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Seed Halo-Priming Improves Seedling Vigor, Grain Yield, and Water Use Efficiency of Maize under Varying Irrigation Regimes

AbdAllah M. El-Sanatawy [1], Salwa M.A.I. Ash-Shormillesy [1], Naglaa Qabil [1], Mohamed F. Awad [2] and Elsayed Mansour [1,*]

[1] Department of Crop Science, Faculty of Agriculture, Zagazig University, Zagazig 44519, Egypt; elsanatawyabdallah2@gmail.com (A.M.E.-S.); dr.salwaalymani@gmail.com (S.M.A.I.A.-S.); naglaaqabil82@yahoo.com (N.Q.)
[2] Department of Biology, College of Science, Taif University, P.O. Box 11099, Taif 21944, Saudi Arabia; m.fadl@tu.edu.sa
* Correspondence: sayed_mansour_84@yahoo.es

Abstract: Water-deficit stress poses tremendous constraints to sustainable agriculture, particularly under abrupt climate change. Hence, it is crucial to find eco-friendly approaches to ameliorate drought tolerance, especially for sensitive crops such as maize. This study aimed at assessing the impact of seed halo-priming on seedling vigor, grain yield, and water use efficiency of maize under various irrigation regimes. Laboratory trials evaluated the influence of seed halo-priming using two concentrations of sodium chloride solution, 4000 and 8000 ppm NaCl, versus unprimed seeds on seed germination and seedling vigor parameters. Field trials investigated the impact of halo-priming treatments on maize yield and water use efficiency (WUE) under four irrigation regimes comprising excessive (120% of estimated crop evapotranspiration, ETc), normal (100% ETc), and deficit (80 and 60% ETc) irrigation regimes. Over-irrigation by 20% did not produce significantly more grain yield but considerably reduced WUE. Deficit irrigation (80 and 60%ETc) gradually reduced grain yield and its attributes. Halo-priming treatments, particularly 4000 ppm NaCl, improved uniformity and germination speed, increased germination percentage and germination index, and produced more vigorous seedlings with heavier dry weight compared with unprimed seeds. Under field conditions, the plants originated from halo-primed seeds, especially with 4000 ppm NaCl, had higher grain yield and WUE compared with unprimed seeds under deficit irrigation regimes. The long-lasting stress memory induced by seed halo-priming, particularly with 4000 ppm NaCl, promoted maize seedling establishment, grain yield, and WUE and consequently mitigated the devastating impacts of drought stress.

Keywords: halo-priming; sodium chloride; germination; water deficit; maize yield; water use efficiency

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1. Introduction

Climate change poses tremendous constraints to sustainable crop production, particularly in arid environments [1]. Increasing temperature, wind speed, and solar radiation are projected due to abrupt climatic change [2]. These weather components are the main contributors to plant evapotranspiration and consequently will influence crop water requirements [3]. The Mediterranean region is considerably impacted by climatic variability and further adverse effects are expected [4]. Water shortage and frequent drought events immensely impede production of field crops, particularly in dry regions [5,6]. Maize (*Zea mays* L.) is one of the essential cereal crops worldwide in terms of its utilization and production [1,7]. Its global cultivated area is nearly 200 million hectares with a global production of about 1150 million tonnes [8]. Globally, maize is a major source of energy, feed, and industrial products, hence, it is constantly in increasing demand. Nevertheless, it is a crop sensitive to water deficit [9,10] as both growth and production decline steeply under drought stress [11–14]. Water scarcity decreases photosynthetic pigments, transpiration rate, and photosynthetic efficiency, which destructively reflect on grain yield [15–18]. For that reason, it is crucial to find proper eco-friendly approaches to promote drought tolerance of maize, especially in arid environments under recent climate changes [19,20]. Recently, several studies have assessed different approaches to mitigate the destructive impacts of drought stress, focusing on seed priming, exogenous application of growth hormones, osmoprotectants, plant mineral nutrients, and nanoparticles [21–24].

Seed priming is an efficacious and easy pre-sowing treatment to strengthen plant defense against abiotic stresses [25–28]. It has beneficial impacts such as quickening germination, stimulating seedling growth, and elevating water use and nutrient uptake, subsequently stimulating plant growth [27]. There are different approaches to seed priming; halo-priming is one of these approaches that relies on soaking seeds in inorganic salt solution, i.e., NaCl, $CaCl_2$, KNO_3, etc. [29–31]. The inorganic salt lowers water potential of seeds, which is similar to drought stress impacts [32]. Halo-priming triggers a physiological response of the seeds that acts on plant stress memory to make plants respond quickly and aggressively to imminent abiotic stress [28]. Plant stress memory is retained from seed halo-priming and exposure to osmotic stress [25,33]. Consequently, mild pretreatment stress can promote tolerance to upcoming other stresses [33]. Therefore, seed halo-priming is significantly beneficial to enhance plant tolerance to adverse environmental conditions and increase grain yield [32,34–37].

Based on the previous studies, the present work hypothesized that the application of seed halo-priming could remarkably enhance maize growth and productivity. Several studies have been performed on seed priming, but more knowledge is still needed about the response of maize to seed halo-priming in arid environments under different irrigation regimes. Thus, the present study aimed at (i) determining the impact of seed halo-priming on maize seed germination and seedling vigor measurements, (ii) investigating the influence of over-irrigation and deficit irrigation regimes on maize yield and WUE under arid conditions, and (iii) assessing the impact of seed halo-priming treatments on maize growth, productivity, and WUE under well-watered and water deficit irrigation conditions.

2. Materials and Methods

2.1. Laboratory Experiment

A set of 600 seeds (hybrid Giza-178) were purified with 0.1% $HgCl_2$ for 90 s and rinsed with distilled water. The seeds were split into three sets; the first one was soaked in 4000 ppm NaCl solution for 12 h (giving an osmotic potential of −0.31 MPa), the second set was soaked in 8000 ppm NaCl solution for 12 h (giving an osmotic potential of −0.62 MPa), and the third set was utilized as a control without any treatment (unprimed). The two treatments of seed halo-priming were performed separately at 20 °C in the dark and the treated seeds were re-dried to their original weight using forced air at room temperature. Two days later after reaching the original weight, germination testing was conducted.

Four replicates of 40 seeds for each treatment were germinated at 25 ± 1 °C in a dark growth chamber with 45% relative humidity in plastic germination plates with moist blotting. Seeds were determined germinated when their radical and coleoptile lengths reached 2 mm. Germination count was performed every day and finished when no more germination was detected (after 10 days). The following germination and seedling vigor parameters were assessed: germination percentage (GP), seedling root length (RL), seedling shoot length (SL), seedling dry weight (SDW), seedling fresh weight (SFW), and seedling vigor index (SVI). Moreover, germination index (GI) was estimated following Abdul-Baki and Anderson [38], mean germination time (MGT) was determined according to Ellis and Roberts [39]; germination coefficient of velocity (GCV) was estimated following Maguire [40].

2.2. Field Trial

2.2.1. Description of Experimental Site

A two-year field experiment was performed on maize (Giza-178) at Abu-Hammad, Sharkia, Egypt (30°32′ N, 31°36′ E), during successive summer seasons of 2018 and 2019. The experimental site is characterized as arid and no precipitation occurs during the summer season (Table 1). The experimental field soil was sandy clay in texture; its analysis is listed in Table 2. The prior crop was faba bean in both growing seasons. The plots were fertilized at rates of 32 kg P ha^{-1}, 94 kg K ha^{-1}, and 285 kg N ha^{-1}. Sowing took place on the first of May in both seasons according to the recommended period of maize growing in the study region. The other recommended agronomic practices in the study region encompassing pest, disease, and weed control were applied.

Table 1. Minimum (min) and maximum (max) temperatures, total precipitation (Prec), relative humidity (RH), and cumulative growing degree days (GDD) in 2018 and 2019 seasons as well as 22-year averages (1998–2019).

Month	Min (°C)	Max (°C)	Prec (mm)	RH (%)	GDD (°C)
			First season (2018)		
May	19.9	32.2	0	43	497.6
June	22.1	34.2	0	45	544.5
July	24.2	34.7	0	56	602.9
August	24.8	35.3	0	56	521.3
			Second season (2019)		
May	20.8	34.3	0	42	544.1
June	23.3	35.3	0	49	579.0
July	24.8	35.9	0	54	630.9
August	25.4	35.6	0	56	508.0
			22-yr average		
May	19.0	32.4	0	45	
June	21.4	34.4	0	47	
July	23.3	35.0	0	57	
August	20.5	31.9	0	61	

Table 2. Soil properties of the experimental site (over two seasons 2018 and 2019).

Soil Depth (cm)	Soil Bulk Density (g cm $^{-3}$)	Field Capacity (%)	Wilting Point (%)	Available Moisture (%)	pH	Organic Matter (%)
0–30	1.45	12.73	6.36	6.72	7.93	0.44
30–60	1.47	12.42	6.21	6.10	7.91	0.40
60–90	1.49	11.87	5.94	6.03	7.91	0.32
	EC (dS m^{-1})	**Nitrogen (mg kg^{-1} soil)**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Texture**
0–30	1.60	19.12	47.52	14.12	38.36	Sandy clay
30–60	1.56	16.91	47.71	14.05	38.24	Sandy clay
60–90	1.54	15.37	48.08	13.99	37.93	Sandy clay

2.2.2. Experimental Design and Studied Treatments

Split-plot design was applied with three replicates. Main plots were allocated to irrigation regimes and the sub-plots were designated for seed halo-priming treatments (Figure 1). Four irrigation regimes were assessed; 120, 100, 80, and 60% of maize evapotranspiration (ETc). In addition, three seed priming treatments were applied, i.e., unprimed seeds, 4000 ppm, and 8000 ppm NaCl using the same procedures performed for the laboratory experiment. Each experimental plot area was 23.4 m^2, which included 6 rows, 0.65 m apart and 6 m long, and the seeds were sown in hills with a distance of 0.25 m. Irrigation was scheduled based on crop evapotranspiration (ETc) replacement following the crop coefficient approach according to Allen et al. [41]. Weather variables data were collected from a weather station sited at the experimental location. The amount of full irrigation (100% ETc) was 800.9 and 814.8 mm ha^{-1} during first and second seasons, in the same order. The irrigation amount was decreased by 40 and 20% for irrigation levels of 60 and 80% ETc and increased by 20% for an irrigation level of 120% ETc. The irrigation treatments were applied after fifteen days from planting in both growing seasons to ensure complete field emergence. The drip irrigation system was applied to provide the experimental goals. Irrigation water amount was determined individually for each irrigation level employing a flow meter. Irrigation water was added in 12 events distributed throughout the growing season. Irrigation was stopped at about 20 days prior to harvesting in mid-August.

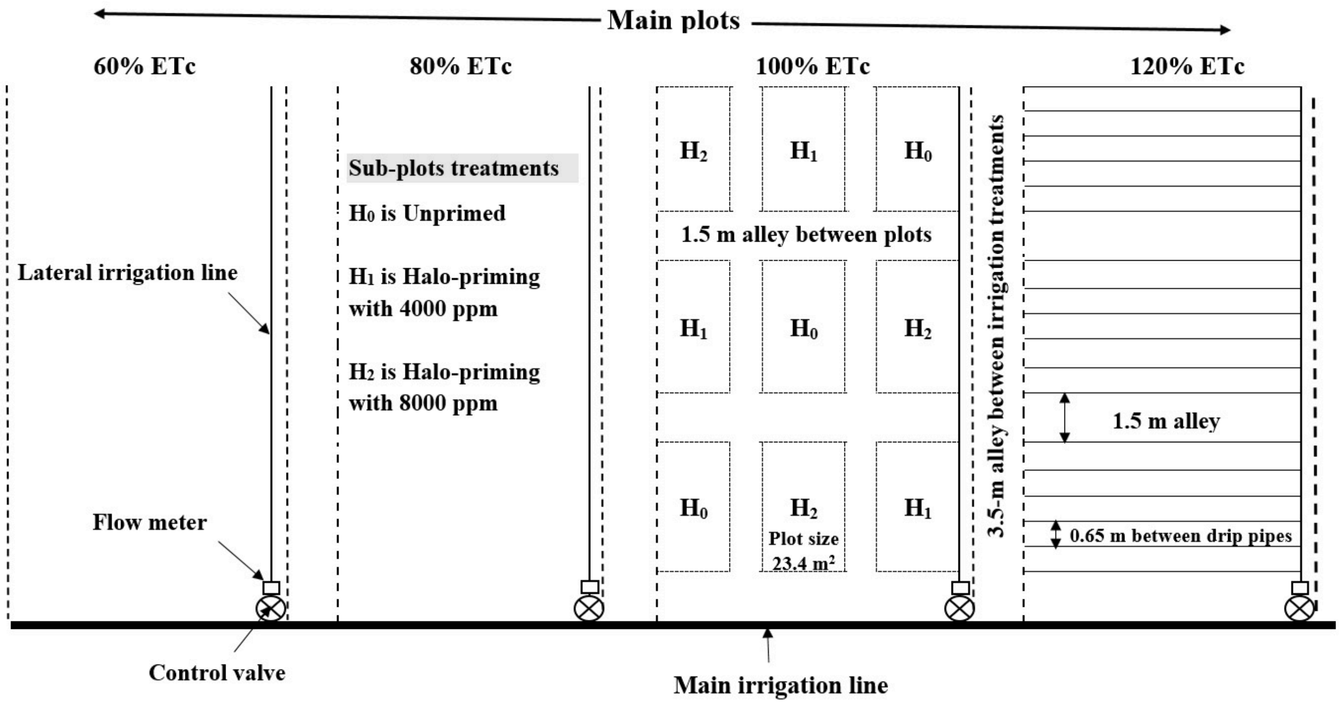

Figure 1. The experiment layout displaying four irrigation regimes in main plots and seed halo-priming treatments in subplots.

2.2.3. Field Measurements

Relative water content (RWC) was evaluated during the period of grain filling (90 DAS as outlined by Barrs and Weatherley [42]. At harvesting, ten plants were randomly collected from each plot to measure cob height (cm), plant height (cm), cob length (cm), number of grains row^{-1}, number of rows cob^{-1}, grain weight cob^{-1}, 100-grain weight (g), and shelling percentage. All maize plants of the central two rows were collected from each plot to estimate grain yield (kg m^{-2}) then converted to kg ha^{-1}. Grain yield was estimated from shelled cobs (was modified to 15.5% moisture content). Harvest index (%) was calculated as the ratio of grain yield divided by above-ground biological yield. Water use efficiency (WUE, kg ha^{-1} mm^{-1}) was estimated as grain yield divided by ET_C according to Greaves and Wang [43].

2.3. Statistical Analysis

Data of laboratory and field experiments were analyzed using completely randomized design and split-plot analysis, respectively, using the package Agricolae [44] in R statistical software version 3.6.1. Differences among treatments were separated by the least significant difference (LSD) at $p \leq 0.05$. Regression model of quadratic-plateau was applied to explore the relationship between irrigation water regimes and grain yield for three priming treatments using GraphPad Prism. The breakpoint in the response curve representing the minimum irrigation amount to produce maximum grain yield for the priming treatments was identified by the program. The principal component analysis was performed using the R statistical software package Factoextra [45].

3. Results

3.1. Laboratory Experiment

The obtained results manifested that seed halo-priming with 4000 ppm NaCl significantly promoted the germination process through increasing germination percentage and germination index. It exhibited 93.3% of germination percentage and a germination index of 18.1 compared with unprimed seeds that had 80.0% and 8.6 representing 16.7% and 109% increases in these parameters, respectively (Table 3). Moreover, the same treatment significantly produced more vigorous seedlings with heavier fresh and dry weight (increased by 11.0 and 26.6%) as well as a higher seedling vigor index (increased by 47.7% in comparison with unprimed seeds). Furthermore, halo-priming treatment with 4000 ppm NaCl substantially hastened the germination process through reducing mean germination time by 11.3% compared with unprimed seeds. Otherwise, halo-priming seeds with 8000 ppm NaCl had a considerably lesser effect on the germination process and seedling vigor (Table 3). This reflects that seed halo-priming with 4000 ppm NaCl has a stimulating impact on seed germination and maize seedling establishment.

Table 3. Impact of seed halo-priming treatments with 4000 and 8000 ppm versus unprimed seeds on maize seed germination and seedling vigor parameters.

Parameter	Unprimed		Halo-Priming with 4000 ppm		Halo-Priming with 8000 ppm		*p*-Value
Germination percentage (%)	80.00	b	93.33	a	74.67	c	0.001
Mean germination time (day)	7.24	a	6.42	b	6.48	b	<0.001
Germination coefficient of velocity (seed day^{-1})	13.79	b	15.56	a	15.41	a	<0.001
Germination index (seed day^{-1})	8.62	b	18.06	a	13.88	c	<0.001
Root length (cm)	14.28		14.79		14.80		0.511
Shoot length (cm)	5.02	b	5.87	a	5.48	a	0.048
Seedling fresh weight (mg)	660.25	b	732.68	a	684.82	b	0.018
Seedling dry weight (mg)	216.07	c	273.62	a	250.50	b	0.001
Seedling vigor index (unitless)	17.28	b	25.53	a	18.70	b	<0.001

Means followed by different letters in each row differ significantly by LSD ($p < 0.05$).

3.2. Field Trial

Excessive irrigation by raising the irrigation regime from 100% to 120% ETc failed to achieve a significant increase in RWC, cob height, plant height, cob length, number of grains row^{-1}, number of rows cob^{-1}, 100-grain weight, grain weight cob^{-1}, shelling percentage, grain yield, and harvest index, but significantly decreased WUE (Tables 4 and 5). In contrast, subjecting plants to water scarcity by decreasing the irrigation level from 100% to 80 or 60% ETc was accompanied by a significant reduction in all aforementioned traits, except WUE, which increased. Moreover, the negative impacts of severe drought (60% ETc) were more pronounced than those of moderate drought stress (80% ETc). Evidently, severe drought stress reduced RWC by 27.8%, plant height by 26.0%, cob height by 16.2%, cob length by 28.5%, number of rows cob^{-1} by 17.2%, number of grains row^{-1} by 32.0%, grain weight cob^{-1} by 36.4%, 100-grain weight by 21.2%, shelling percentage by 7.3%, grain yield by 63.4%, and harvest index by 20.4% compared with well-watered treatments (100% ETc).

Table 4. Effect of irrigation regimes and seed halo-priming treatments on relative water content (RWC), cob height, plant height, cob length, number of grains row^{-1}, and number of rows cob^{-1} during two growing seasons of 2018 and 2019.

Factor		RWC (%)		Cob Height (cm)		Plant Height (cm)	
		2018	2019	2018	2019	2018	2019
Irrigation regimes (I)							
120% ETc		77.24 ^{A}	76.31 ^{A}	140.95 ^{A}	142.16 ^{A}	300.51 ^{A}	297.80 ^{A}
100% ETc		75.89 ^{A}	75.34 ^{A}	137.11 ^{A}	138.52 ^{A}	296.55 ^{A}	294.05 ^{A}
80% ETc		61.92 ^{B}	64.49 ^{B}	126.64 ^{B}	122.20 ^{B}	258.28 ^{B}	261.65 ^{B}
60% ETc		54.52 ^{C}	54.67 ^{C}	116.72 ^{C}	114.31 ^{C}	217.42 ^{C}	219.46 ^{C}
Seed halo-priming (H)							
Unprimed		64.80 ^{b}	65.18 ^{b}	134.99	136.22	264.62 ^{b}	265.19 ^{b}
Halo-priming with 4000 ppm		68.53 ^{a}	68.75 ^{a}	133.35	132.68	268.86 ^{ab}	268.42 ^{ab}
Halo-priming with 8000 ppm		68.86 ^{a}	69.18 ^{a}	131.44	131.81	270.09 ^{a}	270.11 ^{a}
ANOVA	**df**	***p*-Value**					
Irrigation regime (I)	3	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Seed halo-priming (H)	2	<0.001	0.002	0.615	<0.324	0.048	0.047
I × H	6	<0.001	0.031	0.038	<0.001	0.040	0.035

Studied Factors		Cob Length (cm)		Number of Grains Row^{-1}		Number of Rows Cob^{-1}	
		2018	2019	2018	2019	2018	2019
Irrigation regimes (I)							
120% ETc		20.36 ^{A}	21.12 ^{A}	36.38 ^{A}	38.37 ^{A}	13.52 ^{A}	13.44 ^{A}
100% ETc		19.90 ^{A}	20.79 ^{A}	36.22 ^{A}	38.36 ^{A}	13.13 ^{A}	13.27 ^{A}
80% ETc		17.86 ^{B}	17.59 ^{B}	28.62 ^{B}	32.91 ^{B}	12.54 ^{B}	11.63 ^{B}
60% ETc		14.98 ^{C}	14.10 ^{C}	24.69 ^{C}	26.00 ^{C}	11.08 ^{C}	10.77 ^{C}
Seed halo-priming (H)							
Unprimed		17.67 ^{b}	18.05 ^{b}	30.03 ^{b}	32.50 ^{b}	12.46	12.09
Halo-priming with 4000 ppm		18.51 ^{a}	18.46 ^{a}	32.43 ^{a}	34.80 ^{a}	12.61	12.34
Halo-priming with 8000 ppm		18.65 ^{a}	18.69 ^{a}	31.96 ^{a}	34.44 ^{a}	12.64	12.41
ANOVA	**df**	***p*-Value**					
Irrigation regime (I)	3	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Seed halo-priming (H)	2	0.007	0.005	<0.001	<0.001	0.818	0.370
I × H	6	0.039	0.021	<0.001	0.017	0.029	0.047

Means of irrigation levels followed by distinct uppercase letters and means of halo-priming treatments followed by distinct lowercase letters differ significantly by LSD ($p < 0.05$).

Table 5. Effect of irrigation regimes and seed halo-priming treatments on grain weight cob^{-1}, 100-grain weight, shelling percentage, grain yield ha^{-1}, harvest index (HI), and water use efficiency (WUE) during two seasons of 2018 and 2019.

Factor		Grain Weight Cob^{-1}		100-Grain Weight (g)		Shelling Percentage	
		2018	2019	2018	2019	2018	2019
Irrigation regimes (I)							
120% ETc		137.14 ^{A}	128.48 ^{A}	27.85 ^{A}	27.55 ^{A}	75.76 ^{A}	74.18 ^{A}
100% ETc		135.42 ^{A}	126.05 ^{A}	27.35 ^{A}	27.17 ^{A}	74.65 ^{A}	73.82 ^{A}
80% ETc		105.56 ^{B}	101.09 ^{B}	23.54 ^{B}	23.97 ^{B}	72.07 ^{B}	71.69 ^{B}
60% ETc		86.60 ^{C}	79.50 ^{C}	21.30 ^{C}	21.68 ^{C}	68.64 ^{B}	69.05 ^{B}
Seed halo-priming (H)							
Unprimed		110.47 ^{c}	102.80 ^{c}	23.59 ^{c}	23.59 ^{c}	72.26 ^{b}	71.27 ^{b}
Halo-priming with 4000 ppm		121.89 ^{a}	113.85 ^{a}	26.29 ^{a}	26.29 ^{a}	74.08 ^{a}	73.78 ^{a}
Halo-priming with 8000 ppm		116.18 ^{b}	109.70 ^{b}	25.4 ^{b}	25.4 ^{b}	73.51 ^{a}	73.01 ^{a}
ANOVA	**df**	***p*-Value**					
Irrigation regime (I)	3	<0.001	<0.001	<0.001	<0.001	0.001	0.003
Seed halo-priming (H)	2	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
I × H	6	<0.001	<0.001	<0.001	<0.001	0.008	0.029

Table 5. *Cont.*

Studied Factors		Grain Yield (kg ha^{-1})		Harvest Index (%)		WUE (kg ha^{-1} mm^{-1})	
		2018	2019	2018	2019	2018	2019
Irrigation regimes (I)							
120% ETc		7305 A	7348 A	37.23 A	36.62 A	9.49 C	9.37 C
100% ETc		7271 A	7288 A	37.66 A	37.60 A	11.34 B	11.15 B
80% ETc		6145 B	6185 B	32.47 B	32.16 B	11.98 A	11.83 A
60% ETc		4723 C	4532 C	29.32 C	30.61 C	12.28 A	11.55 A
Seed halo-priming (H)							
Unprimed		6141 c	6131 c	32.35 b	32.87 b	10.78 c	10.53 c
Halo-priming with 4000 ppm		6560 a	6538 a	35.50 a	35.23 a	11.71 a	11.41 a
Halo-priming with 8000 ppm		6381 b	6346 b	34.66 a	34.65 a	11.34 b	10.99 b
ANOVA	**df**	***p*-Value**					
Irrigation regime (I)	3	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Seed halo-priming (H)	2	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
I × H	6	0.005	0.007	0.002	<0.001	<0.001	<0.001

Means of irrigation regimes followed by distinct uppercase letters and means of halo-priming treatments followed by distinct lowercase letters differ significantly by LSD ($p < 0.05$).

Halo-primed seeds enhanced RWC, cob length, number of grains row^{-1}, 100-grain weight, grain weight cob^{-1}, shelling percentage, grain yield, harvest index, and WUE values, while no significant alterations were observed in cob height, plant height, and number of rows cob^{-1} due to halo-priming treatments. The stimulating impacts on maize seeds primed with 4000 ppm NaCl exceeded those of priming with 8000 ppm NaCl. The halo-priming with 4000 ppm boosted number of grains row^{-1} by 7.5%, grain weight cob^{-1} by 10.5%, 100-grain weight by 11.4%, grain yield by 6.7%, harvest index by 8.4%, and WUE by 8.5% compared with unprimed treatment.

Significant interaction impacts between irrigation levels and seed halo-priming treatments were observed for all studied traits (Tables 4 and 5) and are presented in Figures 2 and 3. Regardless of seed halo-priming treatments, no significant effects were observed in grain yield and its related attributes with a 20% increase of irrigation above ETc. Moreover, the impact of halo-primed treatments was not significant under well-watered conditions (120 and 100% ETc), while seed halo-priming treatments exhibited statistically significant impacts under moderate and severe drought stress (80% and 60% ETc). The plants originating from halo-primed seeds showed lower reductions in yield-related traits and increased WUE under water deficit conditions (Figure 3). Clearly, the impact of halo-priming with 4000 ppm NaCl surpassed that of 8000 ppm on 100-grain weight, grain weight cob^{-1}, grain yield, and WUE under drought stress conditions. The halo-priming with 4000 ppm elevated number of grains row^{-1} by 22.4%, grain weight cob^{-1} by 26.5%, 100-grain weight by 26.3%, grain yield by 21.3%, harvest index by 24.2%, and WUE by 21.7% in comparison with unprimed treatment under severe drought conditions. Accordingly, it can be concluded that the positive role of seed halo-priming, particularly with 4000 ppm NaCl, was more powerful under water stress conditions.

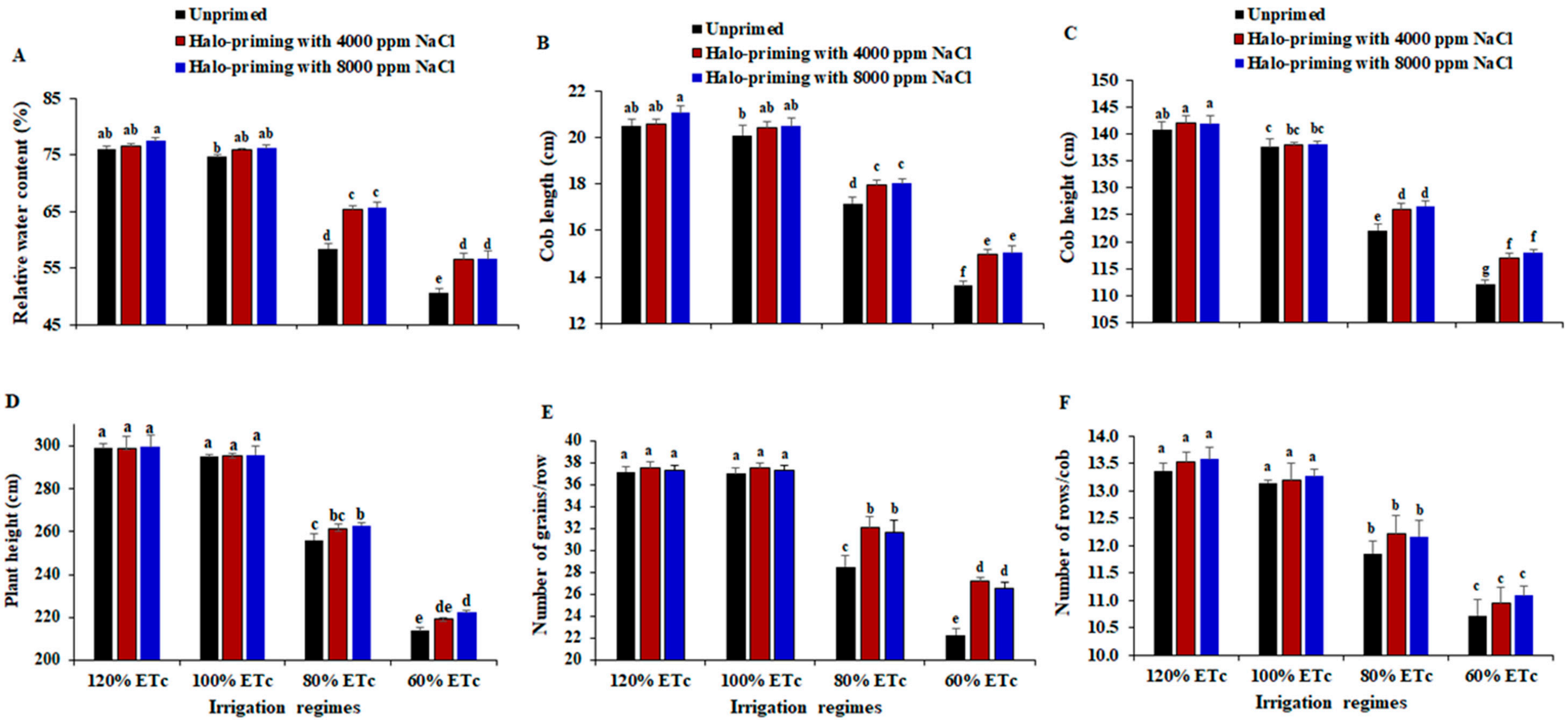

Figure 2. Impact of seed halo-priming treatments on relative water content (**A**), cob length (**B**), cob height (**C**), plant height (**D**), number of grains row^{-1} (**E**), and number of rows cob^{-1} (**F**) of maize grown under four irrigation regimes over two seasons 2018 and 2019. The bars on the columns correspond to SE and different letters differ significantly by LSD ($p < 0.05$).

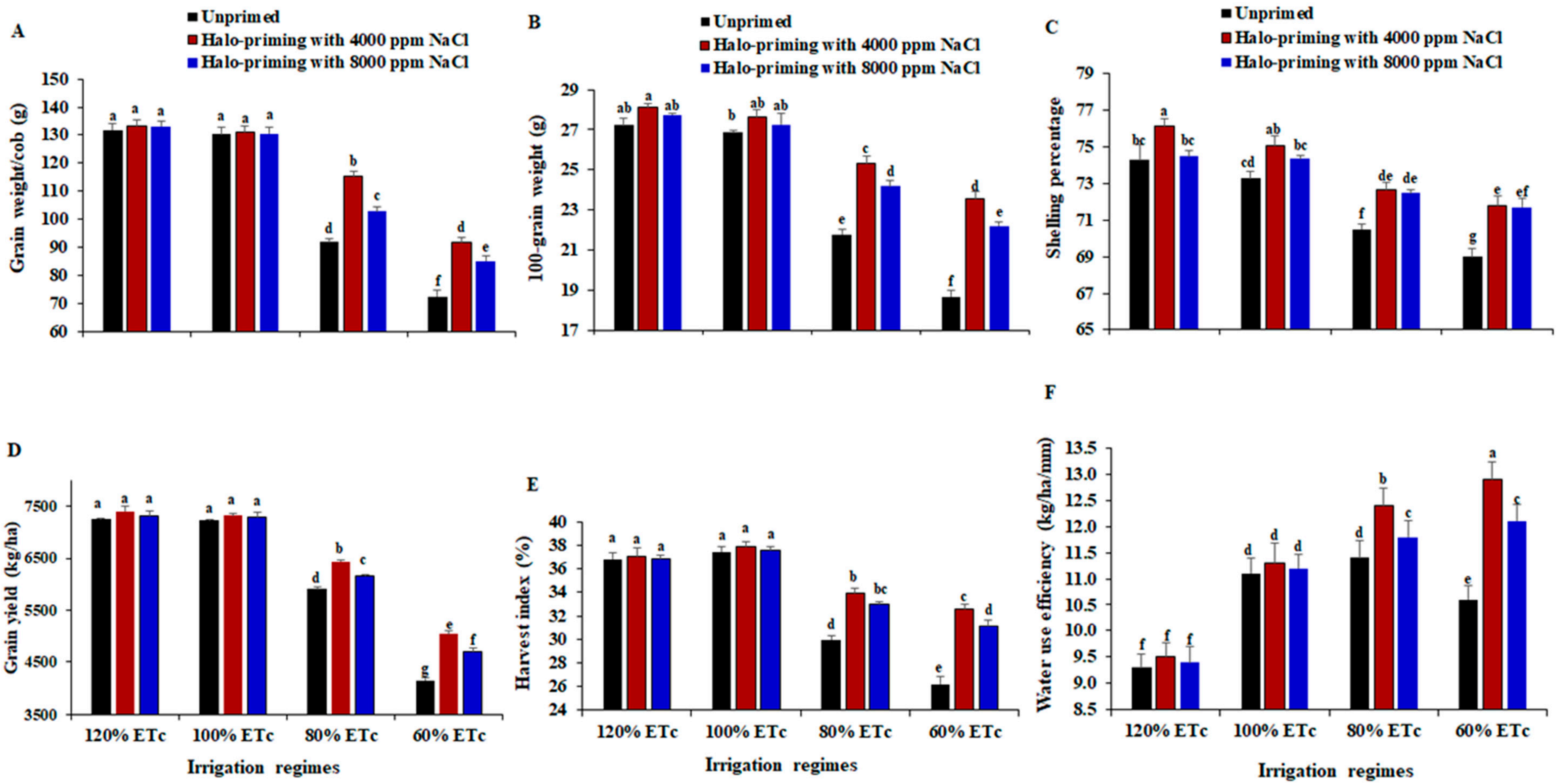

Figure 3. Impact of seed halo-priming treatments on grain weight cob^{-1} (**A**), 100-grain weight (**B**), shelling percentage (**C**), grain yield (**D**), harvest index (**E**), and water use efficiency (**F**) of maize under four irrigation regimes over two seasons 2018 and 2019. The bars on the columns correspond to SE and different letters differ significantly by LSD ($p < 0.05$).

3.2.1. Response of Grain Yield to Irrigation Regimes

The relationship between irrigation regimes and grain yield as influenced by seed halo-priming is described in Figure 4. The three priming treatments showed a quadratic convex diminishing response. The breakpoint in the response curve was detected at 757 mm. This point represents the minimum irrigation amount to produce maximum grain yield for the priming treatments, which were 6799, 7055, and 6919 kg ha^{-1} for seeds unprimed, halo-primed with 4000 ppm NaCl and 8000 ppm NaCl, respectively. Accordingly, the plants originating from seed halo-primed with 4000 ppm could produce a higher grain yield using the same water amount compared to those halo-primed with 8000 ppm and unprimed treatments. Moreover, the predicted economic grain yield for unprimed seeds (6799 kg ha^{-1}) could be produced using a lower irrigation amount (696.2 mm) using seeds halo-primed with 4000 ppm NaCl. This implies that seeds halo-primed with 4000 ppm NaCl produce superior grain yield, especially under drought stress as presented in Figure 4.

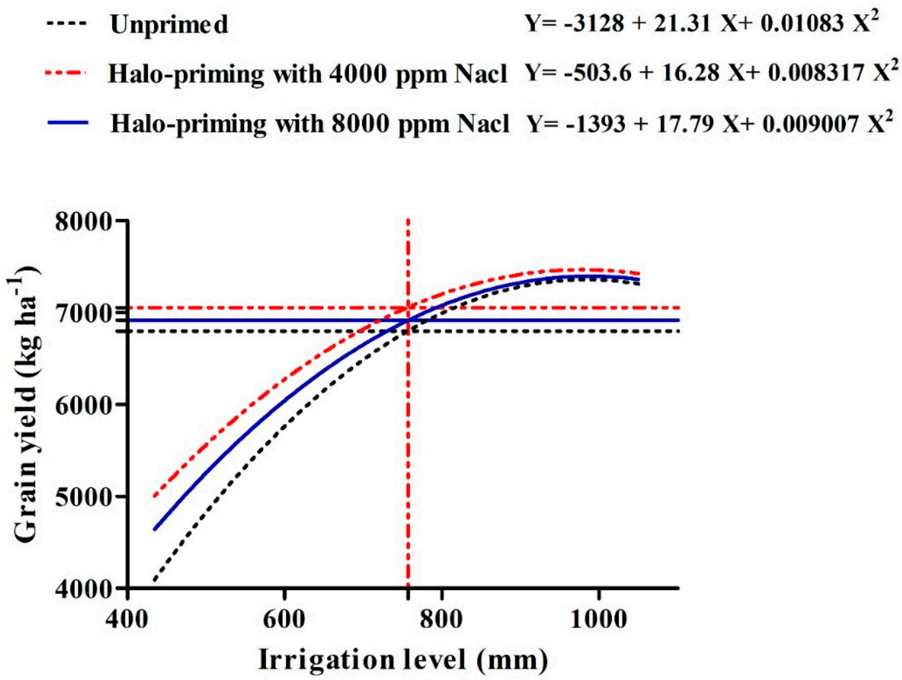

Figure 4. Response of grain yield to irrigation regimes and determining minimum irrigation amount to produce economic grain yield for the three priming treatments.

3.2.2. Interrelationship among Studied Traits and Treatments

Principal component analysis (PCA) was used to assess the association among the investigated traits and treatments as presented in Figure 5. The first two PCAs accounted for 97.79% of the variability. The PCA1 explained 80.8% of the variation and was related to increasing the irrigation regimes from 60% to 120% ETc (Figure 5). The increase from 100% to 120% ETc had a small effect as depicted by the small distance of plots from these treatments along PCA1, while the distance in the multidimensional spaces of 60% and 80% ETc irrigation regimes were much more spread out, implying dissimilarity. The PCA1 divided the irrigation levels into two groups; the excessive and full irrigation regimes were situated on the positive side but those of moderate and severe drought stress were located on the negative side (Figure 5). The PCA2 explained 16.8% of the variation and seems to correspond with seed halo-priming treatments, from bottom to top as unprimed, 8000 ppm and 4000 ppm. Seed treatments were more dissimilar with plots under severe drought conditions (60% ETc) compared with moderated drought (80% ETc) or well-watered irrigation regimes (120 and 100% ETc). Grain yield and its attributes were associated with well-watered irrigation regimes (120 and 100% ETc) in the PCA1, whereas WUE was associated with seeds halo-primed with 4000 ppm NaCl under severe (60% ETc) and moderate (80% ETc) drought stress regimes. Regardless of irrigation regimes, seed treatments were ordered in PCA2 from unprimed to 4000 ppm treatment following an increase of WUE. The adjacent vectors of traits reflect a strong positive association while vectors with larger angles prove a weak association, and opposite vectors (at 180°) reveal a negative relationship. A strong positive association was observed among grain yield and all its attributes, while there was a negative association with WUE. As expected from the results previously presented, grain yield and related traits were positively correlated and opposite to those of WUE. Moreover, no significant difference was detected between 100% and 120% ETc and as well as the positive impact of halo-priming with 4000 ppm on WUE under drought stress. Hence, the PCA biplot reinforced the aforementioned presented results.

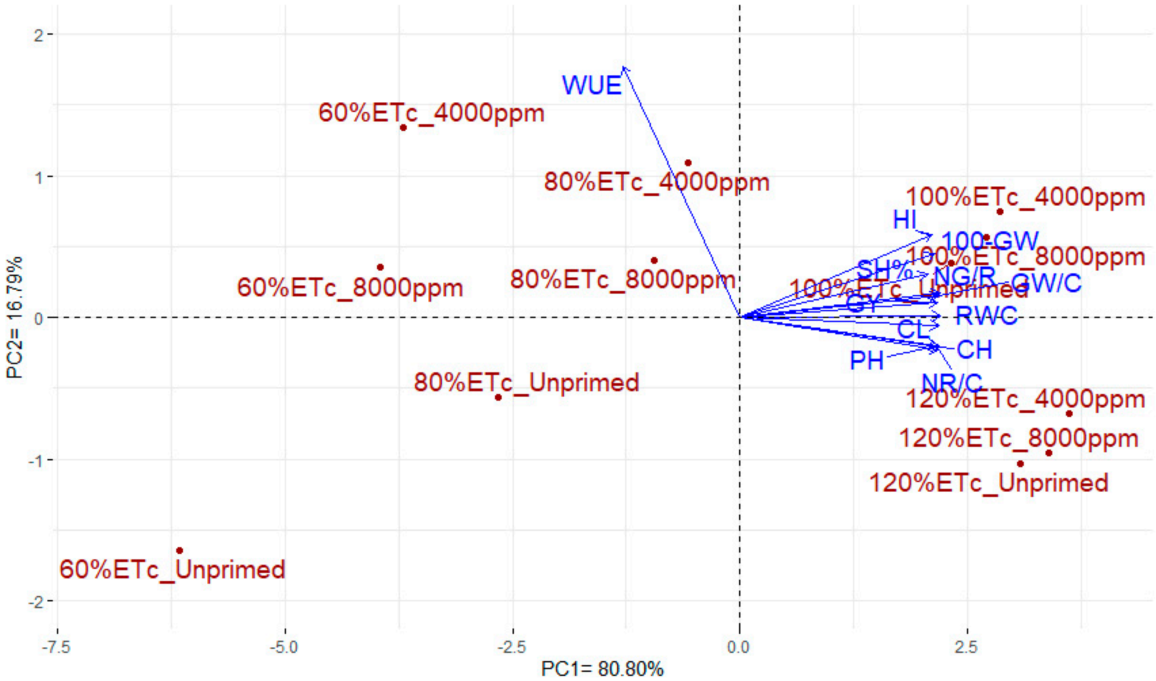

Figure 5. PCA biplot for the evaluated traits of maize under four irrigation regimes and two halo-priming treatments over two seasons 2018 and 2019. RWC: relative water content, CH: cob height, PH: plant height, CL: cob length, NG/R: number of grains row^{-1}, NRC: number of rows cob^{-1}, GW/C: grain weight cob^{-1}, 100-GW: 100-grain weight, SH%: shelling percentage, GY: grain yield, WUE: water use efficiency, and HI: harvest index.

4. Discussion

Maize water requirements are expected to vary with climate change [46,47]. Consequently, it is necessary to assess irrigation requirements regularly to achieve high yields without losing water by over-irrigation or exposing plants to devastating impacts of drought stress. In the current study, four irrigation levels were evaluated (120, 100, 80, and 60% ETc) to study the effects of excessive and deficit irrigation (severe and moderate) conditions on maize grain yield and WUE. Certain researchers deduced that excessive irrigation by 120% and 125% of irrigation water requirements increased maize grain yield [9,48,49]. On the contrary, others proved that excessive irrigation failed to produce a substantial increase in grain yield in comparison with full irrigation level [12,50]. In our case, the results manifested that excessive irrigation up to 120% ETc had no significant influence on all the studied agronomic traits, but it significantly decreased WUE. Enhancing WUE is essential, particularly in arid environments, to cope with the limitation of irrigation water [51]. Accordingly, increasing irrigation amounts by more than 100% ETc is not advised in arid regions due to the decline of water supplies owing to climatic changes [10].

Water deficit substantially reduces photosynthetic efficiency, stomatal conductance, transpiration rate, membrane stability index, water relations, and nutrient uptake which negatively reflects on maize growth and productivity [15,19,52,53]. The obtained results exhibited that deficit irrigation levels (60% and 80% ETc) gradually reduced maize yield and its attributes (Tables 3 and 4). Deficit irrigation caused a decline in RWC (Table 3), which describes the water status of the plant. The reduction in RWC in plant cells resulted in stunted plants and impeded plant growth. Drought stress seriously hindered maize development and growth by reducing cell size and cell division in meristematic tissues [54–57]. Moreover, water deficit causes a reduction in pollen production during the vegetative stage [58], silking rate during flowering stage [59], ovule fertilization during reproductive stage [60,61], accelerating senescence during maturity stage, and reducing grain filling rate and duration [62–64], reducing accumulation of photosynthetic products. Accordingly, yield traits of cob length, number grains row^{-1}, number of rows cob^{-1}, 100-grain weight, and grain weight cob^{-1} gradually declined under deficit irrigation regimes. This was further displayed by the biplot of principal components since the agronomic traits associated with 100% ETc were on opposite sites to 80% and 60% ETc irrigation regimes (Figure 5). Similar adverse impacts of water deficit were demonstrated by Zhang et al. [64]; Bharathi et al. [65]; Siyami et al. [66]; Jiang et al. [67]; Mansour et al. [68]; Sohail et al. [69]; Nawaz et al. [70]; and Attia et al. [71].

Maize is a crop sensitive to water deficit and its production is tremendously influenced by drought stress. Hence, it is crucial to identify proper approaches to ameliorate drought tolerance, particularly under arid environments. Halo-priming is an affordable approach to promote drought tolerance [30,72]. The obtained results revealed that halo-priming treatments hastened the germination development and reduced mean germination period in comparison with unprimed seed, showing superiority of halo-priming seed with 4000 ppm NaCl. Moreover, seed halo-priming with 4000 ppm NaCl boosted germination percentage, germination index, and seedling vigor index in comparison with unprimed seeds. On the other hand, germination percentage and germination index were lower using 8000 ppm NaCl solution, which may be attributed to the toxic effect of high-level accumulation of Na^+ and Cl^- ions in maize seeds. In this context, Bakht et al. [73] disclosed that maize seeds halo-primed with 3480 ppm exhibited significant positive impacts on days to emergence, germination rate, shoot fresh and dry weight, shoot contents of Na^+, K^+, proline, and abscisic acid, leaf area, plant height, and yield traits; but increasing salinity level in halo-priming treatment up to 5120 ppm displayed negative impacts on plant development and growth.

Germination and seedling establishment are crucial stages that greatly impact maize growth and productivity. Fast and uniform emergence, as well as vigorous seedlings, are prerequisites for strong growth, particularly under environmental stresses [74]. Strong established seedlings have a high ability to compete for resources and interact better with biotic stresses and usually have a higher yield [75,76]. Similar results were pointed out by Jisha and Puthur [37] Patade et al. [32] and Gholami et al. [77] who disclosed that halo-priming is an efficacious pre-germination procedure for synchronized and faster seed germination. Besides, Damalas et al. [76] and Eskandari and Kazemi [78] depicted that halo-priming is a useful approach for promoting seedling vigor and establishment. In this context, Shrestha et al. [79] manifested that halo-priming stimulates metabolic activities in the early phases of germination. Subsequently, the accomplishment of pre-germination metabolic activities may be the probable reason for faster and more vigorous emergence of the primed seeds compared to the unprimed ones. Moreover, Gao et al. [80] proved that halo-priming improves seedling emergence and seed germination by enhancing the expression of aquaporins.

Exposure to abiotic stress (as halo-priming) induces stress memory which prepares the plant for faster germination and to better tolerate the upcoming stress events [81–83]. Maize plants originated from halo-primed seeds retained a long-lasting stress memory that promoted the stress scavenging mechanism under water deficit conditions. Drought tolerance induced by halo-priming regulated physiological and biochemical processes and enabled maize plants to sustain their productivity under water deficit conditions. Likewise, Patade et al. [32]; Langeroodi and Noora [84]; Iqbal et al. [34]; Khaing et al. [35] proved the vital role of seed halo-priming in ameliorating plant tolerance of adverse environmental conditions and increasing grain yield. Additionally, Bajehbaj [36] elucidated that NaCl priming elevates K and Ca accumulation in plant cells and induced osmoregulation by elevating the accumulation of proline. Proline accumulation induces water retention and mitigates the devastating impacts of drought stress [84,85].

The obtained results displayed that the influence of halo-primed treatments was not significant under well-watered conditions but was more evident under drought stress. The plants originating from halo-primed seeds exhibited higher RWC than unprimed seeds under deficit irrigation (60% and 80% ETc) with superiority of 4000 ppm NaCl. RWC exposes the water balance in plant cells and is considered a good indicator of plant water status [57]. Moreover, seeds primed with 4000 ppm NaCl significantly produced substantially heavier 100-grain weight, grain weight cob^{-1}, grain yield ha^{-1}, and higher WUE under water deficit conditions compared with 8000 ppm and unprimed treatments. Markedly, seed halo-priming with 4000 ppm NaCl increased grain yield by 21.3%, harvest index by 24.2% and WUE by 21.7% compared with unprimed seeds under severe drought stress conditions. Moreover, the response of grain yield to irrigation regimes revealed that halo-priming with 4000 ppm NaCl could produce higher grain yield utilizing less irrigation water under water shortage in comparison with unprimed treatment (Figure 4). Besides, WUE was associated with seeds halo-primed with 4000 ppm NaCl under severe (60% ETc) and moderate (80% ETc) drought stress conditions (Figure 5). Thereby, the obtained results denoted that halo-priming with 4000 ppm NaCl has a valuable role in promoting plant water status and alleviating destructive impacts of drought stress.

5. Conclusions

Excessive irrigation using 120% ETc did not produce significantly higher grain yield but significantly decreased WUE. Deficit irrigation regimes (60% and 80% ETc) gradually decreased grain yield and its attributes. It is noteworthy that the efficacy of seed halo-priming was more pronounced under drought stress. The results implied that the plant stress memory induced by seed halo-priming, particularly with 4000 ppm NaCl, ameliorated maize seedling establishment, grain yield, and WUE under drought stress. Halo-priming with 4000 ppm NaCl could be exploited to produce higher grain yield utilizing less irrigation water, especially under drought stress.

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