Agronomy Research **23**(X), xxx–ccc, 2025
https://doi.org/10.15159/AR.25.069

Seed priming with polyethylene glycol improved drought tolerance of late sown wheat by enhanced gas exchange attributes

Y. Bani Khalaf, A. Aldahadha*, O. Migdadi and A. Alkaabnh

Department of Field Crops, National Agricultural Research Center (NARC), PO Box 639, Baqa'a 19381, Jordan
*Correspondence: abdallah.aldahadha@narc.gov.jo

Received: March 31st, 2025; Accepted: July 14th, 2025; Published: July 18th, 2025

Abstract. Late sowing, especially in regions prone to drought, significantly hampers crop growth and yield. To address this, field experiments were conducted during the winter of 2021–2022 at Maru and Mushaqar in Jordan to evaluate the effects of seed priming agents as seed priming with water (hydropriming), polyethylene glycol (osmopriming), calcium chloride (osmopriming), and a control (unprimed) on physiological, phenological and yield traits of durum wheat (umqais variety) under normal and late sowing conditions. Results showed that Maru exhibited superior performance in physiology, growth, and yield attributes compared to Mushaqar. While late sown wheat demonstrated better water use efficiency, normal sowing conditions generally favored other yield components. Seed priming by polyethylene glycol (PEG) improved relative water content, stomatal conductance, and grain yield compared to other treatments. Mushaqar recorded higher grain spike^{-1} and spike m^{-2} under normal sowing, while PEG-primed seeds produced significantly higher 1,000-grain weight and harvest index. Notably, PEG-primed seeds improved grain yield and 1,000-grain weight, suggesting enhanced drought resilience under late sowing conditions. The study concludes that seed priming, especially with PEG, effectively improves drought tolerance in late sown wheat by enhancing photosynthetic activity, chlorophyll content (SPAD), and water retention. The findings indicate that PEG seed priming can effectively mitigate the negative impacts of late sowing, supporting its use as a practical strategy for improving wheat performance in semi-arid environments.

Key words: intrinsic water use efficiency, osmopriming, sowing date, stomatal conductance, yield components.

INTRODUCTION

Globally, wheat is among the most essential crop after maize and rice. It is a major dietary staple that withstands the growing global population (Faisal et al., 2023). Durum wheat (*Triticum durum* L.) contributes about five percent of global wheat production (Kobata et al., 2018). Besides, it is considered one of the most important cereals, usually grown in arid and semi-arid regions of the Middle East, including Jordan. However, food security in this region is primarily threatened by climate change, particularly drought (Munaweera et al., 2022). Future climate projections indicate that Middle Eastern countries will experience rising temperatures and declining rainfall, with an expected increase of 1.3 °C in average temperatures and an 11% decrease in annual rainfall by 2050 (Tita et al., 2025). Given climate change challenges, the optimal sowing date is an effective and economical strategy for ensuring proper crop establishment and maximizing yield under dryland conditions (Samarah & Al-Issa, 2006; Serafin-Andrzejewska et al., 2021). Deviating from the recommended sowing schedule, whether advancing or delaying, can negatively affect yield potential of cereal crops throughout the growing season, and also expose them to drought and temperature stress (Liu et al., 2021). For example, Al-Issa (2001) found that sowing wheat one month earlier than the optimal time led to a yield reduction of 292 kg per hectare, whereas delaying sowing by one month resulted in an even greater reduction of 359 kg per hectare.

Recent research has highlighted the relationship between winter wheat yields and sowing dates across different regions (Kanapickas et al., 2024). The findings underscore the importance of regional factors when defining the optimum dates for sowing winter wheat. For instance, Ding et al. (2016) demonstrated that in the semiarid Loess Plateau of China, optimal sowing dates are significantly influenced by local precipitation patterns. Specifically, Christensen et al. (2017) demonstrated that optimal sowing dates generally result in higher yields, primarily due to improved resource utilization and enhanced nitrogen uptake. However, Liu et al. (2021) reported that delaying sowing dates led to reduced yields, primarily due to inhibited crop growth and decreased biomass production. The negative consequences of late sowing arise from environmental constraints such as unfavorable weather conditions during vegetative growth, shortened developmental phases, and elevated temperatures during critical stages like grain filling, which are detrimental to the photosynthesis rate (Garg et al., 2013; Liu et al., 2021). This combination of factors can impede grain filling, leading to reduced yield and quality (Fu et al., 2023). The decline in grain yield associated with postponed sowing dates often results from a shortened period leading up to anthesis, causing plants to enter the reproductive stage earlier and intercept less solar radiation (Maresma et al., 2019). Additionally, both the number of growth days and the overall growth duration of wheat are reduced when sowing is delayed (Ahmed & Fayyaz-ul-Hassan, 2015). As a result, the number of leaves and tillers is reduced (Yin et al., 2018). Thus, delayed sowing significantly impacts various growth parameters, including grain number per spike, 1,000-grain weight, dry matter accumulation, plant height, harvest index, and overall grain yield (Maresma et al., 2019).

Farmers in Jordan may delay wheat sowing until they are assured of sufficient rainfall or water availability. Late sowing can coincide with the onset of seasonal rains, which may improve germination and early growth. Typically, wheat sowing can be delayed until early February in Jordan. To address these challenges and improve wheat production in late-sowing situations, seed priming has emerged as a significant technique for enhancing drought tolerance (Hussein et al., 2017; El-Shazoly et al., 2025). Osmopriming (seeds soaked in osmotic solutions such as polyethylene glycol) and hydropriming (seeds soaked in water) are the most commonly used priming techniques (Singh et al., 2015; Aldahadha et al., 2024). Numerous researchers have previously reported enhancements in wheat grain yield resulting from seed priming (Singhal et al., 2019; Farooq et al., 2020; Mickky, 2022; Aldahadha et al., 2024). Moreover, Hosen et al. (2023) and Singh et al. (2023) recently investigated the impact of seed priming on wheat yield with different sowing dates. Their studies revealed that seed priming enhanced wheat grain yield under late-sown conditions. However, limited information is available on the physiological performance of primed wheat seeds sown at different dates. The primary objective of this study was to evaluate the effects of different seed priming agents including polyethylene glycol (PEG), calcium chloride ($CaCl_2$), and water (hydropriming) on the physiological, phenological, and yield traits of durum wheat (*Triticum durum* L.) under two sowing dates (normal and late) across two distinct locations in Jordan (Maru & Mushaqar), which differ in rainfall and elevation. We hypothesized that late sowing would impose greater drought stress on wheat, particularly during critical growth stages such as anthesis, resulting in reduced physiological performance and yield. However, we expected that PEG osmopriming would enhance gas exchange attributes (e.g., net photosynthesis, stomatal conductance), and mitigate yield losses, especially under late sowing and more drought-prone conditions.

MATERIALS AND METHODS

Locations study

Field experiments were conducted during the 2021–2022 growing season at two locations: Maru station, located in Irbid, northern Jordan (latitude 32° 35' 4.7" N, longitude 35° 54' 0.3" E, elevation 589 meters), and Mushaqar station, located in Madaba, central Jordan (latitude 32° 45' 16.3" N, longitude 35° 48' 1.5" E, elevation 796.3 meters). Average annual rainfall was 400 mm at Maru and 305 mm at Mushaqar. Both locations experience a Mediterranean climate, characterized by hot, dry summers. Chemical soil analyses for both sites are summarized in Table 1, and weather data are presented in Table 2.

Table 1. Soil characteristics of the experimental sites

Soil properties	Maru	Mushaqar
P (ppm)	11.9	12.5
K (ppm)	385.9	566.2
$CaCO_3$ (%)	2.6	18.2
Total N (%)	0.098	0.081
Organic matter (%)	1.23	0.83
PH	7.8	7.7
EC (dS/m)	0.64	0.91
Clay (%)	50.4	51.2
Silt (%)	37.9	35.6
Sand (%)	11.7	13.2
Texture	Clay	Clay

Treatments and experimental design

The field experiment was conducted using a randomized complete block design (RCBD) in a split-plot arrangement with three replicates. The main plots consisted of two sowing dates (normal and late sowing), while the sub-plots included various seed priming treatments. Data from both experimental sites were combined to determine whether significant differences existed between locations. Each location was treated as a separate experimental site, but data were also analyzed in

Table 2. Weather data during the growing seasons of 2021–2022 for both locations

	Maru		Mushaqar	
Month	Temperature (°C)	Rainfall (mm)	Temperature (°C)	Rainfall (mm)
Nov.	14.8	9	13.6	13.2
Dec.	9.6	103.5	8.3	57.4
Jan.	7.5	119	6.9	150.9
Feb.	8.4	62	7.5	29.2
Mar.	12.2	103	10.9	35.8
Apr.	17.1	3	15.7	0
May	20.8	0	19.5	0

a combined ANOVA framework to assess the overall effects. Location was included as a fixed factor, while Replication (block) was nested within location and treated as a random factor. Interactions among location, sowing date, and seed priming were tested to determine location-specific treatment responses. When significant interactions involving location were detected, means were further separated and analyzed within each location using one-way ANOVA.

In the laboratory of the National Agricultural Research Centre (NARC), wheat seeds were surface-sterilized using a 5% sodium hypochlorite solution for 10 minutes, followed by three rinses with distilled water, and then allowed to dry. The seeds were then primed for 12 hours at 24 °C using the following treatments: hydropriming with distilled water; osmopriming with polyethylene glycol (PEG6000; Merck, Germany) at an osmotic potential (Ψs) of −1.2 MPa; and osmopriming with a 1.5% $CaCl_2$ solution. Untreated seeds served as the non-primed (control) treatment. Seed priming was conducted by placing seeds on Petri dishes lined with double-layered Whatman No. 2 filter paper, moistened with 20 mL of the respective priming solution. For osmopriming, seeds were soaked in aerated solutions with low water potential, while hydroprimed seeds were immersed in water without aeration. After priming, the seeds were dried to near their original weight using forced air in a shaded area and stored at 5 °C until sowing. After priming, seeds were dried using forced air in a shaded area until they returned to their original pre-priming weight, as determined by weighing a representative seed sample before and after priming using a digital balance. The durum wheat variety (*Triticum durum* L.) used in this experiment was ‘Umqais’, provided by the Mushaqar Agricultural Research Center in Madaba, Jordan. This variety, with the pedigree *Um Rabi 5*, is one of the most widely cultivated in Jordan and was released in 2004 (Allozi & AlRawashdeh, 2014).

Crop management

The area of each main plot was 120 m² (5×24 m), while each sub-plot measured 10 m². Wheat seeds were sown at a rate of 12 g m^{-2}, with a row spacing of 17.5 cm and a planting depth of 7–10 cm. Seeds from the priming treatments were sown on December 14 and 15, 2021, as the normal sowing date, and on February 2 and 3, 2022, as the late sowing date, for the Maru and Mushaqar locations, respectively. These dates were selected based on local agronomic practices and rainfall patterns specific to each location. The crop had received 10 g m^{-2} of diammonium phosphate (18% N and 46% P_2O_5) at the sowing time, then by 5 g m^{-2} of urea $(NH_2)_2CO$ (45% N) at the tillering stage. As this was a rainfed trial, no supplemental irrigation was applied. However, both sites were regularly monitored for pest and disease pressure. No chemical pest or disease control was necessary during the growing season due to the absence of significant infestations. Manual weeding, were performed uniformly across all plots.

Physiological traits

Relative water content (RWC) of the leaf was measured as described in detail by Aldahadha et al. (2012, 2019). A portable handheld photosynthesis system (CI-340, CID Bio-Science, WA, USA) was used to measure net photosynthetic rate (A), transpiration rate (E), and stomatal conductance (gs). Instantaneous water use efficiency (WUEi) was calculated as A/E, while intrinsic water use efficiency (WUEin) was calculated as A/gs. Chlorophyll content was measured non-destructively using a SPAD 502 Chlorophyll

Meter (Spectrum Technologies Inc., IL, USA). Physiological measurements were taken on the flag leaves at the anthesis stage (GS65), according to the Zadoks scale (Zadoks et al., 1974). In each plot, five flag leaves were randomly selected for gas exchange analysis. Phenological observations, such as days to 50% heading and physiological maturity, were visually scored on the same plots used for physiological and yield measurements, ensuring data consistency across traits.

Phenological and yield traits

Days to 50% heading (DH) were visually recorded as the number of days from seeding until the main spike emerged from the sheath of the flag leaf. Days to 50% physiological maturity (DM) were similarly determined by counting the days from seeding until the plants reached physiological maturity, indicated by the yellowing of the spikes. Plant height (PH) was measured from the soil surface to the top of the spike, excluding the awns. At harvest, 1 m^2 samples were hand-harvested, and shoots were categorized as either fertile (bearing spikes) or infertile (without spikes). For fertile shoots, spikes were separated at the collar, and straw fresh weight was recorded. All plant components were then dried at 80 °C for 48 hours, after which grain and chaff weights were measured. Thousand grain weight (TGW) was determined after removing broken grains. The total dry weight of infertile shoots was also recorded. The number of grains per spike was calculated as the average from 10 randomly selected spikes per plot. Biological yield (BY) was calculated as the sum of grain yield (GY) and straw yield. Harvest index (HI) was calculated as the ratio of total grain weight to total aboveground plant biomass.

Statistical analysis

Data were analyzed using three-way analysis of variance (ANOVA) with location, sowing date, and seed priming treatment. The combined ANOVA was performed across both locations using Statistix 8.1 software (Analytical Software, 2005). When significant interactions were detected ($P < 0.05$), simple effects were analyzed using one-way ANOVA within levels of the interacting factor, followed by Tukey's Honestly Significant Difference (*HSD*) test for mean separation. Significance threshold was set at $P < 0.05$ for all comparisons. For correlation analysis, Pearson's correlation coefficients were calculated to assess relationships between grain yield and physiological traits.

RESULTS

Main effect of location, sowing date, and seed priming on physiological traits

Maru had significantly ($P < 0.05$) higher RWC, SPAD, g_s, E, and A than Mushaqar (Table 3). For example, RWC at Maru was 9.8% higher, and gs was 23.9% higher. Normal sowing resulted in significantly ($P < 0.05$) higher RWC, SPAD, g_s, E, and A by 15.2%, 4.3%, 29.8%, 17%, and 8.2%, respectively, when compared to late sowing. However, normal sowing had significantly ($P < 0.05$) lower WUE_i and WUE_{in} than late sowing (Table 3). Seed priming treatments significantly ($P < 0.05$) boosted some physiological traits. For example, seed priming with polyethylene glycol (PEG) resulted in increases in RWC, g_s, and A by 13.9%, 50.5%, and 42.5%, respectively, compared to the control (Table 3). However, PEG treatment had significantly ($P < 0.05$) lower WUE_{in} than control (Table 3). Seed priming with PEG had significantly ($P < 0.05$) higher RWC and g_s than seed priming with $CaCl_2$ (Table 3).

Table 3. Main effect of location, sowing date, and seed priming treatments on some physiological parameters of wheat

Effect	RWC	SPAD	g_s	E	A	WUE_i	WUE_{in}
Location							
Maru	70.4 ^{a}	50.4 ^{a}	0.388 ^{a}	5.61 ^{a}	16.80 ^{a}	3.015 ^{a}	43.83 ^{a}
Mushaqar	64.1 ^{b}	45.0 ^{b}	0.313 ^{b}	4.72 ^{b}	13.97 ^{b}	2.952 ^{a}	46.16 ^{a}
HSD (0.05)	4.87	4.96	0.0638	0.585	2.65	0.653	14.17
Sowing date							
Normal	72.0 ^{a}	48.7 ^{a}	0.396 ^{a}	5.57 ^{a}	16.00 ^{a}	2.869 ^{b}	40.44 ^{b}
Late	62.5 ^{b}	46.7 ^{b}	0.305 ^{b}	4.76 ^{b}	14.78 ^{b}	3.099 ^{a}	49.55 ^{a}
HSD (0.05)	3.63	1.74	0.0129	0.326	0.897	0.122	4.108
Seed priming							
Control	62.6 ^{d}	44.9 ^{c}	0.277 ^{d}	4.42 ^{c}	12.41 ^{c}	2.810 ^{a}	46.29 ^{a}
Hydropriming	65.7 ^{c}	46.8 ^{b}	0.329 ^{c}	4.90 ^{b}	14.49 ^{b}	2.978 ^{a}	45.40 ^{ab}
$CaCl_2$	69.3 ^{b}	49.2 ^{a}	0.378 ^{b}	5.55 ^{a}	16.97 ^{a}	3.072 ^{a}	45.48 ^{ab}
PEG	71.4 ^{a}	49.9 ^{a}	0.417 ^{a}	5.80 ^{a}	17.68 ^{a}	3.075 ^{a}	42.81 ^{b}
HSD (0.05)	1.58	0.90	0.0227	0.262	0.741	0.273	3.043

RWC: relative water content (%); g_s: stomatal conductance (mol H_2O m^{-2} s^{-1}); E: transpiration rate (mmol H_2O m^{-2} s^{-1}); A: net photosynthesis rate (μmol CO_2 m^{-2} s^{-1}); WUE_i: instantaneous water use efficiency (mmol CO_2 mol^{-1} H_2O); WUE_{in}: intrinsic water use efficiency (μmol CO_2 mol^{-1} H_2O); *HSD*: honestly significant difference at $P < 0.05$ probability level using *Tukey's test*. Different letters within the same columns indicate significant differences.

Main effect of location, sowing date, and seed priming on phenological and yield traits

Maru location had significantly ($P < 0.05$) higher phenological and yield traits than Mushaqar (Table 4), except for DM and TGW. Specifically, PH, GY, and HI increased by 33%, 47%, and 10%, respectively at Maru when compared with Mushaqar. Normal sowing had significantly ($P < 0.05$) higher phenological and yield traits than late sowing. For example, normal sowing increased DM by 36%, spikes m^{-2} by 41%, and GY by 75% (Table 4). Furthermore, seed priming had significantly ($P < 0.05$) higher phenological and yield traits than controls, except for PH, where no significant difference was found between hydropriming and controls. For instance, seed priming with PEG increased DM by 15%, spikes m^{-2} by 22%, and GY by 36% compared to control (Table 4).

Table 4. Main effect of location, sowing date, and seed priming treatments on growth, yield and yield components of wheat

Effect	DH	DM	PH	GN	SN	BY	GY	TGW	HI
Location									
Maru	100 ^{a}	127^a	100^a	25^a	257^a	7.3 ^{a}	2.3 ^{a}	38.1 ^{a}	0.32 ^{a}
Mushaqar	89 ^{b}	121^a	75^b	21^b	203^b	5.4 ^{b}	1.6 ^{b}	36.8 ^{a}	0.29 ^{b}
HSD (0.05)	9.13	7.8	5.82	1.05	7.40	0.32	0.08	2.48	0.02

Table 1 (continued)

Sowing date									
Normal	110 [a]	143 [a]	109[a]	25[a]	269[a]	8.0 [a]	2.5 [a]	39.1 [a]	0.31 [a]
Late	79 [b]	105[b]	67[b]	21[b]	191[b]	4.7 [b]	1.4 [b]	35.7 [b]	0.29 [b]
HSD (0.05)	3.58	5.37	3.49	0.51	8.94	0.20	0.07	1.27	0.01
Seed priming									
Control	88 [d]	115[d]	82[b]	21[c]	204[d]	5.8 [c]	1.6 [d]	36.1 [c]	0.27 [c]
Hydropriming	93 [c]	121[c]	85[b]	23[b]	227[c]	6.2 [b]	1.9 [c]	37.2 [b]	0.30 [b]
$CaCl_2$	97 [b]	128[b]	91[a]	23[a]	240[b]	6.6 [a]	2.1 [b]	38.1 [a]	0.32 [a]
PEG	100 [a]	132[a]	92[a]	24[a]	249[a]	6.8 [a]	2.2 [a]	38.3 [a]	0.33 [a]
HSD (0.05)	2.02	3.14	4.30	0.50	6.49	0.29	0.07	0.55	0.01

DH: days to heading; DM: days to maturity; PH: plant height (cm); GN: grain number per spike; SN: spike number per meter square; BY: biological yield (ton ha^{-1}); GY: grain yield (ton ha^{-1}); TGW: 1,000-grain weight (g); HI: harvest index; *HSD*: honestly significant difference at $P < 0.05$ probability level using *Tukey's test*. Different letters within the same columns indicate significant differences.

Effect of interaction between location and sowing date on some physiological and yield traits

A significant ($P < 0.05$) interaction between location and sowing date was presented for A, SPAD, and WUE_{in} (Fig. 1), as well as a significant ($P < 0.05$) interaction including grains $spike^{-1}$ and spikes m^{-2} (Fig. 2). In Maru, normal sowing increased A by 13.4% compared to late sowing, while in Mushaqar, the difference was not significant. This likely reflects Maru's higher seasonal rainfall, which may have supported stronger photosynthetic activity in timely sown crops (Fig. 1A). Conversely, SPAD values increased significantly ($P < 0.05$) by 10.4% with normal sowing in Mushaqar, but not in Maru, indicating that light or nutrient limitations may have been more responsive to sowing time in the drier location (Fig. 1B). Moreover, late sowing in Mushaqar significantly ($P < 0.05$) increased WUE_{in} by 34.8% compared to normal sowing, but not in Maru, suggesting adaptive stomatal regulation under more severe drought conditions (Fig. 1, C).

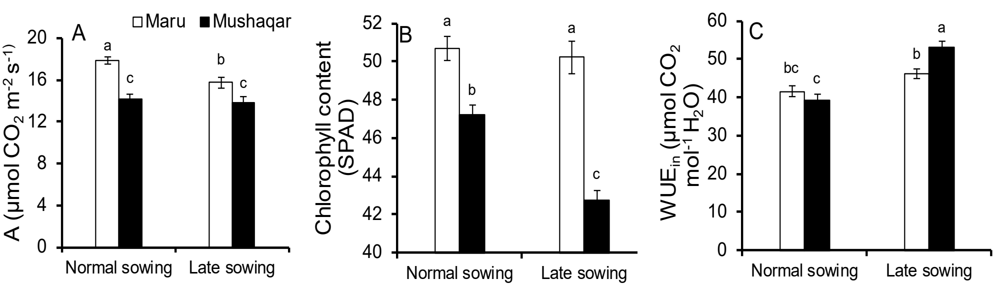

Figure 1. Location x sowing date interaction effect on (A) net photosynthetic rate, (B) total chlorophyll content by SPAD, and (C) intrinsic water use efficiency for wheat grown under seed priming treatments. Bars with the same letters are not significantly different, *Tukey's Range Test* at $P < 0.05$. Error bars show standard errors, $n = 3$.

In Maru and Mushaqar locations, normal sowing resulted in significant ($P < 0.05$) increases in grains $spike^{-1}$ by 11.6% and 22.8%, respectively (Fig. 2, A), as well as significant increases in spikes m^{-2} by 28.7% and 57.4%, respectively, when compared to late sowing (Fig. 2, B).

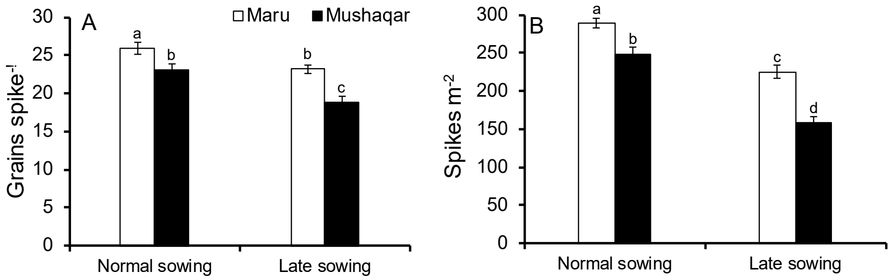

Figure 2. Location x sowing date interaction effect on (A) grain number per spike, and (B) spike number per meter square for wheat. Bars with the same letters are not significantly different, *Tukey's Range Test* at $P < 0.05$. Error bars show standard errors, $n = 3$

Effect of interaction between location and seed priming on some physiological and yield traits

In Maru location, seed priming with PEG significantly ($P < 0.05$) increased E by 5.5% compared to $CaCl_2$, but not significant in Mushaqar (Fig. 3). Furthermore, E improved significantly ($P < 0.05$) by 34.8% in seeds primed with PEG in Maru, while in Mushaqar, E increased by 26.7% (Fig. 3).

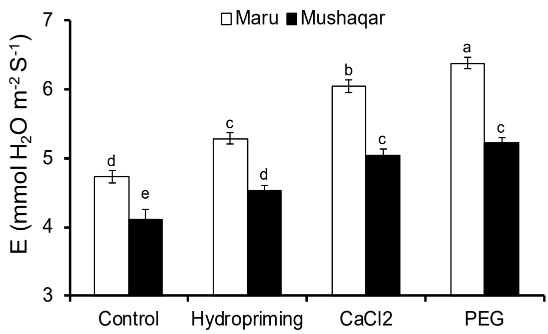

Figure 3. Location x seed priming interaction effect on transpiration rate (E) for wheat. Bars with the same letters are not significantly different, *Tukey's Range Test* at $P < 0.05$. Error bars show standard errors, $n = 3$.

In Mushaqar, seed priming with PEG significantly ($P < 0.05$) increased DH by 3.6% compared to seed priming with $CaCl_2$, but not in Maru (Fig. 4, A). Furthermore, DH increased significantly ($P < 0.05$) by 9.3% with PEG-primed seeds in Maru, whereas, in Mushaqar, DH increased by 19.6% (Fig. 4, A). In Maru, seed priming with PEG, $CaCl_2$, and water significantly ($P < 0.05$) increased spikes m^{-2} by 15.6%, 12.3%, and 8.1%, respectively compared to control (Fig. 4, B). In Mushaqar location, the increases in spikes m^{-2} were 31.6%, 25.4%, and 16.4% for seed priming with PEG, $CaCl_2$, and water, respectively compared to control (Fig. 4, B). In Mushaqar, seed priming with water significantly ($P < 0.05$) increased TGW by 5.1% compared to the control, but not in Maru (Fig. 4, C). Moreover, the TGW improved significantly ($P < 0.05$) by 3.1% in PEG-primed seeds in Maru, while in Mushaqar, it increased by 9.3% (Fig. 4, C). In Mushaqar, seed priming with $CaCl_2$ significantly ($P < 0.05$) increased HI by 7.8% compared to seed priming with water, but not in Maru (Fig. 4, D).

Also, HI improved significantly ($P < 0.05$) by 13.5% in PEG-primed seeds in Maru, while in Mushaqar, HI increased by 28.9% (Fig. 4, D).

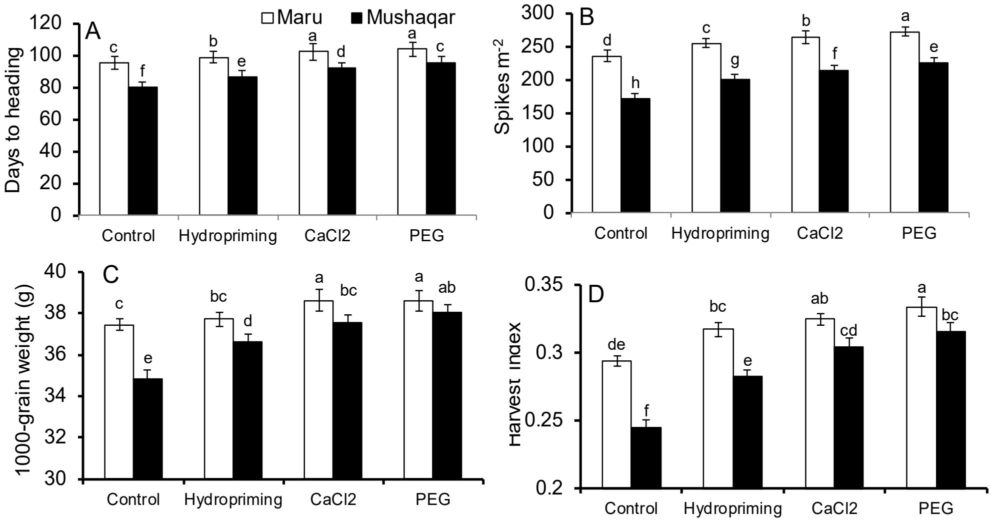

Figure 4. Location x seed priming interaction effect on (A) days to heading, (B) spike number per meter square, (C) 1,000-grain weight, and (D) harvest index for wheat grown at different sowing dates. Bars with the same letters are not significantly different, *Tukey's Range Test* at $P < 0.05$. Error bars show standard errors, $n = 3$.

Effect of interaction between sowing date and seed priming on some physiological and yield traits

In normal sowing, seed priming with PEG, $CaCl_2$, and water significantly ($P < 0.05$) increased RWC by 10.4%, 7.4%, and 2.7%, respectively compared to control (Fig. 5, A). In late sowing, seed priming with PEG, $CaCl_2$, and water increased RWC by 18.2%, 14.5%, and 7.7%, respectively compared to control (Fig. 5, A). Seed priming with PEG under late sowing did not significantly ($P < 0.05$) differ in RWC from unprimed seeds or control under normal sowing (Fig. 5, A). Moreover, seed priming with PEG significantly ($P < 0.05$) increased A by 4.7% compared to seed priming with $CaCl_2$ under normal sowing, while no significant difference was observed between seed priming with PEG and those with $CaCl_2$ under late sowing (Fig. 5, B). Seed priming with PEG increased A by 30.5% and 57.6% under normal and late sowing, respectively compared to control (Fig. 5, B). Seed priming with PEG significantly ($P < 0.05$) increased SPAD values by 1.9% compared to seed priming with $CaCl_2$ under normal sowing, but no significant difference was found between seed priming with PEG and those with $CaCl_2$ under late sowing (Fig. 5, C). SPAD values showed a significant ($P < 0.05$) increase of 11.2% and 10.9% in PEG-primed seeds under normal and late sowing, respectively compared to control (Fig. 5, C). In addition, seed priming with PEG significantly ($P < 0.05$) reduced WUE_{in} by 10.5% compared to the control under late sowing, while no significant difference was found between seed priming with PEG and the control under normal sowing (Fig. 5, D).

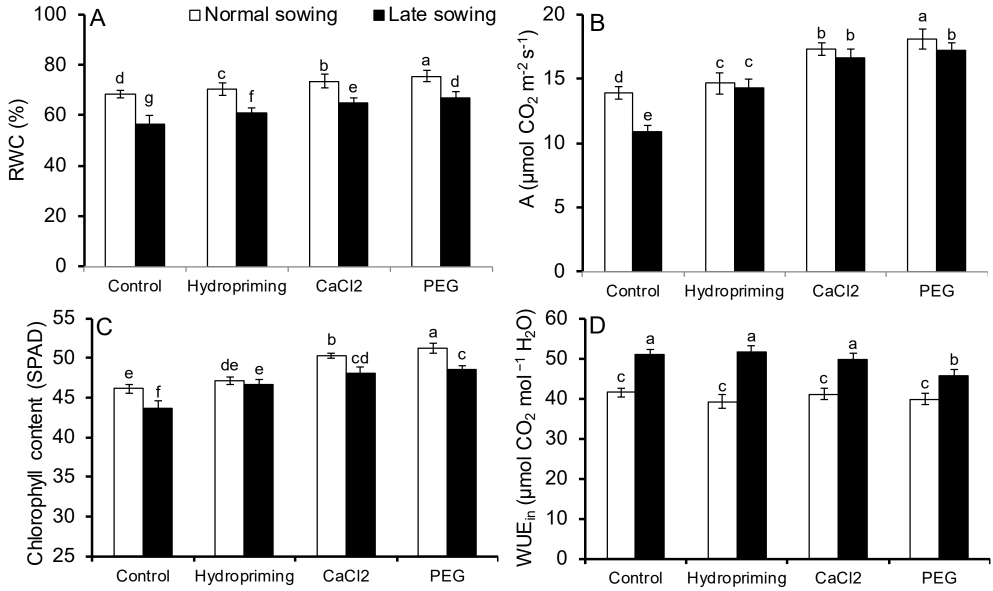

Figure 5. Sowing date x seed priming interaction effect on (A) relative water content, (B) net photosynthetic rate, (C) chlorophyll content by SPAD, and (D) intrinsic water use efficiency for wheat grown in both locations. Bars with the same letters are not significantly different, Tukey's Range Test at $P < 0.05$. Error bars show standard errors, $n = 3$.

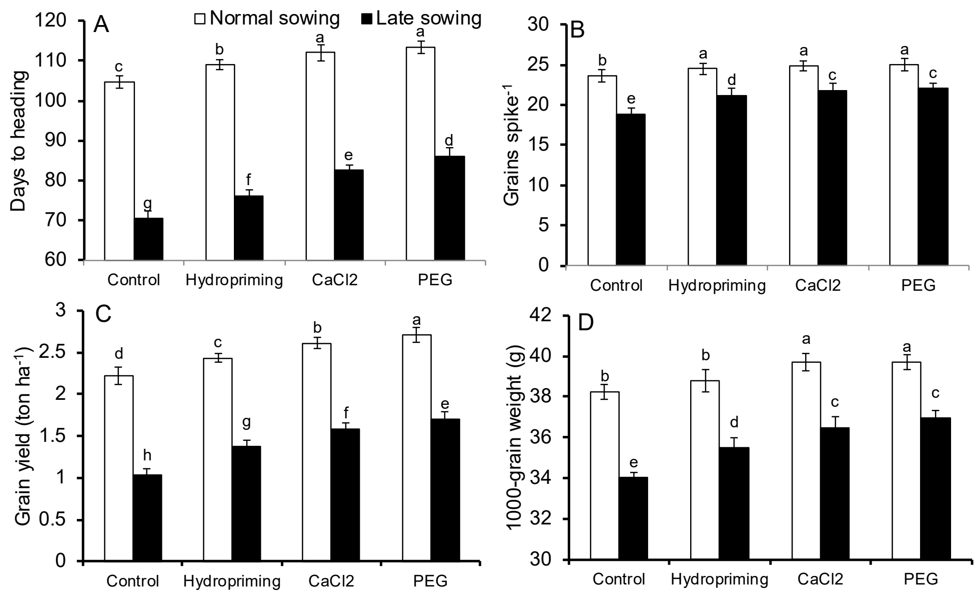

Figure 6. Sowing date x seed priming interaction effect on (A) days to heading, (B) grain number per spike, (C) grain yield, and (D) 1000-grain weight for wheat grown in both locations. Bars with the same letters are not significantly different, *Tukey's Range Test* at $P < 0.05$. Error bars show standard errors, $n = 3$.

Seed priming with PEG significantly ($P < 0.05$) increased DH by 4.4% compared to seed priming with $CaCl_2$ under late sowing, while no significant difference was found between seed priming with PEG and those with $CaCl_2$ under normal sowing (Fig. 6, A). Moreover, DH revealed a significant ($P < 0.05$) increase of 8.4% in PEG-primed seeds during normal sowing and an increase of 22.2% in late sowing (Fig. 6, A). Seed priming with PEG significantly ($P < 0.05$) increased grains spike^{-1} by 4.3% compared to seed priming with water under late sowing, although no significant difference was found under normal sowing (Fig. 6, B). Seed priming with PEG increased grains spike^{-1} by 5.8% and 16.8% under normal and late sowing, respectively compared to control (Fig. 6, B). In normal sowing, seed priming with PEG, $CaCl_2$, and water significantly ($P < 0.05$) increased GY by 22.1%, 17.8%, and 9.8%, respectively compared to control (Fig. 6, C). These seed priming treatments also increased GY in late sowing by 65.9%, 54.7%, and 33.8%, respectively compared to control (Fig. 6, C). In normal and late sowing, TGW showed significant ($P < 0.05$) increases of 3.8% and 8.6%, respectively, in PEG-primed seeds compared to the controls (Fig. 6, D).

Correlation between grain yield and physiological traits

Grain yield (GY) showed a positive correlation with all measured physiological traits, except of WUE_i and WUE_{in} (Table 5). The strongest significant ($P < 0.01$) correlation was observed between GY and RWC ($r = 0.94$), followed by GY and g_s ($r = 0.87$), and then GY and E ($r = 0.83$). A significant positive correlation ($P < 0.01$) was found between A and the other physiological traits, except for WUE_{in}. The most significant correlation among the physiological traits was found between RWC and g_s ($r = 0.90$). Instantaneous water use efficiency (WUE_i) was positively correlated with all measured physiological parameters except for RWC and E. Furthermore, WUE_i showed a significant correlation only with A and WUE_{in}. However, WUE_{in} exhibited a negative correlation with all measured physiological parameters except for WUE_i. A highly significant ($P < 0.01$) correlation was found between WUE_{in} and RWC, E, and g_s (Table 5).

Table 5. Pearson's correlation coefficients between grain yield (GY) of wheat and other physiological parameters under two sowing dates and four seed priming conditions at two locations

	A	GY	RWC	SPAD	E	WUE_i	WUE_{in}
GY	0.67**						
RWC	0.75**	0.94**					
SPAD	0.75**	0.73**	0.71**				
E	0.82**	0.83**	0.86**	0.69**			
WUE_i	0.45**	-0.12	-0.03	0.20	-0.13		
WUE_{in}	-0.19	-0.67**	-0.62**	-0.37*	-0.43**	0.30*	
g_s	0.84**	0.87**	0.90**	0.73**	0.86**	0.12	-0.69**

**, * are significant at $P < 0.01$ and $P < 0.05$, respectively. A: net photosynthesis rate; RWC: relative water content; E: transpiration rate; WUE_i: instantaneous water use efficiency, WUE_{in}: intrinsic water use efficiency, and g_s: stomatal conductance.

DISCUSSION

Location effects

The present study highlights the significant impact of location on physiological (Table 3) and yield traits (Table 4) in wheat. The Maru location demonstrated a clear advantage over Mushaqar in both aspects. This improvement is likely due, in part, to the greater rainfall received in Maru, which experienced 39.4% more precipitation during the growing season (Table 2). Specifically, during the vegetative stage, wheat in Maru received approximately 114.2 mm and 103 mm more rainfall than in Mushaqar under normal and late sowing conditions, respectively. Mushaqar represents the drier regions of central Jordan, where water scarcity is common, while Maru is located in the northern region, which typically has better water availability. The increased water availability in Maru likely facilitated improved physiological responses and overall plant growth, both of which are critical for optimizing photosynthesis (Qiao et al., 2024). However, it is noteworthy that no significant differences were observed in instantaneous water use efficiency (WUE_i) and thousand grain weight (TGW) between the two locations, suggesting that these traits may be more influenced by crop management practices than by environmental conditions (Bani-Khalaf et al., 2024).

Sowing date effects

Normal sowing significantly outperformed late sowing in nearly all measured physiological, growth, and yield parameters of wheat (Tables 3 and 4). This aligns with the findings of Ma et al. (2018), who emphasized the importance of sowing timing in achieving higher physiological efficiency and yield potential in wheat. Under normal sowing conditions, the crop benefits from increased water availability, which enhances physiological responses and ultimately boosts both biomass and yield (Wu et al., 2023). In contrast, late-sown wheat exhibited a decline in photosynthetic rate, likely due to stomatal closure and reduced CO_2 diffusion, as plants experienced significant stress, particularly during anthesis. Our results showed that late sowing reduced the number of days to heading and maturity, decreased plant height, and ultimately lowered yield and its components. Similar findings were reported by Sial et al. (2005) and Hosen et al. (2023), who attributed the higher grain yield under normal sowing to the production of a greater number of heavier grains per spike.

In this study, the interaction observed between location and sowing date for some physiological and yield parameters (Figs 1 and 2) indicates notable variability in how these factors influence wheat performance. While normal sowing significantly improved net photosynthesis in Maru, such improvements were not observed in Mushaqar, suggesting that the higher rainfall in Maru played a critical role in maximizing the benefits of timely sowing. In contrast, normal sowing improved total chlorophyll content only in Mushaqar. The lack of a significant increase in chlorophyll content with sowing date in Maru could indicate that plants there are already optimized for their environment and are not limited by light capture. Furthermore, normal sowing resulted in greater percentage increases in grain and spike numbers in Mushaqar, approximately twice those observed in Maru compared to late sowing, suggesting that Mushaqar may benefit more from normal sowing conditions than Maru.

Seed priming effects

Seed priming, particularly with polyethylene glycol (PEG), significantly enhanced physiological parameters (Table 3), suggesting its effectiveness in mitigating drought stress, especially under late sowing conditions. Similarly, previous studies reported that PEG-based seed priming increased transpiration rates, total leaf chlorophyll, and relative water content (RWC) in wheat and other crops (Hussain et al., 2017; Abdolahi et al., 2018; Aldahadha et al., 2024). Our findings indicate that osmopriming is more effective than hydropriming in enhancing certain physiological traits. This may be attributed to improved stress tolerance conferred by PEG (Zhang et al., 2015; Marthandan et al., 2020), or the potential role of $CaCl_2$ in stabilizing membranes under stress conditions (Hepler, 2005).

In this study, seed priming with PEG increased transpiration only in Maru when compared with $CaCl_2$ priming (Fig. 3). This could be attributed to better water availability in Maru, which allows the plants to respond more effectively to the osmotic adjustment benefits provided by PEG, along with improved leaf water status that enhances stomatal conductance and gas exchange. Moreover, PEG priming was more effective under late sowing than normal sowing in increasing relative water content (Fig. 5, A) and photosynthetic rate (Fig. 5, B), potentially enabling plants to better cope with stress (Mahboob et al., 2015; Aswathi et al., 2022). However, PEG priming significantly decreased intrinsic water use efficiency (WUE_{in}) under late sowing compared to unprimed seeds (Fig. 5, D). Although the PEG-primed plants exhibited higher photosynthesis and stomatal conductance, the proportional increase in stomatal conductance exceeded that of photosynthesis. This imbalance led to a reduction in intrinsic WUE. The photosynthetic rate is primarily regulated by stomatal conductance, although biochemical limitations also play a role (Chaves et al., 2009). In unprimed seeds, the concurrent reduction in stomatal conductance serves as a conservative strategy to enhance water use efficiency (Rouhi et al., 2007), supporting plant survival under water-limited conditions (Fuganti-Pagliarini et al., 2017).

Seed priming generally improved wheat growth and yield traits across different sowing dates, with PEG priming proving to be the most effective (Fig. 6). Recent studies by Aldahadha et al. (2024) and Tabassum et al. (2018) confirmed that seed priming with PEG or $CaCl_2$ resulted in higher yields compared to hydropriming. Osmoprimed seeds tend to absorb more water, promoting better stand establishment (Farooq et al., 2015). In this study, seed priming also improved the harvest index of wheat, which may be attributed to increased dry matter allocation to spikelets (Faisal et al., 2023). Moreover, seed priming led to a notable increase in grain yield under late sowing conditions, likely due to increased thousand grain weight (TGW) and a higher number of spikes. Therefore, implementing seed priming appears to be a viable strategy to mitigate yield losses typically associated with late sowing.

This study highlights the critical role of seed priming in enhancing wheat physiological traits, ultimately leading to increased grain yield. Our findings revealed a strong and significant positive correlation between grain yield and physiological traits (Table 5), particularly relative water content (RWC). These results are consistent with observations by Baloch et al. (2013) and Guizani et al. (2023). Higher RWC typically indicates better water availability within the plant, which is essential for maintaining cellular functions and supporting photosynthesis (Qiao et al., 2024). Among the physiological traits, the most pronounced correlation was observed between RWC and stomatal conductance (g_s), aligning with the findings of Wang et al. (2024). Thus, wheat plants that maintain elevated RWC are likely to exhibit enhanced gs, and conversely, those capable of sustaining higher g_s are better positioned to preserve RWC. Interestingly, our study found no significant relationship between grain yield and intrinsic water use efficiency (WUE) in PEG-primed seeds, or between grain yield and photosynthetic rate in hydroprimed seeds, suggesting a complex interplay of physiological mechanisms affecting yield under specific environmental conditions. Nonetheless, significant correlations were observed between grain yield and both transpiration rate and g_s across all seed priming treatments. This suggests that seed priming can effectively enhance grain yield by improving gas exchange and water utilization efficiency.

CONCLUSIONS

This study presents a novel multi-factorial field assessment of seed priming effects across two agro-ecological locations, two sowing dates, and multiple priming treatments. By integrating physiological, phenological, and yield traits, the research provides a comprehensive understanding of how seed priming modulates drought responses in durum wheat under realistic field conditions. This study underscores the pivotal role of seed priming, particularly osmopriming with PEG, in mitigating the adverse effects of late sowing and drought stress on durum wheat under arid and semi-arid conditions in Jordan. The results revealed that osmopriming significantly enhances key physiological parameters such as relative water content (RWC), net photosynthetic rate, and stomatal conductance, all of which are critical for improving wheat growth and yield. While normal sowing remains optimal for maximizing yield due to favorable water availability and longer growth duration, PEG-primed seeds demonstrated a strong capacity to alleviate the constraints associated with late sowing. Grain yield improvements with PEG priming were attributed to enhanced photosynthesis, improved gas exchange, and increases in both 1,000-grain weight and spike number, indicating superior drought resilience. While PEG priming generally improved photosynthetic activity and yield, it also resulted in a reduction in intrinsic water use efficiency (WUE_{in}) under drought conditions due to a proportionally greater increase in stomatal conductance than in CO_2 assimilation. The study also highlights significant interactions between location and sowing date, with the Maru site exhibiting better outcomes due to higher rainfall. These findings emphasize the importance of tailored crop management practices combining optimal sowing dates and advanced seed priming techniques to address climatic variability and ensure sustainable wheat production in arid regions. Future research should incorporate multi-season trials and explore genotypic variability to validate the consistency of seed priming effects. Additionally, further investigation into the underlying physiological mechanisms is needed, along with broader application of seed priming strategies to support global food security.

ACKNOWLEDGEMENTS. This study was a part of a project of 'Enhancing Food Security in Arabic Countries'. We thank International Center for Agricultural Research in the Dry Areas (ICARDA) for their support.

REFERENCES

Abdolahi, M., Shekar, F., Saba, J. & Zangani, E. 2018. Seed priming with salicylic acid enhanced gas exchange parameters and biological yield of wheat under late sowing date. *Agriculture and Forestry* **64**(1), 145–157.

Ahmed, M. & Fayyaz-ul-Hassan, F.U. 2015. Response of spring wheat (*Triticum aestivum* L.) quality traits and yield to sowing date. *PLoS ONE* **10**(4), e0126097. doi: 10.1371/journal.pone.0126097

Aldahadha, A.M., Warwick, N.W.M. & Backhouse, D. 2019. Water relations and yield of wheat (*Triticum aestivum* L.) exposed to interactions of drought and fungal root diseases (*Rhizoctonia* and *Pythium*). *Archives of Agronomy and Soil Science* **65**(4), 507–520.

Aldahadha, A.M., Warwick, N.W.M. & Backhouse, D. 2012. Effects of *Pythium irregulare* and root pruning on water-use efficiency of hydroponically grown wheat under PEG-induced drought. *Journal of Phytopathology* **160**(7-8), 397–403.

Aldahadha, A., Alhajaj, N., Shakhatreh, Y., Bani Khalaf, Y., Samarah, N. & Alzoubi, E. 2024. Seed priming improved the physiological parameters, growth, and yield of durum wheat varieties under tillering and anthesis drought stress conditions. *Australian Journal of Crop Science* **18**(3), 178–186.

Al-Issa, T.A. 2001. *Farm machinery management and the impact of conservation tillage systems on soil erosion and the sustainability of wheat production in rainfed areas of northern Jordan*. Doctoral dissertation, Oklahoma State University, Stillwater, Oklahoma, USA.

Allozi, S. & AlRawashdeh, I. 2014. Screening of Jordan certified wheat seedlings for drought tolerance. *Jordan Journal of Agricultural Sciences* **10**(3), 484–492.

Analytical Software. 2005. *Statistix 8.1 User's Manual.* Analytical Software, Tallahassee, Florida.

Aswathi, K.R., Kalaji, H.M. & Puthur, J.T. 2022. Seed priming of plants aiding in drought stress tolerance and faster recovery: a review. *Plant Growth Regulation* **97**(2), 235–253.

Baloch, M.J., Dunwell, J., Khan, N.U., Jatoi, W.A., Khakhwani, A.A., Vessar, N.F. & Gul, S. 2013. Morpho-physiological characterization of spring wheat genotypes under drought stress. *International Journal of Agriculture and Biology* **15**(5), 945–950.

Bani-Khalaf, Y., Aldahadha, A., Migdadi, O., Khasawneh, Y., Bsharat, S. & Nukta, R.A. 2024. Foliar boron application and row spacing effects on growth, yield, and protein contents of lentil (*Lens culinaris* Medic.). *Journal of Ecological Engineering* **25**(10), 307–317.

Chaves, M.M., Flexas, J. & Pinheiro, C. 2009. Photosynthesis under drought and salt stress: regulation mechanisms from whole plant to cell. *Annals of Botany* **103**(4), 551–560.

Christensen, B.T., Jensen, J.L. & Thomsen, I. K. 2017. Impact of early sowing on winter wheat receiving manure or mineral fertilizers. *Agronomy Journal* **109**(4), 1312–1322.

Ding, D.Y., Feng, H., Zhao, Y., He, J.Q., Zou, Y.F. & Jin, J. 2016. Modifying winter wheat sowing date as an adaptation to climate change on the Loess Plateau. *Agronomy Journal* **108**(1), 53–63.

El-Shazoly, R.M., Othman, A.A., Zaheer, M.S., Al-Hossainy, A.F. & Abdel-Wahab, D.A. 2025. Zinc oxide seed priming enhances drought tolerance in wheat seedlings by improving antioxidant activity and osmoprotection. *Scientific Reports* **15**(1), 3863. doi: 10.1038/s41598-025-86824-z

Faisal, S., Muhammad, S., Luqman, M., Hasnain, M., Rasool, A., Awan, M.U.F., Khan, Z.I. & Hussain, I. 2023. Effects of priming on seed germination, physico-chemistry, and yield of late sown wheat crop (*Triticum aestivum* L.). *Polish Journal of Environmental Studies* **32**(2), 1113–1124.

Farooq, M., Hussain, M., Habib, M.M., Khan, M.S., Ahmad, I., Farooq, S. & Siddique, K.H. 2020. Influence of seed priming techniques on grain yield and economic returns of bread wheat planted at different spacings. *Crop and Pasture Science* **71**(8), 725–738.

Farooq, S., Shahid, M., Khan, M.B., Hussain, M. & Farooq, M. 2015. Improving the productivity of bread wheat by good management practices under terminal drought. *Journal of Agronomy and Crop Science* **201**(3), 173–188.

Fu, Z.P., Zhang, K., Zhang, J.Y., Zhang, Y., Cao, Q., Tian, Y.C., Zhu, Y., Cao, W.X. & Liu, X.J. 2023. Optimizing nitrogen application and sowing date can improve environmental sustainability and economic benefit in wheat-rice rotation. *Agricultural Systems* **204**, 103536. doi: 10.1016/j.agsy.2022.103536

Fuganti-Pagliarini, R., Ferreira, L.C., Rodrigues, F.A., Molinari, H.B., Marin, S.R., Molinari, M.D., Marcolino-Gomes, J., Mertz-Henning, L.M., Farias, J.R., De Oliveira, M.C. & Neumaier, N. 2017. Characterization of soybean genetically modified for drought tolerance in field conditions. *Frontiers in Plant Science* **8**, 448. doi: 10.3389/fpls.2017.00448

Garg, D., Sareen, S., Dalal, S., Tiwari, T. & Singh, R. 2013. Grain filling duration and temperature pattern influence on the performance of wheat genotypes under late planting. *Cereal Research Communications* 41, 500–507.

Guizani, A., Askri, H., Amenta, M.L., Defez, R., Babay, E., Bianco, C., Rapanà, N., Finetti-Sialer, M. & Gharbi, F. 2023. Drought responsiveness in six wheat genotypes: identification of stress resistance indicators. *Frontiers in Plant Science* **14**, 1232583. doi: 10.3389/fpls.2023.1232583

Hepler, P.K. 2005. Calcium: a central regulator of plant growth and development. *Plant Cell* **17**(8), 2142–2155.

Hosen, I., Moonmoon, S., Hannan, A., Hoque, M.N., Shaila, S., Islam, S.K., Islam, M.S. & Hasan, A.K. 2023. Seed priming influences on yield and protein content of wheat sown at different times. *Archives of Agriculture and Environmental Science* **8**(2), 214–220.

Hussain, M., Farooq, M. & Lee, D.J. 2017. Evaluating the role of seed priming in improving drought tolerance of pigmented and non-pigmented rice. *Journal of Agronomy and Crop Science* **203**(4), 269–276.

Kanapickas, A., Vagusevičienė, I. & Sujetovienė, G. 2024. The effects of different sowing dates on the autumn development and yield of winter wheat in Central Lithuania. *Atmosphere* **15**(6), 738. doi: 10.3390/atmos15060738

Kobata, K., Koc, M., Barutcular, C., Tanno, K. & Inagaki, M. 2018. Harvest index is a critical factor influencing the grain yield of diverse wheat species under rain-fed conditions in the Mediterranean zone of southeastern Turkey and northern Syria. *Plant Production Science* **21**(2), 71–82.

Liu, K., Zhang, C., Guan, B., Yang, R., Liu, K., Wang, Z., Li, X., Xue, K., Yin, L. & Wang, X. 2021. The effect of different sowing dates on dry matter and nitrogen dynamics for winter wheat: An experimental simulation study. *PeerJ* **9**, e11700. doi: 10.7717/peerj.11700

Ma, S.C., Wang, T.C., Guan, X.K. & Zhang, X. 2018. Effect of sowing time and seeding rate on yield components and water use efficiency of winter wheat by regulating the growth redundancy and physiological traits of root and shoot. *Field Crops Research* **221**, 166–174. doi: 10.1016/j.fcr.2018.02.028

Mahboob, W., ur Rehman, H., Basra, S.M., Afzal, I., Abbas, M.A., Naeem, M. & Sarwar, M. 2015. Seed priming improves the performance of late sown spring maize (*Zea mays*) through better crop stand and physiological attributes. *International Journal of Agriculture and Biology* **17**(3), 491–498.

Maresma, A., Ballesta, A., Santiveri, F. & Lloveras, J. 2019. Sowing date affects maize development and yield in irrigated Mediterranean environments. *Agriculture* **9**(3), 67. doi: 10.3390/agriculture9030067

Marthandan, V., Geetha, R., Kumutha, K., Renganathan, V.G., Karthikeyan, A. & Ramalingam, J. 2020. Seed priming: a feasible strategy to enhance drought tolerance in crop plants. *International Journal of Molecular Sciences* **21**(21), 8258. doi: 10.3390/ijms21218258

Mickky, B.M. 2022. Seed priming as a strategy to improve wheat productivity under abiotic stress: global meta-analysis. *Journal of Plant Growth Regulation* **41**(4), 1397–1410.
Munaweera, T.I., Jayawardana, N.U., Rajaratnam, R. & Dissanayake, N. 2022. Modern plant biotechnology as a strategy in addressing climate change and attaining food security. *Agriculture and Food Security* **11**(1), 1–28.
Qiao, M., Hong, C., Jiao, Y., Hou, S. & Gao, H. 2024. Impacts of drought on photosynthesis in major food crops and the related mechanisms of plant responses to drought. *Plants* **13**(13), 1808. doi: 10.3390/plants13131808
Rouhi, V., Samson, R., Lemeur, R. & Van Damme, P. 2007. Photosynthetic gas exchange characteristics in three different almond species during drought stress and subsequent recovery. *Environmental and Experimental Botany* **59**(2), 117–129.
Samarah, N.H. & Al-Issa, T.A. 2006. Effect of planting date on seed yield and quality of barley grown under semi-arid Mediterranean conditions. *Journal of Food Agriculture and Environment* **4**(2), 222–225.
Serafin-Andrzejewska, M., Helios, W., Jama-Rodzeńska, A., Kozak, M., Kotecki, A. & Kuchar, L. 2021. Effect of sowing date on soybean development in South-Western Poland. *Agriculture* **11**(5), 413. doi: 10.3390/agriculture11050413
Sial, M.A., Arain, M.A., Khanzada, S.H.A.M.A.D.A.D., Naqvi, M.H., Dahot, M.U. & Nizamani, N. A. 2005. Yield and quality parameters of wheat genotypes as affected by sowing dates and high temperature stress. *Pakistan Journal of Botany* **37**(3), 575–584.
Singh, H., Jassal, R.K., Kang, J.S., Sandhu, S.S., Kang, H. & Grewal, K. 2015. Seed priming techniques in field crops - A review. *Agricultural Reviews* **36**(4), 251–264.
Singh, J., Aulakh, G.S. & Singh, S. 2023. Effect of seed priming on growth and yield of late sown wheat (*Triticum aestivum*) in central plain region of Punjab. *Research on Crops* **24**(1), 1–7.
Singhal, R.K., Kumar, V. & Bose, B. 2019. Improving the yield and yield attributes in wheat crop using seed priming under drought stress. *Journal of Pharmacognosy and Phytochemistry* **8**(2), 214–220.
Tabassum, T., Farooq, M., Ahmad, R., Zohaib, A., Wahid, A. & Shahid, M. 2018. Terminal drought and seed priming improves drought tolerance in wheat. *Physiological and Molecular Biology of Plants* **24**(5), 845–856.
Tita, D., Mahdi, K., Devkota, K.P. & Devkota, M. 2025. Climate change and agronomic management: Addressing wheat yield gaps and sustainability challenges in the Mediterranean and MENA regions. *Agricultural Systems* **224**, 104242. doi: 10.1016/j.agsy.2024.104242
Wang, L., Zhang, Y., Luo, D., Hu, X., Feng, P., Mo, Y., Li, H. & Gong, S. 2024. Integrated effects of soil moisture on wheat hydraulic properties and stomatal regulation. *Plants* **13**(16), 2263. doi: 10.3390/plants13162263
Wu, L., Quan, H., Wu, L., Zhang, X., Feng, H., Ding, D. & Siddique, K. H. 2023. Responses of winter wheat yield and water productivity to sowing time and plastic mulching in the Loess Plateau. *Agricultural Water Management* **289**, 108572. doi: 10.1016/j.agwat.2023.108572
Yin, L. J., Dai, X.L. & He, M.R. 2018. Delayed sowing improves nitrogen utilization efficiency in winter wheat without impacting yield. *Field Crops Research* **221**, 90–97. doi: 10.1016/j.fcr.2018.02.015.
Zadoks, J.C., Chang, T.T. & Konzak, C.F. 1974. A decimal code for the growth stages of cereals. *Weed Research* **14**(6), 415–421.
Zhang, F., Yu, J., Johnston, C.R., Wang, Y., Zhu, K., Lu, F., Zhang, Z. & Zou, J. 2015. Seed priming with polyethylene glycol induces physiological changes in sorghum (*Sorghum bicolor* L. Moench) seedlings under suboptimal soil moisture environments. *PLoS ONE* **10**(10), e0140620. doi: 10.1371/journal.pone.0140620