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Impact of Water Scarcity on Maize Productivity in Egyptian Conditions for Climate Change Adaptation

Ahmed S. Hegab, Mohamed M. Abdel Wahab, Essam Hammad, E., Yosri N. Ahmed, Alaa A. Khalil and **Beelal A. A. Ali***

Biological Agricultural Research Department, Central Laboratory for Agricultural Climate, (ARC), Giza, Egypt

A WATER scarcity is one of the detrimental consequences of climate change reflected in agricultural productivity. The primary focus of this study is to investigate the profitability of maize production for smallholder farmers in Egypt, considering the influence of climate change on limited water resources and the requirements of suitable irrigation methods that could help solve this critical issue. Therefore, two field experiments were conducted at Wadi El Natrun-El-Beheira Governorate during the summer seasons of 2022 and 2023. This work aimed to investigate the effects of three irrigation levels (60%, 80%, and 100%) and two irrigation systems (surface drip irrigation and subsurface drip irrigation) on growth, yield, and the economic assessments, of production costs and returns of maize (*Zea mays* L.) hybrid planted on sandy soil. Results indicated that the subsurface drip irrigation system performs better than the surface drip irrigation. The economic assessments revealed that subsurface drip irrigation yielded a higher average yield, meeting 100% of irrigation requirements (3.74 t fed^{-1}). Modernizing the subsurface drip irrigation system for maize crop is economically feasible, with a benefit-cost ratio of 2.58, indicating significant returns by reducing production costs and increasing revenues. As a result, the study recommends scaling up this system to all agricultural lands for maize crops because it has economic benefits and saves irrigation water

Keywords: Maize (*Zea mays* L.), water use efficiency, surface drip irrigation, subsurface drip irrigation, and climate change.

Introduction

Maize (*Zea mays* L.) is a staple crop grown in many different agroecological zones and farming practices, and it is considered one of the foremost important cereals in the world. People with diverse culinary tastes and socioeconomic backgrounds commonly consume it (Abayomi, *et al*., 2023). Maize contains vitamins C, E, K, B1 (thiamine), B2 (niacin), B3 (riboflavin), B5 (pantothenic acid), B6 (pyridoxine), folic acid, selenium, N-p-coumaric tryptamine, and N-ferrulyl tryptamine (Rouf Shah, *et al*. 2016). For the Egyptian national economy, maize is considered a strategic and significant crop as it's a constituent and indispensable part of the Egyptian human food and diet, as well as animal, and poultry feed. Generally, there is a great gap between the consumption and production of such crops. Maize globally ranks third among cereal crops after wheat and rice, according to the FAO, (2012).

A sufficient irrigation level significantly increased maize crop growth, yield, and productivity, where Hegab, *et al*., (2019) found that the highest irrigation levels, 100% ETc, and 80% ETc, have the highest growth and productivity, while 60% ETc has the lowest growth and yield in the maize crop. On the other hand, Yu, *et al*., 2021 reported that even with a high nitrogen supply, deficiency watering lowers yield. Cao, *et al*., 2021 proposed that more effective nutrient usage results from balanced soil water levels.

In a drip irrigation system, water is applied to the soil continuously and steadily at low pressure. This technique supplies water straight to the plant's root zone using applicators (drippers) situated on or below the ground's surface and operated at low pressure. Furthermore, contemporary irrigation systems, such as surface drip irrigation and subsurface drip irrigation, as essential systems implemented for water management. Both systems are employed to lower the quantity of water needed, evaporation, increase water use efficiency, and deliver nutrients to the root zones, leading to an increase in vegetative growth and crop production (Ayars **et al.**, 2015, Irmak *et al*., 2016 and Çolak *et al*., 2018).

Subsurface drip irrigation (SSDI) is considered one of the best irrigation techniques for increasing water use efficiency (WUE), which delivers small amounts of water at frequent irrigation intervals while causing little to no water loss through soil evaporation, runoff, and deep percolation (Hussein, 2015). Al-Mansor *et al.* (2015) concluded that deficit irrigation techniques and subsurface irrigation technologies boost tomato yield and water use efficiency in open fields when water is scarce. This improves plant water and nutrient uptake and

*Corresponding author email: beelalclac@gmail.com- beelal.ali@arc.sci.eg- Orcid ID: 0000-0003-2450-1371
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increases WUE. Water is saved, crop yields and quality are improved, and fertilizer delivery is easier using subsurface drip irrigation; nonetheless, system effectiveness depends on expert management (Waller and Yitayew, 2016). Low irrigation efficiency and excessive soil evaporation hinder crop root uptake. Relying on soil capillary action to supply water for crop development, subsurface irrigation is a water-saving irrigation technology whereby water is directly sent to crop roots in the soil via a network of percolation pipes or pipe pores buried under ground. (Jin *et al*., 2022). Muneer *et al*. (2022) concluded that subsurface drip irrigation can achieve maximum grain production and water productivity compared to drip irrigation in semi-arid regions. Likewise, Cao *et al*. (2022) found that conventional drip irrigation produced the lowest yield and water productivity, while alternate surface and subsurface drip irrigation enhanced grain production and water productivity.

Moreover, Imam (2021) confirmed that the most effective technique to apply and distribute water, while providing nutrients to plants, is through drip irrigation systems, which showed greater performance for sandy soils under desert conditions. In subsurface irrigation, the root system can easily absorb water and flourish because the water from subsurface irrigation deeply penetrates the soil within the active layer (Lamm *et al*., 2023). Guo *et al*. (2023) evaluated the influence of subsurface irrigation on crop output, Water Productivity, and Irrigation water productivity by conducting a meta-analysis of 528 pairs of research from 64 publications worldwide. Subsurface irrigation resulted in an overall increase in yield, water Productivity, and Irrigation water productivity of 5.96%, 21.62%, and 27.72%, respectively, higher than surface irrigation.

This investigation aimed to study the effect of three irrigation levels and two irrigation systems on growth, yield components, seed yield, and the economic assessments, of production costs and returns of maize hybrid planted on sandy soil to reveal the ideal mix between two irrigation systems and irrigation levels that would be advised to raise maize output under Wadi El Natrun-El-Beheira Governorate conditions.

Materials and Methods

Experimental design

Two field experiments were accomplished through the two successive summer seasons of 2022 and 2023, at a maize farm located in Wadi El Natrun, El-Beheira, Egypt, with latitude and longitude of the cultivated location of 30°26'51.9"N and 30°19'05.3"E, respectively (**Image 1)**. The experiment was designed using a split-plot design, with 3 replicates of two irrigation systems (surface drip irrigation and subsurface drip irrigation) at different irrigation levels, i.e. 60, 80, and 100% of Irrigation requirements (IR).

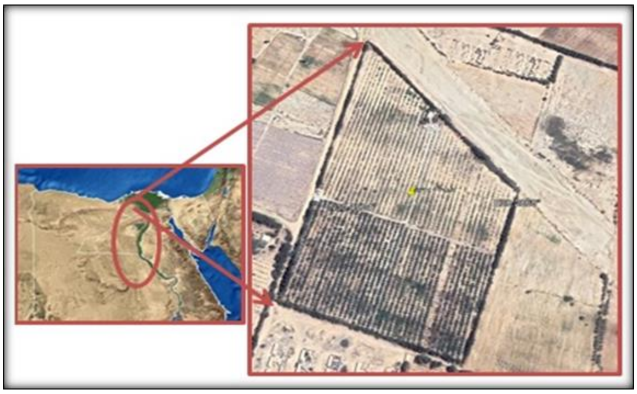

Image 1. Location map of Wadi El Natrun Experimental farm.

The distance between plants was 0.30 m apart; and 0.70 m between the rows, with a 2m distance left between each irrigation system. Soil chemical properties were examined before cultivation (Table 1) according to Page *et al*. (1982).

The climatic data concerning weather parameters, such as (temperatures, humidity, solar radiation, wind speed, and evapotranspiration (ETo) during both successive cultivation seasons (2022 and 2023) were obtained from the weather station, which belongs to the Central Laboratory for Agricultural Climate, and are demonstrated in Table 2. The evapotranspiration (ETo) value was calculated using Penman-Monteith method (Allen *et al*., 1998).

Plant used

Grains of maize (*Zea mays* L.) cultivar hybrid, three-way cross (T.W.C. 321) were procured from the Agricultural Research Center in Cairo, Egypt's Field Crops Research Institute. The sowing date was June 1st for the two consecutive seasons of 2022 and 2023.

Table 1. Chemical properties of experimental soil.

ECe (dS/m)	pH	meq/l							
		Cations				Anions			
		Ca^{++}	Mg^{++}	Na^{+}	K^{+}	CO_3^{--}	HCO_3^{-}	Cl^{-}	SO_4^{--}
3.77	6.7	13.53	12.13	24.33	0.83	0.0	5.73	10.93	44.46

Table 2. Monthly climatic data of the experimental site during the summer growth season of maize in both 2022/2023 seasons.

Month	First season (2022)				
	Max. Temp. °C	Min. Temp. °C	Ave. RH %	Wind Speed m/sec.	ETo mm/day
June	35.39	20.26	54.28	4.49	5.3
July	36.57	20.95	55.66	4.62	5.5
August	36.37	22.12	56.72	4.25	5.2
September	35.47	21.41	56.35	4.14	5.1
Second season (2023)					
June	36.10	20.06	53.21	4.65	6.4
July	38.56	22.12	53.97	4.63	6.6
August	37.32	21.69	55.40	4.18	6.2
September	36.41	22.26	54.82	3.95	6.1

Application of chemical fertilizers to maize plants.

Chemical fertilizers were applied during the season following the fertigation approach recommended by the Egyptian Ministry of Agriculture and Land Reclamation. Except for phosphorus fertilizer, that applied before cultivation during land preparation. Nitrogen and potassium fertilizers were injected into the irrigation system during cultivation (Anonymous, 2021).

Water requirements assessment.

According to the FAO Penman-Monteith Allen *et al*. (1998) approach, the total irrigation water levels were estimated. This approach accurately predicted ETo over a wide variety of locations and climates. The following formula was used to calculate the water use efficiency (WUE), according to FAO (1982). followed by obtaining crop water consumptive use values (ET_{crop}) as described by Doorenbos and Pruitt (1977):

$ET_{crop} = ET_o \times Kc$ mm/day (2)

Where:

ETo = The rate of evapotranspiration produced by an excessive surface of green cover of uniform height (8 to 15 cm), actively growing, totally shading the ground, and not experiencing water scarcity.

Kc = Crop coefficient (between 0.4 - 1.2, based on crop age).

Water requirements (WR) for each treatment were calculated as follows:

$WR = ETcrop \times LR$ % mm/day (3)

Where:

LR % = Leaching requirement percentage (21% of the water requirement based on the leaching fraction equation – according to equation 5).

Irrigation requirement (IR) is calculated as follows:

$IR = (ET_o * Kc)*(LR)* 4.2/Ea$ (m^3/feddan/day) (4)

Where:

Ea = The irrigation system's efficiency, assuming 85% of the total water applied.

LF = ECiw / ECd (5)

Where:

LF = leaching fraction

ECiw = Electrical conductivity of irrigation water (0.36 dS/m).

ECd = Electrical conductivity of drainage water 1.7 dS/m – maize salinity threshold (Allen *et al.*, 1998). Then, LF = 0.36 / 1.7 = 0.2117

A water flow meter was used to determine the overall amount of irrigation water (Metrotec, EGYPT) for each treatment. Table 3 shows how the seasonal water consumption (ETc) for maize plants during two successive seasons (2022/2023) under different irrigation levels. Drippers of 2 L/hr. were used to irrigate the plants.

Table 3. Seasonal irrigation amounts for maize plants under different irrigation levels during the growing seasons of 2022 and 2023.

Seasonal irrigation requirements (m^3/feddan/season)			
Season (2022)			
60%	**80%**	**100%**	**Mean**
1765	2354	2942	2354
Season (2023)			
1872	2496	3120	2496

Data recorded.

Growth parameters.

Random samples of ten plants from each plot were collected after 75 days of seeding to assess the number of leaves/plant and the leaf area index (LAI) (measured by a laser leaf area meter), whereas plant height and stem diameter (cm) were measured at harvest.

Yield and its component parameters.

At harvest, a random sample of ten plants per plot were used to measure, for i.e. ear diameter (cm), number of grains/row, weight of 100 grains (g), weight of ears per plant (g), and grain weight yield (t fed^{-1}). Values of maize grains and biological yields per plot were used to calculate the grain yield/fed (t fed^{-1}) and biological (t fed^{-1}).

Determination of photosynthetic pigments.

Based on the procedure outlined by Lichtenthaler & Wellburn, (1983) and chlorophylls a & b and carotenoids values modified by Porra, (2002), chlorophylls were measured by crushing the fresh leaves with acetone up to a final volume of 10 ml. Using a UV-Spectrophotometer (SPAD-502Plus) at wavelengths of 645, 663, and 470 nm, respectively. Chlorophyll a, b, and β-carotene in maize leaves were determined and calculated according to the subsequent formula:

$$\mu g \text{ Chl } a/g \text{ FW} = [(12.7 \times A_{663}) - (2.64 \times A_{645})(V/(1000 \times W))]$$

$$\mu g \text{ Chl } b/g \text{ FW} = [(22.9 \times A_{645}) - (4.68 \times A_{663})(V/(1000 \times W))]$$

$$\mu g \text{ β-Carotenoids}/g \text{ FW} = [(4.6 \times A_{470}) - 0.268(Cl.a + b)](V/(1000 \times W))$$

Where:

V= the final volume of the extract; W= weight of the sample.

Determination of proline.

Proline content of maize leaves was measured using a UV-Spectrophotometer (SPAD-502Plus) set to 528 nm wavelength, following the procedures outlined by Troll & Lindsley (1955) and modified by Benlaribi *et al*. (1990).

Proline content was calculated using the subsequent formula:

$$Y = \frac{0.62 \times \text{OD}\ (528)}{\text{DW}}$$

Where:

Y, proline content µmol / g FW; OD, optical density; DW, Dry Weight (g).

Water use efficiency (WUE).

Maize water use efficiency (WUE) was calculated according to FAO (1982) as follows: grain crop yield ratio (Y) to the total amount of irrigation water used in the field along the growth season (IR);

WUE (kg/m^3) = Y (kg)/IR (m^3).

Economic analyses.

The economic analysis is based on two methodologies: First, to evaluate the economic feasibility of using a new subsurface drip irrigation system for maize crops, key economic indicators include net present value (NPV) and benefit-cost ratio (BCR). The NPV assesses the difference between the present value of benefits (increased crop yields and water savings) and costs (installation and maintenance). Threat, net percent value of the new irrigation system can be estimated by the following formula:

$$NPV = \sum_{t-1}^{T} \frac{B_t - C_t}{(1+r)^t}$$

where B_t and C_t are the benefits and costs at the same time $t-1$, and r is the discount rate. A positive NPV suggests economic feasibility. The BCR compares the benefits to costs (Gittinger, 1972).

$$BCR = \frac{\sum_{t-1}^{T} \frac{B_t}{(1-r)^t}}{\sum_{t-1}^{T} \frac{C_t}{(1-r)^t}}$$

Second, we use the IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) model methodology, primarily to identify the economic effects of implementing the most economically feasible subsurface drip irrigation on all lands planted with maize.

The IMPACT model, developed by Robinson *et al.* (2015), is a prominent multi-market framework that assesses the long-term economic and environmental effects of agricultural productivity, trade, and policy changes. It connects agricultural markets with socioeconomic factors and analyzes the interactions among crops, livestock, and food sectors, evaluating how global shifts, like population growth and trade policy changes impact agricultural production and food security (Rosegrant *et al*., 2012). The model provides insights into price adjustments, consumption patterns, and trade flows while accounting for natural resource constraints. It also aids in understanding market responses to external pressures for instance climate change and economic crises (Valin *et al*., 2014). Its multi-market approach is essential for analyzing the impacts of changes in one market on others, informing policy decisions regarding food security, agricultural productivity, and environmental sustainability (Rosegrant *et al*., 2017).

Statistical analyses.

The data were statistically analyzed using the SAS program using a mean of at least three independent replicates. The variations in averages for all attributes were assessed for significance at the 5% level, according to Waller and Duncan (1969).

Results and Discussion

Effect of irrigation systems, irrigation levels, and their interaction on vegetative growth parameters.

Table 4 reveals the influence of irrigation systems and levels and their interaction on the mean values of growth parameters in the two growing seasons (2022/2023).

A significant increase was noted in values of plant height, stem diameter, number of leaves/plant, and leaf area index (LAI) in plants subjected to subsurface drip irrigation. Values of such traits, herein amounted to 251.0, 2.54 (cm), 18.44, and 6.70 respectively; when compared to values of analogous traits under the surface drip irrigation method (238.9, 2.46 (cm), 17.11, and 6.29 respectively). The positive impact of subsurface drip irrigation on the growth traits of maize plants may be attributed to the efficient function of such irrigation systems in supplying plant roots with the optimum amount of irrigation water and nutrients. Our results agreed with those obtained by Ragab *et al*. (2019), who found that the sub-surface drip irrigation system increased plant length, the number of flowers and fruits/plants, and marketable fruit production in tomato plants compared to the surface drip irrigation system.

Regarding the influence of the irrigation levels (IR) on maize growth parameters, i.e. plant height, stem diameter, number of leaves/plants, and (LAI), the highest significant increment was recorded in maize plants subjected to 100 % irrigation level. Values of such traits, herein were estimated by 262.5, 2.59 (cm),19.00, and 7.44, respectively, followed by plants subjected to 80 % IR treatment, whereas the lowest growth trait values were recorded from maize plants watered at 60% IR treatment. Interception of our results was reported by Hegab *et al*. (2019), who stated that the most significant vegetative growth was achieved with a full irrigation level, indicating that a sufficient irrigation level may be required to address the water consumption of maize plants during the summer season, resulting in an increase in the photosynthesis process and plant nutrient uptake. The obtained results also agreed with Beiragi *et al*. (2011), who showed that enough water for irrigation made plant growth factors parameters.

Concerning the interaction effect, maize plants grown under subsurface irrigation system at 100% irrigation recorded the highest values of plant height, stem diameter, number of leaves/plants, and leaf area index (LAI). Mean values of the respective traits of such potent interacted treatment amounted to 265.0, 2.64 cm, 19.67, and 7.70, respectively, followed by plants subjected to subsurface irrigation system at 80% of irrigation levels, whereas the lowest values of growth parameters were noted by maize plants grown at 60% of IR level and surface drip irrigation system. A similar results trend was documented by Wang *et al*. (2018) and Guo *et al*. (2023). Also, Hédi BEN ALI *et al*. (2014) showed that water content within the root zone was always higher under subsurface drip irrigation system and that its fluctuation is especially more restricted than that recorded under surface drip irrigation system.

Effect of irrigation systems, irrigation levels, and their interaction on maize yield and yield components.

Table 5 reveals the influence of irrigation systems and irrigation levels and their interaction on the mean values of maize yield parameters, i.e. grain weight /ear (g), weight of ears/plant (g), weight of 100 grains (g), ear diameter (cm), number of grains/row and grain yield /t fed^{-1} of maize in the two growing seasons (2022/2023).

It is worth noting that yield is the quantity per plant or unit land area of harvested economic crop. Vegetative growth has also directly led to optimizing the yield obtained. The effect of the irrigation system on vegetative characteristics is therefore first reflected on the components of the yield and then on the yield harvested. Therefore, the impact of irrigation systems on the obtained maize parameters showed that the subsurface irrigation system was superior in the mean values of grain weight /ear (g), weight of ears/plant (g), weight of 100 grains (g), ear diameter (cm), number of grains/row and grain yield /t fed^{-1}. Values of the studied previous yield traits were higher under a subsurface drip irrigation system than those obtained under a surface drip irrigation system. The superiority of maize grain yield components assessments under the subsurface drip irrigation method is attributed to the potency of such irrigation system in vegetative growth parameters (Table 4), which positively reflected on the photosynthetic area of maize plant and increased translocation of assimilates from source (green leaves and stem) to the sink (grains). Similar results trends on maize and other crops were investigated by Abou El-Azem *et al.* (2002), Ayars *et al.* (2015) and Ragab *et al*. (2019).

Regarding the influence of irrigation levels, results indicated that 100% followed by 80% of irrigation levels recorded the highest mean values for yield parameters. In contrast, 60% of the IR treatment resulted in the lowest mean values. The obtained results also agree with those of Kotb and Mansour (2012). The observed findings can be attributed to adequate soil moisture, which creates favorable conditions for nutrient availability and uptake. With all, a higher photosynthesis process, which might be reflected in the higher number of leaves per plant (Table 4), then produces a higher weight of ears per plant (g), the weight of 100 grains (g), and grain yield (t fed^{-1}) (Hegab *et al.* 2019), Youssef, *et al*., 2025 proved that maize plants irrigated with 100% of ETc produced the most significant values for vegetative and yield parameters.

The effect of interaction between irrigation systems and irrigation levels, on the weight of ears/plant (g), the weight of 100 grains (g), ear diameter (cm), number of grains/rows, and grain yield (t./fed.) is significant. Maize plants watered with subsurface irrigation system and recorded the highest yield parameter at 100% of the irrigation level followed by the same irrigation system at 80 %. On the contrary, the lowest mean values of the yield parameters were obtained in plants subjected to 60% of the irrigation levels under surface drip irrigation system. Our results are compatible with those reported by Ayars *et al*. (2015), who indicated that the subsurface drip irrigation system boosted the yield of vegetable crops (tomato, sweet corn, and cantaloupe) compared to the surface drip irrigation system. Likewise, Ragab *et al*., 2019, showed that using a subsurface drip irrigation system instead of a surface drip irrigation system increased fruit production of tomatoes, whereas Abd El-Fattah *et al.* (2023) observed a significant difference in yield parameters in maize plants subjected to 80% of irrigation levels. Subsurface irrigation can enhance soil nutrient levels and reduce the bulk of deep soil, which positively affects crop productivity (Wang, *et al*., 2018). In the same line, comparing traditional irrigation, negative pressure irrigation a new type of subsurface irrigation technology considerably increased crop yields, water use efficiency, quality, and fertilizer uptake (Guo *et al*., 2023).

Table 4. The mean values of vegetative growth parameters of maize plants grown under two irrigation systems, and different irrigation levels (combined of the two growing seasons of 2022 and 2023).

Irrigation levels (IR)	Irrigation systems (S)					
	Plant height (cm)			Stem diameter (cm)		
	S1	S2	Mean	S1	S2	Mean
60%	234.6	207.3	221.0	2.43	2.38	2.41
80%	253.3	249.6	251.5	2.56	2.44	2.54
100%	265.0	260.0	262.5	2.64	2.55	2.59
Mean	251.0	238.9		2.54	2.46	
	Number of leaves/plants			Leaf area index (LAI)		
	S1	S2	Mean	S1	S2	Mean
60%	17.33	15.67	16.50	5.75	5.27	5.51
80%	18.33	17.33	17.83	6.66	6.42	6.54
100%	19.67	18.33	19.00	7.70	7.18	7.44
Mean	18.44	17.11		6.70	6.29	

L.S.D 5%				
	Plant height (cm)	Stem diameter (cm)	No. of leaves/plant	(LAI)
S	4.38	0.029	0.53	0.16
IR	4.30	0.063	0.65	0.19
S*IR	6.08	0.089	0.92	0.27

S irrigation systems S1 subsurface drip irrigation S2 surface drip irrigation
IR irrigation levels S*IR irrigation systems* Irrigation levels

Table 5. The mean values of yield parameters of maize plants grown under two irrigation systems, and different irrigation levels (combined of the two growing seasons of 2022 and 2023).

Irrigation levels (IR)	Irrigation systems (S)					
	Grain weight /ear (g)			Weight of ears per plant (g)		
	S1	S2	Mean	S1	S2	Mean
60%	166.0	142.0	154.0	197.0	184.0	190.5
80%	212.7	164.3	188.5	274.0	222.0	248.0
100%	234.0	202.0	218.0	275.3	252.7	264.0
Mean	204.2	169.4		248.8	219.6	
	Weight of 100 grains (g)			Number of grains/row		
	S1	S2	Mean	S1	S2	Mean
60%	36.53	35.30	35.92	32.67	34.33	33.50
80%	42.87	39.50	41.18	37.33	33.67	35.50
100%	44.93	42.17	43.55	41.33	35.67	38.50
Mean	41.44	38.99		37.11	34.56	
	Ear diameter (cm)			Grain yield (t fed^{-1})		
	S1	S2	Mean	S1	S2	Mean
60%	4.61	4.16	4.38	2.66	2.27	2.47
80%	4.73	4.50	4.62	3.40	2.63	3.02
100%	4.80	4.46	4.63	3.74	3.23	3.49
Mean	4.72	4.37		3.27	2.71	
L.S.D. 5%						
Parameters	Grain weight/ear (g)	Weight of ears per plant (g)	Weight of 100 grains (g)	Number of grains/row	Ear diameter (cm)	Grain yield/(t fed^{-1})
S	1.72	3.91	0.51	0.98	0.086	0.027
IR	4.54	6.81	0.62	1.20	0.074	0.072
S*IR	6.42	9.64	0.88	1.69	0.104	0.102

S irrigation systems S1 subsurface drip irrigation S2 surface drip irrigation
IR irrigation levels S*IR irrigation systems* Irrigation levels.

Effect of irrigation systems, irrigation levels, and their interaction on maize biochemical analysis.

Table 6 revealed the influence of different irrigation methods and irrigation levels on mean values of chlorophyll a, b, beta carotene, and proline concentrations in maize leaves. Chlorophyll content results revealed that plants irrigated by sub-surface irrigation at 100% and 80% of ETc levels were superior to other treatments and with a slight difference when compared to each other. On the other hand, the lowest chlorophyll content was recorded in plants subjected to drip irrigation at 60% of the irrigation levels. The mean value of chlorophyll a of this treatment was decreased than that of the potent treatment (sub-surface irrigation at 100% ETc level) by 11.55% and than that of sub-surface irrigation at 60% ETc level treatment by 7.94%.

Chlorophyll b and β-carotene content, plants subjected to sub-surface irrigation at both 100% and 80% of ETc levels were in the same line with chlorophyll a and achieved the highest concentration. Otherwise, the lowest chl. b, and β-carotene values were also obtained from leaves of maize plants subjected to 60% ETc level under drip irrigation system.

Proline content showed a different trend than chlorophyll, data in Table (6) revealed that the highest proline content was achieved in plants subjected to drip irrigation at 60% of ETc followed by plants subjected to subsurface irrigation at the same irrigation level. On the other side, the lowest proline content was achieved with subsurface irrigation at 100% of the irrigation level, followed by plants subjected to the same irrigation method at 80% of the irrigation levels.

Table 6. Chlorophylls, carotenoids, and proline contents of maize leaves as affected by irrigation levels and irrigation methods and their interaction (combined of 2022 and 2023 seasons).

Parameters \ Treatment	Sub-surface irrigation			Drip Irrigation		
	60%	80%	100%	60%	80%	100%
Chlorophyll A (µg/g FW)	22.263	23.944	24.184	21.389	23.273	23.448
Chlorophyll B (µg/g FW)	21.671	22.818	23.032	19.116	22.185	22.592
β Carotene (µg/g FW)	6.260	7.047	7.232	6.180	6.844	7.190
Proline (µmol/g FW)	20.303	18.851	18.676	20.940	19.476	19.266

S irrigation systems S1 subsurface drip irrigation S2 surface drip irrigation
IR irrigation levels S*IR irrigation systems* Irrigation levels

Previous results deduced that water deficit resulting from either low irrigation level (60% ETc) or inadequate water pressure distribution in drip irrigation method adversely affects the formation of new photosynthetic pigments in plant cells. And, may destroy the older native pigment molecules. Therefore, concentrations of each of chl. a, chl. b and beta carotene were decreased. On the contrary, proline content in leaves of drought-stressed maize plants was increased. Formation of proline in leaves of drought-stressed plants is a natural plant tolerance method against the harmful impact of water deficit on plants. Proline acts as a regulator osmotic substance for conserving cell water balance. Moreover, proline saves protoplasmic cell membranes from the hazardous effect of free radicals emitted from stress oxidation.

Our results agreed with those obtained by Efeoğlu *et al*. (2009) who demonstrated that under drought stress, all maize cultivars' chlorophyll chl a, chl b, total chl (a + b), and carotenoid levels were dramatically reduced, whereas proline content increased significantly. Also, (Sampathkumar *et al*., 2014; Youssef, *et al*., 2025) mentioned that under severe water stress treatments in maize, proline concentration increased, with mild water shortage, chlorophyll contents were highest and the leaf proline concentration was lowest.

Effect of irrigation systems; irrigation levels and their interaction on water use efficiency (WUE).

Table 7. shows the WUE mean value calculated in the plants treated with different irrigation systems, and irrigation levels. The WUE of plants subjected to subsurface irrigation was significantly higher than those subjected to surface irrigation. The WUE mean values of the compared treatments were 1.40, and 1.16 (kg/m^3), respectively. At the same time, plants subjected to 60% of irrigation levels recorded the most significant increment compared to the control (100% of irrigation levels) by 1.39, and 1.16 (kg/m^3), respectively. Regarding the influence of interaction between different irrigation systems and irrigation levels, plants subjected to subsurface irrigation at 60% of irrigation level were superior to other treatments by 1.53 (kg/m^3).

Those results agreed with Ahmed (2011) who reported that the subsurface drip irrigation system increased the WUE of cultivated crops compared to the surface drip irrigation system. Our results are also in line with those obtained by Irmak *et al*., (2016) who illustrated that water use efficiency (WUE) of maize plants significantly responded to limited water irrigation level (60%), contrarily, the lowest WUE value was obtained from the well-watered (100%) of irrigation level. Abd El-Fattah, *et al*., (2021) reported that broccoli plants subjected to 75% irrigation level showed the highest significant values of WUE among other treatments at 60% and 100% of irrigation levels. Finally, it is worth mentioning that subsurface irrigation can increase plant water content **(**Hegab *et al*., 2019; Fu, *et al*., 2021; Al-Aridhee & Mahdi, 2022, Abd El-Fattah *et al*., 2023) and reduce soil water evaporation after irrigation (Kim, *et al*., 2023).

Table 7. Effect of irrigation systems, irrigation levels, and their interactions on water use efficiency (kg/m^3) for maize hybrid under Wadi El-Natrun experimental, Behira Governorate, conditions, as a combined of 2022 and 2023 growing seasons.

Irrigation levels (IR)	Combined of the two growing seasons		
	Irrigation systems (S)		
	Water use efficiency (kg/m^3)		
	S1	S2	Mean
60%	1.53	1.25	1.39
80%	1.42	1.19	1.31
100%	1.26	1.06	1.16
Mean	1.40	1.16	
L.S.D 5%			
S	0.09		
IR	0.11		
S*IR	0.16		
S*IR	0.16		

Economic considerations

The financial metrics indicate strong economic feasibility for modernizing the subsurface irrigation system for maize crops. The total costs for the new system and its maintenance are estimated at $625, while projected benefits over five years amount to $1,611. This results in a net present value (NPV) of $2,020, suggesting significant returns on investment. The benefit-cost ratio (BCR) of 2.58 indicates that every dollar invested yields $2.58 in benefits. The modernization is expected to lower production costs and increase revenues through enhanced productivity and reduced irrigation costs.

Adopting the subsurface drip irrigation system may take approximately seven years to convince farmers, with key features for widespread implementation expected to be clear by 2030. Yield projections show an increase from about 3.11 tons per fed to 3.74 tons per fed, leading to an anticipated rise in overall maize production to approximately 9.5 million tons by 2030 as shown in Figure 1, compared to 8.72 million tons under the current surface irrigation system, representing a 9% increase.

The increase in production will reduce imports, as part of the new domestic production will replace imports. Figure 2 indicates that Egypt's maize imports will decrease to approximately 10.27 million tons compared to around 11.03 million tons (2030). The study previously mentioned the rise in production due to enhanced productivity from the modernized irrigation system as the reason for this decline in imports.

In general, these results are in accordance with (Genaidy *et al*, 2016) and (Ragab *et al*., 2019) which recorded that subsurface irrigation was more effective was more effective resulting in yield increases of 10–15% in maize and tomatoes compared with surface one. Also, similar results were obtained by (Martínez and Reca, 2014) who discovered that the alternative subsurface irrigation method appears to function better than the drip irrigation method since the yield and irrigation water use efficiency were higher for the first one. Also (Hani and Abdullah, 2020) recorded that the interaction between irrigation methods: at the start there are significant differences between surface and sub-surface drip irrigation. While in both of end and middle values there are significant differences between surface and subsurface drip irrigation and subsurface was greater than the surface drip.

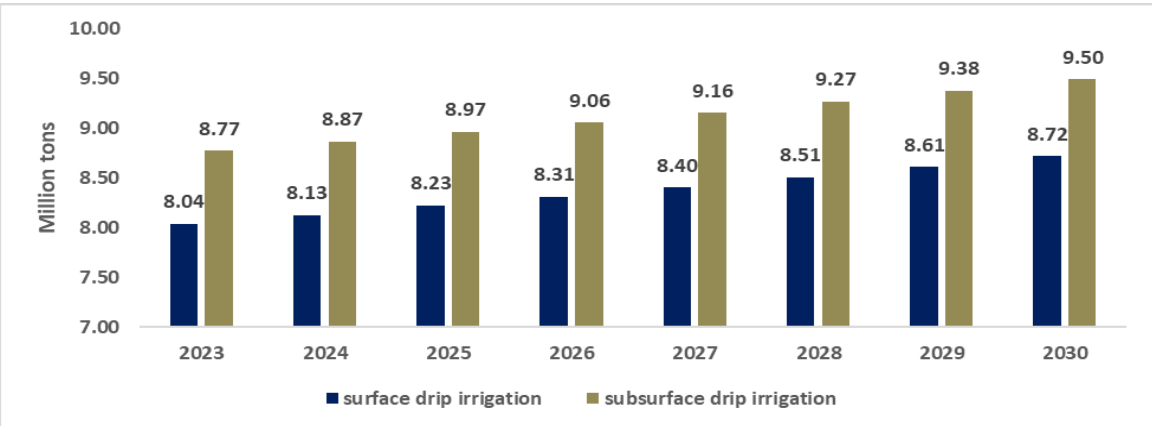

Fig. 1. Expected total production in a million tons (2023-2030).

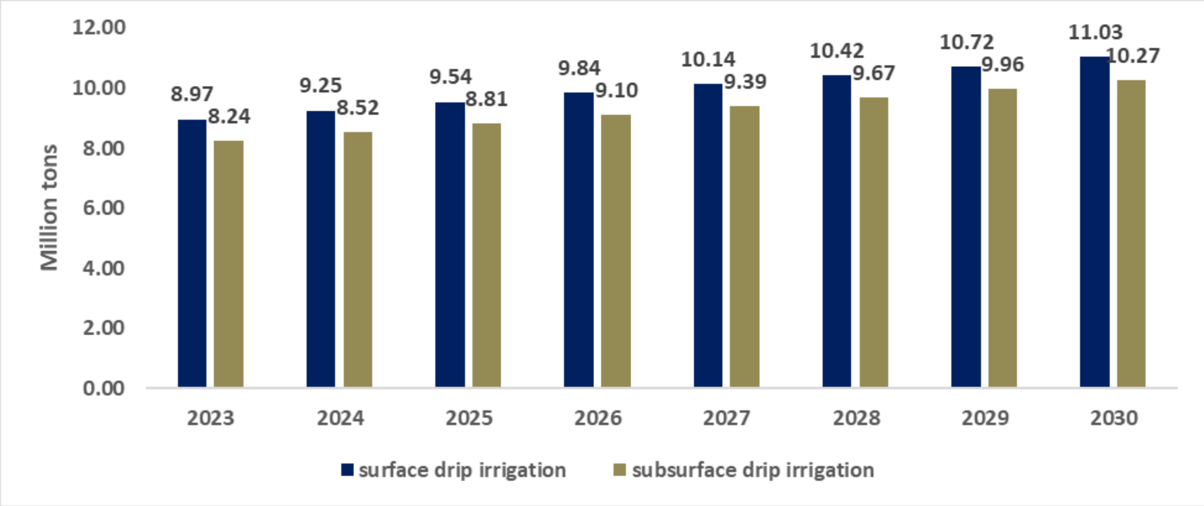

Fig. 2. Total imports during the period (2023-2030).

Conclusion

Climate change and water scarcity present serious problems in agriculture. Improving agricultural management practices is essential to mitigate the impact of climate change on crop production. Optimizing water use efficacy and crop productivity in arid regions requires implementing developed irrigation techniques, such as subsurface drip irrigation, which can enhance maize yields and sustainably preserve water resources. In the Wadi El Natrun-El-Beheira Governorate of Egypt, a 60% irrigation level proved optimal for maize production and yielded the highest water use efficiency (WUE). In comparison, 100% watering resulted in greater seed yield. Therefore, a 60% irrigation level is preferable to 100% in water is limited. From an economic perspective, an estimated investment of $625 with projected benefits of $ 1,611 was recorded over the five years, which supports the feasibility of modernizing the subsurface irrigation system for maize. This approach yields a net value of $2,020 with a benefit-cost ratio of 2.58. It lowered the irrigation costs and raised maize yields from 3.23 to 3.74 tons per feddan. It also suggested potentially increasing the total maize production to 9.5 million tons by 2030, which equals a 9% rise compared to surface irrigation. This increase could lower Egypt's maize imports to 10.27 million tons by 2030.

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