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Hydrogel Application as a Sustainable Strategy to Improve Maize Yield and Water Productivity under Deficit Irrigation in Uralsk , Kazakhstan

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SHORTAGE of water ranks among the most significant problems facing the world in arid and semi-arid regions, especially the western areas of Kazakhstan. Field experiment was conducted in sequential two crop seasons of 2023 and 2024, on trial fields of Zhangir Khan West Kazakhstan Agrarian-Technical University, Uralsk, Kazakhstan. This two crop growing seasons experiment was conducted, to explore the effects of different levels of hydrogel and deficit irrigation on yield, yield attributes, amount of applied water, water use efficiency (WUE), and economic analysis of maize crop grown in sandy soils. Field trials were conducted in RCBD with varying rates of hydrogel application (0 H_0, 0.1% H_1, 0.2% H_2, and 0.4% H_3 w/w; equivalent to 0, 2.5, 5.0, and 10.0 g/kg soil) and three irrigation regimes (full irrigation at 100% ET_c (E_1), moderate deficit at 80% ET_c (E_2), and severe deficit at 60% ET_c (E_3). This trial showed that hydrogel is highly beneficial in increasing water retention capacity in sandy soil, delaying wilting time, and increasing biomass and grain yield under conditions of moisture stress. The combination of 0.4% hydrogel and full irrigation (H_3E_1) gave the highest maize yield and growth indices, namely plant height, leaf area index, and number of ears per plant. However, applying hydrogel at 0.4% under severe deficit irrigation,60% ET_c, (H_3E_3) on the other hand, increased the WUE value to1.33 kg/m³ compared to 0.74 kg/m³ in the control (no hydrogel, full irrigation). The ET_c for seasonal maize was 730.3 mm and 779.0 mm for 2023 and 2024, respectively, whereas irrigation requirements were 575.3 mm and 611.0 mm, respectively, implying the need for supplemental irrigation.

Water deficit application of hydrogel can conserve water with minimal yield loss. Intermediate treatments with hydrogel at low to moderate concentration rates (0.1-0.2%) and 80% ET_c irrigation supported acceptable yields and significantly enhanced WUE (above 1.2 kg/m³). The hydrogel application along with varying irrigation treatments improved profitability and water productivity in a two-year study. While having a higher cost, treatments with hydrogel improved net returns by up to 37% and increased water use efficiency. This study brings out that in the face of inter-annual climatic variability, water should be applied based on real-time data of evapotranspiration. Above all, the aim of study provides evidence in favor of technological adoption, i.e., hydrogel application together with regulated deficit irrigation, as sustainable means to improve maize yields and conservation of water resources in the arid and semi-arid regions.

Keywords: Hydrogel, Water use efficiency, Drought stress, Maize yield, Arid agriculture, Western Kazakhstan, Soil moisture retention, Climate resilience.

1. Introduction

Water shortage is one of the increasing global environmental issues that ultimately affect environmental sustainability, food production, and socio-economic development. More than 2 billion people presently inhabit regions markedly affected by water stress, and by 2050, this scenario could mean that almost 5.7 billion people will experience at least a month's worth of water shortage annually due to a combination of demographic growth, climate change, and ineffective water management (UN-Water, 2021). Scarcity is divided into physical scarcity (situation where water resources are insufficient) and economic scarcity (situation where infrastructure or governance keeps the population from accessing available water) (WWAP, 2018). Yet another emerging issue within Central Asia, particularly Kazakhstan, is water supply. Nearly all transboundary rivers-from the great Syr Darya, Irtysh- remain a potential concern considering upstream withdrawals, pollution, and climatic variability. The vast part of the country influenced by their flow has a population density considered low relative to water resources; consequently, more than 60% comes from outside the national boundary, creating an absolute dependency on international water cooperation (UNECE, 2011). The country's waters are further stressed due to

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climate change as precipitation patterns and temperatures have changed and reduced river flows due to receding glaciers of Tien Shan mountains and rising demand for irrigation from arid southern areas (World Bank, 2020 a; Birimbayeva et al. 2025). This is why Kazakhstan adopted measures such as the application of integrated water management policies, the renovation of irrigation infrastructures, and the agreement to regional cooperation frameworks for the sake of long-term water security.

Hydrogels are soluble polymer networks in three-dimensional structures with the capability of absorbing and retaining huge amounts of water or biological fluids. Their mechanical and chemical properties, such as high water absorption capacity, biocompatibility, and responsiveness to the environment, have enabled extensive applications of hydrogels in agriculture, biomedicine, and environmental engineering (Ahmed, 2015). Currently hydrogels are being used as soil conditioners and water-retaining agents for improving the use-efficiency under drought conditions. They absorb and retain water during irrigation or rainfall and release it slowly to the plant roots which in turn increases the productivity of crops and sustainability by significantly reducing water loss by evaporation or leaching (Mohammed Ashraf et al., 2021; Farooq et al.,2009). Therefore, as the world faces looming water scarcity and adverse impacts of climate change, integrating the hydrogel technologies within arid and semi-arid farming systems may offer a significant promising strategy towards the sustainable development of agriculture. Hydrogels are thus considered a recent technology source in sustainable agriculture for greater balance of soil moisture, minimizing drought stress, loss of production, and optimizing use of water in water-scarce regions (Saha et al., 2020; Ahmed, 2015; Doğaroğlu et al. 2024).

A study in Kazakhstan's arid and semi-arid zones showed that hydrogel-treated soils retained 11% more water and had 4-8% higher mobile moisture content than untreated soils (Naushabayev et al., 2022). Hydrogel application also reduces drought stress on plants because it will stabilize the water supply to the crop, thereby positively influencing physiological functions and potentially reducing crop wilting while promoting root development. It becomes critically effective in southern regions of Kazakhstan where temperature rises and river flows decrease with melting glaciers, which restrict irrigation options (World Bank, 2020). Hydrogel improves water use efficiency (WUE) by reducing the frequency of irrigation needs. In research done in Central Asia, it integrated into the soil reduced the use of irrigation up to 40% while keeping or increasing crop yield (Abobatta, 2018). Such a case would give credence to the role of hydrogel as a novel and practical means for congestion of agricultural resilience and productivity in water-scarce regions of Kazakhstan.

Maize (*Zea mays L.*) is recognized as one of the most vital cereal crops in the world today. It is a multi-purpose crop for the human diet, animal consumption, and various industrial products. The Food and Agriculture Organization of the United Nations (FAO) stated that worldwide maize production was around 1,163.5 million metric tons in 2022. In this order comes the United States, China, and Brazil as its major producers (FAOSTAT, 2023). From this account, the United States alone was around 346.7 million tons compared with China's producing 277.2 million tons and Brazil's with 137 million tons. While Kazakhs are not among the leaders in maize production worldwide, it is being conscientiously developing in the southern areas, namely Almaty and Turkestan. In 2022, Kazakhstan produced about 1.1 million metric tons of maize. Much maize has been produced for use in livestock feed and other food industries (FAOSTAT, 2023). The expansion of maize cultivation reveals domestic demand tightening and government efforts at diversifying crop production in reaction to climatic and economic changes.

The objective of this study is to investigate the effect of applying different rates of hydrogel and irrigation deficit on maize (*Zea mays* L.) productivity, water use efficiency, and economic returns in sandy soil in the Uralsk region of western Kazakhstan. This is crucial to identify the optimal rates of hydrogel and irrigation levels for achieving sustainable maize production under limited water resources.

2. Materials and methods

Field experiment was carried out in experimental fields of Zhangir Khan West Kazakhstan Agrarian-Technical University, Uralsk, Kazakhstan (51°13′N, 51°22′E) during two crop seasons 2023 and 2024 to study the effects of different rates of hydrogel and deficit irrigation levels on maize yield and water use efficiency (WUE). Meteorological conditions of the experimental field are given in **(Table 1)**. In 2023, the mean temperature increased stepwise from 8.3°C in April to a peak of 23.0°C in July and then dropped to 8.4°C in October. The relative humidity varied between 55% and 68%, the most precipitated (43 mm) was in July. Wind speeds were moderately oscillating, and sunshine hours were the maximum in June and July. Climatic conditions did not change in 2024 compared to 2023, and mean temperatures varied between 7.0°C and 23.0°C. Relative humidity rose minimally in October to 73% compared to 2023. Rainfall was fairly uniform with considerable rainfall in July (43 mm). Sunshine hours and wind speeds were slightly higher in the course of 2024.

2.1. Experimental Layout

Field experiments were carried out over two consecutive growing seasons (2023 and 2024) to investigate the effect of various Potassium polyacrylate hydrogel application rates (0.0%, 0.1%, 0.2%, and 0.4% w/w on soil dry weight basis) and three levels of irrigation (100%, 80%, and 60% of crop evapotranspiration [ET_c]) (**Table 2)**. ET_c was estimated using Class A pan evaporation according to FAO guidelines (1998). The study focused on evaluating maize yield, water use efficiency (WUE) and economic returns in sandy soil under these treatment conditions.

Table 1. The meteorological data of the experimental site during the two growing seasons 2023 and 2024.

Months	Temperature (c^0)			Relative humidity (%)	Precipitation (mm)	Wind speed (m/hr)	Sun shine (hr.)
	Maximum	Minimum	Mean				
				2023			
Apr.	14.2	2.4	8.3	65	21	15.6	7.6
May	22.7	8.8	15.8	55	29	13.5	8.5
June	26.5	13.5	20.0	60	32	12.9	10.1
July	29.9	16.0	23.0	58	43	11.9	10.1
Aug.	28.1	14.0	21.0	60	32	12.4	9.5
Sep.	21.6	9.0	15.3	65	28	12.2	7.3
Oct.	13.2	3.5	8.4	68	36	13.1	5.2
				2024			
Apr.	14.1	2.4	8.3	65	21	16.6	7.6
May	19.4	8.8	14.1	55	29	16.1	10.1
June	28.1	14.0	21.1	57	29	14.5	10.1
July	29.9	16.0	23.0	58	43	14.0	10.5
Aug.	28.2	14.1	21.2	57	29	14.3	9.5
Sep.	21.6	8.0	14.8	61	32	14.3	7.3
Oct.	12.0	1.9	7.0	73	40	14.5	4.4

Table 2. Summary of experimental treatments.

i.	H_0E_1	Hydrogel Rate (0 % w/w) + 100 % of crop evapotranspiration (ETc)
ii.	H_1E_1	Hydrogel Rate (0.1 % w/w) + 100 % of crop evapotranspiration (ET_c)
iii.	H_1E_2	Hydrogel Rate (0.1 % w/w) + 80 % of crop evapotranspiration (ET_c)
iv.	H_1E_3	Hydrogel Rate (0.1 % w/w) + 60 % of crop evapotranspiration (ET_c)
v.	H_2E_1	Hydrogel Rate (0.2 % w/w) + 100 % of crop evapotranspiration (ET_c)
vi.	H_2E_2	Hydrogel Rate (0.2 % w/w) + 80 % of crop evapotranspiration (ET_c)
Vii	H_2E_3	Hydrogel Rate (0.2 % w/w) + 60 % of crop evapotranspiration (ET_c)
Viii	H_3E_1	Hydrogel Rate (0.4 % w/w) + 100 % of crop evapotranspiration (ET_c)
Ix	H_3E_2	Hydrogel Rate (0.4% w/w) + 80 % of crop evapotranspiration (ET_c)
X	H_3E_3	Hydrogel Rate (0.4% w/w) + 60 % of crop evapotranspiration (ET_c)

Potassium polyacrylate hydrogel was also pre-seeded applied to the soil at a depth of 10 to 15 cm. The treatment was done according to the treatment rates as per the prescribed quantity: 0% (control), 0.1%, 0.2%, and 0.4% by soil weight. Treatment was performed in the first-year experiment (2023) before sowing. Maize hybrid variety "Stepnyak MV" was sown on May 1st of the 2023 and 2024 crop years. Fertilizer recommendations recommended by the Ministry of Agriculture for the area were adopted. Nitrogen was added at a rate of 85 kg/ha in three split dressings each growing season, a common practice to enhance nitrogen use efficiency and reduce leaching losses in sandy soils (Fageria & Baligar, 2005). Phosphorus (P_2O_5) was used at 150 kg/ha in a two-split application: one during planting and the other 21 days after emergence because phosphorus plays an essential role in early root formation (Vance et al., 2003). Potassium (K_2O) was applied at the level of 50 kg/ha as potassium sulfate (48% concentration), divided between the pre-planting and the first vegetative growth stages to facilitate water adjustment and enzyme activation (Marschner, 2012). In addition, farmyard manure that was well decomposed was incorporated into the sandy soil prior to planting at 20 tons/ha to improve water-holding capacity, soil structure, and nutrient content (Diacono, 2010). The drip irrigation system applied to maize (Zea mays L.) production included a centrifugal pump and a combination of sand and screen filters to use the purest water. Fertigation was achieved by using a hydraulic fertilizer injection unit to apply nutrients accurately. The mainline was composed of 63 mm diameter PVC pipes, which supplied water to sub-main lines, which in turn connected to 16 mm diameter polyethylene laterals. All the laterals were 50 meters in length and were equipped with inline emitters at 0.5-meter spacings, each delivering 4 liters per hour of water. Two laterals were installed per crop row to ensure uniform distribution of moisture in the maize root zones. The installation was meant to ensure maximum water use efficiency and encourage uniform crop growth under sandy soil.

A Class A evaporation pan was utilized to estimate the volume of irrigation water applied across the evaluated irrigation treatments. Potential evapotranspiration (ETp) was calculated using the Class A pan method based on the following equation:

ETp = Epan × Kpan (Doorenbos and Pruitt, 1977)

Where:
Epan represents the measured pan evaporation (mm/day), and
Kpan is the pan coefficient, which varies depending on factors such as relative humidity, wind speed, and the location of the pan (whether situated over vegetative cover or bare soil).

At the experimental site, a Kpan value of 0.75 was adopted, reflecting the prevailing local weather conditions.

2.2. Soil water relations

The volumetric soil moisture content was monitored using a Time Domain Reflectometry (TDR) device. Sensors were installed at 20 cm intervals down to a depth of 100 cm to cover the root zone of maize plants. Measurements were taken 24 hours before and after each irrigation event, starting from planting and continuing until harvest. Field capacity, wilting point, and available water content were in situ measured employing the technique described by Michael (1978). Soil bulk density was quantified employing the core technique of Vomocil (1957) to a depth of 100 cm. The mean values thus determined are presented in **(Table 3)**. Moreover, some of the physical and chemical soil properties were also estimated following the standard procedure outlined by Black (1965) and Page et al. (1982), and the findings have been included in **(Table 4)**.

Table 3. Field capacity (FC), wilting points (WP), available soil moisture (ASM) and bulk density (D_b) values of the soil of the experimental farm.

Soil Depth (cm)	Field Capacity (FC) [%]	Wilting Point (WP) [%]	Available Soil Moisture (ASM) [%]	Bulk Density (~~Db~~) [g/cm³]
0–20	13.5	4.5	9.0	1.50
20–40	13.2	4.4	8.8	1.52
40–60	12.8	4.2	8.6	1.54
60–80	12.5	4.0	8.5	1.57
80–100	12.0	3.8	8.2	1.60
Average	12.8	4.2	8.62	1.55

Table 4. Chemical and Mechanical Properties of Sandy Soil in the experimental farm.

Soil depth (cm)	Chemical analysis				Particle size distribution				
	EC (dS/m)	pH	O.M. (%)	$CaCO_3$ (%)	Coarse Sand (%)	Fine Sand (%)	Silt (%)	Clay (%)	Texture
0-20	0.35	8.00	0.42	1.20	45.0	40.0	8.0	7.0	Sandy
20-40	0.32	7.95	0.38	1.10	44.0	41.0	8.5	6.5	Sandy
20-60	0.30	7.90	0.36	1.00	43.0	42.0	9.0	6.0	Sandy
60-80	0.28	7.85	0.33	0.90	42.0	43.0	9.0	6.0	Sandy
80-100	0.25	7.80	0.30	0.85	41.0	44.0	9.5	5.5	Loamy Sand
Average	0.30	7.90	0.36	1.01	43.0	42.0	8.8	6.2	Sandy

2.3. Water consumptive use (WCU)

Water consumption use was determined to assess the effective water utilized by maize during the growing period. Time Domain Reflectometry recorded the soil water content in five layers of soil continuously (0-20, 20-40, 40-60, 60-80, and 80-100 cm) . The readings were observed prior to irrigation, after irrigation for 24 hours, and during the crop harvest.

The estimation of WCU was obtained by applying the soil water balance method described by Israelsen and Hansen (1962), via the formula:

$$\mathbf{WCU = (M_1 - M_2) + I + R - D - R_o}$$

Where:
- M_2 = soil moisture content before irrigation (mm)
- M_1 = soil moisture content after irrigation or at harvest (mm)
- I = depth of irrigation water applied (mm)
- R = rainfall (mm)
- D = deep percolation losses (mm)
- R_o = surface runoff (mm).

Due to the sandy character of the soil and implementation of the drip irrigation system, surface runoff and deep percolation were assumed to be negligible. This method provided good estimation of seasonal water use under the given agro-environmental conditions in the Uralsk region.

2.3.1. Applied Irrigation Water (AIW)

While conducting research in the research station of Zhangir Khan University, I calculated Applied Irrigation Water (AIW) required for maize by using drip irrigation in sandy soil based on crop evapotranspiration (ETc), effective rainfall (Peff), and efficiency of irrigation system (FAO, 2010). Since sandy soil has low water holding capacity, frequent and timed irrigation was essential for maize (Hillel, 2004). I determined the crop evapotranspiration (ETc) by multiplying reference evapotranspiration (ETo) with the crop coefficient (Kc), which varies for different growth stages (Allen et al., 1998). Effective rainfall was subtracted from ETc to obtain the net irrigation requirement. As I used a drip irrigation with an average efficiency of 90–95% the gross irrigation requirement (AIW) was calculated considering that there is negligible water loss (Shock et al., 2000). The formula utilized was:

$$\mathbf{AIW = (ET_c - P_{eff}) / Drip\ Irrigation\ Efficiency}$$

2.3.2. Water use efficiency (WUE)

It was calculated according to the following equation (Vites, 1962; Stanhill,1986).

$$\mathbf{WUE} = \frac{Ya}{AIW}$$

Where:
WUE : the water use efficiency (kg/m^3).
Y_a : the actual yield (kg/ ha.)
AIW : the amount of applied irrigation water (m^3/ha.)

2.4. Sampling and Measurements

2.4.1. Stand Growth Index

Plant height: Ten plants were randomly sampled from each treatment at flowering and maturity, to record the height from the ground surface to the apex of the maize plant using a tape measure (Gong, L.S.et al., 2021).

Leaf area index (LAI): ten plants of the same growth vigor were randomly selected from each treatment at flowering and maturity stages. Leaf area: in destructive sampling, the length and width of leaves were measured with a tape measure, then multiplied by 0.75 to get the leaf area per plant (Zhang, G.Q. et al.2021).

LAI = Leaf area per plant ×Number of maize plants per unit of land area/Unit land area.

Dry matter content determination: At the flowering and maturity stages, four representative maize plants with stable growth were randomly selected from the third film and the fourth film in every plot. The aerial components of the plants were harvested from the plants at the plant base and categorized into leaves, stems, and reproductive organs (Wang and Zhang,2018). Leaves and other organs were placed in paper sampling bags, labeled, placed in an oven, dried at 105◦C for 30 min, dried to constant weight at 75◦C, and weighed and recorded on a balance precise to 0.01.

2.4.2. Grain Yield and Yield Components

At the stage of maturity, 20 ears were cut from the middle two rows of each plot, and number of grains per ear was counted. 10 plants were randomly selected from each plot, and observations on grain number as well as row number were recorded and then an average thereof was obtained. 1000 seeds were randomly collected from every plot's batch of seeds, and seed weight was measured with an electronic balance scale. Ear number, moisture content in grains, and grain yield were also recorded in each plot. Grain yield and kernel weight were expressed at 14% moisture content (Yang et al., 2004).

2.5. Economic Analysis

The prices in-puts and out-puts were calculated for the different treatments for Maize. Concerning costs of irrigation in the two seasons for different treatments was calculated on the basis of rent of water (Singh and Singh, 2014).

2.5.1. Total production costs ($/ha.) was calculated with the following equation:

Total production costs **($/ha.)** = Irrigation system costs (fixed and running cost) + cost of cultivation (Preparation of soil, different agriculture practices, price of seed, labours and harvesting)

2.5.2. Total return ($/ha.): was calculated with the following equation:

Total return = Price (350 $/ton) × Grain yield (ton/ha.)

2.5.3. Net return: was calculated with the following equation:

Net return = Total return - Total costs

2.5.4. Economic Water productivity, (WP, LE/m^3): was calculated by using the following formula:

$$W\textbf{ater productivity} = \frac{\textbf{Net return}\ (\$/\textbf{ha.})}{\textbf{Amount of water applied}\ (\textbf{m}^3/\textbf{ha.})}\ \$/\textbf{m}^3$$

2.6. Statistical Analyses

All data collected were tested for variance employing ANOVA in a comparison of the effects of ten treatments using SPSS version 25.0. (as developed from the combinations of hydrogel rates and irrigation regimes) on maize growth, grain yield, and water use efficiency. Three replicates per treatment and a total of 30 experimental units resulted. Means. were separated if the F-test indicated differences among treatments at the 5% level of probability. (P < 0.05) using the Least Significant Difference. (LSD) test to separate treatment effects. Means are represented by the results and differences in treatments at significant levels are marked by different letters in tables.

3. Results

3.1. Vegetative growth characteristics

The effect of the hydrogel application rates and irrigation regimes on the growth parameters of maize plant height, leaf area index (LAI) and leaves per plant differed considerably in the 2023 and 2024 seasons (Fig. 1, 2 and 3). The Least Significant Difference (LSD) at 0.05 level was used in testing the significance of difference among the treatment means. Maximum concentration hydrogel treatments (0.4% w/w) with full irrigation (H_3E_1) always had the largest values for all parameters measured. As a sample, plant height was 180 cm and 184 cm in 2023 and 2024, respectively; LAI = 4.4 and 4.6; and number of leaves per plant = 11.8 and 11.5. These were significantly ($p < 0.05$) greater than the values recorded in less hydrogel rate and/or deficit irrigation treatments. Conversely, treatments with highly deficit irrigation (60% ETc) with low or without hydrogel application (e.g., H_1E_3 and H_2E_3) had the lowest growth parameters with heights ranging from 140 to 150 cm, LAI from 2.7 to 3.1, and leaves from 8.4 to 9.5. They were statistically distinguishable from the best performing treatments. Intermediate treatments such as moderate hydrogel rates (0.1% and 0.2%) together with moderate deficit irrigation (80% ET_c) showed intermediate values significantly different from both ends, validating the interactive effect of hydrogel concentration and irrigation level on maize growth.

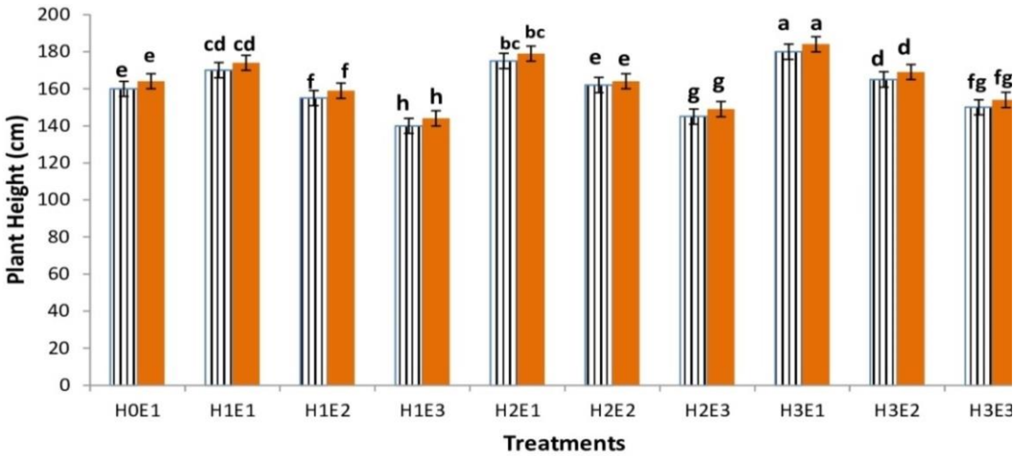

Fig. 1. Effect of hydrogel application rates and water regime on Plant Height of Maize **during the growing seasons 2023 and 2024.**

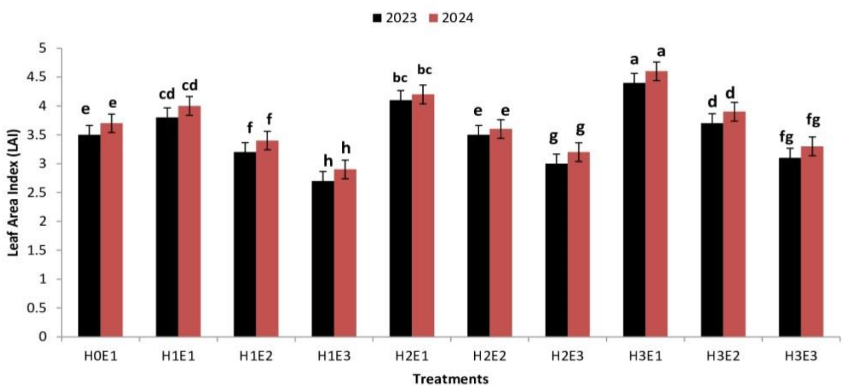

Fig. 2. Effect of hydrogel application rates and water regime on Leaf Area Index (LAI) of Maize **during the growing seasons 2023 and 2024.**

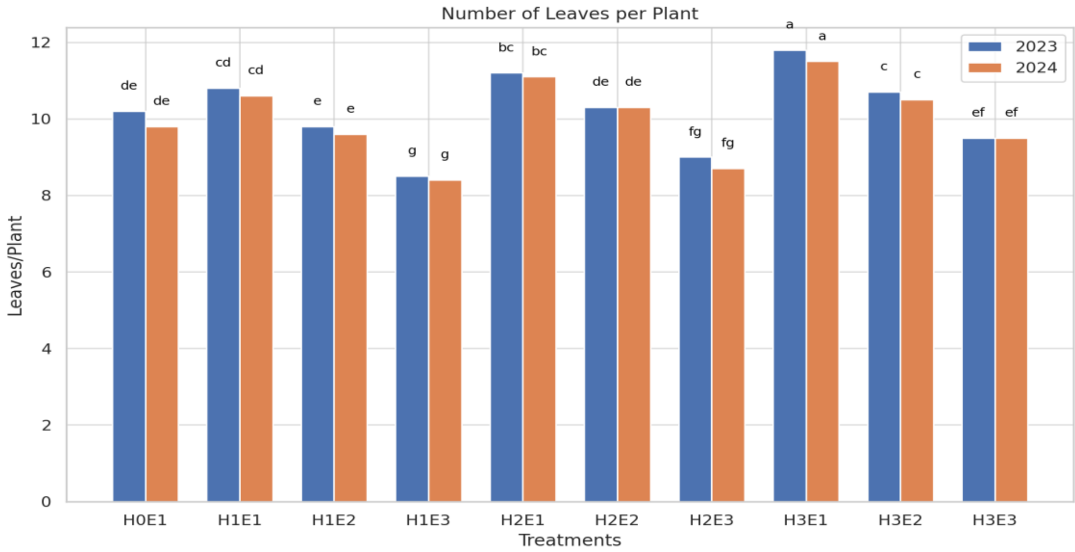

Fig. 3. Effect of hydrogel application rates and water regime on Number of Leaves per Plant of Maize during the growing seasons 2023 and 2024.

3.2. Yield and Yield components

The joint interaction of hydrogel application and irrigation regimes significantly influenced all measured maize yield components plant dry weight, number of ears per plant, grains per ear, and grain yield, during the 2023 and 2024 crop seasons **(Table 5)**. The Least Significant Difference (LSD) statistical analysis at 0.05 revealed significant and regular treatment differences for all characters. Treatments with the highest concentration of hydrogel (0.4% w/w) in combination with full irrigation (H_3E_1) always maintained maximum values across all yield parameters. H_3E_1 interestingly gave the highest number of ears per plant, 1.60 and 1.65 ears; dry weight of ears per plant was 170 g and 175 g; number of kernels per ears were 272 and 278; and grain yield was 6.5 and 6.7 tons/ha in 2023 and 2024, respectively. Statistically, these treatments were different ($p < 0.05$) from all abroad treatments, including the control (H_0E_1), which conversely produced the lowest or near-lowest values for these traits. Under extreme water deficit treatments with reduced/no hydrogel application, like H1E3 and H_2E_3, the bottom performing treatments were observed in every yield parameter-list-wise; ears ranged from 1.05 to 1.12, dry weight from 115 to 125 g, number of kernels per ears from 242 to 244, and grain yield 4.9 to 5.3 tons/ha. These were significantly different from the respective ones in treatments having greater greater hydrogel rates and irrigation levels. Intermediate levels of treatment, such as moderate hydrogel levels (0.1% and 0.2%) under moderate deficit irrigation (80% ET_c), exhibited intermediate values for all the measured characteristics significantly different from both the highest and lowest treatment levels. This trend confirms the synergistic impact of hydrogel level and irrigation level on maize productivity.

Table 5. Effect of hydrogel application rates and irrigation regimes on yield and yield component of Maize (Zea mays L.) during the growing seasons 2023 and 2024.

Treatments	No. of Ears		Dry weight (gm)		No.of kernels/ear		Grain Yield (ton/ha)	
	2023	2024	2023	2024	2023	2024	2023	2024
H_0E_1	1.25 de	1.30 de	140 de	145 de	249 e	256 e	5.0 e	5.3 d
H_1E_1	1.35 cd	1.40 cd	150 cd	155 cd	255 d	261 d	5.8 c	6.1 c
H_1E_2	1.20 e	1.25 e	132 e	137 e	246 f	252 e	5.5 d	5.8 c
H_1E_3	1.05 g	1.10 g	115 g	120 g	242 g	245 e	4.9 e	5.2 d
H_2E_1	1.45 bc	1.50 bc	160 bc	165 bc	263 b	271 b	6.2 b	6.5 b
H_2E_2	1.28 d	1.33 d	142 de	147 de	251 e	258 e	5.9 c	6.2 b
H_2E_3	1.12 fg	1.17 fg	125 fg	130 fg	244 g	247 e	5.3 d	5.6 d
H_3E_1	1.60 a	1.65 a	170 a	175 a	272 a	278 a	6.5 a	6.7 a
H_3E_2	1.38 c	1.43 c	152 c	157 c	259 c	264 c	6.0 c	6.3 b
H_3E_3	1.20 e	1.25 e	130 ef	135 ef	244 g	249 e	5.4 d	5.7 c
$LSD_{0.05}$	0.07	0.08	6.0	6.5	2.8	3.1	0.19	0.21

3.3. Reference Evapotranspiration (ET_0), Actual or Crop Evapotranspiration (ET_c) and Irrigation Requirements (IR.)

Season and month-to-month fluctuation of maize crop evapotranspiration (ET_c) and reference evapotranspiration (ET_0) in 2023 and 2024 growing seasons in Uralsk, Kazakhstan, are shown in **(Table 6)**. The results reveal that ET_0 and ET_c values increased gradually from April to July, again decreasing slowly towards September, as is the common climatic seasonality such as rising temperature and solar radiation in mid-summer and a decrease in late summer. In 2023, ET_c for the maize season (April–September) amounted to 730.3 mm, whereas in 2024 it was a little larger at 779 mm, on account of elevated ET_0 values and marginally elevated atmospheric demand. Maximum ET_c was noted in July in both years, being 223.2 mm and 228.5 mm in 2023 and 2024, respectively, which coincide with the maximum development stage of the crop (K_c = 1.15) and maximum ET_0 (6.26 and 6.41 mm/day, respectively). By comparison, April registered the lowest ETc values at the beginning of the cropping season (K_c = 0.4), with readings of 32.1 mm and 33 mm in 2023 and 2024, respectively. Rainfall during the stud period made some contribution towards fulfilling crop water needs. However, the full irrigation requirement had to be fulfilled, especially during the most severe summer months. For 2023, the total irrigation requirement was 575.3 mm and in 2024 was a little higher at 611 mm, indicating supplemental irrigation in maize under semi-arid climatic conditions. These results highlight the significance of proper irrigation scheduling in order to secure maximum water use efficiency and maintain yield stability. The findings also indicate inter-annual climatic fluctuation and its direct effect on crop water demand over the region.

Table 6. Monthly reference evapotranspiration (ET_0), crop evapotranspiration, effective rainfall and irrigation requirements during the growing seasons 2023 and 2024.

Months	ET_0 (mm/ day)	K_c	ET_c (mm/ day)	ET_c (mm/ month)	Effective Rainfall (mm/ month)	Irr. Req. (mm/ month)
				2023		
Apr.	2.67	0.4	1.07	32.1	21	11.1
May	4.55	0.7	3.19	98.9	29	69.9
June	5.95	1.0	5.95	178.5	32	146.5
July	6.26	1.15	7.20	223.2	43	180.2
Aug.	5.26	1.0	5.26	163.1	32	131.1
Sep.	3.07	0.7	2.15	64.5	28	36.5
∑				730.3	185	575.3
				2024		
Apr.	2.74	0.4	1.10	33	18	15
May	4.65	0.7	3.26	101.1	27	74.1
June	6.08	1.0	6.08	182.4	29	153.4
July	6.41	1.15	7.37	228.5	35	193.5
Aug.	5.40	1.0	5.40	167.4	29	138.4
Sep.	3.17	0.7	2.22	66.6	30	36.6
∑				779	168	611

3.4. Amount of applied irrigation water and crop water use efficiency

3.4.1. Amount of applied irrigation water (AIW)

Figure (4) illustrates the distribution of applied irrigation water on maize for three levels of irrigation 100% ET_c (E_1), 80% ET_c (E_2), and 60% ET_c (E_3) during the growing seasons of 2023 and 2024. For both seasons, a clear upward trend of AIW from April to July is consistent with the increasing water requirement of maize during its critical growth stages, specifically flowering and grain filling. The peak AIW was always determined in July for all irrigation treatments, where the peak was in the full irrigation treatment (E_1), followed by the moderate (E_2) and severe deficit (E_3) treatments. The lowest AIW values were utilized in April because it was the minimum water requirement of the crop at its vegetative growth stage. There are differences among the three regimes over all of the months, with E_1 receiving the largest water quantities always, E_2 getting medium quantities, and E3 getting the lowest. The trend shows the capacity of regulated deficit irrigation to reduce total water applied without compromising temporal coordination of irrigation with crop water needs. Interestingly, there is a relatively minor increase in AIW during 2024 compared to 2023, particularly for the summer season months (June to August), which may be accounted for by alterations in climatic conditions or increased crop water stress. Overall, the findings highlight the importance of using reliable irrigation scheduling through crop evapotranspiration and growth stage. The use of deficit irrigation strategies (E_2 and E_3) indicates unequivocally the saving of water, particularly desirable in those countries with low water resources. Nevertheless, the provision of adequate irrigation at the most critical phases of growth remains imperative for the optimization of maize production.

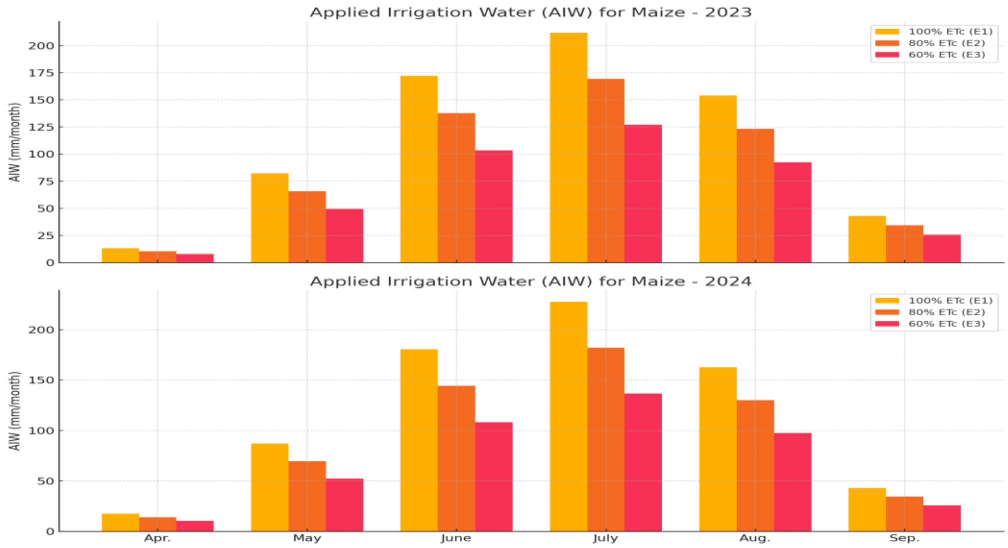

Fig. 4. Effect of hydrogel application rates and water regime on Applied Irrigation Water (AIW) of Maize (Zea mays L.) during the growing seasons 2023 and 2024.

3.4.2. Crop water use efficiency (WUE)

Figure **(5)** reveals water use efficiency (WUE) of maize under different hydrogel application rates and irrigation treatments in the 2023 and 2024 seasons. Data reveal clear and distinguishable differences in WUE between treatments. The control (H_0E_1), applied with zero hydrogel and 100% of crop evapotranspiration (ET_c), recorded the lowest WUE values (0.74 kg/m3for seasons). There was a marginal increase using 0.1% hydrogel under complete irrigation (H_1E_1), where WUE was 0.86 and 0.85 kg/m³ in 2023 and 2024, respectively. With increased rate of hydrogel and deficit irrigation level, a great improvement a great improvement in WUE was observed. H_1E_3 (0.1% hydrogel + 60% ET_c), for example, had constant WUE values of 1.21 kg/m³ during the two years, while H2E3 (0.2% hydrogel + 60% ET_c) raised WUE to 1.31 and 1.30 kg/m³. Maximum efficiency was recorded in H_3E_3 (0.4% hydrogel + 60% ET_c) at 1.33 and 1.32 kg/m³, that is, water use at maximum under extreme deficit irrigation when used in combination with the highest rate of hydrogel. In addition, the treatments of deficit irrigation (H_2E_2 and H_3E_2: 0.2% and 0.4% hydrogel + 80% ET_c) also presented considerably better WUE than their full irrigation counterparts, indicating the benefit of combining hydrogel treatment with restricted irrigation. Overall, the results clearly demonstrate that increasing hydrogel rates, especially under deficit irrigation, is an effective measure to achieve maximum water use efficiency in maize growth, especially worth considering for water-limited conditions.

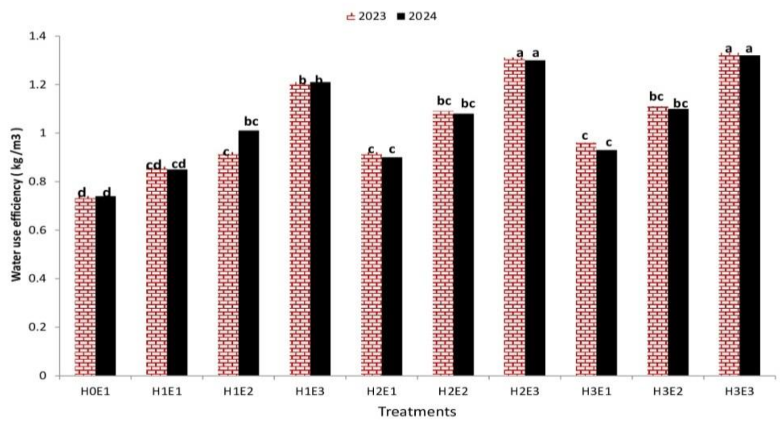

Fig. 5. Effect of hydrogel application rates and water regime on Water use efficiency (WUE) of Maize **(Zea mays L.) during the growing seasons 2023 and 2024.**

3.5. Economic Analysis

The economic evaluation of different hydrogel application rates at different levels of irrigation revealed significant increases in profitability as well as water productivity over the two years of research (2023–2024) **(Tuble 7)** . Costs rose rose proportionately with hydrogel concentration from $714/ha under control treatment (H_0E_1) to $856.8/ha under maximum hydrogel rate treatment (H_3E_1). Despite higher costs of inputs, the hydrogel treatments consistently over performed the control in their total and net returns. The most net returns were seen in the H_3E_1 treatment at $1419.2/ha and $1488.2/ha in 2023 and 2024, respectively, an increment of approximately 30–37% compared to that of the control. Notably, at deficit irrigation levels (60% and 80% of crop evapotranspiration), hydrogel application minimized yield losses to achieve greater net returns than non-amended controls. Water productivity, expressed as economic return per cubic meter water applied, was also enhanced with hydrogel application, particularly under water-conserving treatments. Treatments wherein hydrogel and 60% ET_c irrigation were used exhibited the highest rates of water productivity (0.29 $/m³ or higher), indicating superior water use efficiency. Such trends being repeatable during both years confirms that hydrogel treatments can effectively increase profitability of crops and improve water utilization, representing a good means for sustainable water management under water deficiency conditions.

Table 7. Economic performance and water productivity of different hydrogel application rates combined with varying irrigation levels (2023–2024).

Treatments	Total cost ($/ha.)	Total return ($/ ha.)	Net return ($/ ha.)	W.P. ($/m^3)
		2023		
H_0E_1	714.0	1750.0	1036.0	0.15
H_1E_1	761.6	2030.0	1268.4	0.19
H_1E_2	737.8	1925.0	1187.2	0.22
H_1E_3	714.0	1715.0	1001.0	0.25
H_2E_1	809.2	2170.0	1360.8	0.20
H_2E_2	785.4	2065.0	1279.6	0.24
H_2E_3	737.8	1855.0	1117.2	0.28
H_3E_1	856.8	2276.0	1419.2	0.21
H_3E_2	809.2	2100.0	1290.8	0.24
H_3E_3	761.6	1890.0	1128.4	0.28
		2024		
H_0E_1	714	1855.0	1141.0	0.16
H_1E_1	761.6	2135.0	1373.4	0.19
H_1E_2	737.8	2030.0	1292.2	0.22
H_1E_3	714.0	1820.0	1106	0.26
H_2E_1	809.2	2275.0	1465.8	0.20
H_2E_2	785.4	2170.0	1384.6	0.24
H_2E_3	737.8	1960.0	1222.2	0.28
H_3E_1	856.8	2345.0	1488.2	0.21
H_3E_2	809.2	2205.0	1395.8	0.24
H_3E_3	761.6	1995.0	1233.4	0.29

4. Discussion

The results of the present work highlight the significant impacts of hydrogel application and irrigation regimes towards enhancing maize growth performance, i.e., plant height, leaf area index (LAI), and leaves per plant. The improved result from the 0.4% hydrogel application with full irrigation (H_3E_1) is in agreement with other studies that cite the high ability of hydrogels to improve soil water retention and supply plants with water (Salemi et al., 2011). The decrease of growth parameters recorded under extreme water stress (60% ET_c) and lower hydrogel contents (e.g., H_1E_3, H_2E_3) is consistent with the established effect of drought stress on morphometry in maize. Decreased water availability inhibits photosynthesis as well as cell expansion, thereby affecting leaf growth and plant height (Farooq et al., 2009). However, the application of hydrogel under deficit irrigation (especially at 60% ET_c) still had a relative advantage over no hydrogel, indicating its water storage ability and delayed soil drying (Hüttermann et al., 2009). Worth mentioning is that intermediate values with 0.1%,0.2% hydrogel concentrations and 80% ET_c irrigation indicate that water input can be optimized without affecting plant growth. This agrees with findings by Ammar et al. (2022), who observed that partial deficit irrigation combined with soil amendments will save water without satisfactory crop growth. This is particularly important in water-limited climates like Western Kazakhstan, where water saving should be weighed against productivity. The notably distinct effects confirmed by LSD analysis and minimal coefficient and minimal coefficient of variations between traits highlight the experimental precision and dependability of the observed effects. The results reinforce the proposal that certain hydrogel treatment and deficit irrigation combinations could be an efficient alternative for sustainable maize cultivation in arid and semi-arid conditions (Farooq et al.2009).

The present research clearly demonstrates that the combined application of hydrogel and irrigation regimes significantly influences the maize yield and its fractions, consistent with previous research on water management and soil amendments in agriculture. The improved yield by the treatment with the maximum hydrogel concentration (0.4% w/w) using complete irrigation (H_3E_1) in all yield indicators, number of ears per plant, plant dry matter, grains per ear, and grain yield, validates earlier studies highlighting the effectiveness of hydrogel in enhancing the retention and availability of water in the soil to increase crop yields (Sojka and Entry, 2000). Hydrogels are root-zone soil conditioners that increase the capacity for water retention and mitigate water stress at critical growth stages, enabling constant nutrient uptake (Agbna, and Zaidi, 2025). Such an improvement can serve as the foundation for the significantly increased ear number and grain yield realized under H_3E_1 and which was statistically superior to all other treatments, including the control (H_0E_1). These results are consistent with Rajanna et al. (2022), who stated that enhanced soil water holding capacity due to polymer amendments is able to substantially increase maize yield and biomass. Conversely, the poorest yield performance was achieved with treatments under severe deficit irrigation (60% ET_c) with little or no application of hydrogel (e.g., H_1E_3 and H_2E_3).This finding aligns with the widely reported harmful effects of water stress on reproductive growth in maize, which reduces ear development, grain establishment, and subsequently yield (Lobell et al., 2014). The heavy dramatic depressions in yield during these treatments accentuate the weaknesses of deficit irrigation when not supplemented by soil storage moisture technology.

In particular, intermediate treatments with moderate levels of hydrogel (0.1% and 0.2%) under moderate deficit irrigation (80% ET_c) had yield components statistically distinct from the highest and lowest groups. This finding reveals the potential to integrate moderate hydrogel application and partial deficit irrigation as a water- saving practice without losing yield significantly. The same was published by Kassim et. al. (2017), who determined that integrated soil amendment with partial deficit irrigation can maximize water use efficiency at reasonable crop yields. Low LSD values of all the parameters recorded confirm the accuracy of the experiment and lend support to the credibility of these observations. In conclusion, this study supports the argument that tailor-made application rates of hydrogel, in conjunction with favorable irrigation regimes, have the potential to enhance maize productivity and water use efficiency, a significant parameter in consideration of increasing water stress and climatic uncertainty (Agaba et al., 2010; Ahmed., 2015). The inter-monthly and inter-seasonal variations in reference evapotranspiration (ET_o) and crop evapotranspiration (ET_c) of maize at Uralsk, Kazakhstan, for the 2023 and 2024 growing seasons are in fair agreement with well-established agro climatic regimes under semi-arid conditions.

The continuously increasing ET_0 and ETc values from April until July , and subsequently reversing its trend towards September, reflect the natural seasonal fluctuations in temperature, radiation from the sun, and atmospheric demand (Allen et al., 1998; Pereira et al., 2002). Such a trend is necessary for understanding crop water demand and making appropriate arrangements for irrigation. The annual ETc amounts of 730.3 mm in 2023 and 779 mm in 2024 are equal to the cumulative water demand of maize during its phenologic stages. The difference in 2024 results from extreme ET_0 rates and rising atmospheric evaporative demand, as cited by Payero, Jose and Irmak, Suat. (2011), which demonstrated that inter-annual climatic variability greatly influenced crop water use. Maximum ET_c values in July would refer to the critical growth phase of the crop with a high crop coefficient (K_c = 1.15) and maximum ET_o rates according to guidelines suggested by Doorenbos and Pruitt (1977) for crop coefficients. The low ET_c values in the early phases of the crop season refer to the low water demand during initial vegetative growth. Despite contributions from effective rainfall, the high irrigation requirements, 575.3 mm for 2023 and 611 mm for 2024, indicate the necessity for complementarp

irrigation to meet maize water requirements in the semi-arid climatic conditions of the study region. The observation is consistent with studies by Kalhapure et. al. (2016), who reported the contribution of irrigation towards mitigating water deficit and enhancing crop yields in water-stressed environments.

The inter-annual variability in ET_0 and ET_c spells the challenge posed by climate variability and change, necessitating adaptive irrigation management strategies. Precise irrigation scheduling based on real-time evapotranspiration data has the promise of optimizing water use efficiency and yield stabilization, as attested by research from Allen et al. (1998). Such adoption is essential for sustainable maize cultivation under semi-arid conditions with increasing water scarcity under climate change.

In summary, the results confirm the central role of accurate ET_0 and ETc estimation in irrigation planning and underscore the need to integrate climatic variability into water management for the advancement of food security and resource sustainability. Monthly applied irrigation water (AIW) distribution for maize under various irrigation regimes, as presented in Figure 4, follows well-established crop water demand and irrigation management principles. The progressive increase of AIW from April to July witnessed is in conformity with the phenological growth of the maize crop, in which water demand grows at critical stages such as flowering and grain filling (Doorenbos and Kassam, 1979; Allen et al., 1998).

The maximum July irrigation need across all treatments coincides with highest rates of evapotranspiration and crop factors, underlining the necessity for ample water supply under such key stages to maximize yield development (Kang et al., 2019). The clear discrimination between the three irrigation regimes—full irrigation (100% ETc), moderate deficit (80% ET_c), and severe deficit (60% ET_c)—corresponds to the real-life adoption of regulated deficit irrigation (RDI) practices. The consistent reduction in AIW across E1 to E3 without any temporal lag with the crop water requirement indicates the water-saving efficiency of RDI while maintaining crop growth patterns (Fereres & Soriano, 2007). This approach is particularly critical where there is limited water since the efficiency of water must be optimized (Zegbe-Dominguez et al., 2010, Pereira et al. 2002).

The marginal increase in AIW during the 2024 season compared to 2023, especially during peak months, is indicative of inter-annual climatic variation influencing crop water demands. Such variations necessitate adaptive irrigation scheduling based on real-time climatic and crop development data to achieve optimal water use efficiency (Jones ,2004). The finding concurs with study on requirement for flexible management of irrigation based on prevailing weather conditions (Allen et al., 1998).

Overall, data substantiate the critical role of precise irrigation scheduling on the basis scheduling on the basis of crop evapotranspiration and phenological stage in bringing about a balance between yield maximization and water conservation. While deficit irrigation strategies (E_2 and E_3) offer high water conservation, maintenance of proper irrigation even at phenological stages of high-water demand is still required to prevent yield loss (Fereres and Soriano, 2007). This balance is key to sustainable maize farming under semi- arid conditions with increasing water shortages.

The information presented in Table 7 and Figure 5 clearly shows the significant impact of hydrogel application rates combined with irrigation regimes on maize water use efficiency (WUE) during the 2023 and 2024 crop growing seasons. The lowest WUE was recorded under control treatment (H_0E_1), where hydrogel was not applied and full irrigation (100% ET_c) was applied, with values of 0.74 kg/m³ for both years. This finding agrees with the earlier studies that conventional irrigation without soil amendment usually results in low water use efficiency (Farooq et al., 2017).

A slight but notable increase in WUE was observed with 0.1% hydrogel under full irrigation (H_1E_1), corresponding to the role of hydrogels to enhance soil moisture retention and reduce water loss through evaporation and deep percolation (Dorraji et al., 2010). Such increases correspond with findings by Hüttermann et al. (2009), who observed improved crop water productivity with the

incorporation of hydrogels into soil.

Most notably, the results indicate a dramatic improvement of WUE when hydrogel content as well as deficit irrigation stress severity increased. Treatments like H_1E_3 (0.1% hydrogel + 60% ET_c) and H_2E_3 (0.2% hydrogel + 60% ET_c) exhibited significant improvements in WUE to values greater than 1.2 kg/m³. The highest WUE was achieved by H_3E_3 (0.4% hydrogel + 60% ET_c), and their values were found to be higher than 1.3 kg/m³, indicating maximum water productivity under severe water stress levels when supplemented with intensive hydrogel applications. This harmonization is in support of Dorraji et al. (2010) who stated that supplementing soil amendments with deficit regulated irrigation can enhance water use efficiency significantly without yield loss.

Furthermore, moderate deficit irrigation (80% ET_c) treatments and application rates of moderate to high hydrogels (H_2E_2 and H_3E_2) also exhibited considerably higher WUE compared to the treatments under full irrigation. This illustrates the prospect of integrating hydrogel application with deficit irrigation methods for achieving water savings without compromising or even increasing crop water productivity, a critical parameter in water-limited environments (Fereres and Soriano, 2007).

Collectively, these findings emphasize the promise of the optimal exploitation of hydrogel application rates, particularly under deficit irrigation, as a viable agronomic practice to maximize water use efficiency in the production of maize. Such practices are even more applicable in arid and semi-arid regions where there are water scarcity problems and where maximizing water productivity is a condition for the development of sustainable agriculture (Liu et al., 2023).

The economic analysis of hydrogel use in combination with varying levels of irrigation clearly indicates its potential to enhance profitability and water productivity in agriculture under water-deficient conditions.

The greater total and net yields with higher hydrogel concentration are in agreement with previous studies that have provided evidence of improved crop yield and economic value on the basis of greater moisture retention in the soil and nutritional availability (Zheng et al., 2023). Whereas the cost of input rose with improved hydrogel rates, the excessive boosts in net returns up to 37% relative to the control are justifiable, consistent with the findings of Farooq et al. (2014), who emphasized the cost-utility of hydrogel amendments in semi-arid and arid agriculture. Significantly, the mitigation of yield loss under deficit irrigation (80% and 60% ETc) highlights the potential of hydrogels in sustaining crop performance in water stressed conditions, as also demonstrated by Kishor et al. (2024), whose studies indicated that hydrogels increase water retention and availability to crops and hence improve drought tolerance. The enhancement of water productivity, particularly in deficit irrigation conditions, also emphasizes the utility of hydrogels as a water-saving technology because, as noted by Terry A. H. (2001), hydrogel-fertilized soil was linked with enhanced water use efficiency. In general, these findings also emphasize the value of hydrogel application as a cost-effective irrigation management practice that can optimize water utilization as well as improve economic return in water-stressed conditions.

Conclusion

This study clearly demonstrates the effect of the concurrent use of hydrogel and regulated deficit irrigation is significantly positive on maize growth, yield, and water use efficiency in the semi-arid climate of Western Kazakhstan. It has been observed that the use of hydrogel, particularly the application rate of 0.4%, and full or moderate deficit irrigation (80% ET_c), produces notable growth in plant height, leaf area index, ears per plant, and grain yield compared to local practices. Even under extreme water stress (60% ET_c), hydrogel treatment increased soil water retention and time to wilting of the crop and hence increased water use efficiency more than 1.3 kg/m³ in the most favorable treatment compared to 0.74 kg/m³ in the control treatment. Hydrogel treatment immensely enhances crop profitability and water productivity at varying levels of irrigation. Though it involves initial cost, the increased net revenues and better performance in conditions of water shortage make it an economic and sustainable water conservation strategy for water-stressed agriculture. The findings highlight the importance of precise irrigation management through real-time evapotranspiration to optimize water productivity and adaptation to climatic variability. Partial deficit irrigation with moderate hydrogel rates also performed well to conserve water without significant yield reduction, as a suitable long-term management practice for maize production under water-limiting conditions. Generally speaking, this research gives validity to the application of tailored hydrogel and irrigation management techniques to enhance crop yield and resource conservation in arid and semi-arid regions faced with increased water shortage and climate change.

Declarations
Ethics approval and consent to participate
Author Contributions: All authors helped prepare the MS and agree to publish it.
Institutional Review Board Statement: Not applicable.
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Conflicts of Interest: There is no conflict of interest among the authors.

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