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Seed priming improves irrigation water use efficiency, yield, and yield components of late-sown wheat under limited water conditions

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Abstract: A randomized complete block design field study with split plot arrangements was conducted during 2006–2007 and 2007–2008 at the Agronomic Research Station in Khanewal, Pakistan, to evaluate if seed priming could improve grain yield and water use efficiency of late-sown wheat under limited water supply conditions. Seeds of cultivar Inqlab-91 received one of the following treatments: they were soaked in aerated distilled water for 12 or 24 h (hydropriming), layered between moist gunny bags for 12 or 24 h (matriconditioning), soaked in tap water for 12 h (on-farm priming), or hydroprimed for 12 h and then kept at –20 °C for 12 h (hydropriming + chilling). Crops were subjected to 5 irrigation regimes in which irrigation was applied equivalent to 120%, 100%, 80%, 60%, or 40% of evapotranspiration (ETo). Seed priming treatments reduced the mean emergence time and promoted germination, early canopy development, and tillering in comparison to the untreated control. The number of fertile tillers, plant height, 1000-grain weight, and grain and biological yield were also increased by different priming techniques. On-farm priming and hydropriming for 12 h gave higher grain and biological yields and higher harvest index than other priming treatments. Seed priming increased the irrigation water use efficiency (IWUE) of all irrigation regimes. Grain yields were linearly increased at 100% ETo while maximum IWUE was achieved at 80% ETo. Results suggest that the use of either on-farm priming or hydropriming of seeds for 12 h can be helpful in improving grain yields in late-sown wheat under both optimum as well as limited water conditions.

Key words: Irrigation, late sowing, seed priming, water deficit, wheat, yield

1. Introduction

In the cotton zone of Punjab, Pakistan, only 20% of wheat is sown at the optimum sowing time, i.e. the first fortnight of November, while the remaining sowing is done from late November (30%) to December (50%) (Khan et al. 2002). Wheat has a determinate growth habit and a delay of each day in sowing from mid-November onward decreases the number of tillers, leaf area, and total dry matter. Moreover, late sowing of wheat also delays anthesis, which ultimately reduces grain yield at a rate of 30–40 kg day^{-1} ha^{-1} (Hussain et al. 1998; Akmal et al. 2011). Late-sown wheat has to complete its life cycle in a short duration because starch accumulation terminates at the same time in both normal and late-sown plants (Khan et al. 2010). Late sowing results in poor germination and delayed emergence due to the prevalence of low temperatures at that time. In consequence, a weak crop stand and less tillering affect grain yields. Moreover, high temperatures at later growth stages enforce shortening of the grain filling period and early maturity.

Limited availability of canal irrigation water and low precipitation are also common in the cotton-wheat cropping system of the South Punjab, Pakistan, and when coupled with late sowing, they severely affect wheat yields. Crop production in this region mainly depends on irrigation, but unfortunately per capita water availability is declining at an alarming rate, from 5260 m^3 in 1951 to 1066 m^3 in 2010, and it will be less than 870 m^3 per capita by 2025 (Ahmad et al. 2009). Due to scarcity in irrigation and water supply, and increasing competition for water demand from nonagricultural sectors, the focus is already shifting from maximizing the production per unit area towards the maximization of the production per unit of water consumed, often termed as water productivity (Fereres and Soriano 2007). For that purpose, and to optimize crop economic returns under conditions of less irrigation water use (irrigation supply below full crop water requirement, evapotranspiration [ETo]), new strategies should be developed. These challenges may be overcome either by minimizing the water losses or by improving the crop water use efficiency. These can be achieved by promoting a large and early canopy development of growing plants.

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Seed priming is a pregermination treatment that provides a moisture level sufficient to start pregermination metabolic processes but prevents radical protrusion (Bradford 1986). Seed priming techniques are used to improve germination, to reduce the time between sowing and emergence, and for uniform emergence in the field, especially under adverse environments (Gupta et al. 2008). The commonly used seed priming techniques are osmopriming (priming with osmotic solutions such as polyethylene glycol or inorganic salts), hydropriming (soaking in water), matripriming (hydrated solid materials), thermopriming (temperature treatment), hormonal priming, biopriming (coating of seeds with bioagents), and on-farm priming (reviewed by Girolamo and Barbanti 2012). Moreover, seed priming with solutions of antioxidants such as ascorbic acid, tocopherol, and glutathione is also useful in improving seed germination and seedling growth under adverse conditions (Draganic and Lekic 2012). In hydropriming, seeds are soaked in aerated water for a specific period of time, dried back to their original moisture level, and stored for future use (McDonald 2000). On-farm seed priming is a low-cost, low-risk method in which seeds are soaked in water overnight, surface-dried, and then sown on the same day while seeds are in a hydrated state (Harris et al. 1999). This technique was shown to improve crop stand, lead to faster growing and early flowering, and increase yields of maize, chickpea, rice, and sorghum (Harris 1996, Harris et al. 1999). It is more successful in arid environments and in conditions where sowing is delayed. In 2 previous techniques, water is freely taken up by seeds (noncontrolled), depending on the affinity of seed tissues for water (Taylor et al. 1998). Matriconditioning refers to the presowing treatment of seeds with moist solid carriers having matric properties (Khan et al. 1995; Basra et al. 2003). This method provides gradual, controlled hydration of seeds and avoids the development of temperature gradients in seed mass (Taylor et al. 1998). Matriconditioning is shown to improve the speed of germination and germination percentage of vegetable seeds under suboptimal low temperatures (Khan et al. 1992, 1995).

Seed priming has been shown to improve the performance of late-sown wheat (Farooq et al. 2008) as it reduces time between sowing and seedling emergence and promotes synchronized emergence, giving better crop stand and final yield (Parera and Cantliffe 1994; Harris et al. 2001; Khan et al. 2011). The aim of the present study was to reduce yield losses and to improve water use efficiency of late-sown wheat under limited water conditions.

2. Materials and methods

Field experiments were conducted during 2006–2007 and 2007–2008 at the Agronomic Research Station in Khanewal, Pakistan (30°180′N, 71°55′60 E; latitude of 128 m), in the arid region of the southern Punjab (Arnon 1992). The soil was a loam having pH 8.5, EC 253 µS cm^{-1}, organic matter 0.77%, total suspended solids 0.85%, and N contents 0.089%. Available P and available K were 7.2 and 115 ppm, respectively. The experiments were laid out in randomized complete block design with split plot arrangements with 3 replications. Irrigation regimes were kept in main plots (35.4 m × 15 m) while the seed priming techniques were in subplots (4.4 m × 15 m). The laser-leveled experimental field was irrigated to field capacity and the seedbed was prepared when the field reached proper moisture conditions. Seeds of wheat cultivar Inqlab-91 were obtained from Punjab Seed Corporation, Khanewal. The cultivar is recommended by the Punjab Agriculture Department and occupies a major portion of the area under wheat cultivation in Punjab, Pakistan.

Seeds were subjected to different priming treatments: (P_0) no priming, untreated control; (P_1) hydropriming for 12 h; (P_2) matriconditioning for 12 h; (P_3) on-farm priming for 12 h; (P_4) hydropriming for 12 h followed by chilling stress; (P_5) hydropriming for 24 h; or (P_6) matriconditioning for 24 h. Prior to priming, seeds were dipped in a 5% (v/v) sodium hypochlorite (NaClO) solution for 3 min to protect them from fungal infestation (Ruan et al. 2002). Seeds were subsequently washed and surface dried. On-farm seed priming was performed by soaking seeds in tap water for 12 h, surface drying them for 1 h, and then using them for fresh sowing (Harris et al. 2001; Harris 2004; Farooq et al. 2008). Matriconditioning was carried out in gunny bags as described by Basra et al. (2003). Gunny bags were soaked overnight in distilled water and then spread on a perforated floor. After leaching out the excess water from the gunny bags, seeds were uniformly layered between gunny bags. The gunny bags were kept moist for the whole treatment period of 12 h or 24 h (Basra et al. 2003). In hydropriming, seeds were soaked in aerated distilled water for 12 h or 24 h. Primed seeds were washed 3 times with deionized water and redried to original weight with forced air under shade at 27 ± 3 °C for 48 h (except for on-farm priming, where seeds were surface dried; Farooq et al. 2008). For chilling treatment, the hydroprimed seeds (after redrying to original moisture) were sealed properly in polythene bags and kept at –20 ± 2 °C for 12 h (Khan et al. 2010). All primed seeds (except for on-farm priming) were sealed properly in polythene bags and stored in a refrigerator at 7 ± 2 °C until further use for sowing (Bennett and Waters 1987).

The sowing was done on 15 December during 2006–2007 and on 16 December during 2007–2008 by using a single-row hand drill. Sowing done at this time of the year is considered late for sowing wheat in this region (Punjab, Pakistan). The recommended normal sowing time in the region is until 15 November (Khan et al. 2002). The seeds were sown in rows 22 cm apart with a seed rate of 150 kg ha^{-1} (approximately 325 seeds m^{-2}). Nitrogen, phosphorus, and potassium fertilizers were applied at the rates of 105, 85, and 62 kg ha^{-1}, respectively. All the phosphorus and potassium fertilizer was applied at the time of sowing in the form of triple super phosphate (46% P_2O_5) and sulfate of potash (50% K_2O), respectively. Nitrogen was applied in the form of urea (46% N) in 2 splits, i.e. half of the nitrogen was applied as a basal dose at the time of sowing and the remaining half was top-dressed with the first irrigation. The irrigations were applied as per treatments. Herbicides Buctril Super 60EC (bromoxynil + MCPA) and Topik (clodinafop propargyl + cloquintocet mexyl) were used to control the broad-leaf weeds and grasses, respectively. All other cultural practices were kept standard and uniform for all the treatments. The treatments included 5 irrigation regimes, namely I_0 (~120% ETo), I_1 (~100% ETo), I_2 (~80% ETo), I_3 (~60% ETo), and I_4 (~40% ETo). ETo measures the evaporative demand of the atmosphere at a particular location during a specific period and is estimated by using the FAO Penman–Monteith method (Allen et al. 1998; Zhang et al. 2002).

The first irrigation (75 mm) was applied uniformly to all the treatments at crown root initiation stage (23 days after sowing). The subsequent irrigations were applied when needed using a measured quantity of irrigation water as per treatment (Table 1). Irrigation was done with the help of a water pump of known discharge fitted with 4 outlet pipes. The pipes were placed in the plot at equal spacing (11.5 m) for uniform distribution of water. Mean monthly rainfall (mm) and maximum/minimum temperatures were recorded for both experimental years (Figure 1). The amount of water applied in different irrigation regimes and by rainfall during the crop growth period a given in Table 1. The amount of water applied at each irrigation was equal to the differences between reference ETo and rainfall. Daily ETo values were calculated by the FAO computer program CROPWAT 4, Windows version 4.3, based on the Penman–Monteith formula.

Table 1. Amount of water applied and rainfall during crop seasons.

	Irrigation (mm)	Rainfall (mm)	Total
2006–2007			
I_0	202	151	353
I_1	168	151	319
I_2	134	151	285
I_3	101	151	252
I_4	67	151	218
2007–2008			
I_0	263	39	302
I_1	219	39	258
I_2	176	39	215
I_3	132	39	171
I_4	88	39	127

2.1. Measurements

The numbers of emerged seeds were counted daily from 4 spots, each having an area of 1 m^2, and averaged for each plot. Mean emergence time (MET, days) was calculated according to the equation of Ellis and Roberts (1981) as:

$$MET = \frac{\Sigma^{Dn}}{\Sigma^{n}}$$

where n is the number of seeds emerged on day D (number of days counted from beginning of the emergence). Germination count (m^2) was recorded after seedling emergence but before the start of tillering. To count the total number of tillers and number of productive tillers, a unit area of 1 m^2 in each treatment at 4 different locations was selected. At harvest, agronomic traits and different yield components were recorded as per standard procedures.

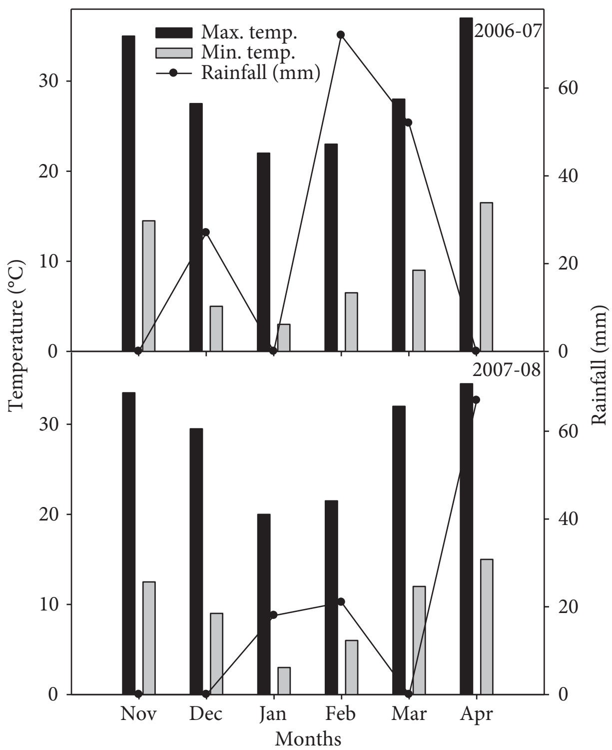

Figure 1. Metrological data for crop growth seasons during 2006–2007 and 2007–2008.

2.2. Statistical analysis

Data were statistically analyzed using the computer program MSTAT-C. Significance of the variance sources was analyzed using Fisher's analysis of variance. The least significant difference (LSD) test at $P < 0.05$ was used to compare the differences among treatment means.

3. Results

Comparison of treatment means showed that seed priming had a significant effect on mean emergence time of late-sown wheat (Table 2). The minimum mean emergence time was recorded with on-farm priming treatment followed by hydropriming for 12 h of treatment, while the differences between these treatments were statistically not significant during 2006–2007. All seed priming techniques except matriconditioning for 24 h significantly enhanced the germination count m^{-2} as compared to no-priming treatment during both experimental years (Table 2). The results further showed that treatments of on-farm priming for 12 h and hydropriming for 12 h significantly increased the number of tillers m^{-2} as compared to the no-priming treatment. During the 2007–2008 cropping season, matriconditioning for 12 h also had a significant increase in tiller number. The maximum number of tillers m^{-2} were recorded with on-farm priming of seeds for 12 h.

The data from both experimental years showed that irrigation regimes had significantly influenced the growth and yield components of late-sown wheat (Table 3). The maximum plant height, number of productive tillers m^{-2}, grains $spike^{-1}$, spike length, and 1000-grain weight were recorded by irrigation regime 120% ETo, followed by irrigation regime 100% ETo. However, the differences between these 2 irrigation regimes were not statistically significant. With a decrease in irrigation water supply from 100% ETo onward, a significant reduction in different growth and yield components was observed at each increment. In comparison to irrigation regime 120% ETo, 40% ETo reduced the productive tillers m^{-2} by almost 50% and grains $spike^{-1}$ and 1000-grain weight by 25% during both years, indicating that the wheat crop suffered severe water stress at irrigation regime 40% ETo. Seed priming treatments also significantly improved the plant height, productive tillers m^{-2}, and 1000-grain weight as compared to nonprimed seeds, with on-farm priming hydropriming for 12 h producing the maximum (Table 3). The priming treatments did not significantly affect grains per spike during both seasons. Spike length also remained unaltered by priming treatments during 2006–2007; however, a slight increase in spike length by on-farm priming for 12 h and by hydropriming for 12 h was recorded during 2007–2008.

Biological yield is an indirect index of photosynthetic machinery that along with different yield components determines the final grain yield in a given set of environmental conditions. Both seed priming techniques and irrigation regimes exerted a significant effect on biological and grain yields during both crop growth seasons. The data showed that both biological and grain yields were significantly increased with each increment in irrigation level (Table 4). The highest biological and grain yields were recorded at irrigation regime 120%

Table 2. Effect of seed priming on mean emergence time, germination count, and number of tillers.

Treatments	Mean emergence time (days)		Germination count (m^{-2})		Number of tillers (m^{-2})	
	2006–2007	2007–2008	2006–2007	2007–2008	2006–2007	2007–2008
No-priming	13.88 a	15.55 a	127 b	122 bc	293 c	280 c
Hydropriming for 12 h	10.15 cd	12.25 c	148 a	142 a	383 ab	360 a
Matriconditioning for 12 h	11.41 bc	13.52 bc	144 a	140 a	340 bc	338 ab
On-farm priming for 12 h	9.25 d	10.63 d	149 a	145 a	393 a	371 a
Hydropriming for 12 h + chilling stress for 12 h	12.93 ab	14.85 ab	142 a	134 ab	321 c	292 bc
Hydropriming for 24 h	12.18 ab	13.96 ab	146 a	141 a	337 bc	327 abc
Matriconditioning for 24 h	11.55 bc	13.85 b	123 b	119 c	306 c	283 c
LSD (5%)	1.79	1.59	14.17	14.28	53.05	48.78
CV (%)	8.66	6.74	5.68	5.94	8.79	9.51

Any 2 means not sharing a letter within a column differ significantly ($P < 0.05$).

Table 3. Effect of seed priming and irrigation regimes on plant height, productive tillers, grains per spike, spike length, and 1000-grain weight of late-sown wheat.

Treatments	Plant height (cm)		Productive tillers (m^{-2})		Grains per spike		Spike length (cm)		1000-grain weight (g)	
	2006–2007	2007–2008	2006–2007	2007–2008	2006–2007	2007–2008	2006–2007	2007–2008	2006–2007	2007–2008
Irrigation (% of ETo)										
120	96.90 a	92.55 a	314 a	295 a	41.47 a	39.40 a	14.69 a	13.15 a	36.66 a	35.03 a
100	93.42 a	86.72 b	306 a	289 a	40.73 a	39.01 a	14.64 a	12.70 ab	35.59 ab	34.38 a
80	86.82 b	78.82 c	278 b	256 b	40.50 a	36.96 b	14.36 a	12.25 bc	34.21 b	32.63 b
60	77.31 c	62.59 d	231 c	211 c	37.51 b	33.54 c	13.58 b	11.79 c	32.56 c	29.00 c
40	59.84 d	46.46 e	151 d	129 d	31.59 c	28.93 d	12.47 c	9.85 d	28.54 d	26.12 d
LSD (5%)	5.322	5.442	16.46	14.13	2.05	2.16	0.71	0.79	1.56	1.68
Seed priming										
No-priming	75.35 d	67.51 d	220 e	195 e	37.42	33.95	13.49	11.31 b	31.49 c	29.26 e
Hydropriming for 12 h	87.58 ab	77.70 ab	287 a	267 b	38.80	36.42	14.25	12.26 a	35.60 a	32.95 ab
Matriconditioning for 12 h	85.89 ab	74.04 a-c	259 b	248 c	38.28	35.50	14.15	12.03 ab	33.99 b	31.69 bc
On-farm priming for 12 h	89.87 a	78.85 a	301 a	282 a	39.27	37.08	14.36	12.63 a	35.96 a	33.69 a
Hydropriming for 12 h + chilling stress for 12 h	78.77 cd	70.05 cd	242 cd	215 d	37.95	34.99	13.62	11.48 b	32.10 c	30.01 de
Hydropriming for 24 h	82.57 bc	73.25 bc	253 bc	239 c	38.44	35.41	13.90	11.89 ab	32.70 bc	31.14 cd
Matriconditioning for 24 h	79.97 cd	72.59 c	231 de	206 de	38.36	35.61	13.87	12.03 ab	32.72 bc	31.28 cd
LSD (5%)	5.05	4.91	15.56	13.25	ns	ns	ns	0.78	1.51	1.62
CV (%)	9.58	10.21	8.30	9.65	7.36	8.13	6.94	8.98	6.20	7.06

Any 2 means not sharing a letter within a column differ significantly ($P < 0.05$).

Table 4. Effect of seed priming and irrigation regimes on yield and yield components of late-sown wheat.

Treatments	Grain yield (kg ha^{-1})		Biological yield (kg ha^{-1})		Harvest index (%)	
	2006–2007	2007–2008	2006–2007	2007–2008	2006–2007	2007–2008
Irrigation (% of ETo)						
120	3856 a	3554 a	9160 a	8013 a	41.90 b	44.13 c
100	3753 ab	3469 a	8629 b	7457 b	43.29 a	46.29 a
80	3544 b	2874 b	8179 c	6318 c	43.13 a	45.23 b
60	2581 c	1846 c	6291 d	4189 d	40.92 bc	43.93 c
40	1124 d	823 d	2805 e	1954 e	39.94 c	41.96 d
LSD (5%)	214	204	382	356	0.989	1.039
Seed priming						
No-priming	2341 e	1903 d	5681 e	4346 e	40.89 de	43.36 d
Hydropriming for 12 h	3536 a	3105 a	8103 b	6718 a	43.19 ab	45.66 ab
Matriconditioning for 12 h	3095 b	2623 b	7227 c	5776 b	42.45 bc	44.92 bc
On-farm priming for 12 h	3722 a	3234 a	8461 a	6944 a	43.50 a	45.97 a
Hydropriming for 12 h + chilling stress for 12 h	2648 d	2221 c	6426. d	5076 c	40.90 de	43.37 d
Hydropriming for 24 h	2886 c	2468 b	6886 c	5545 b	41.48 cd	43.95 cd
Matriconditioning for 24 h	2572 d	2039 d	6307 d	4698 d	40.43 e	42.93 d
LSD (5%)	199	179	353	306	0.97	1.02
CV (%)	9.19	9.78	8.89	9.50	6.19	7.17

Any 2 means not sharing a letter within column differ significantly ($P < 0.05$).

ETo, followed by irrigation at 100% ETo. However, the differences between irrigation regimes 120% and 100% ETo regarding grain yield were statistically not significant. Results further indicated that a decrease in irrigation supply to 40% of ETo induced drought stress, which depressed the biological as well as grain yields of late-sown wheat (Table 4) by more than 70%. Among different seed priming techniques, on-farm priming significantly produced the maximum biological yield, followed by hydropriming for 12 h, during 2006–2007, whereas these treatments were statistically on par during 2007–2008 regarding biological yield. Likewise, the maximum grain yield (3722.6 and 3234.4 kg ha^{-1} during 2006–2007 and 2007–2008, respectively) was recorded with treatment on-farm priming, followed by treatment of hydropriming for 12 h (3536.6 and 3105.7 kg ha^{-1} during 2006–2007 and 2007–2008, respectively). However, the differences between these 2 treatments were not significant. The experimental year 2007–2008 was relatively drier with an annual rainfall of only 39 mm as compared to 151 mm of rainfall during 2006–2007 (Table 1; Figure 1). Dry weather conditions during 2007–2008 affected crop growth and reduced the various growth and yield attributes by about 5%–10% as compared to 2006–2007.

Harvest index (HI) is a key parameter that indicates the efficiency of a crop in the transformation of photosynthates into economic yield. Each increment in irrigation level significantly increased the harvest index and maximum HI was recorded at irrigation regime 100% ETo (Table 4). An additional increment of irrigation after 100% ETo caused a significant decline in the harvest index. Similar trends regarding HI were observed during both experimental years. Data regarding seed priming techniques showed that almost all priming treatments, except matriconditioning for 24 h, improved the harvest index over the no-priming treatment. During both of the crop growth seasons, the maximum HI was achieved with the on-farm priming treatment, followed by hydropriming for 12 h. However, the differences between these 2 treatments were statistically on par (Table 4).

Table 5 presents the interactions between irrigation regimes and seed priming techniques. The results show

Table 5. Interactive effect of seed priming and irrigation regimes on number of productive tillers, grain yield, and biological yield of late-sown wheat.

Interactions	Productive tillers (m^{-2})		Grain yield (kg ha^{-1})		Biological yield (kg ha^{-1})	
	2006–2007	2007–2008	2006–2007	2007–2008	2006–2007	2007–2008
$I_0 \times P_0$	266 k–n	238 h–l	3041 i–l	2715 e–h	7447 i–m	6305 fg
$I_0 \times P_1$	359 ab	344 a	4579 ab	4392 a	10645 ab	9704 ab
$I_0 \times P_2$	320 cd	310 bc	4004 c–e	3710 b	9477 c–e	8341 c
$I_0 \times P_3$	384 a	363 a	4985 a	4555 a	11340 a	9858 a
$I_0 \times P_4$	287 d–i	264 e–h	3349 g–j	3146 cd	8180 f–i	7286 de
$I_0 \times P_5$	306 c–g	297 cd	3768 e–g	3530 bc	8935 d–f	7949 cd
$I_0 \times P_6$	278 f–k	246 g–k	3267 h–k	2831 d–g	8096 g–j	6650 ef
$I_1 \times P_0$	261 h–o	231 i–l	2901 k–n	2609 f–i	6873 l–o	5769 g–i
$I_1 \times P_1$	356 ab	338 ab	4549 ab	4351 a	10116 bc	9069 b
$I_1 \times P_2$	312 c–f	303 c	3903 d–f	3632 b	8844 e–g	7708 cd
$I_1 \times P_3$	379 a	360 a	4901 a	4525 a	10889 ab	9424 ab
$I_1 \times P_4$	272 g–n	256 f–i	3265 h–l	2999 d–f	7738 h–k	6635 ef
$I_1 \times P_5$	293 c–h	289 c–e	3610 e–h	3427 bc	8445 f–h	7489 d
$I_1 \times P_6$	269 h–m	245 g–k	3143 i–l	2743 e–h	7499 i–l	6104 fg
$I_2 \times P_0$	239 m–q	218 k–n	2820 l–o	2175 jk	6703 m–p	4925 j
$I_2 \times P_1$	317 c–e	283 c–f	4242 b–d	3643 b	9467 c–e	7764 cd
$I_2 \times P_2$	284 e–j	269 d–g	3749 e–g	3023 de	8534 fg	6565 f
$I_2 \times P_3$	328 bc	295 cd	4357 bc	3719 b	9689 cd	7901 cd
$I_2 \times P_4$	255 i–p	240 g–l	3110 i–l	2483 g–j	7398 i–m	5625 g–i
$I_2 \times P_5$	275 g–l	254 f–j	3472 e–i	2708 e–i	8156 f–i	6060 f–h
$I_2 \times P_6$	251 j–p	231 i–l	3056 i–m	2365 h–j	7309 j–m	5387 h–j
$I_3 \times P_0$	206 q	189 n	2077 p	1461 m	5172 q	3386 m
$I_3 \times P_1$	243 l–p	226 j–m	2995 j–m	2133 jk	7086 k–n	4709 jk
$I_3 \times P_2$	231 o–q	215 l–n	2627 m–o	1874 kl	6324 n–p	4208 kl
$I_3 \times P_3$	249 k–p	241 g–l	3051 i–m	2314 ij	7198 k–m	5098 ij
$I_3 \times P_4$	238 m–q	199 mn	2454 op	1677 lm	6104 op	3886 lm
$I_3 \times P_5$	232 n–q	213 l–n	2471 n–p	1820 k–m	6108 op	4187 kl
$I_3 \times P_6$	221 pq	199 mn	2393 op	1642 lm	6043 p	3846 lm
$I_4 \times P_0$	126 s	98 q	866 r	555 p	2207 s	1346 p
$I_4 \times P_1$	162 r	144 op	1315 q	1007 no	3204 r	2341 n
$I_4 \times P_2$	147 rs	143 op	1195 qr	873 n–p	2955 rs	2057 no
$I_4 \times P_3$	164 r	149 o	1317 q	1057 n	3186 r	2438 n
$I_4 \times P_4$	159 rs	116 pq	1061 qr	802 n–p	2708 rs	1947 n–p
$I_4 \times P_5$	162 r	141 op	1109 qr	854 n–p	2784 rs	2042 no
$I_4 \times P_6$	134 rs	108 q	1004 r	615 op	2589 s	1505 op
LSD (5%)	34.79	29.62	445	401	789	684
CV (%)	8.30	9.65	9.19	9.78	8.89	9.50

Any 2 means not sharing a letter within a column differ significantly ($P < 0.05$).I_0: 120% ETo; I_1: 100% ETo; I_2: 80% ETo; I_3: 60% ETo; I_4: 40% ETo

P_0: No priming; P_1: hydropriming for 12 h; P_2: matriconditioning for 12 h; P_3: on-farm priming for 12 h; P_4: hydropriming for 12 h followed by chilling stress; P_5: hydropriming for 24 h; P_6: matriconditioning for 24 h.

that on-farm priming and hydropriming for 12 h in comparison to nonprimed treatment remarkably improved the productive tillers m^{-2}, and biological and grain yields in all irrigation regimes. Nevertheless, the maximum values were attained where the treatment combination of on-farm priming and irrigation regime of 120% ETo was applied, and that was followed by on-farm priming + 100% ETo. Hydropriming of seeds for 12 h applied either at 120% or 100% ETo produced statistically identical productive tillers m^{-2} and grain yields as those produced by on-farm priming of seeds applied either at 120% or 100% ETo.

Data regarding irrigation water use efficiency (IWUE) showed that an increase in irrigation at each increment increased the IWUE almost linearly up to irrigation regime 80% ETo (Figure 2). Further increase in the irrigation level (100% ETo) did not change the IWUE; however, at irrigation regime 120% ETo, a decrease in IWUE was observed during both crop seasons. Moreover, it was observed that in comparison to no-priming treatment, on-farm priming and hydropriming for 12 h of seeds significantly enhanced the IWUE of late-sown wheat under different irrigation regimes (Figure 2).

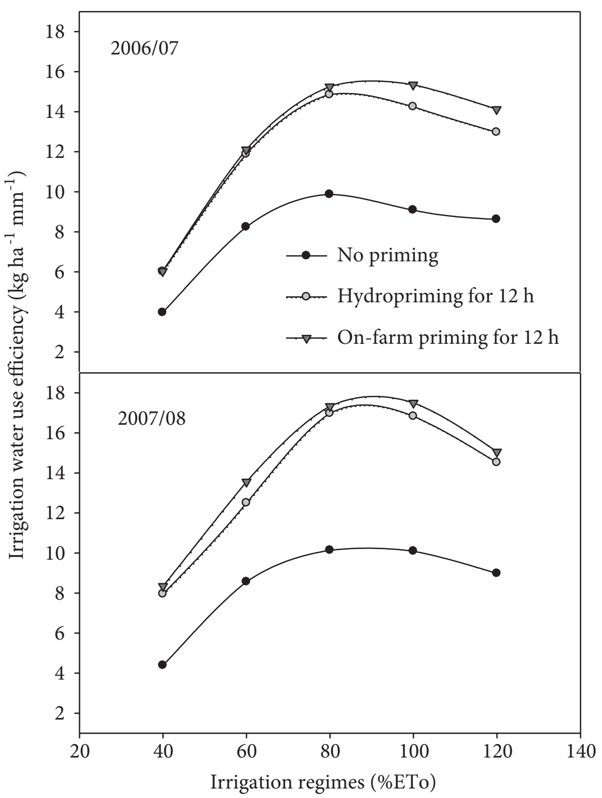

Figure 2. Effect of on-farm priming and hydropriming for 12 h on Irrigation Water Use Efficiency of late-sown wheat subjected to different irrigation regimes during 2006–2007 and 2007–2008.

4. Discussion

Uniform and early field emergence enable crops to best utilize the available resources under stressful conditions. Low temperatures (below 10 °C) at the time of sowing adversely affect seed germination and seedling establishment of wheat (Sattar et al. 2010). Late sowing in the present study resulted in poor germination count during both seasons. Poor germination percentage due to low temperature in late-sown wheat has been reported by many researchers (Shah et al. 2006; Tahir et al. 2009). Results of the present study showed that on-farm priming and hydropriming for 12 h improved germination and reduced the mean emergence time of late-sown wheat by almost 4 days. Our results are in agreement with the findings of Farooq et al. (2008), who showed that hydropriming and on-farm priming decreased the mean emergence time of late-sown wheat by 4 and 5 days, respectively. This decrease in emergence resulted in early seedling establishment and an increase in tillering. Similar results have also been reported for other crops such as sorghum, maize, chickpea, and rice, where on-farm priming overnight (12 h) induced early emergence by 2–3 days, better germination percentage, more vigorous growth, and uniform crop stand (Harris et al. 2001).

Moreover, it was shown that matriconditioning for 24 h did not affect the germination count; however, it significantly reduced the emergence time. In contrast, Basra et al. (2003) found that matriconditioning of wheat seeds with gunny bags for 24 h reduced the germination time and increased the germination percentage under controlled conditions (25 °C, 60% humidity). This variation seems to be the result of adverse effects of low temperature on germination count in this study. On-farm priming and hydropriming for 12 h produced lower mean emergence time than hydropriming for 24 h, matriconditioning, and hydropriming along with chilling stress. The lower germination count and less seedling vigor by hydropriming along with chilling stress might have occurred due to membrane rupture during chilling treatment (Farooq et al. 2004). It was also observed that seed priming duration of more than 12 h increased the mean emergence time, resulting in a decline in germination count and total number of tillers per unit area. Rahnavard et al. (2009) noticed that longer priming periods might produce free radicals that may damage the cell membrane. Similarly, Giri and Schillinger (2003) observed a decrease in rate and extent of germination when priming duration was increased from 12 h and hence proposed an optimum soaking time of 12 h for wheat seeds.

Results of this study showed that seed priming significantly influenced the growth and yield attributes of late-sown wheat. Researchers observed that early plant establishment in late-sown wheat favors crops to complete tillering in time, which results in more productive tillers, more grains per spike, higher grain weight, and eventually a higher grain yield (Kant et al. 2006; Farooq et al. 2008). The maximum grain and straw yields were obtained by on-farm priming and hydropriming for 12 h. Rashid et al. (2006) also reported that on-farm seed priming for 12–16 h significantly increased the grain and straw yields of barley under normal and saline conditions. They found that priming gave more benefit under saline conditions (a 53% increase in grain yield). On-farm priming was also found successful in enhancing the kernel and straw yield of direct-seeded rice (Rehman et al. 2011). Enhancements in grain yields by on-farm priming under adverse arid conditions were also reported for other crops (Harris et al. 2001; Murungu et al. 2004).

Late sowing when coupled with water deficits (drought periods or less available irrigation water) severely affects crop growth and yields of wheat. In this situation, farmers are left with no choice but to use deficit irrigation. The present study was an attempt to investigate whether seed priming techniques could help in improving the economic returns when water availability is low, especially in the case of late planting of wheat. Our results showed that by decreasing irrigation below maximum ETo potential (100% ETo), grain yield of late-sown wheat was linearly reduced. The reductions in grain yields are associated with linear decreases in biomass yield and yield components, especially the grains per spike. Increase in irrigation supply from 40% to 100% ETo increased the number of productive tillers, grains per spike, 1000-grain weight, and grain yield. However, a further increase in irrigation level (from 100% to 120% ETo) did not improve these traits, but rather reduced the HI, indicating that this additional water was not efficiently utilized in improving the economic portion of the crop. This is evident from the fact that water productivity measured in terms of IWUE reached its maximum at irrigation equal to 80% ETo and remained stable at 100% ETo, and then declined when irrigation was increased to 120% ETo. This implies that increase in irrigation water supply results in a linear increase in IWUE up to a point where this relationship becomes curvilinear because a portion of water applied is not used in ETo. Instead, it is lost, and at this point the crop yield attains its maximum value with no further improvement by additional water application. An increase in water productivity under conditions of deficit irrigation (water supply below full crop water requirement) has also been reported for other crops (Zwart and Bastiaansen 2004).

Seed priming improved the various yield and growth attributes and IWUE of late-sown wheat under both optimum and limited water supply conditions. The higher biomass and grain yields were exhibited by on-farm priming and hydropriming for 12 h subjected to an irrigation regime of 100% or 120% ETo. This may be attributed to early and synchronized field emergence, which resulted in more leaf area and early canopy development. Better ground cover provided by these treatments reduced the evaporation from the soil, saving sufficient water for transpiration. Moreover, early emergence resulted in vigorous plants that may have deeper and more extensive root systems capable of extracting water efficiently, even under lower irrigation regimes. On the other hand, it was noticed that at irrigation levels equal to 40% and 60% ETo, crops suffered from drought stress as expressed by reduced number of grains per spike, lower grain weight, and a drastic decrease in grain yield. Leaf area reduction during the vegetative phase due to water stress promoted the E (evaporation from the soil) component of ETo, which resulted in a lower IWUE (Fereres and Soriano 2007). Our results showed that under limited water availability (40% and 60% ETo), on-farm priming and hydropriming for 12 h treatments increased the IWUE and hence conferred drought tolerance in late-sown wheat. Harris et al. (2001) also suggested that seed priming (on-farm priming) can be helpful in increasing the drought tolerance of crop plants. Seed priming improved WUE at all irrigation regimes. However, the maximum gain in WUE was recorded in treatments where water supply was sufficient.

The results of the present study show that adverse effects of low temperatures in delayed sowing on germination, plant growth, and establishment can be minimized by using different priming methods. The priming technique promoted early emergence and improved the total germination count and growth of late-sown wheat. Moreover, increase in the number of productive tillers, grain weight, and biological yield by seed priming increased the grain yield. It was further shown that seed priming improves grain yields under water stress conditions by increasing water use efficiency. It is concluded that the techniques of on-farm priming and hydropriming for 12 h can be best employed to improve grain yields of late-sown wheat under varying moisture conditions ranging from moderate to no drought stress.

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