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Research
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Osmo- and hydropriming enhance germination rate and reduce thermal time requirement of pea (*Pisum sativum* L. cv. Winner) seeds

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Abstract

The effects of various seed priming treatments and seed soaking durations on germination performance of pea (*Pisum sativum* L. cv. Winner) seeds were examined. Seeds were osmoprimed in polyethylene glycol (PEG 6000) (-0.5, -1.0 and -1.5 bar) or in mannitol (1%, 2% and 3%) and hydroprimed with water for 12 or 24 h at 25 ± 0.5 °C in darkness. Primed seeds were subjected to germination tests at ten different constant temperatures ranging from 5 to 32 ± 0.5 °C. Priming treatments had no significant effect on germination percentage. But, osmo- and hydroprimig treatments improved germination rate and decreased thermal time requirements significantly and induced more synchronous germination at some of the temperatures tested. Reductions in thermal time requirements ranged between 3.4 °C d and 11.3 °C d, 6.6 °C d and 17.4 °C d, and 11.6 °C d and 27.5 °C d for 10%, 50% and 90% germination, respectively. As compared with the priming duration of 12 h, priming duration of 24 h had generally negative effect on the 50% germination time and thermal time requirement. Among the osmopriming treatments, seeds treated with -0.5 bar solution of PEG and 1% solution of mannitol, and also hyropriming gave the best results. Consequently, above osmo- and hydropriming treatments for 12 h might be recommended for better germination of pea.

Key words: Germination rate, germination synchrony, mannitol, polyethylene glycol (PEG), thermal time requirement.

Ozmo- ve hidropriming uygulamalarının bezelye (*Pisum sativum* L. cv. Winner) tohumlarının çimlenme performansı ve termal zaman ihtiyacı üzerine etkisi

Öz

Çeşitli priming uygulamalarının ve priming uygulama sürelerinin bezelye (*Pisum sativum* L. cv. Winner) tohumlarının çimlenme performansı üzerindeki etkisi araştırılmıştır. Tohumlar ozmopriming uygulamasında polietilen glikol (PEG 6000) (-0.5, -1.0 ve -1.5 bar) veya mannitol (%1, %2 ve %3) solüsyonunda; hidropriming uygulamasında ise su içerisinde 12 veya 24 saat süreyle olmak üzere 25 °C'de karanlık koşullarda bekletilmişlerdir. Priming uygulanmış tohumlar 5 ile 32 ± 0.5 °C arasında değişen on farklı sıcaklık derecesinde çimlenme testlerine alınmışlardır. Priming uygulamaları çimlenme oranı üzerine önemli etkide bulunmamıştır. Ancak, ozmo- ve hidropriming uygulamaları çimlenme hızını artırıp termal zaman ihtiyacını önemli seviyede azaltmış ve ayrıca test edilen bazı sıcaklık derecelerinde eş zamanlı çimlenmeyi teşvik etmiştir. Uygulamalara bağlı olarak, termal zaman ihtiyacındaki azalma %10, %50 ve %90 çimlenme için sırasıyla 3.4 °C gün ile 11.3 °C gün, 6.6 °C gün ile 17.4 °C gün ve 11.6 °C gün ile 27.5 °C gün arasında değişmiştir. Priming uygulama süresinin 12 saatten 24 saate uzatılması, %50 çimlenme zamanı ve termal zaman ihtiyacı üzerine çoğunlukla olumsuz etki yapmıştır. En iyi sonuçlar -0.5 bar PEG, %1 mannitol ve su (hidropriming) uygulanmış tohumlardan elde edilmiş ve 12 saat süreyle bezelye tohuma yapılacak bu uygulamaların daha iyi bir çimlenme için tavsiye edilebileceği kanısına varılmıştır.

Anahtar kelimeler: Çimlenme hızı, eş zamanlı çimlenme, mannitol, polietilen glikol (PEG), termal zaman ihtiyacı

Introduction

Rapid germination and emergence are important determinants of successful stand establishment and crop production (Almansouri et al., 2001; Murungu et al., 2003). However, during germination, cool and wet soil conditions cause poor germination, cotyledon injury and differential seedling growth in a number of legume crops such as pea (Rowland and Gusta, 1977). Pea seeds are generally sown in autumn or early-spring in Turkey and commonly exposed to low temperature stress during germination, which can result in a reduced stand and low seedling vigour because of low-temperature imbibitional damage (Perry and Harrison, 1970; Rowland and Gusta, 1977; Powell, 1985). In spring planting areas where the plant growing season is short, peas are drilled into cool soils to maximize the length of the production season. Therefore, soil temperatures below optimum also suppress pea germination in early-spring planting areas.

Soaking of seeds in water or an osmotic solution permits partial seed hydration so that pre-germination metabolic activities proceed but primary root protrusion is prevented. Such a treatment, which is usually followed by drying of the seeds, is known as priming (Heydecker and Gibbins, 1978). Priming of seeds in osmoticums such as mannitol, polyethylene glycol (PEG) and sodium chloride (osmopriming) and in water (hydropriming) has been reported to be an economical, simple and a safe technique for increasing the capacity of seeds to osmotic adjustment and enhancing seed germination, seedling establishment and crop production under stress conditions (Kaur et al., 2002; Elkoca et al., 2007). Rapid seed germination and seedling emergence substantially contribute to high yield. It has also been reported that priming improves speed, synchrony and percentage of seed germination in many crop species particularly under sub-optimal temperatures (Yan et al., 1989; Zheng et al., 1994; McDonald, 1999; Elkoca et al., 2007; Farooq et al., 2008) and yield gains in priming treatments result from earlier, faster germination and emergence (Harris et al., 1999; Musa et al., 2001). But, there is only one report (Sivritepe and Dourado, 1995) about the effects of seed priming on germination of pea. In the present study, the germination response of pea seeds was examined at several temperatures in relation to various priming treatments and seed soaking durations in the laboratory in order to obtain more detailed information about seed priming treatments on germination performance of pea seeds.

Materials and Methods

Seed material

This study was conducted under controlled environmental conditions at University of Ataturk, Faculty of Agriculture, Department of Field Crops, Erzurum, Turkey using a pea cultivar (*Pisum sativum* L. cv. Winner) obtained from University of Ankara, Faculty of Agriculture, Department of Field Crops, Ankara.

Priming treatments and durations

The seeds were divided into lots. In osmopriming treatments, the seed lots were fully immersed in an aerated solution of polyethylene glycol [(PEG 6000) at three water potentials (-0.5 (50 g L^{-1}), -1.0 (80 g L^{-1}) and -1.5 bar (101 g L^{-1})] obtained according to Michel and Kaufmann (1973) were fully immersed in 1%, 2% and 3% mannitol. The seed lots were imbibed in distilled water in hydropriming treatments. The seeds without any treatment were termed as unprimed. Treated seed lots with PEG, mannitol and water were kept in darkness in an incubator at 25 ± 1 °C (Elkoca et al., 2007) for 12 or 24 h. The imbibed seeds were then washed three times with tap water and dried on filter paper at 25 ± 1 °C for 24 h (Elkoca et al., 2007).

Germination experiment and experimental design

The germination experiment consisted of a completely randomized design with three replicates in a factorial arrangement. The first factor was the priming treatments [unprimed, PEG (-0.5, -1.0 and -1.5 bar), mannitol (1%, 2% and 3%), and hydropriming] and the second factor was the priming durations (12 h and 24 h). The experiment was carried out in a darkened growth chamber at ten different (5, 8, 11, 14, 17, 20, 23, 26, 29 and 32 ± 0.5 °C) constant temperatures. Twenty seeds were placed on two sheets of filter paper in three 12-cm Petri dishes for each treatment (Okçu et al., 2005; Elkoca et al., 2007) and distilled water (20 ml) was added to each Petri dish. Benomyl (0.5 g L-1) was added into the distilled water to prevent fungal development. Germinated seeds were counted and removed when radicle extension about 10 mm was observed at 4-h intervals to determine the germination courses (Cheng and Bradford, 1999; Okçu et al., 2005; Elkoca et al., 2007; Sağlam et al., 2010).

Data collection

Total percentage germination, time required to reach 10%, 50%, and 90% germination based on the total number of germinated seeds (Garcia-Huidobro et al., 1982; Elkoca et al., 2007) and germination synchrony (hours between 10% and 90% germination rate) (Elkoca et al., 2007) were calculated for each treatment and temperature. Times required to achieve 10%, 50%, and 90% germination were calculated by interpolation from the cumulative germination curve (Covell et al., 1986).

Thermal time equation is $\theta T(g) = (T - Tb)tg$, where $\theta T(g)$ is the thermal time [degree-days (°C d)] to primary root emergence of percentage g, T is the actual temperature at which the germination test is conducted, Tb is the base temperature for germination, and tg is the actual time to germination of percentage g (Bierhuizen and Wagenvoort, 1974; Garcia-Huidobro et al., 1982; Covell et al., 1986; Dahal et al., 1990; Cheng and Bradford, 1999; Elkoca et al., 2007).

Thermal time is equivalent to the inverse slope of the regression line (Garcia-Huidobro et al., 1982; Hardegree et al., 2002). Therefore, a linear regression equation was derived to relate germination rate (reciprocal of the time taken for 10%, 50%, and 90% of total germination to be achieved) to temperature in the sub-optimal temperature range (Hardegree et al 1999) and thermal time requirements were estimated as the inverse slope of the regression line (Garcia-Huidobro et al., 1982; Dumur et al., 1990; Hardegree et al., 2002; Elkoca et al., 2007) for 10%, 50%, and 90% germination.

Statistical analysis

The data were subjected to analysis of variance using MSTATC Statistical Package (version 1.4, Michigan State University). Germination percentage values were subjected to arcsine transformation to obtain normal distribution before running analysis of variance. Mean values were separated according to least significant differences (LSD) test.

Results

Germination percentage

Analysis of variance showed that priming treatments, priming durations and priming treatment (x) priming duration interaction had no significant effect on germination percentage at all of the temperatures (Table 1).

Unprimed seeds had similar germination percentages to primed seeds at all temperatures tested. Also, as an average of priming treatments, priming duration of 24 h had no stimulatory effect on germination percentage as compared to 12 h.

Germination rate

Priming treatments induced faster germination compared with the unprimed seeds (Figure 1). At all of the germination temperatures, hours required to reach 10%, 50%, and 90% germination were significantly reduced by priming treatments (10% and 90% germination data not shown) and were also significantly influenced by priming duration (Figure 2 and Figure 3). On the other hand, interaction effect was insignificant at all temperatures tested Among the priming treatments, seeds treated with -/0.5 bar solution of PEG, mannitol (1%, 2% or 3%) and water for 12 or 24 h had generally low 50% germination time, whereas seeds treated with -1.5 bar solution of PEG had the longest 50% germination time at all of the germination temperatures (Figure 2).

As an average of priming durations, reductions in the hours required to reach 50% germination under different priming treatments ranged between 8.1% (PEG -1.5 bar at 17 °C) and 32.9% (mannitol 1% at 11 °C), over the unprimed treatment. Compared with the seeds primed for 12 h, priming duration of 24 h significantly reduced hours required to reach 50% germination at 17, 20, 29 and 32 °C. However, at the other tested temperatures, priming duration of 24 h had detrimental effect on the mean germination time (Figure 3)

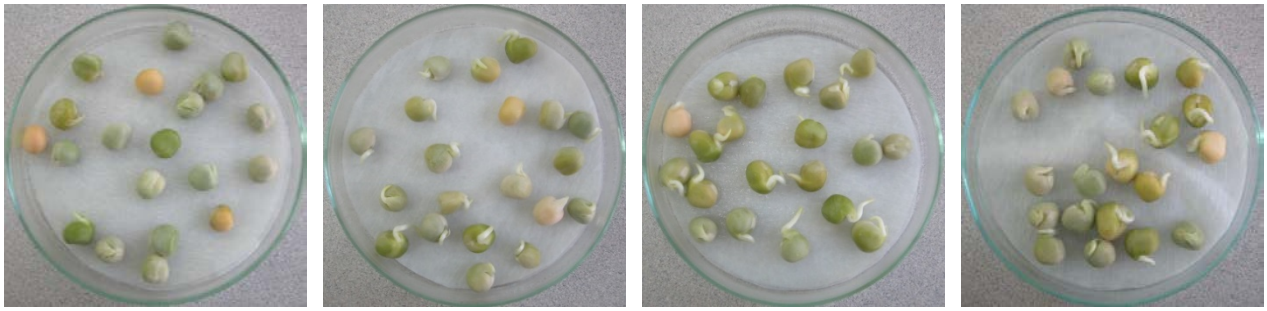
Germination synchrony

On average of priming durations, seed priming significantly decreased hours between 10% and 90% germination (germination synchrony) at only 17, 23 and 26 °C (Table 2). Compared with the unprimed treatment, the best results obtained from seeds treated with mannitol solution of 3% which increased germination synchrony by 46.0% and 32.8% at 17 and 23 °C, respectively and seeds treated with mannitol solution of 1% which increased germination synchrony by 28.6% at 26 °C . But, germination synchrony of unprimed seeds was similar or better as compared with the priming treatments at the other temperatures. In general, seeds treated with water (hydropriming) had the worst germination synchrony (Table 2).

Table 1. Effects of seed priming and priming duration on germination percentage of pea seeds at different temperatures

	Germination (%)									
Temperature (°C)	5	8	11	14	17	20	23	26	29	32
Priming treatments (Pt)										
Unprimed	100.0	96.7	96.7	98.3	98.3	98.3	98.3	96.7	100.0	93.3
PEG (-0.5 bar)	97.5	98.3	100.0	100.0	99.2	97.5	99.2	97.5	99.2	98.3
PEG (-1.0 bar)	98.3	98.3	99.2	97.5	99.2	97.5	97.5	95.0	98.3	95.0
PEG (-1.5 bar)	95.8	99.2	97.5	98.3	95.8	95.0	97.5	97.5	97.5	95.0
Mannitol (1%)	100.0	97.5	95.0	98.3	100.0	98.3	97.5	97.5	98.3	95.8
Mannitol (2%)	100.0	100.0	97.5	97.5	96.7	100.0	99.2	97.5	98.3	96.7
Mannitol (3%)	100.0	96.7	98.3	97.5	100.0	99.2	100.0	97.5	98.3	97.5
Hidropriming	96.7	99.2	98.3	98.3	98.3	99.2	97.5	92.5	97.5	96.7
Priming durations (Pd)										
12 h	98.3	97.9	97.3	98.3	98.5	97.9	98.1	97.1	97.9	96.0
24 h	98.8	98.5	98.3	98.1	98.3	98.3	98.5	95.8	98.9	96.0
Mean	98.5	98.2	97.8	98.2	98.4	98.1	98.3	96.5	98.4	96.0
cv (%)	6.3	8.1	8.8	7.2	7.0	7.7	7.8	10.1	7.0	10.7
Source	*P* values									
Pt	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Pd	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Pt x Pd	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

ns: not significant



(a) Unprimed (b) 12 h Hydropriming (c) 12 h Mannitol (1%) (d) 12 h PEG (-0.5 bar)

Figure 1. Germination of pea seeds at 200th hour under the lowest temperature (5 °C) conditions

Priming duration had a significant effect on germination synchrony at 11, 14, 17, 23 and 29 °C. Compared with priming duration of 12 h, priming duration of 24 h significantly increased germination synchrony at 17 and 29 °C, but significantly decreased at 11, 14, 23 °C (Table 2).

The interaction between priming treatment and priming duration was significant for germination synchrony at 8, 11, 14 and 17 °C. In terms of germination synchrony, the best combination of priming treatment and priming duration differed among germination temperatures (Table 2).

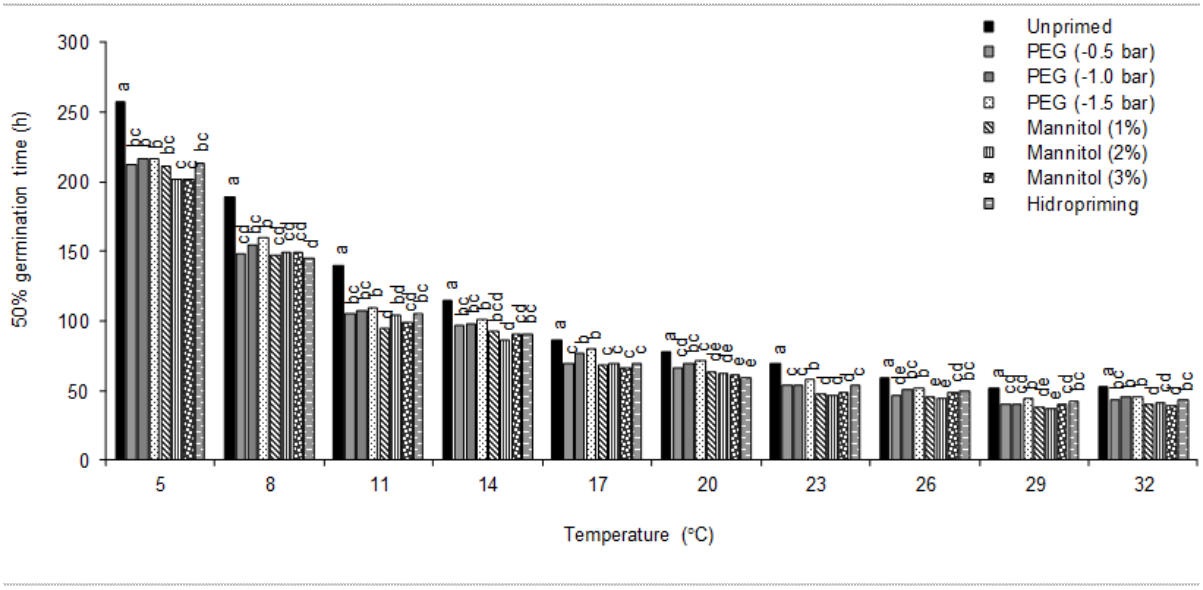


Figure 2. Time to 50% germination at different temperatures in relation to different priming treatments

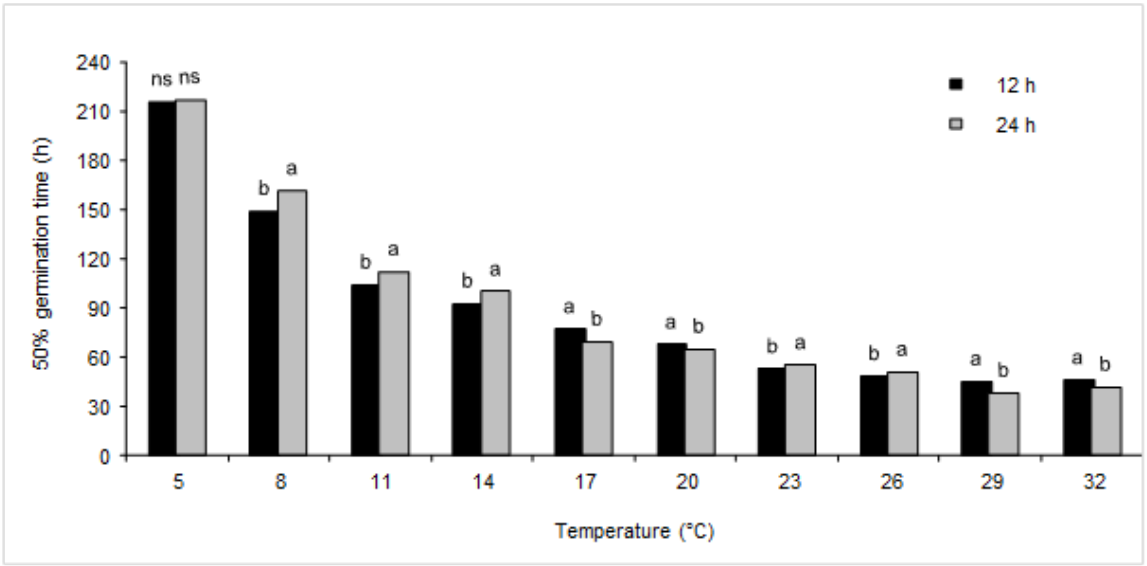


Figure 3. Time to 50% germination at different temperatures in relation to different priming durations; ns, not significant.

Compared with the unprimed treatment, the best priming treatment (x) priming duration interactions increased germination synchrony by 12.4, 26.7, 16.5 and 50.9% at 8, 11, 14 and 17 °C, respectively.

Thermal time requirement

Priming treatments significantly decreased thermal time requirements as compared with the unprimed treatment. These reductions ranged between 3.4 °C d and 11.3 °C d, 6.6 °C d and 17.4 °C d, and 11.6 °C d and 27.5 °C d for 10%, 50% and 90% germination, respectively (Table 3).

As an average of priming treatments, priming duration of 24 h increased the thermal time requirements for 10%, 50% and 90% germination but, these increases were not significant. Analysis of variance also showed that thermal time requirements for 10% and 50% germination were significantly influenced by interaction of priming treatment (x) priming duration (Table 3). The best thermal time requirement results for 10%, 50% and 90% germination were generally obtained from seeds treated with mannitol solution of 1% and 2% for 12 h.

Table 2. Effects of seed priming and priming duration on germination synchrony (hours between 10% and 90% germination rate) of pea seeds at different temperatures

	Germination synchrony									
Temperature (°C)	5	8	11	14	17	20	23	26	29	32
Priming treatments (Pt)										
Unprimed	107.7	91.3	72.3	66.7	71.3	40.7	47.3	42.7	31.7	19.7
PEG (-0.5 bar)	132.7	95.3	82.2	78.7	56.5	57.8	40.8	41.3	30.3	32.8
PEG (-1.0 bar)	120.7	88.5	72.8	65.8	54.7	53.2	38.5	35.0	31.0	32.3
PEG (-1.5 bar)	118.7	90.0	76.3	70.3	48.5	51.0	40.0	36.3	29.8	28.7
Mannitol (1%)	134.2	95.7	84.8	71.2	59.3	40.5	41.8	30.5	31.2	32.2
Mannitol (2%)	121.7	97.7	68.2	67.7	49.8	49.3	36.2	38.5	27.0	29.5
Mannitol (3%)	122.2	88.7	74.0	66.8	38.5	39.0	31.8	37.8	29.7	30.0
Hidropriming	123.0	115.0	88.3	86.2	57.8	50.5	41.0	41.0	35.2	38.5
LSD	15.4	15.6	12.6	11.9	8.8	8.6	6.6	7.2	ns	5.6
Priming durations (Pd)										
12 h	124.7	93.2	71.1	63.8	56.5	47.9	37.5	37.6	33.3	31.1
24 h	120.5	97.4	83.7	79.5	52.6	47.5	41.8	38.2	28.1	29.8
LSD	ns	ns	8.4	5.9	3.3	ns	3.3	ns	3.1	ns
Pr treatment x Pr duration										
12 h										
PEG (-0.5 bar)	129.7	88.7	76.0	70.3	56.7	61.7	40.0	47.0	36.0	35.3
PEG (-1.0 bar)	120.0	97.0	68.3	58.0	54.7	50.3	35.0	33.7	31.3	31.7
PEG (-1.5 bar)	120.0	85.0	67.0	72.0	46.0	51.3	39.3	35.7	33.0	28.0
Mannitol (1%)	124.7	87.0	91.3	63.0	68.7	39.7	34.7	26.7	36.7	32.7
Mannitol (2%)	139.3	101.0	53.0	62.0	48.0	51.3	35.0	38.0	27.3	29.3
Mannitol (3%)	128.7	90.3	58.7	55.7	42.0	40.3	30.0	35.3	33.3	29.3
Hidropriming	127.7	105.0	82.0	63.0	65.0	48.3	39.0	41.7	37.3	43.0
24 h										
PEG (-0.5 bar)	135.7	102.0	88.3	87.0	56.3	54.0	41.7	35.7	24.7	30.3
PEG (-1.0 bar)	121.3	80.0	77.3	73.7	54.7	56.0	42.0	36.3	30.7	33.0
PEG (-1.5 bar)	117.3	95.0	85.7	68.7	51.0	50.7	40.7	37.0	26.7	29.3
Mannitol (1%)	143.7	104.3	78.3	79.3	50.0	41.3	49.0	34.3	25.7	31.7
Mannitol (2%)	104.0	94.3	83.3	73.3	51.7	47.3	37.3	39.0	26.7	29.7
Mannitol (3%)	115.7	87.0	89.3	78.0	35.0	37.7	33.7	40.3	26.0	30.7
Hidropriming	118.3	125.0	94.7	109.3	50.7	52.7	43.0	40.3	33.0	34.0
Unprimed	107.7	91.3	72.3	66.7	71.3	40.7	47.3	42.7	31.7	19.7
LSD	ns	16.4	17.8	16.8	12.5	ns	ns	ns	ns	ns
Mean	122.6	95.3	77.4	71.7	54.6	47.8	39.7	37.9	30.7	30.5
cv (%)	10.7	10.4	13.8	10.5	10.3	11.4	10.6	12.0	12.9	11.7
Source	*P values*									
Pt	0.044	<0.001	0.032	<0.001	<0.001	<0.001	<0.001	<0.001	0.085	<0.001
Pd	0.269	0.149	<0.001	<0.001	0.019	0.915	<0.001	0.986	<0.001	0.205
Pt x Pd	0.061	0.031	0.021	<0.001	0.006	0.658	0.125	0.054	0.088	0.157

ns: not significant

Table 3. Thermal time estimate for hours to 10%, 50%, and 90% germination in the sub-optimal temperature range of 5-26 °C

	10 % germination		50 % germination		90 % germination	
Temperature (°C)	Thermal time (^{o}d)	Regression (r^2)	Thermal time (^{o}d)	Regression (r^2)	Thermal time (^{o}d)	Regression (r^2)
Priming treatments (Pt)						
Unprimed	45.4	0.95	67.0	0.99	98.9	0.98
PEG (-0.5 bar)	34.1	0.95	52.9	0.97	83.5	0.94
PEG (-1.0 bar)	39.0	0.94	56.6	0.95	82.9	0.95
PEG (-1.5 bar)	42.0	0.96	60.4	0.97	87.3	0.96
Mannitol (1%)	34.7	0.90	49.6	0.95	71.4	0.95
Mannitol (2%)	34.5	0.90	52.4	0.93	81.0	0.93
Mannitol (3%)	37.0	0.96	52.5	0.95	75.6	0.91
Hidropriming	37.0	0.91	54.7	0.95	82.3	0.93
LSD	5.2		4.8		9.9	
Priming durations (Pd)						
12 h	36.6	0.95	54.9	0.97	81.7	0.96
24 h	39.3	0.93	56.6	0.95	84.0	0.94
LSD	ns		ns		ns	
Pr treatment x Pr duration						
12 h						
PEG (-0.5 bar)	31.2	0.94	52.1	0.97	87.6	0.95
PEG (-1.0 bar)	38.8	0.94	55.1	0.95	79.4	0.95
PEG (-1.5 bar)	43.3	0.95	62.3	0.96	89.0	0.95
Mannitol (1%)	31.8	0.90	50.5	0.95	68.6	0.95
Mannitol (2%)	31.7	0.95	48.3	0.97	75.0	0.95
Mannitol (3%)	37.2	0.98	52.5	0.98	74.7	0.96
Hidropriming	33.5	0.97	51.4	0.98	80.7	0.95
24 h						
PEG (-0.5 bar)	37.0	0.96	53.7	0.97	79.4	0.94
PEG (-1.0 bar)	39.1	0.95	58.0	0.96	86.3	0.95
PEG (-1.5 bar)	40.6	0.97	58.4	0.98	85.7	0.98
Mannitol (1%)	37.6	0.91	48.6	0.96	74.3	0.96
Mannitol (2%)	37.4	0.85	56.5	0.89	87.1	0.91
Mannitol (3%)	36.7	0.95	52.5	0.93	76.4	0.87
Hidropriming	40.5	0.86	58.0	0.92	83.9	0.92
Unprimed	45.4	0.95	67.0	0.99	98.9	0.98
LSD	5.5		5.0		ns	
Mean	38.0		55.7		82.9	
cv (%)	8.7		5.4		7.6	
Source			*P values*			
Pt	<0.001		<0.001		<0.001	
Pd	0.205		0.059		0.219	
Pt x Pd	0.019		0.022		0.207	

ns: not significant

Discussion

Primed seeds can improve germination of many crop species, particularly under adverse conditions such as low temperature (Zheng et al., 1994; Hardegree and Van Vactor, 2000; Kaya et al., 2010). Thus, priming the seeds with water or osmotic solution before sowing is widely adopted to overcome adverse effects of temperature on germination (Yan et al., 1989; McDonald, 1999). In this study, germination percentage of unprimed pea seeds was high and thus unprimed seeds had similar germination percentages to primed seeds at all temperatures tested (Table 1). But, compared with the unprimed seeds, priming treatments induced faster germination at all of the germination temperatures (Figure 2). Similar increases in germination speed of chickpea (Elkoca et al., 2007), maize (Harris et al., 1999), soybean (Yan et al., 1989), pea (Sivritepe and Dourado, 1995) grass seeds (Hardegree and Van Vactor, 2000), canola (Zheng et al., 1994), wheat and barley (Al-Karaki, 1998) through seed priming have been reported in previous studies. These beneficial effects of priming on seed germination rate are related to the repair and build-up of nucleic acid, enhanced synthesis of RNA and proteins, repair of membranes and some age-induced damage (Bray et al., 1989; Dell'Aquila and Bewley, 1989; Davison and Bray, 1991; Bray, 1995), and enhanced respiratory activity of seeds (Halpin-Ingham and Sundstrom, 1992; Benamar et al., 2003).

In this study, only some priming treatments were able to improve germination synchrony at only 17, 23 and 26 °C (Table 2). Similarly, McDonald (2000) has also reported that the seed priming treatments sometimes do not stimulate germination synchrony because an equal amount of water can not be taken by each seed under seed priming conditions and this prevents a uniform physiological activity in seeds.

Thermal germination models generate coefficients that integrate potential response over a wide range of temperature conditions (Garcia-Huidobro et al., 1982; Covell et al., 1986; Hardegree et al., 1999). These coefficients can be compared directly to rank relative potential performance of seed lots (Covell et al., 1986) and can be validated by confirming the germination response under variable temperature conditions (Hardegree et al., 1999; Hardegree and Van Vactor, 2000). Earlier and faster germination and emergence has been associated with a lower value of thermal time requirement (Mohamed et al., 1988). In cold soils, low thermal time requirement is of great importance for rapid germination (Bierhuizen and Wagenvoort, 1974) because germination of seeds will be delayed until thermal time requirement is met. I also quantified the priming effect by calculating the thermal-response parameter from the sub-optimal temperature data (Table 3). In this study, compared with the unprimed treatment, priming treatments significantly decreased thermal time requirements. Dahal et al. (1990), Hardegree and Van Vactor (2000), Hardegree et al. (2002) and Elkoca et al. (2007) also investigated priming effects on thermal germination response. They also found that priming significantly decreased thermal time requirements.

Rate of water uptake, which is necessary to activate the physiological processes in seed, is directly related to the osmotic potential of the priming solution (Hardegree and Emmerich, 1992) and decreasing water potential adversely affects rate of water uptake in seeds (Al-Karaki, 1998; Kader and Jutzi, 2002). In the current study, -0.5 bar solution of PEG, which had the highest water potential among the PEG treatments, also gave the best results in the PEG treatments. But, lower water potentials in PEG treatments, especially -1.5 bar, adversely affected germination speed and thermal time requirement (Figure 4). These adverse effects may be related to the decreased water uptake in the presence of greater levels of PEG. Similar results have been reported by Danneberger et al. (1992), Al-Karaki (1998) and Elkoca et al. (2007). But, this effect was not clear in the presence of greater levels of mannitol (Figure 4).

The effect of seed priming on seed germination can vary depending on priming duration (Elkoca et al., 2007; Ghassemi-Golezani et al., 2008). In this study, compared with the priming duration of 12 h, priming duration of 24 h had generally negative effect on the 50% germination time and thermal time requirements for 10%, 50% and 90% germination (Figure 3 and Table 3). Similar reductions in germination parameters with increasing priming duration were observed for soybean (Khalil et al., 2001), chickpea (Elkoca et al., 2007) and bean (Ghassemi-Golezani et al., 2010). These results show that over priming is detrimental. This is supported by Murray (1989), who concluded that over priming may cause oxygen deficiency and the build-up of inhibitors. The findings of this study suggested that priming duration of 12 h was generally safer for pea

as compared with 24 h. Similarly, soaking the seeds from overnight to 24 h has also been recommended for many crops such as chickpea, maize, rice and bean (Harris et al., 1999; Elkoca et al., 2007; Ghassemi-Golezani et al., 2010).

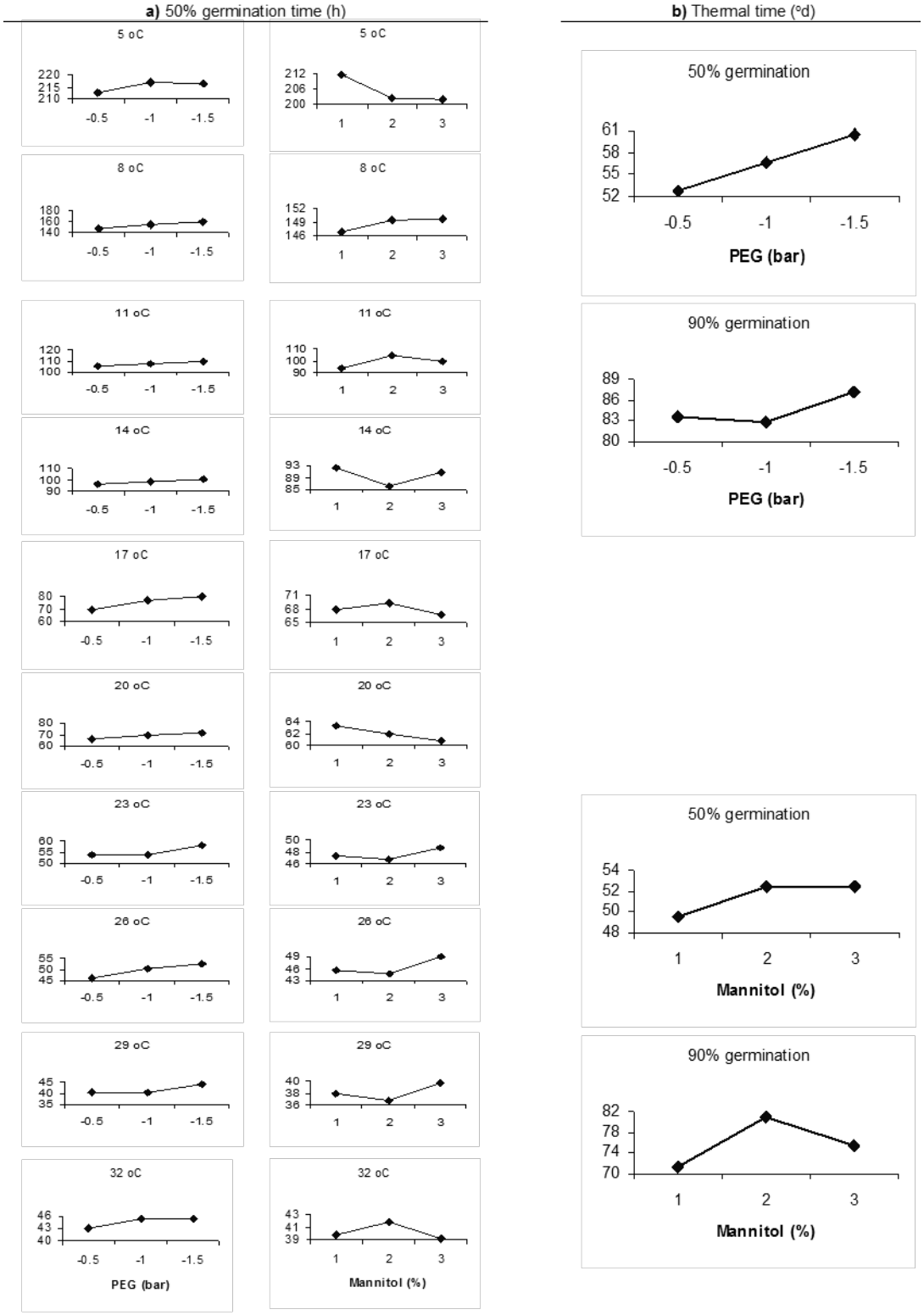


Figure 4. a) Time to 50% germination and b) thermal time requirement in relation to different levels of PEG and mannitol

Conclusion

Priming treatments induced faster germination and significantly decreased thermal time requirements of pea (*Pisum sativum* L. cv. Winner) seeds. As compared to the unprimed and the other osmopriming treatments, seeds treated with - 0.5 bar solution of PEG and 1% solution of mannitol had generally higher germination rate and lower thermal time requirements. However, seeds treated with water had generally similar results to seeds treated with -0.5 bar PEG and 1% mannitol. Consequently, above osmo- and hydropriming treatments for 12 h might be recommended for better germination of pea.

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