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Enhancing Maize Productivity Through AquaCrop Modeling Under Modern Irrigation Systems and Drought Stress Conditions

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DROUGHT stress is a major abiotic stress resulting from conditions including decreased humidity, elevated salinity, thermal stress, and insufficient light intensity, among others. Intense water stress in maize plants results in a reduction of yield and its constituents. Maize productivity declines by 15-30% as a result of drought stress. This study aimed to identify the ideal irrigation technique for enhancing maize genotype efficiency and attaining the highest possible yields per unit area, utilizing the AquaCrop model to calibrate water productivity. The present investigation was executed at the El-Noubaria Research Station of the National Research Centre in El-Behaira Governorate.This study involved sixteen distinct maize varieties, cultivated under three varying irrigation regimes. The maize genotypes were assessed during the 2022 and 2023 growing seasons under three distinct irrigation levels: 40% (m3/ha), 60% (m3/ha), and 80% (m3/ha), all administered using spray irrigation. The findings indicate that hybrids SC 168, SC 164, and SC 124 are strongly endorsed for maize breeding initiatives focused on enhancing drought resistance in arid areas. The comparison of observed and simulated water productivity (WP) indicated that achieving high WP, together with elevated yield and its components, is attainable through the calibration of the AquaCrop model. These findings underscore the potential of advanced irrigation management and modeling tools in improving maize performance under drought stress.

Keywords: Maize cultivars, irrigation systems, drought stress, water productivity (WP), AquaCrop model.

Introduction

Water is essential for the growth and development of plants. Without water, the plant endures drought conditions, significantly affecting its growth and ultimately diminishing crop yield. Yield efficiency denotes the productivity of a plant grown in an optimal environment, characterized by adequate availability to water and nutrients, alongside effective management of pests and diseases (Evans, 1993). Water is the principal factor influencing plant growth and markedly improves agricultural productivity. Water is a fundamental requirement for the growth and development of plants. Without irrigation, the plant undergoes stress, causing substantial interruptions in its growth phases and ultimately leading to reduced agricultural yields. CIMMYT prioritizes the development of tropical maize varieties that provide high and reliable yields, especially in adverse conditions. This is essential as access to drought-resistant cultivars may be the only feasible answer for many small-scale farmers (Monneveux et al. 2006). Consequently, the development of drought-resistant maize varieties is deemed crucial for enhancing global maize production (Campos et al. 2004 and Xiong et al. 2006) and safeguarding global food security (Mir et al. 2012). Recent years have seen substantial global assessments of crop yield fluctuations (Neumann et al., 2010). Assessing potential crop output and distinguishing the disparity between actual yield and maximum attainable yield can elucidate the factors that constrain crop production and formulate strategies to improve agricultural productivity (Aggarwal and Kalra, 1994) (Wu et al., 2022; Li et al., 2022). In contrast, executing prolonged field tests would enhance the likelihood of identifying the factors that impede agricultural productivity. Corn (Zea mays L.) is an extensively grown crop that is greatly esteemed by both humans and livestock. It functions as an essential industrial energy source and provides various supplementary benefits. To meet the increasing production demands of a swiftly

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growing population, it is essential to substantially improve maize grain yields (Cassman et al., 2003). Maize is an essential crop that provides food, bioenergy, and grains. In 2021, it encompassed a substantial harvested area of 197 million hectares and yielded 7,811,135 metric tonnes, as reported by FAO 2019. Corn (Zea mays L.) exhibits greater vulnerability to drought stress during the flowering stage relative to other cereals. This may lead to considerable decreases in yield, particularly for the quantity of kernels per ear (Bolanos and Edmeades, 1996).

The quality of agricultural yields in simulation models depends on the availability of necessary inputs for their implementation. Simulating crop models serves as an essential instrument for comprehending the biophysical mechanisms that regulate the soil-plant-atmosphere system (Ran et al., 2017).

The assessment evaluated grain yield and biological yield using the modified coefficient of correlation and both absolute and normalized root mean square errors (RMSEn). The results indicated that the RMSEn for forecasting grain yield during the validation and calibration stages for Ali Kazemi, Dorfak, and Bahar varied from 6 to 8 percent and 8 to 9 percent, respectively. The RMSEn for forecasting biological yield in the validation and calibration phases for rice genotypes varied from 3 to 13 percent and 7 to 15 percent, respectively. The results indicated that the AquaCrop model shown adequate accuracy in predicting both the grain production and biological yield of the crop (Roshani et al., 2021).

This can be accomplished by utilizing computer-based mathematical models to simulate the grain production process while considering critical factors that significantly affect crop output. A model serves as a fundamental representation of a system, whereas simulation entails examining the system's behavior through the model. Crop simulation models are essential instruments for comprehending the biophysical interactions among soil, plants, and the atmosphere (Ran et al., 2017). These models replicate climate fluctuations, plant genetic traits, soil parameters, and management factors, including irrigation, on plant development. Evaluating farms through experiments often entails examining a limited set of factors that substantially influence plant growth within a certain region and during a single growing season. Model simulations can assess the effects of climatic and managerial fluctuations on plant growth. Furthermore, these models possess the capability to utilize the acquired data across various regions and locations (Hawkesford and Griffiths, 2019). Model simulations can be employed to measure yield variability across various management levels (Behera and Panda, 2009) .

The concept, named AquaCrop, seeks to establish a balanced integration of precision, simplicity, robustness, and user-friendliness. This research analyzes the conceptual framework, structure, algorithms, and distinctive features of AquaCrop. It encompasses an evaluation of the performance of several crops grown under differing degrees of water availability, as recorded by Steduto et al. in 2007 and 2009.

AquaCrop utilizes the assessment of the degree of ground coverage by the crop canopy. Water stress impacts physiological processes such as canopy expansion, stomatal conductance, canopy senescence, and harvest index. Both low and high-temperature stresses are considered when evaluating their effects on pollination and harvestable output. The impact of cold temperature stress on biomass production is also analyzed. Evapotranspiration is modeled as comprising two distinct components: crop transpiration and soil evaporation. The daily transpiration is utilized to calculate the increase in biomass through the normalized biomass water productivity. The objective of normalization is to accommodate fluctuations in atmospheric evaporative demand and carbon dioxide content, hence allowing the model to be applicable across many locations and seasons, as well as under prospective climatic conditions. AquaCrop can accommodate diverse fertility levels and water management options, including rainfed, supplementary, deficit, and full irrigation. Simulations are often executed in thermal time; however, they may also be carried out in calendar time. Future iterations will incorporate factors related to salt equilibrium and capillary rise, as recorded by Wu and Gtilin (1975), and by Abd-Elmabod et al., (2019a and 2019b).

AquaCrop is crucial for evaluating the difference between prospective and actual crop yields in a field, farm, or region. This facilitates the identification of constraints that limit crop output and water productivity, functioning as a benchmarking instrument. Moreover, economists, water agencies, and managers can employ it for scenario analysis and strategic planning. It is suitable for prospective research, including studies on future climate change scenarios. This tool is well designed for formulating strategies for agricultural water management. It can serve multiple purposes and applications, as evidenced by numerous studies (Eldardiry et al., 2015; El-Hagary et al., 2015; Mansour et al., 2019a,b,c,d,e; Hellal et al., 2019; Mansour et al., 2012a,b; Mansour et al., 2016a,b,c; Mansour et al., 2015a,b,c; Mansur et al., 2014; Mansour, 2015a,b; Mansour and Aljughaiman, 2012, 2015; Mansour and Elmelhem, 2015).

The aim of this research was to determine the most efficient irrigation method to improve maize genotype performance and optimize yield per unit area. Additionally, the study employed the AquaCrop model to optimize water productivity.

Materials and Methods

Field Experiments

The present investigation was conducted at the National Research Centre, El-Noubaria Research Station, located in El-Behaira Governorate. The aim was to assess the effects of 16 distinct cultivars of Maize (Zea Mays L.) on vegetative growth traits, yield, and water productivity (WP) over the successive summer seasons of 2022 and 2023.

Botanical Resources

Grains from 16 maize (Zea mays L.) genotypes, comprising 10 single crossings and 6 three-way crosses (Table 1), were sourced from the Agricultural Research Center (ARC), with one genotype imported from China.

Methodological Protocols

The sowing date was May 1st in both summer seasons (2022 and 2023). Sowing occurred in rows, each measuring 4 meters in length and 0.7 meters in width. Seeds were oversown in hills spaced 25 cm apart and subsequently trimmed to one plant per hill after 21 days from planting to attain a plant density of 24,000 plants per feed. Each experimental plot comprised five rows, with a plot size of 14 m².

Experimental Design

A split-plot design in a randomized complete block (RCB) configuration with three replications was employed. Main plots were assigned to three irrigation regimes: 80% ET (6664 m³/ha) as the control, 60% ET (4998 m³/ha), and 40% ET (3332 m³/ha). Subplots were allocated to sixteen maize genotypes.

The physical, chemical, and hydric qualities of the soil were analyzed in accordance with Klute (1986) for soil characteristics and Rebecca (2004) for moisture retention at field capacity and wilting point. The soils at both examined locations displayed a sandy loam texture. The soil moisture parameters of the studied area are recorded in Table (2). The examination of soil water parameters employed in the tests produced the subsequent results: Electrical conductivity: 2.6 dSm–1 (1:20 dilution); pH: 8.2 (1:20 dilution); organic matter content: 1.3%; calcium carbonate content: 3.8%; field capacity: 12.6%; wilting point: 4.7%; accessible water: 7.9%. Table (3) illustrating the physical characteristics of the soil.

The area of the land was 21 m² (1 x 21). The water levels were recorded in relation to the tested levels as follows:

% 80ET as control,

% 60ET, and

% 40ET.

Irrigation systems

The elements of irrigation networks are depicted in Fig. 1 and 2.

1. Control head: It was located at the water source. The system consists of a 4" / 4" centrifugal pump, driven by a diesel engine, with a discharge capacity of 100m3/h and a lift of 50m. The system comprises a sand media filter including two 48-inch tanks, a 2-inch screen filter with a 120 mesh, a backflow prevention device, a pressure regulator, pressure gauges, a flow meter, control valves, and a chemical injection system.

2. Principal conduit: 125mm outer diameter (OD) PVC pipes utilized for the conveyance of water from the source to the primary control stations in the field.

3. Sub-main lines: PVC pipes with an outer diameter of 75mm were affixed to the main line utilizing a control apparatus including a 2" ball valve and pressure gauges.

4. The sub main line was connected to the manifold lines via control valves with a diameter of 40mm (OD) constructed from PVC pipes.

5. Distributors: The interline spacing was 0.5 meters. The utilized emitters were GR emitters, incorporated inside polyethylene tubes with an outer diameter of 16mm and a length of 63m. The emitters exhibit a discharge rate of 4 liters per hour at an operating pressure of 1.0 bar, with a separation of 30 centimeters between them.

1-Surface Drip Irrigation Systems (SD).

Sprinkler irrigation systems (SP).

Armored vehicles

Three polyethylene tanks, each with a capacity of 1 m³, were linked to the control head via a float. The tanks are being filled with water using a 63 mm PVC pipe rated for 6 bar pressure, originating from the farm's main line.

Growth, Yield and its component characteristics

Plant height (PH) (cm): The mean height of five randomly chosen plants measured in centimeters from ground level to the apex of the tassel, recorded 15 days prior to harvest.

Ear Diameter (inches): (ED)

Ear length (cm) (EL): measured for five ears.

Grain yield per plant (GYPP) (g): It was calculated by dividing the grain yield per plot (adjusted to 15.5% grain moisture) by the number of plants per plot during harvest.

Grain yield per hectare (GYPH) (ton): It was calculated by converting the grain yield per plot at 15.5% moisture content to grain yield per hectare .

Count of rows ear-1 (RPE): Employing 10 random ears plot-1 at the time of harvest.

Kernels per row (KPR): Assessed using the same 10 random ears in plot 1. 8. 100-kernel weight (100KW) (g): Standardized at 155g water per kilogram of grain.

Straw yield per plant (kg) (SYPP)

Harvest index (%) (HI).

Water productivity (WP): WP (kg /m3) = Yield (kg /ha) /calculated ETc (m3 /ha). According to (Hillell, 1971).

Table 1. Classification, provenance, and kernel pigmentation of the maize genotypes under examination.

Genotype No.	Designation	Origin	Genetic nature	Grain colour
1	SC--166	ARC, Egypt	Single cross	Yellow
2	SC-162	ARC, Egypt	Single cross	Yellow
3	SC-168	ARC, Egypt	Single cross	Yellow
4	SC-167	ARC, Egypt	Single cross	Yellow
5	SC-164	ARC, Egypt	Single cross	Yellow
6	SC-124	ARC, Egypt	Single cross	White
7	SC-130	ARC, Egypt	Single cross	White
8	SC-131	ARC, Egypt	Single cross	White
9	Chinese	China	Single cross	Yellow
10	SC-10	ARC, Egypt	Single cross	White
11	TWC-352	ARC, Egypt	Three-way cross	Yellow
12	TWC-324	ARC, Egypt	Three-way cross	White
13	TWC-310	ARC, Egypt	Three-way cross	White
14	TWC-329	ARC, Egypt	Three-way cross	White
15	TWC-354	ARC, Egypt	Three-way cross	Yellow
16	TWC-321	ARC, Egypt	Three-way cross	White

SC= single cross, TWC= three way cross

Table 2. Soil water properties of National Research Center Research Station.

Site	pH	EC dSm^{-1}	OM	$CaCO_3$	(Soil water content %vb)		
			%		FC	WP	AW
NRC Farm	8.2	2.6	1.3	3.8	12.6	4.7	7.9

pH: (1.25), EC: electrical conductivity in the extracted soil paste, OM organic matter, FC: field capacity, WP: wilting point, AW available water, vb volume basis.

Table 3. Some soil physical characteristics.

Depth, cm	Particle Size distribution, %				Texture class	θ_S % on weight basis			HC (cmh^{-1})	BD (g/cm^3)	P (cm^3 voids /cm^3 soil)
	C. Sand	F. Sand	Silt	Clay		F.C.	W.P.	AW			
0-15	9.3	78.2	7.9	4.6	Sandy	14	6	8	6.68	1.69	0.36
15-30	9.1	77.1	8.2	5.6	Sandy	14	6	8	6.84	1.69	0.36
30-45	8.7	76.9	9.1	5.3	Sandy	14	6	8	6.91	1.69	0.36
45-60	9.0	78.5	7.7	4.8	Sandy	14	6	8	6.17	1.67	0.37

Model Description

Model Growth-Engine and Flowchart in Fig. 2.

Conceptually, AquaCrop is an expression of Eq. (1) but with refinements.

$$\left(\frac{Y_x - Y_a}{Y_x}\right) = k_y\left(\frac{ET_x - ET_a}{ET_x}\right) \qquad (1)$$

Let Yx be the maximum yield and Ya denote the actual yield. ETx denotes the maximal evapotranspiration, while ETa signifies the actual evapotranspiration. Furthermore, ky represents the proportionality constant that correlates the relative yield loss to the relative decrease in evapotranspiration. Numerous adaptations of Equation (1) are documented in the literature (Stewart et al., 1974; Tanner and Sinclair, 1983) .

To mitigate the impact of non-productive water usage (E), crop evapotranspiration (ET) is partitioned into soil evaporation (E) and crop transpiration (Tr). It is particularly vital when canopy cover is inadequate, as soil evaporation (E) may be the predominant component influencing evapotranspiration (ET). The harvestable yield (Y) is ascertained by the interplay of biomass (B) and harvest index (HI) to distinguish the effects of environmental stress on B from its effects on HI.

The distinction between these two types of impacts, which possess fundamental differences, facilitates the establishment of functional connections grounded in underlying physiological processes. The aforementioned alterations led to the establishment of the following equations that underpin the AquaCrop growth model:

$$B=WP\times\sum Tr \qquad (2)$$

$$Y=B\times HI \qquad (3)$$

WP denotes the water productivity parameter, quantified in kg (biomass) m⁻² (land area) mm⁻¹ (water transpired). The shift from Equation (1) to Equation (2) improves the model's robustness and relevance. This is ascribed to the prudent disposition of WP when modified for climatic conditions, as elucidated by Steduto et al. (2007). Both equations delineate the design of a water-driven crop model, as articulated by Steduto (2003). Equation (2) in AquaCrop utilizes daily time periods to account for the variable fluctuations in water availability, soil evaporation, crop transpiration, and air temperature. This contrasts with Equation (1), which calculates production over prolonged periods, spanning weeks to months. Further notable improvements include a novel method to simulate canopy development, the differentiation of stress effects on canopy growth, stomatal conductance, canopy senescence, and pollination, as well as other components of harvest index (HI), which will be detailed later. AquaCrop, similar to other models, comprises the complete soil-plant-atmosphere system. The system includes the soil, which regulates its water balance; the plant, which involves its growth, development, and production; and the atmosphere, which encompasses its thermal patterns, precipitation, evaporation needs, and carbon dioxide concentrations. The model emphasizes irrigation in its management strategy, while also considering soil fertility, especially nitrogen content, and water-related characteristics, like soil borders and mulches. These variables influence the soil water balance and the development and growth of crops. Management rules encompass stipulations for the production of forage crop cuttings. Omitting pests, illnesses, and weeds. Figure 1 illustrates the linkages among the various model components. Table 3 delineates the crop parameters for maize, encompassing both conservative and non-conservative values, derived from multiple references.

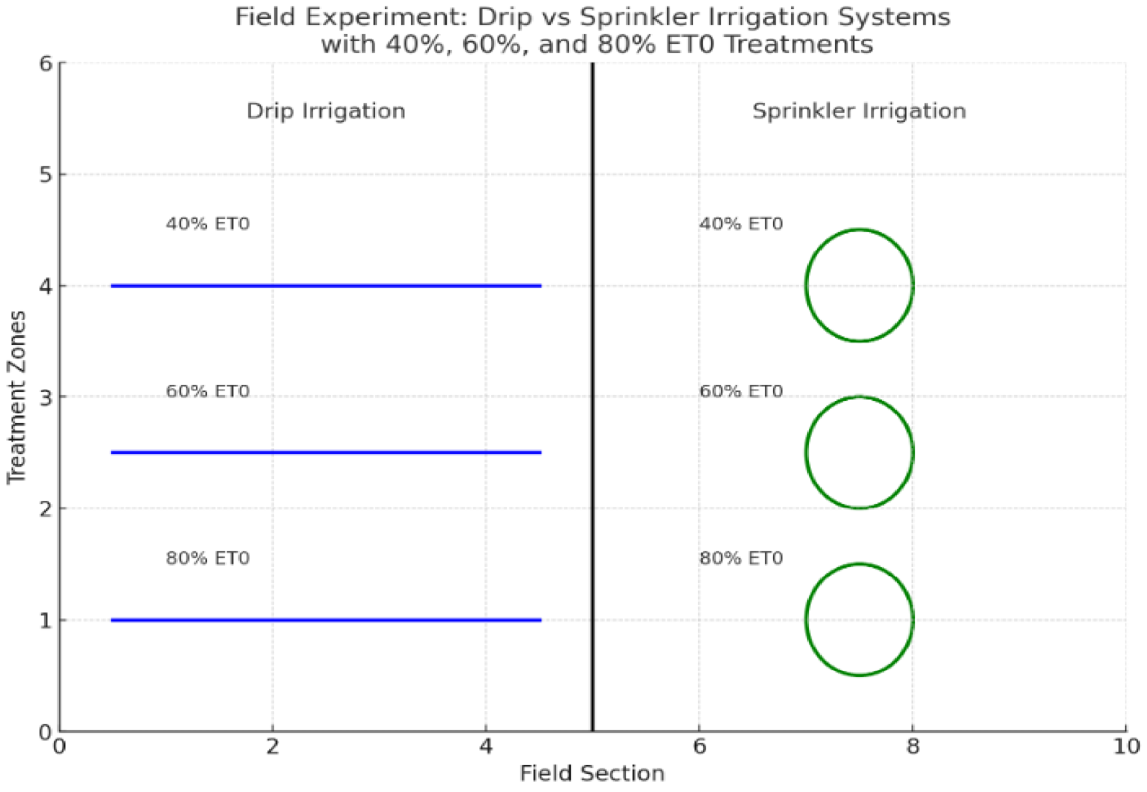

Fig. 1. Layout of the field experiments for the effect of different water treatments and irrigation systems on Maize crop at NRC's Farm, El-Noubaria region, Elbuhaira Governorate).

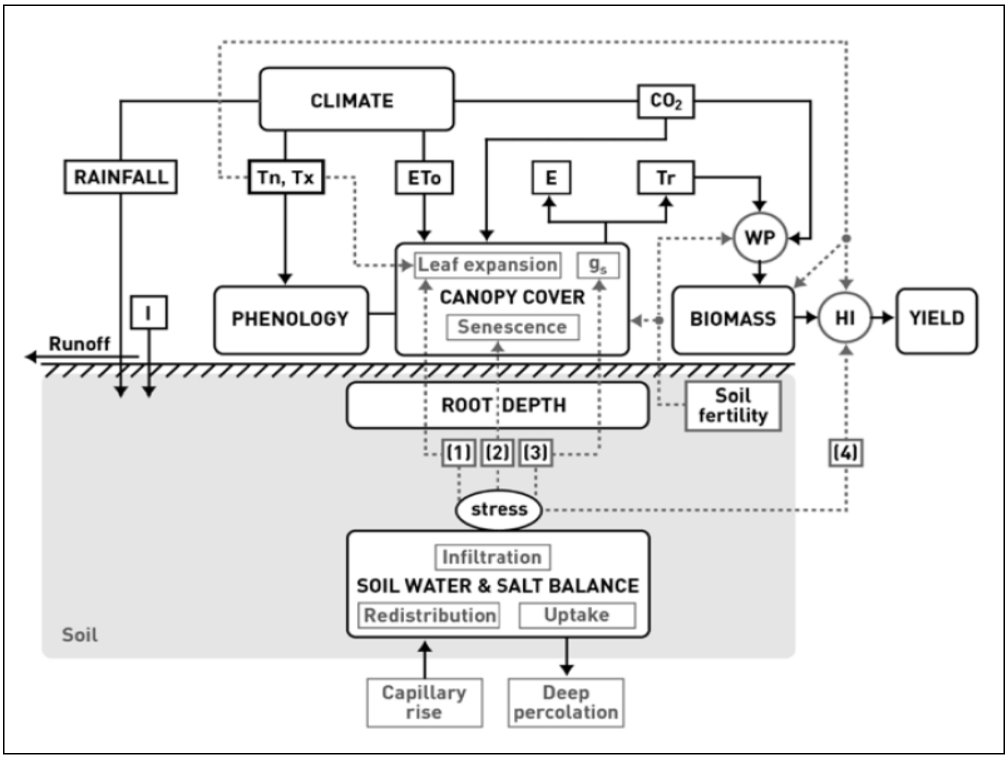

Fig. 2. Presents a chart of AquaCrop illustrating the primary elements of the soil–plant–atmosphere continuum, along with the parameters influencing phenology, canopy cover, transpiration, biomass production, and final yield (I – Irrigation; Tn – Minimum air temperature; Tx – Maximum air temperature; ETo – Reference evapotranspiration; E – Soil evaporation; Tr – Canopy transpiration; gs – Stomatal conductance). WP – Water Productivity; HI – Harvest Index; CO_2 – Atmospheric Carbon Dioxide Concentration; (1), (2), (3), (4) – Various Water Stress Response Functions. Solid lines denote direct connections between variables and processes. Dashed lines denote feedback. Refer to the description of procedures for clarification.

Table 4. Conservative and non-conservative crop parameters for maize obtained from various sources.

Non-conservative parameters	**maize**
The base temperature (°C) at which crop development halts when falling below it.	8.0
The upper temperature (°C) above which crop growth no longer accelerates with increasing temperature.	30.0
The number of plants per hectare.	74000.0
The maximum depth (m) of effective root penetration.	2.0
The harvest index (HIo) expressed as a percentage.	45.0
Conservative parameters:	
Water productivity (WP*) adjusted for reference evapotranspiration (ETo) and CO2 levels (gram/m²).	33.7
Water productivity adjusted for ETo and CO2 during the yield formation period (as a percentage of WP*).	100.0
The minimum air temperature (°C) below which pollination failure begins due to cold stress.	10.0
The maximum air temperature (°C) beyond which pollination fails due to heat stress.	40.0
The percentage of potential fruits that exceed the threshold.	50.0
Canopy growth coefficient (CGC): The daily increase in canopy cover, expressed as a fraction of soil covered.	0.182
Maximum canopy cover (CCx) as a fraction of soil cover.	0.900
Canopy decline coefficient (CDC): The reduction in canopy cover per day, expressed as a fraction.	0.117
Soil surface area (cm²) covered by an individual seedling when 90% of emergence has been reached.	3.000
The crop coefficient (Kcb,x) when the canopy is fully developed but before senescence begins.	1.070
The maximum rate of root water extraction (m³ water/m³ soil.day) in the top quarter of the root zone.	0.010
The maximum rate of root water extraction (m³ water/m³ soil.day) in the bottom quarter of the root zone.	0.003
The impact of canopy cover in decreasing soil evaporation during the late growth stage.	50.000
The upper threshold for soil water depletion affecting canopy expansion (p-exp).	0.150
The shape factor for the water stress coefficient affecting canopy expansion (0.0 = straight line).	3.000

Source: AquaCrop model (Version 4.0) as described by Raes et al. (2009a) and Steduto et al. (2009).

Water productivity (WP)

WP (kg /m3) = Yield (kg /fed) /calculated ETc (m3 /ha). According to (Hillell, 1971).

Where:

ETc = evapotranspiration for grape crop (m 3/fed) and WP = Water productivity or water use efficiency (kg/ m).

Water Requirements

Evapotranspiration (ET) is a crucial factor in determining the amount of water needed for irrigation. The term "crop water consumption" refers to the amount of water that a cultivated soil absorbs through both crop transpiration and soil evaporation. In order to determine the maximum water needed for irrigation, it is necessary to identify the highest water demand or peak evapotranspiration (ET). The maximum rates vary from 5-6 mm/d in places with moderate dryness to 8-9 mm/d in regions with high temperatures and low humidity. To calculate the irrigation demand, subtract the amount of rainfall, if any, from the evapotranspiration (ET). Additionally, it is important to take into account the water losses caused by deep percolation and runoff. The water loss is often expressed as a fraction or percentage of the total water demand. If F l represents the fraction of water loss, then the total amount of irrigation water required, I w (mm/d), is equal to E− R.

Statistical analysis

The study employed a split-plot design with three replicates, allocating the full plot to water irrigation and the subplot to genotypes. The gathered data was subjected to a thorough analysis of variance, using the methods outlined by Snedecor and Cochran (1980). The importance of mean differences was assessed using the Least Significant Differences (LSD) test at a significance threshold of 0.05.

Results and Discussion

1. Analysis of Variance

Table 5 presents the analysis of variance for the split-plot design investigating the performance of 16 commercial maize hybrids under three irrigation levels across the 2022 and 2023 growing seasons. The analysis partitions the total variation into sources attributable to years (Y), irrigation levels (I), genotypes (G), and their interactions. The whole-plot is irrigation, while genotypes are the sub-plot.

The results indicate that the mean squares for years were not statistically significant for all parameters, with the exception of ear length (EL), rows per ear (RPE), and plant height (PH), which were very significant. This indicates that climatic conditions do not influence the majority of the features examined. The irrigation exerted a substantial influence on the assessed characteristics. The mean squares for water irrigation and genotypes were very significant for all examined characteristics, except for water productivity, which exhibited no significant effect from water irrigation. This indicates that water amount significantly influences all examined variables, with the exception of water productivity. Furthermore, genotype exhibited a distinct and substantial impact on all examined traits. The mean squares from the first-order interaction between factors I (irrigation) and Y (year) were statistically significant ($P < 0.05$) for the characteristics RPE (root penetration effectiveness) and PH (plant height). The interaction between the parameters G (genotype) and Y was statistically significant ($P \leq 0.05$ or 0.01) for the traits EL (ear length), RPE, PH, and KPP (kernel per plant). The interaction between genotype and years (G×I) was very pronounced for all examined characteristics. The mean squares from the second-order interaction, specifically the interaction of genotype, drought, and year (G×D×Y), were statistically significant ($P \leq 0.05$ or 0.01) for the attributes of ear diameter, rows per ear, and plant height. The analysis of variance indicates that both irrigation levels and genotypes significantly affected the evaluated attributes, with their interaction also being crucial in predicting hybrid performance under different water availability situations.

The results in Table (6) indicate that maize genotype performance fluctuates based on irrigation methods and the year, highlighting the potential for selecting genotypes that excel under particular water conditions, as previously indicated by studies from Tollenaar (1999), Sabra et al. (2024), Al-Naggar et al. (2011, 2014, 2015), Younis et al. (2021), and Duvick (1984). The effect of diminished water irrigation on the average grain yield per plant mirrored its effect on grain production per hectare, resulting in reductions of around 60.40% and 38.14%, respectively. Other studies have recorded reductions in grain output due to drought stress, as evidenced by the findings of Al-Naggar et al. (2004, 2008a, 2008b, 2009, 2011a). Denmead and Shaw (1960) noted that water deficiency during the vegetative stage of maize growth led to a 25% reduction in grain yield. Water scarcity during silking caused a 50% loss in grain output, but water scarcity during grain filling resulted in a 21% decrease in grain yield.

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Table 5. Combined analysis of variance of mean of squares across 2022 and 2023 years of split plot design for studied 16 maize genotypes under three water irrigation.

Source	df	Mean Square				
		EL	ED	RPE	KPR	KWPP
Year (Y)	1	9.58**	0.004	4.01**	10.5	242
Irrigation (I)	2	720.81**	20.75**	137.34**	3765**	205216**
Y×I	2	0.89	0.09	1.42*	11.22	15.85
Error	12	0.49	0.04	0.31	3.71	106
Genotype(G)	15	56.22**	0.96**	12.57**	425.9**	9806**
Y×G	15	1.02**	0.02	1.59**	4.03	158
I×G	30	8.25**	0.15**	2.75**	38.42**	2293**
Y×I×G	30	0.5	0.04**	0.92**	5.16	55.6
Error	180	0.38	0.02	0.19	3.79	197.2
C V%		3.72	3.75	3.31	5.46	11.07
		100-KW	PH	KPP	GYPP	SYPP
Year (Y)	1	0.003	264.5**	5645	18.21	1.69
Irrigation (I)	2	1812**	139589**	1501290**	254683**	59012**
Y×I	2	0.1	136.9*	4299	69.15	29.02
Error	12	0.81	24.9	2336	226	241
Genotype(G)	15	159.7**	15499**	86431**	11218**	31630**
Y×G	15	0.06	124.6*	1985*	12.08	46.42
I×G	30	33.31**	6215**	7817**	1823**	12506**
Y×I×G	30	0.13	109.5*	1064	8.44	23.35
Error	180	0.76	70.02	1173	120.9	336
C V%		3.53	4.7	7.29	9.13	14.2
		HI%	GYPH(t)	WP		
Year (Y)	1	0.58	0.04	0.17		
Irrigation (I)	2	5179**	715.4**	9.89		
Y×I	2	8.49	0.21	0.04		
Error	12	29.68	1.38	8.13		
Genotype(G)	15	1108**	27.76**	0.49**		
Y×G	15	3.54	0.03	0.01		
I×G	30	589**	4.66**	0.52**		
Y×I×G	30	1.66	0.02	0.02		
Error	180	34.98	0.31	0.06		
C V%		11.43	9.26	11.98		

EL= Ear length, ED= Ear dimeter, RPE= row per ear, KPR= kernnl per row, KWPP= kernal weight per plant, 100-KW= 100 kernel weight, PH= plant height, BYPP= biological yield per plant, KPP= noumber of kerenel per plant, GYPP= grain yield per plant, SYPP= straw yield per plant, HI% = harvest index, GYPH= grain yield per hectar, WP= water productivity.

Table 6. Means of studied traits under three water quantities across all studied genotypes and across 2022 and 2023 seasons.

Water irrigation	40%	Ch%	60%	Ch%	80%	LSD $_{0.05}$	LSD $_{0.01}$
EL	13.91	28.26**	16.68	13.98**	19.39	0.22	0.31
ED	3.29	21.85**	3.82	9.26**	4.21	0.07	0.09
RPE	12.05	16.20**	12.72	11.54**	14.38	0.17	0.24
KPR	29.48	29.83**	35.46	15.59**	42.01	0.61	0.85
KWPP	81.93	52.99**	124.44	28.61**	174.30	3.23	4.53
100-KW (g)	20.16	30.07**	24.97	13.39**	28.83	0.28	0.40
PH (cm)	146.16	33.65**	167.77	23.84**	220.30	1.57	2.20
BYPP (g)	181.50	45.31**	235.41	29.07**	331.88	3.48	4.88
KPP	355.92	41.04**	450.05	25.45**	603.66	15.20	21.31
GYPP(g)	72.99	58.34**	113.04	35.48**	175.21	4.73	6.63
SYPP (g)	108.51	30.74**	122.37	21.89**	156.67	4.88	6.85
HI%	59.41	-32.70**	50.99	-13.89**	44.77	1.71	2.40
GYPH(t)	3.54	60.40**	5.53	38.14**	8.94	0.37	0.52
WP (kg/m3)	2.42	-36.10	2.12	-19.47	1.78	ns	ns

EL= Ear length, ED= Ear dimeter, RPE= row per ear, KPR= kernnl per row, KWPP= kernal weight per plant, 100-KW= 100 kernel weight, PH= plant height, BYPP= biological yield per plant, KPP= noumber of kerenel per plant, GYPP= grain yield per plant, SYPP= straw yield per plant, HI% = harvest index, GYPH= grain yield per hectar, WP= water productivity.

Table 7. Means of studied traits of all genotypes under sandy soil across 2022 and 2023.

	EL	**ED**	**RPE**	**KPR**	**KWPP(g)**	**100-KW(g)**	**PH(cm)**
SC-166	17.5c	3.88bc	12.67ef	33.53g	123.0efg	26.73c	147.1gh
SC-162	19.5a	3.78def	13.06d	40.06bc	147.2b	25.52f	203.6c
SC-168	17.7c	4.03a	14.00ab	40.36b	145.6b	25.81f	205.4c
SC-167	18.4b	3.96ab	13.11d	40.22bc	145.3b	26.72c	215.6b
SC-164	17.6c	3.77def	12.89de	42.36a	126.2ef	24.64g	229.1a
SC-124	17.8c	4.00a	13.78bc	38.33de	141.6bc	26.55cd	213.4b
SC-130	17.4c	3.77def	14.28a	35.75f	135.8cd	23.69h	163.4f
SC-131	18.2b	3.81cdef	12.50f	38.36de	158.2a	29.10a	179.5e
Chinese	15.5f	4.02a	14.22a	27.31j	114.9g	27.56b	161.6f
SC-10	16.3de	3.73fg	12.17g	39.00cd	126.1ef	22.39i	151.0g
TWC-352	15.9ef	3.84cde	13.83bc	29.36i	121.7efg	26.17cde	143.4h
TWC-324	15.8f	3.66g	11.83h	37.39e	141.1bc	23.84h	179.2e
TWC-310	14.2g	3.76ef	13.67c	34.97f	119.3fg	22.43i	147.8gh
TWC-329	12.3h	3.19i	11.67h	26.06j	62.7i	17.72k	136.1i
TWC-354	15.7f	3.32h	12.44fg	32.17h	92.1h	19.50j	191.5d
TWC-321	16.6d	3.86cd	12.67ef	35.19f	129.4de	26.07def	181.4e
LSD $_{0.05}$	0.41	0.09	0.28	1.28	9.24	0.57	5.50
	BYPP(g)	**KPP**	**GYPP(g)**	**SYPP(g)**	**HI%**	**GYPH(t)**	**WP (kg/m3)**
SC-166	191.5l	429.4ef	119.7cd	71.82j	39.17g	5.96dc	2.21abc
SC-162	258.2f	528.8bc	135.5b	122.64f	47.91f	6.74b	2.21abc
SC-168	312.6c	569.6a	147.8a	164.74bc	53.00e	7.35a	2.09cde
SC-167	252.1g	533.4bc	147.3a	104.78g	40.50g	7.34a	2.20bc
SC-164	360.0a	547.9ba	136.9b	223.13a	59.66bc	6.80b	2.23abc
SC-124	321.0b	533.8bc	146.3a	174.64b	55.38ed	7.30a	2.33ab
SC-130	287.2d	515.0c	125.9c	161.30cd	55.92cde	6.28c	2.37a
SC-131	245.2h	484.6d	147.8a	97.45gh	40.69g	7.37a	2.00edf
Chinese	243.4h	393.4h	110.7ef	132.72f	54.42e	5.51ef	1.85fg
SC-10	201.3k	475.8d	111.9ef	89.44hi	46.86f	5.59ef	1.81g
TWC-352	214.0j	418.1fg	117.1ed	96.89hg	48.45f	5.85de	1.99def
TWC-324	261.4f	444.2e	109.7f	151.77de	58.74bcd	5.46f	1.97defg
TWC-310	199.4k	482.8d	112.6efd	86.76hi	45.06f	5.61def	1.94efg
TWC-329	140.5m	307.8i	57.4h	83.07ij	60.85ab	2.87h	2.12cd
TWC-354	237.6i	402.8gh	80.4g	157.24cde	64.72a	4.00g	2.19bc
TWC-321	268.2e	450.5e	119.7cd	148.52e	56.25cde	5.96cd	2.19bc
LSD $_{0.05}$	5.60	22.53	7.23	12.07	3.89	0.37	0.17

EL= Ear length, ED= Ear dimeter, RPE= row per ear, KPR= kernnl per row, KWPP= kernal weight per plant, 100-KW= 100 kernel weight, PH= plant height, BYPP= biological yield per plant, KPP= noumber of kerenel per plant, GYPP= grain yield per plant, SYPP= straw yield per plant, HI% = harvest index, GYPH= grain yield per hectar, WP= water productivity.

Values followed by the different letters within a column are significantly different at $P < 0.05$, as determined by the LSD test.

The relatively smaller decrease in grain production shown in this study as a result of drought during the silking stage, in comparison to earlier findings, could be attributed to variations in soil characteristics and climatic circumstances that were present throughout different seasons and locations of the several investigations. The decrease in water irrigation percentage resulted in significant reductions in various aspects of maize grain yield. These include a decrease in ear length by 28.26% and 13.98%, ear diameter by 21.85% and 9.26%, row per ear by 16.20% and 11.54%, kernels per row by 29.83% and 15.59%, kernels weight per plant by 52.99% and 28.61%, 100-kernel weight by 30.07% and 13.39%, plant height by 33.65% and 23.84%, biological yield per plant by 45.31% and 29.07%, kernels per plant by 41.04% and 25.45%, and straw yield per plant by 30.74% and 21.89%. In contrast, reducing water irrigation resulted in significant improvements in the harvest index, with increases of 32.70% and 13.89%. This can be attributed to the fact that both the biological yield and straw yield were low when subjected to water stress. Although the water irrigation quantity led to an increase in water productivity by 36.10% and 19.47% under 40% and 60% water irrigation, respectively, this increase was not statistically significant. The elongation of the results in this investigation, caused by water stress, was consistent with the findings of Monneveux et al. (2005) and Al-Naggar et al. (2004, 2008 a,b, 2009, and 2011a), Wu et al. (2022), Li et al. (2022) and Luan (2021).

2.b. Effect of genotype

The yield and yield components of maize hybrids are adversely impacted by inadequate water supply and inappropriate irrigation schedule. The available irrigation water must be utilized in accordance with the water requirements of maize.

Maize genotypes × irrigation quantity interaction

In general, the maize crosses exhibited significant variation across all studied traits (Table 8). Higher values for these traits were considered favorable. The top-performing crosses were identified based on their means for grain yield per plant and hectare, as well as related characters. The five leading crosses were SC.164, SC.124, SC.162, SC.168, and SC.167, which demonstrated the highest means for most traits. Specifically; SC.164 ranked first for eight traits; plant height, kernels per row, kernels per plant, grain yield per plant, biological yield per plant, straw yield per plant, grain yield per hectare, and water productivity. SC.124 ranked second, showing the highest values for seven traits: plant height, ear diameter, rows per ear, kernels per plant, grain yield per plant and hectare, straw yield per plant, and water productivity. SC.162, SC.168, and SC.167 followed closely, ranking second for seven out of 14 traits. They exhibited high and significant means for ear length, kernels per row, kernel weight per plant, kernels per plant, grain yield per plant and hectare, water productivity, and other traits. SC.131 ranked third, recording high values for five traits. Conversely, TWC.329 ranked last, recording the lowest values for all traits in this study. These results highlight the superior performance of certain maize crosses, which can inform breeding programs and irrigation strategies to enhance maize productivity under varying water conditions.

Table 8. Means of studied traits of interaction of genotypes and water irrigation under sandy soil across 2022 and 2023.

	40%	60%	80%	40%	60%	80%
GEN		EL			ED	
SC-166	13.81	19.59	19.13	3.39	3.93	4.33
SC-162	16.89	19.99	21.76	3.35	3.80	4.20
SC-168	15.50	17.34	20.24	3.65	4.10	4.33
SC-167	14.69	18.15	22.35	3.48	4.05	4.36
SC-164	15.94	17.33	19.53	3.31	3.71	4.30
SC-124	15.70	17.32	20.31	3.64	4.07	4.29
SC-130	14.44	17.83	20.07	3.21	4.07	4.02
SC-131	14.00	19.47	21.16	3.28	3.88	4.26
Chinese	14.34	15.33	16.88	3.49	4.10	4.46
SC-10	13.69	15.33	19.74	3.16	3.75	4.27
TWC-352	11.39	16.74	19.63	2.97	3.83	4.70
TWC-324	12.68	14.53	20.23	3.02	3.63	4.32
TWC-310	12.02	13.64	17.00	3.38	3.68	4.22
TWC-329	9.66	11.06	16.21	2.81	3.20	3.55
TWC-354	14.50	15.51	17.10	3.03	3.33	3.59
TWC-321	13.26	17.68	18.87	3.41	3.98	4.19
LSD0.05		0.53			0.12	
LSD0.01		0.93			0.21	
		RPE			KPR	
SC-166	12.00	12.00	14.00	22.67	37.25	40.67
SC-162	12.00	12.50	14.67	35.92	38.08	46.17
SC-168	13.33	13.33	15.33	33.50	40.75	46.83
SC-167	12.00	12.67	14.67	34.25	40.33	46.08
SC-164	12.00	12.00	14.67	40.75	42.00	44.33
SC-124	12.00	13.33	16.00	36.58	35.42	43.00
SC-130	13.50	14.00	15.33	27.33	35.42	44.50
SC-131	11.50	12.00	14.00	30.00	39.75	45.33
Chinese	12.00	14.67	16.00	22.83	27.83	31.25
SC-10	12.00	12.00	12.50	32.25	37.58	47.17
TWC-352	12.00	13.00	16.50	20.83	30.17	37.08
TWC-324	11.50	12.00	12.00	29.83	39.75	42.58
TWC-310	12.50	14.00	14.50	27.25	34.17	43.50
TWC-329	10.50	12.00	12.50	20.75	23.33	34.08
TWC-354	12.00	12.00	13.33	26.92	32.33	37.25
TWC-321	12.00	12.00	14.00	30.08	33.25	42.25
LSD $_{0.05}$		0.38			1.69	
LSD0.01		0.66			2.93	

		KWPP(g)			100-KW(g)	
SC-166	62.37	139.19	167.48	20.91	28.92	30.37
SC-162	92.73	145.81	203.18	24.83	25.49	26.23
SC-168	110.23	142.68	183.93	24.47	26.20	26.77
SC-167	89.29	145.73	200.90	20.60	27.72	31.83
SC-164	78.69	133.69	166.35	22.44	23.59	27.88
SC-124	108.22	134.55	182.00	22.33	25.03	32.30
SC-130	104.99	139.62	162.81	20.23	23.03	27.81
SC-131	80.69	161.23	232.77	22.04	29.34	35.92
Chinese	101.34	101.48	141.84	24.28	27.52	30.88
SC-10	69.66	98.44	210.26	16.97	18.63	31.58
TWC-352	59.33	104.74	200.95	18.48	28.65	31.39
TWC-324	81.46	140.50	201.41	16.66	26.10	28.76
TWC-310	76.50	127.82	153.45	17.88	22.50	26.91
TWC-329	39.80	56.21	92.04	13.54	17.98	21.64
TWC-354	60.57	96.07	119.55	14.99	21.19	22.32
TWC-321	95.02	123.25	169.93	21.92	27.60	28.70
LSD $_{0.05}$		12.19			0.76	
LSD0.01		21.11			1.31	
		PH(cm)			BYPP(g)	
SC-166	123.92	155.00	162.25	112.50	211.67	250.42
SC-162	196.33	203.33	211.25	220.83	238.25	315.42
SC-168	180.58	192.92	242.75	242.25	326.75	368.75
SC-167	163.58	219.17	264.17	159.17	250.33	346.67
SC-164	137.83	266.67	282.92	210.00	397.92	472.08
SC-124	166.58	171.08	302.50	242.08	267.08	453.75
SC-130	131.17	137.92	221.25	199.75	219.75	442.08
SC-131	117.50	143.83	277.08	151.58	209.50	374.58
Chinese	145.83	156.92	182.17	168.75	207.08	354.42
SC-10	138.17	146.00	168.75	162.50	198.33	243.08
TWC-352	122.58	140.33	167.42	165.42	218.92	257.58
TWC-324	147.92	153.25	236.42	182.50	245.17	356.67
TWC-310	137.08	146.58	159.83	177.25	198.33	222.50
TWC-329	125.08	132.00	151.25	117.75	131.25	172.50
TWC-354	134.75	141.75	297.92	157.08	182.08	373.75
TWC-321	169.58	177.58	196.92	234.58	264.08	305.83
LSD $_{0.05}$		7.26			7.39	
LSD0.01		12.58			12.81	
		KPP			GYPP(g)	
SC-166	272.00	447.00	569.33	56.87	129.31	172.96
SC-162	431.00	477.00	678.33	107.03	121.48	178.08
SC-168	445.00	543.83	720.00	108.30	141.82	193.42
SC-167	411.00	510.00	679.17	84.40	141.44	216.01
SC-164	489.00	504.00	650.67	109.74	118.90	181.95
SC-124	439.00	474.50	688.00	97.99	118.85	222.16
SC-130	369.17	495.83	680.00	74.65	113.93	189.10
SC-131	342.00	477.00	634.67	75.40	140.00	227.93
Chinese	274.00	406.33	500.00	66.10	111.90	154.08
SC-10	387.00	451.00	589.50	65.71	83.95	185.95
TWC-352	250.00	392.00	612.33	46.22	112.24	192.80
TWC-324	344.50	477.00	511.00	57.46	124.49	147.06
TWC-310	340.00	478.33	630.00	61.06	107.61	169.13
TWC-329	217.00	280.00	426.50	29.47	50.34	92.49
TWC-354	323.00	388.00	497.50	48.33	82.24	110.62
TWC-321	361.00	399.00	591.50	79.16	110.13	169.66
LSD $_{0.05}$		29.72			9.54	
LSD0.01		51.48			16.53	
		SYPP(g)			HI%	
SC-166	55.63	82.36	77.46	48.37	38.80	30.34
SC-162	113.80	116.77	137.34	51.52	48.91	43.31
SC-168	133.95	184.93	175.33	55.25	56.23	47.51
SC-167	74.77	108.89	130.66	40.20	43.61	37.69
SC-164	100.26	279.01	290.13	47.63	70.12	61.24
SC-124	144.10	148.24	231.59	59.52	55.56	51.05
SC-130	125.10	105.82	252.99	62.38	48.16	57.23
SC-131	76.19	69.50	146.65	49.96	33.03	39.08
Chinese	102.65	95.19	200.34	60.83	45.90	56.53

SC-10	96.79	114.39	57.14	59.47	57.56	23.56
TWC-352	119.20	106.68	64.78	71.73	48.56	25.06
TWC-324	125.04	120.68	209.60	68.16	49.19	58.86
TWC-310	116.19	90.72	53.37	65.55	45.71	23.93
TWC-329	88.28	80.91	80.01	74.84	61.50	46.21
TWC-354	108.76	99.84	263.13	69.23	54.66	70.28
TWC-321	155.42	153.95	136.17	65.91	58.31	44.54
LSD $_{0.05}$		15.91			5.13	
LSD0.01		27.55			8.89	
		GYPH(t)			WP(kg/m3)	
SC-166	2.76	6.32	8.82	2.17	2.40	2.07
SC-162	5.19	5.94	9.08	2.16	2.44	2.02
SC-168	5.25	6.94	9.86	2.11	2.15	1.99
SC-167	4.10	6.91	11.02	2.41	2.15	2.04
SC-164	5.32	5.81	9.28	2.48	2.15	2.06
SC-124	4.75	5.82	11.33	2.48	2.43	2.07
SC-130	3.62	5.57	9.64	2.59	2.45	2.08
SC-131	3.65	6.85	11.62	2.56	2.40	1.03
Chinese	3.20	5.47	7.86	2.62	1.87	1.04
SC-10	3.18	4.10	9.48	2.52	1.86	1.05
TWC-352	2.24	5.49	9.83	2.52	1.91	1.53
TWC-324	2.79	6.09	7.50	2.49	1.87	1.54
TWC-310	2.95	5.26	8.63	2.38	1.86	1.56
TWC-329	1.43	2.46	4.72	2.37	1.87	2.12
TWC-354	2.35	4.02	5.64	2.40	2.08	2.11
TWC-321	3.83	5.38	8.65	2.41	2.06	2.10
LSD0.05		0.48			0.21	
LSD0.01		0.84			0.37	

EL= Ear length, ED= Ear dimeter, RPE= row per ear, KPR= kernnl per row, KWPP= kernal weight per plant, 100-KW= 100 kernel weight, PH= plant height, BYPP= biological yield per plant, KPP= noumber of kerenel per plant, GYPP= grain yield per plant, SYPP= straw yield per plant, HI% = harvest index, GYPH= grain yield per hectar, WP= water productivity.

A significant range of means was evident across the various maize crosses for grain yields and related traits under different irrigation conditions: well-watered at 80% (normal irrigation), and water-stressed at 60% (moderate stress) and 40% (severe stress) of water requirement over two years, as detailed in Table 7. For plant height, the top three crosses under 80% irrigation were SC.168, SC.124, and TWC.321, while under moderate irrigation, they were SC.162, SC.167, and SC.164. The best performers under severe stress were SC.162, SC.168, and TWC.321. The highest mean values for ear length were achieved by SC.162, SC.167, and SC.131 under well-watered conditions, and by SC.166, SC.162, and SC.131 under moderate stress. Under severe stress, SC.162, SC.164, and SC.124 exhibited the highest values. Ear diameter was notable for crosses SC.162, SC.164, and SC.124 under severe water stress, SC.166, SC.162, and SC.131 under moderate stress, and SC.162, SC.167, and SC.131 under normal irrigation. SC.162 consistently performed well across all water irrigation levels for ear length and ear diameter, while SC.131 excelled under well-watered and moderate conditions. The crosses SC.124, Chinese cross (SC. China), and TWC.352 displayed the highest number of rows per ear under well-watered conditions, with SC.130, SC. China, and TWC.310 excelling under 60% irrigation, and SC.168, SC.130, and TWC.310 under severe stress. SC.10, SC.168, and SC.162 ranked highest for kernels per row under well-watered conditions, while SC.168, SC.167, and SC.164 led under 60% irrigation, and SC.162, SC.164, and SC.124 excelled under severe irrigation. For kernel weight per plant, SC.162, SC.131, and SC.10 performed well, with SC.162, SC.167, and SC.131 under different irrigation levels. The highest values for 100-kernel weight varied across different crosses under different irrigation levels. SC.167, SC.124, and SC.131 excelled for biological yield per plant under various irrigation levels. SC.168, SC.164, and SC.130 showed high values for kernels per plant under different irrigation conditions. Grain yield per plant and per hectare were highest for specific crosses under different irrigation levels. Straw yield per plant varied among crosses under different irrigation conditions. Harvest index was influenced by different crosses under varying irrigation levels. Water productivity (WP) was highest for specific crosses under different irrigation conditions. Table 7 show the comparison between observed and simulated water productivity using the AquaCrop model, indicating the potential to achieve high yields and components simultaneously through model calibration. The positive correlation between observed and simulated water productivity, grain yield, and yield components validates the results.

The analysis of Tables 4-9 revealed that the top-performing genotype across various traits and irrigation levels was SC.168, excelling in 16 out of 33 cases. Specifically; SC.168 ranked first for one trait (KPP) under all three water stress levels, four traits (BYPP, GYPP, GYPH, and SYPH) under both 60% and 40% water irrigations, one trait (KPR) under moderate and well-watered conditions, and three traits (KWPP, 100-KW, and PH) exclusively under severe water stress. The second-ranked genotype was SC.164, leading in 14 out of 33 cases; SC.164 excelled in traits KPR and KPP under 40% and 60% water irrigations, PH, BYPP, SYPP, and HI% under moderate and normal irrigation, and GYPP and GYPH under severe water stress. The third-ranked cross, SC.124, demonstrated strong performance in 13 out of 33 cases across the three water irrigation levels; SC.124 excelled in traits such as BYPP under all three water stress levels, KPP under both 40% and 80% water irrigation, KPR, KWPP, and SWPP under 40% water irrigation, 100-KW, PH, GYPP, and GYPH under well-watered conditions, and WP only under moderate stress. These three hybrids, SC.168, SC.164, and SC.124, show promise and are recommended for maize breeding programs focused on enhancing drought tolerance in their respective stress environments.

Table 9. Means of studied traits of genotypes under sandy soil across 2022 and 2023.

Irrigation system	Drought treatment	Geno -type	EL	ED	RPE	KPR	KWPP	100-KW	PH
Drip	40%	1	17.5c	3.88bc	12.67ef	33.53g	123.0efg	26.73c	147.1gh
		2	19.5a	3.78def	13.06d	40.06bc	147.2b	25.52f	203.6c
		3	17.7c	4.03a	14.00ab	40.36b	145.6b	25.81f	205.4c
	60%	1	18.4b	3.96ab	13.11d	40.22bc	145.3b	26.72c	215.6b
		2	17.6c	3.77def	12.89de	42.36a	126.2ef	24.64g	229.1a
		3	17.8c	4.00a	13.78bc	38.33de	141.6bc	26.55cd	213.4b
	80 %	1	17.4c	3.77def	14.28a	35.75f	135.8cd	23.69h	163.4f
		2	18.2b	3.81cdef	12.50f	38.36de	158.2a	29.10a	179.5e
		3	15.5f	4.02a	14.22a	27.31j	114.9g	27.56b	161.6f
Sprinkler	40%	1	16.3de	3.73fg	12.17g	39.00cd	126.1ef	22.39i	151.0g
		2	15.9ef	3.84cde	13.83bc	29.36i	121.7efg	26.17cde	143.4h
		3	15.8f	3.66g	11.83h	37.39e	141.1bc	23.84h	179.2e
	60%	1	14.2g	3.76ef	13.67c	34.97f	119.3fg	22.43i	147.8gh
		2	12.3h	3.19i	11.67h	26.06j	62.7i	17.72k	136.1i
		3	15.7f	3.32h	12.44fg	32.17h	92.1h	19.50j	191.5d
	80 %	1	16.6d	3.86cd	12.67ef	35.19f	129.4de	26.07def	181.4e
		2	14.5g	3.77e	11.58h	29.66i	128.5e	22.67i	158.6g
		3	16.4d	4.05a	12.54f	27.6j	127.3eg	21.89h	144.2h
LSD $_{0.05}$			0.41	0.09	0.28	1.28	9.24	0.57	5.50
Irrigation system	Drought treatment	Geno -type	BYPP	KPP	GYPP	SYPP	HI%	GYPH(t)	WP (kg/m3)
Drip	40%	1	191.5l	429.4ef	119.7cd	71.82j	39.17g	5.96dc	2.21abc
		2	258.2f	528.8bc	135.5b	122.64f	47.91f	6.74b	2.21abc
		3	312.6c	569.6a	147.8a	164.74bc	53.00e	7.35a	2.09cde
	60%	1	252.1g	533.4bc	147.3a	104.78g	40.50g	7.34a	2.20bc
		2	360.0a	547.9ba	136.9b	223.13a	59.66bc	6.80b	2.23abc
		3	321.0b	533.8bc	146.3a	174.64b	55.38ed	7.30a	2.33ab
	80 %	1	287.2d	515.0c	125.9c	161.30cd	55.92cde	6.28c	2.37a
		2	245.2h	484.6d	147.8a	97.45gh	40.69g	7.37a	2.00edf
		3	243.4h	393.4h	110.7ef	132.72f	54.42e	5.51ef	1.85fg
Sprinkler	40%	1	201.3k	475.8d	111.9ef	89.44hi	46.86f	5.59ef	1.81g
		2	214.0j	418.1fg	117.1ed	96.89hg	48.45f	5.85de	1.99def
		3	261.4f	444.2e	109.7f	151.77de	58.74bcd	5.46f	1.97defg
	60%	1	199.4k	482.8d	112.6efd	86.76hi	45.06f	5.61def	1.94efg
		2	140.5m	307.8i	57.4h	83.07ij	60.85ab	2.87h	2.12cd
		3	237.6i	402.8gh	80.4g	157.24cde	64.72a	4.00g	2.19bc
	80 %	1	268.2e	450.5e	119.7cd	148.52e	56.25cde	5.96cd	2.19bc
		2	254.4fl	433.4ej	145.5a	99.35hj	47.48f	5.81dj	1.84g
		3	264.2em	511.4ck	124.4c	87.5ik	56.3e	7.52ab	2.24a
LSD $_{0.05}$			5.60	22.53	7.23	12.07	3.89	0.37	0.17

EL= Ear length, ED= Ear dimeter, RPE= row per ear, KPR= kernnl per row, KWPP= kernal weight per plant, 100-KW= 100 kernel weight, PH= plant height, BYPP= biological yield per plant, KPP= noumber of kerenel per plant, GYPP= grain yield per plant, SYPP= straw yield per plant, HI% = harvest index, GYPH= grain yield per hectar, WP= water productivity.

Values followed by the different letters within a column are significantly different at $P < 0.05$, as determined by the LSD test., Gynotypes 1, 2; 3: Three hybrids maize1= SC 168, 2=SC164 and 3=SC124.

Table 9. Comparison of Water Productivity (WP) Using AquaCrop Model Across Different Irrigation Systems, Drought Treatments, and Genotypes in Sandy Soil for the Years 2022 and 2023.

Irrigation system	Drought treatment	Genotype	Observed WP		Simulated WP by AquaCrop	
			GYPF(kg)	**(kg/m3)**	**GYPF(kg)**	**(kg/m3)**
Drip	40%	1	2504	1.23	4806	2.37
		2	2832	1.40	5435	2.68
		3	3088	1.52	5927	2.92
	60%	1	3084	1.52	5919	2.92
		2	2857	1.41	5484	2.70
		3	3067	1.51	5887	2.90
	80%	1	2639	1.30	5065	2.50
		2	3097	1.53	5944	2.93
		3	2315	1.14	4444	2.19
Sprinkler	40%	1	2349	1.16	4508	2.22
		2	2458	1.21	4718	2.33
		3	2294	1.13	4403	2.17
	60%	1	2357	1.16	4524	2.23
		2	1206	0.59	2315	1.14
		3	1681	0.83	3226	1.59
	80%	1	2504	1.23	4806	2.37
		2	2441	1.20	4685	2.31
		3	3160	1.56	6065	2.99
LSD $_{0.05}$			37	0.17	24	0.12

Gynotypes 1, 2; 3: Three hybrids maize1= SC 168, 2=SC164 and 3=SC124

Conclusion

In conclusion, the observed and simulated water productivity (WP) results suggest that it is feasible to achieve high WP, yields, and yield components simultaneously by calibrating the AquaCrop model. This is supported by the positive correlation between observed and simulated WP, grain yield, and yield components, as mentioned in the review. The study's findings confirm that the AquaCrop model can effectively simulate WP and yield components under varying irrigation conditions. Based on the results, the three hybrids - SC.168, SC.164, and SC.124 - are recommended for maize breeding programs aiming to improve drought tolerance in corresponding drought-stressed environments. These hybrids demonstrated superior performance across various traits and irrigation levels, making them suitable candidates for breeding programs focused on enhancing drought resilience in maize.

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