al. (2006) and

Table 8 Effects of irrigation levels, plant densities, antitranspirants, and their interaction on grain weight ear^{-1} (g) of maize during 2019 and 2020 seasons

Treatments		Antitranspirants (An)			Mean of IL × PD	Antitranspirants (An)			Mean of IL × PD
Irrigation levels (IL)	Plant densities (PD)	An_1: control	An_2: chitosan	An_3: kaolin		An_1: control	An_2: chitosan	An_3: kaolin	
		2019 season				2020 season			
IL_1: 80%	PD_1:17.500	158.68	164.22	165.26	162.72	159.94	165.23	165.30	163.49
	PD_2:23.333	153.16	156.23	156.49	155.30	154.40	157.35	157.60	156.45
	PD_3:35.000	147.36	152.18	152.89	150.81	148.48	153.30	154.16	151.98
Mean of IL_1		153.07	157.55	158.21	156.28	154.27	158.62	159.02	157.31
IL_2: 70%	PD_1:17.500	149.82	155.77	156.07	153.89	150.15	156.14	156.23	154.18
	PD_2:23.333	146.71	153.46	154.33	151.50	147.29	154.20	155.05	152.18
	PD_3:35.000	142.98	147.02	147.10	145.70	143.34	149.46	150.13	147.65
Mean of IL_2		146.50	152.09	152.50	150.36	146.93	153.27	153.80	151.33
IL_3: 60%	PD_1:17.500	141.70	144.01	144.98	143.57	142.15	145.11	145.32	144.19
	PD_2:23.333	139.64	142.67	143.00	141.77	138.88	143.41	143.49	141.93
	PD_3:35.000	135.22	137.24	138.40	136.95	134.46	136.62	137.04	136.04
Mean of IL_3		138.85	141.31	142.13	140.76	138.50	141.71	141.95	140.72
Mean of (PD × An)	PD_1:17.500	150.07	154.67	155.44	153.39	150.75	155.49	155.62	153.95
	PD_2:23.333	146.51	150.79	151.28	149.52	146.86	151.65	152.05	150.19
	PD_3:35.000	141.85	145.48	146.13	144.49	142.09	146.46	147.11	145.22
Mean of An		146.14	150.31	150.95	–	146.57	151.20	151.59	–
$LSD_{0.05}$		IL: 0.39		PD: 0.62		IL: 0.20		PD: 0.23	
		An: 0.42		IL × PD: 0.61		An: 0.17		IL × PD: 0.13	
		IL × An: 0.74		PD × An: NS		IL × An: 0.29		PD × An: NS	
		IL × PD × An: 1.27				IL × PD × An: 0.50			

Kiziloglu et al. (2009). On the other hand, a quadratic relationship has been mentioned by Karasu et al. (2015), and Huang et al. (2022).

Discussion

Number of leaves plant.$^{-1}$ and leaf area index (LAI)

The plots that received sufficient water produced a faster rate of leaf expansion, which increased radiation interception and photosynthates, therefore having a better chance for more vigorous vegetative growth, and the net assimilation rate for dry matter accumulation, which led to an increment in the number of leaves. Under the lowest irrigation levels (IL_3), a reduction of these traits occurred, which might be due to the reduction of leaf water status that controls cell division and expansion. A similar trend was obtained by Gomaa et al. (2021) and Shemi et al. (2021) who reported that drought stress negatively affects maize growth in terms of the number of leaves plant^{-1} and LAI. Ulameer and Ahmed (2018) and Hegab et al. (2019) found a significant reduction in the number of leaves and LAI by subjecting plants to the irrigation shortage. Guo et al. (2021) and Lubajo and Karuku (2022) found that deficit water reduced LAI as a result of leaf size reduction.

The high level of plant density produced the lowest values of the number of leaves, and this could be attributed to the low competition impact of low plant density on resources such as water requirements, sunlight, and intra-plant spacing. Sarwar et al. (2016), Absy and Abdel-Lattif (2020) and Rahouma (2021) stated that lower plant densities produced a higher number of leaves plant^{-1}. Moreover, Sidi et al. (2019) reported that the number of leaves plant^{-1} was gradually increased with decreasing plant density from 28,000 to 20,000 plants fed^{-1}.

The possible reason for the highest leaf area index (LAI) is that by increasing the plant density, having the lowest land area plant^{-1} and more total leaves produced is due to the increased number of plants per unit area. Sibonginkosi et al. (2019) indicated that increasing plant density from 44.444 to 57.143 plants ha^{-1} increased the LAI from 3.95 to 4.38 in maize. In maize, LAI increased with increasing plant density from 20,000 to 28,000 plants fed^{-1} (Sidi et al. 2019). Also, Rahouma (2021) indicated that the highest maize plant density (166.66 plants ha^{-1}) produced the highest LAI (3.65). Similar results were obtained by Mian et al. (2021), AL-Naggar et al. (2021), and Guo et al. (2021).

Table 9 Effects of experimental treatments on grain yield (ton fed^{-1}) during the 2019 and 2020 seasons, drought depression (DD), and relative yield reduction (RYR %) as an average of both seasons

Grain yield (ton fed^{-1})

Treatments		**Antitranspirants (An)**			**Mean of IL × PD**	**Antitranspirants (An)**			**Mean of IL × PD**
Irrigation levels (IL)	**Plant densities (PD)**	**An_1: control**	**An_2: chitosan**	**An_3: kaolin**		**An_1: control**	**An_2: chitosan**	**An_3: kaolin**	
		2019 season				**2020 season**			
IL_1: 80%	PD_1:17.500	2.69	2.96	3.05	2.90	2.55	2.70	2.79	2.68
	PD_2:23.333	2.95	3.17	3.34	3.15	2.88	3.22	3.29	3.13
	PD_3:35.000	3.13	3.41	3.63	3.39	3.20	3.59	3.67	3.49
Mean of IL_1		2.92	3.18	3.34	3.15	2.88	3.17	3.25	3.10
IL_2: 70%	PD_1:17.500	2.52	2.83	2.96	2.77	2.37	2.91	3.06	2.78
	PD_2:23.333	2.67	2.96	3.06	2.90	2.75	3.01	3.13	2.96
	PD_3:35.000	3.00	3.26	3.38	3.21	2.97	3.32	3.41	3.23
Mean of IL_2		2.73	3.01	3.13	2.96	2.70	3.08	3.20	2.99
IL_3: 60%	PD_1:17.500	2.16	2.38	2.53	2.36	2.16	2.35	2.63	2.38
	PD_2:23.333	2.35	2.42	2.66	2.48	2.42	2.53	2.65	2.53
	PD_3:35.000	2.52	2.68	2.94	2.71	2.58	2.74	2.96	2.76
Mean of IL_3		2.34	2.49	2.71	2.52	2.39	2.54	2.75	2.56
Mean of (PD × An)	PD_1:17.500	2.46	2.72	2.85	2.68	2.36	2.65	2.83	2.61
	PD_2:23.333	2.66	2.85	3.02	2.84	2.68	2.92	3.02	2.88
	PD_3:35.000	2.88	3.12	3.32	3.11	2.92	3.22	3.34	3.16
Mean of An		2.67	2.90	3.06	–	2.65	2.93	3.06	–
$LSD_{0.05}$		IL: 0.03		PD: 0.04		IL: 0.04		PD: 0.04	
		An: 0.03		IL × PD: 0.06		An: 0.02		IL × PD: 0.02	
		IL × An: 0.05		PD × An: 0.05		IL × An: 0.04		PD × An: 0.04	
		IL × PD × An: NS				IL × PD × An: 0.07			

Treatments		**Antitranspirants (An)**			**Mean of IL × PD**	**Antitranspirants (An)**			**Mean of IL × PD**
Irrigation levels (IL)	**Plant densities (PD)**	**An_1: control**	**An_2: chitosan**	**An_3: kaolin**		**An_1: control**	**An_2: chitosan**	**An_3: kaolin**	
		Drought depression (DD)*				**Relative yield reduction (RYR%)****			
IL_2: 70%	PD_1:17.500	0.17	−0.04	−0.09	0.01	6.49	−1.41	−3.08	0.67
	PD_2:23.333	0.21	0.21	0.22	0.21	7.19	6.56	6.63	6.79
	PD_3:35.000	0.18	0.21	0.26	0.22	5.68	6.00	6.85	6.18
Mean of IL_2		0.19	0.19	0.13	0.13	0.15	6.45	3.72	3.47
IL_3: 60%	PD_1:17.500	0.46	0.46	0.34	0.42	17.56	16.25	11.64	15.15
	PD_2:23.333	0.53	0.72	0.66	0.64	18.15	22.50	19.88	20.18
	PD_3:35.000	0.62	0.79	0.70	0.70	19.56	22.57	19.18	20.44
Mean of IL_3		0.54	0.54	0.66	0.57	0.59	18.42	20.44	16.90
Mean of (PD × An)	PD_1:17.500	0.32	0.21	0.13	0.22	12.03	7.42	4.28	7.91
	PD_2:23.333	0.37	0.47	0.44	0.43	12.67	14.53	13.26	13.49
	PD_3:35.000	0.40	0.50	0.48	0.46	12.62	14.29	13.02	13.31
Mean of An		0.36	0.40	0.35	–	12.44	12.08	10.19	–

* Drought depression (DD) = Y_{normal} − Ystress (Hossain et al. 1990)

** Relative yield reduction (RYR %) = 1 − (Y_{stress}/Y_{normal}) × 100 (Golestani and Assad 1998)

Kaolin treatment increased number of leaves and LAI which might be due to the important role of kaolin in improving plant growth by controlling transpiration, CO_2 uptake, which led to keeping a higher water quantity in plant tissues, thus supporting plant metabolism, photosynthetic rate, and many other essential functions that affect plant growth immediately during the deficit of water. Similar findings were reported by Guleria and

Table 10 Effects of irrigation levels, plant densities, antitranspirants, and their interaction on water use efficiency (WUE) of maize during 2019 and 2020 seasons

Treatments		Antitranspirants (An)			Mean of IL × PD	Antitranspirants (An)			Mean of IL × PD
Irrigation levels (IL)	Plant densities (PD)	An_1: control	An_2: chitosan	An_3: kaolin		An_1: control	An_2: chitosan	An_3: kaolin	
		2019 season				2020 season			
IL_1: 80%	PD_1:17.500	1.10	1.21	1.25	1.19	1.04	1.10	1.14	1.10
	PD_2:23.333	1.21	1.29	1.37	1.29	1.18	1.32	1.34	1.28
	PD_3:35.000	1.28	1.40	1.48	1.39	1.31	1.47	1.50	1.43
Mean of IL_1		1.20	1.30	1.37	1.29	1.18	1.30	1.33	1.27
IL_2: 70%	PD_1:17.500	1.18	1.32	1.39	1.30	1.11	1.36	1.43	1.30
	PD_2:23.333	1.25	1.38	1.43	1.35	1.28	1.41	1.46	1.38
	PD_3:35.000	1.40	1.52	1.58	1.50	1.39	1.55	1.59	1.51
Mean of IL_2		1.28	1.41	1.47	1.38	1.26	1.44	1.49	1.40
IL_3: 60%	PD_1:17.500	1.18	1.30	1.38	1.29	1.17	1.28	1.43	1.30
	PD_2:23.333	1.28	1.32	1.45	1.35	1.32	1.38	1.44	1.38
	PD_3:35.000	1.37	1.46	1.61	1.48	1.41	1.50	1.61	1.51
Mean of IL_3		1.28	1.36	1.48	1.37	1.30	1.39	1.50	1.39
Mean of (PD × An)	PD_1:17.500	1.15	1.28	1.34	1.26	1.11	1.25	1.33	1.23
	PD_2:23.333	1.24	1.33	1.42	1.33	1.26	1.37	1.42	1.35
	PD_3:35.000	1.35	1.46	1.56	1.46	1.37	1.51	1.57	1.48
Mean of An		1.25	1.36	1.44	–	1.25	1.37	1.44	–
$LSD_{0.05}$		IL: 0.02		PD: 0.02		IL: 0.02		PD: 0.02	
		An: 0.01		IL × PD: 0.02		An: 0.01		IL × PD: 0.02	
		IL × An: 0.02		PD × An: NS		IL × An: 0.02		PD × An: 0.02	
		IL × PD × An: NS				IL × PD × An: 0.03			

Shweta (2020), who found that applying antitranspirants to the leaves of plants led to reducing water loss without causing a momentous change in the different important processes of the plant, such as growth and photosynthesis. A similar result was obtained with the application of some different antitranspirants on several crops (El-Hadidi et al. 2020 on rice and Gomaa et al. 2021 on maize).

Number of days from planting to 50% tasselling and 50% silking

The 50% of tasselling and 50% of silking were significantly affected by irrigation levels, where water stress may cause plants to mature earlier as a physiological mechanism to surmount any type of stress (Halli et al. 2021), and also the ability of the plant to complete its life cycle before exposure to dangerous water stress (Ulameer and Ahmed 2018). Water deficit may cause the plant to increase the effectiveness of old age hormones while decreasing the effectiveness of growth hormones, resulting in the plant's early entry of 50% tasseling (Abd et al. 2021). Kar and Kumar (2015) found that plants took from 47 to 51 days to attain 50% of tasseling and from 59 to 60 days to attain 50% of silking under irrigation levels from 120 to 360 mm, respectively.

The dense sowing might have slowed down the rate of plant development due to increased competition among plants rather than low plant density. Likewise, plant density influences the required period for pollen shedding and silk emergence resulting takes long days as plant density of maize increases. Our results are in line with Sarwar et al. (2016) and Sidi et al. (2019) who reported that the time of tasseling and silking was delayed by high plant density. AL-Naggar et al. (2021) illustrated that higher plant density (71.400, 95.200 and 119.000 plants ha^{-1}) caused a significant increase day to 50% anthesis by 3.18, 6.43, and 9.76 days, days to 50% silking by 3.19, 6.32, and 4.40 days, respectively, as compared with low plant density (47.600 plants ha^{-1}). The shortest period to tasseling (49.00 days) and silking (55.0 days) under 55,555 plants ha^{-1} and longest periods to tasseling (50.13 days) and silking (56.06 days) under 83,333 plants ha^{-1} were recorded (Shrestha et al. 2018).

The increases as a result of using kaolin and chitosan antitranspirants treatments might be attributed to stimulating the physiological and metabolic processes which in turn decreased the harm caused by water deficiency and then pushed the plant to continue its growth instead of early flowering and ending the life cycle early. Using kaolin clay 6% gave higher values of the number of days

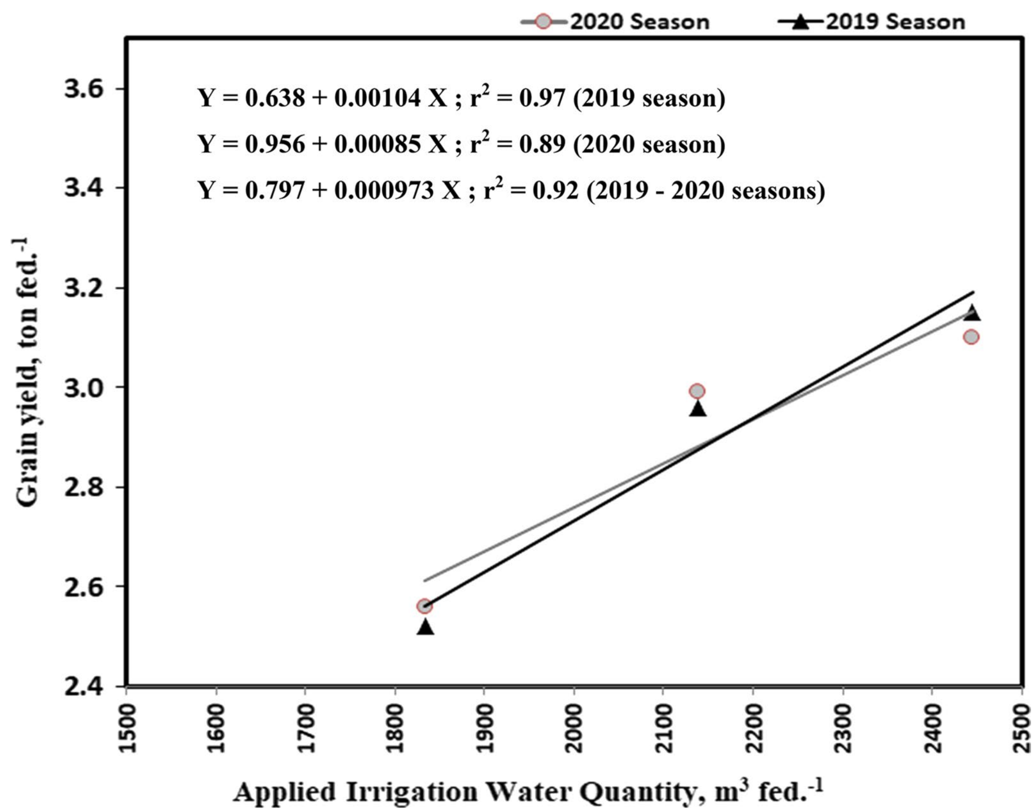

Fig. 1 The relationship between grain yield and the applied irrigation water quantity

till 50% of tasseling (74.22 and 73.77 days) in comparison with the untreated plants, which gave fewer values of the same traits (73.78 and 73.44 days) for the two seasons, respectively (Ulameer and Ahmed 2018).

Ear diameter, 100-grain weight, and grain weight ear^{-1}

Sufficient moisture through the grain filling period leads to facilitate the assimilation of dry matter to the grains and increases pollen production in plants before anthesis, resulting in an increased number of well-developed grains. Lubajo and Karuku (2022) stated that water stress in the reproductive period reduces the grain weight of maize. Gharib et al. (2016) pointed out that increasing available soil moisture in the root zone during ear formation resulted in a substantial increase in ear dimensions and the ability of maize plants to accumulate dry matter through the increase in the area of photosynthesizing leaves which in turn produced more photosynthetic available for filling grains during the reproductive period. Gomaa et al. (2021) and Saad-Allah et al. (2022) showed that soil water stress caused a considerable weakness in ear development and poor grain filling, leading to a considerably lower number and weight of grains ear^{-1}.

The superiority of 17.500 plants fed^{-1} in these traits might be due to enabling plants to make good use of environmental resources such as sunlight, moisture, and nutrients owing to low intraspecific competition, which is reflected in yield components. Low density resulted in low competition for resources and an increase in ear diameter due to the increase of dry matter partitioning to the ear (Sarwar et al. 2016). These results, reported by several investigators by Du et al. (2021); Mian et al. (2021); Djaman et al. (2022), and Zhai et al. (2022), showed that increasing the plant density reduced both grain weight ear^{-1} and 1000-grain weight.

Spraying of antitranspirants might have decreased plant water loss through transpiration, resulting in increased photosynthetic activity, total chlorophyll, leaf area, water use efficiency, and translocation of photosynthates toward the grain, and consequently reflected in increasing ear yield. Adelian et al. (2019) pointed out that the application of antitranspiration produces the highest quantitative and qualitative yield of maize in regions where water is the main limiting factor. The results were close to those found by Abdallah et al., (2019) for wheat and Abdulameer and Ahmed (2021) for maize.

Grain yield, drought depression (DD), and relative yield reduction (RYR %)

Grain yield

The greatest grain yield was gained from the 1st irrigation level of 80% (IL_1) due to providing soil moisture throughout the growing period at the root zone, enhanced root distribution, increased root surface area, and good distribution of nutrients that reflected on the yield of maize. This result is consistent with the findings of Eissa et al. (2017); Asibi et al. (2022); Saad-Allah et al. (2022); Wang et al. (2022) and Huang et al. (2022), who reported that grain yield was reduced when the irrigation levels were reduced.

The increase in grain yield under dense plants was mainly owing to the increased number of plants, grain numbers, biomass, and ear number per unit area compared with low plant density (Shrestha et al. 2018; Du et al. 2021; Asibi et al. 2022 and Zhang et al. 2022). These results are in closed conformity with the results of Worku et al. (2020); Mian et al. (2021); Zhang et al. (2021), and Zhai et al. (2022), who reported that the increased grain yield was accompanying by increasing planting densities per unit area, and efficient utilization of available resources, which is one of the main techniques to further increase maize yield.

Antitranspirants may play an enormous role in improving various physiological traits, and the drought tolerance during the early stages of growth by enhancing photosynthetic pigments that improve qualitative characteristics and improve the grain yield and yield-related components of different cereal crops (Guleria and Shweta 2020). The use of antitranspiration on maize increased the growth traits, i.e., the number of leaves, leaf area, leaf area index, plant dry matter, and crop growth, which might help in increasing the grain yield (Ulameer and Ahmed 2018; and Abdulameer and Ahmed 2021).

Drought depression (DD) and relative yield reduction (RYR %)

Water deficit has several potentially negative results for a plant, e.g., not enough for maize requirements during growth stages, consequently reducing crop yield. The same trend of these results was by Bayisa et al. (2021) who showed that the DD and RYR% correspond to the relative water deficit.

The high-density plants under drought conditions increased plant stress and RYR%, particularly if the drought occurs during the tasselling and silking stages (Ajayo et al. 2021).

Foliar spraying with kaolin at the rate of 6% caused an increase in the seed yield and the lowest RYR%, and this could be due to the role of kaolin particularly under water stress conditions inducing an increase in the grain yield by 15.04% (0.40 ton fed^{-1}) compared to without kaolin treatment as an average of both seasons, plus its role in alleviating the adverse effects of water stress.

Water Use Efficiency (WUE) of drip-irrigated maize

The higher values of WUE are observed under IL_2 as compared to IL_1 due to increasing the grain yield per unit of water consumed, and WUE is influenced by crop yield potential and irrigation levels. Enhancing WUE is to increase crop yield per unit of water applied or lower the amount of water needed to achieve a unit of production. Lubajo and Karuku (2022) indicated that irrigating maize with a 50% water deficit improved water use efficiency without much reduction in yield. Previous studies revealed that the increase in irrigation levels decreased WUE (Eissa et al. 2017; Usama 2019; Wang et al. 2022; and Zhang et al. 2022).

Higher planting density PD_3 can maximize WUE, due to increased light interception, grain yield, and decreased evapotranspiration, hence enabling the plants to grab large amounts of water due to the increased ratio of roots. Similar results obtained by Asibi et al. (2022); Djaman et al. (2022); Wang et al. (2022) and Zhai et al. (2022) indicated that increasing the plant density significantly increases the WUE of maize.

Using antitranspirants on maize plants increased leaf area, leaf water potential, total chlorophyll, relative water content, and improved grain yield through the reduction of transpiration, and hence, the amount of used water improved the water use efficiency of maize. Yang et al. (2019) showed that the increase in grain yield and WUE was achieved by applying antitranspirants to maize plants. The use of antitranspirants results in reducing water and drought stress, detaining more water in the leaves, improving the rate of photosynthesis, and chlorophyll content, and improving the water use efficiency (WUE) in maize plants (Guleria and Shweta 2020). Foliar spraying of antitranspirants can increase WUE and produce a high grain yield while requiring less irrigation (Gomaa et al. 2021). Treating cereals with antitranspirants will reduce the negative effects of drought, contribute to higher yields, and improve WUE (Kocięcka and Liberacki 2021).

Conclusion

Generally, increasing irrigation levels from 60 up to 80 ETc significantly increased all studied traits. The use of Kaolin at 6% improved the phenology, growth traits, yield, and WUE of maize under optimum and limited water supply and was beneficial to alleviate the negative effects of water stress. All traits were increased significantly at low planting density, but grain yield was decreased.

Eventually, sowing maize of 35.000 plants fed^{-1} + kaolin at 6% + irrigation level with 80% of ETc achieved the maximum maize productivity, more efficient use of available resources, and could be recommended under El-Minia conditions, Egypt. There is a linear relationship between maize grain yield and the applied irrigation water under the experimental conditions.

Abbreviation

Fed: The abbreviation of the area unit feddan which is equal to 0.42 hectare.

Acknowledgements

Not applicable.

Author contributions

ASMM did the field work and analyzed the gained data as well as shared in writing the manuscript, and HMM did some field work, good contribution in writing the manuscript, and language corrections. All authors read and approved the final manuscript.

Funding

Not applicable.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Received: 19 May 2022 Accepted: 8 September 2022
Published online: 24 September 2022

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