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Water use and water-use efficiency of Isabgol (*Plantago ovata*) and French psyllium (*Plantago psyllium*) in different irrigation regimes

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Abstract
Water supply is a major constraint to crop production in Mediterranean climate. This study examined water use, water-use efficiency, mucilage and seed yield of Isabgol (*Plantago ovata*) and French psyllium (*Plantago psyllium*) from 2 experiments over 2005 to 2006. In this study, Isabgol and French psyllium which are used as an anti-diabetic plant were exposed to three different irrigation regimes and three different plant densities. Combined analysis results showed that year effect was significant in all traits. Limited irrigation regimes significantly decreased seed yield, biological yield and water use in compared to control although, WUEs and mucilage percentage in both species significantly increased. The highest biological yield belongs to control and R2 (Irrigation terminated at the start of flowering with a complementary irrigation at the seed formation stage) in medium density and the highest mucilage percentage were observed in R3 (irrigation terminated at the start of flowering) and low density in both species. Totally, seed yield, biological yield and mucilage percentage were higher in Isabgol compare with French psyllium. Contrary to $WUE_{b,}$ WUEs in Isabgol was more than French psyllium. Our results showed that there is a high potential for saving water through medium stress (R2) using locally adapted plants in the semi-arid conditions of Karaj. These crops can serve as alternative sources of income in dry years.

Keywords: Drought Stress, Density, Psyllium, Water use efficacy
Abbreviations: WU- Water use; WUEs - Water use efficiency for seed yield; WUE_b - Water use efficiency for herbage biomass

Introducton

Isabgol (*Plantago ovata* Forsk.) and French psyllium (*P.psyliium* L.) are the two annual species that have originated from arid and semi-arid zones and are used widely in traditional and industrial pharmacology (Patel et al., 1996; D'Antuno et al., 2002). Seeds and husks of Isabgol are also used widely in pharmacology as laxatives (Ainechii, 1986; Patel et al., 1996). Interest in Isabgol has risen primarily due to its use in high fiber breakfast cereals and from claims that it is effective in reducing cholesterol (Gupta et al., 1994; Chadho and Ragender, 1995; Davidson et al., 1996; Trautwein et al., 1997; Segawa et al., 1998). Some studies have shown that black cumin (Mozzafari et al., 2000) and Isabgol (Patra et al., 1999) are able to tolerate moderate levels of water stress. Plant sensitivity to environment and management factors varies according to the developmental stage. To meet agricultural demands and growing competition for water, a more effective use of water in both irrigated and rainfed agriculture is essential. In regions where water scarcity is the principal limiting factor for cultivation, farmers are interested in growing crops that are able to adapt to drought conditions (Muchow, 1989; Bannayan et al., 2008). Shortage of water in arid and semi-arid parts of this region where annual precipitation is less than 220mm with almost no rainfall during the summer is a prominent limiting factor of crop production. Agricultural production in Iran decreased by 9.1% in 2006, and a further decrease in 2007 (FAO, 2008) due to drought. A considerable number of medicinal and aromatic plants are locally adapted and considered as native to arid zones of the world (Bannayan et al., 2006; Nadjafi et al., 2006), thus these regions support a high portion of plants rich in secondary compounds. Plants rich in essential oils, gums and mucilage are more abundant in arid zones than in humid habitats (Bannayan et al., 2008). In Iran water is a scarce resource due to the high variability of rainfall. Irrigation scheduling based on developmental stage or deficit irrigation is the technique of applying water on a timely and accurate basis to the crop, and is the key to conserving water and improving irrigation performance and sustainability of irrigated agriculture (Mpelasoka et al., 2001). Local farmers in this study region use plant developmental stages as keys to irrigation timing. Any success in encouraging farmers toward irrigation-planting change should be in accordance with their method and understanding of field management practices. When new species introduced, local farmers want to know whether they demand less water and how water deficit will affect the final yield. Therefore, our objectives and methodology for this study were based on the above fact. Few researches have been carried

Table 1. Effect of irrigation regimes on seed and herbage biomass yield, Mucilage percentage, WU and WUE of *P.ovata* and *P.psyllium*

Irrigation regime	Seed Yield (Kg/ha)		Herbage biomass (Kg/ha)		Mucilage (%)		WU (mm)		WUEs (Kg/mm)		WUE_b (Kg/mm)	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
P.ovata												
R1	1016 a	859 a	3940 a	3151 a	21.3 c	21.8 c	264 a	263 a	0.39 b	0.34 b	1.49 b	1.23 b
R2	880 b	760 b	3842 b	2766 b	27.8 a	27.1 b	206 b	202 b	0.43 a	0.35 b	1.86 a	1.16 b
R3	640 c	582 c	2190 c	1846 c	26.4 a	30.3 a	159 c	174 c	0.41 a	0.38 a	1.38 b	1.31 a
P.psyllium												
R1	833 a	643 a	6274 a	5594 a	14.7 b	15.1 b	298 a	268 a	0.26 b	0.24 b	14.7 b	2.09 a
R2	764 b	400 b	5988 b	4658 b	18.6 a	16.4 b	253 b	216 b	0.33 a	0.27 a	15.7 a	2.20 a
R3	503 c	605 c	4401 c	3320 c	16.0 b	19.1 a	170 c	151 c	0.27 b	0.28 a	15.9 a	2.17 a

Means followed by the same letters in each column are not significantly different at the 5% probability

out on responses of Isabgol (Ganpat et al., 1992; Patel et al., 1996; Nadjafi, 2001; Tabrizi, 2004) to different irrigation intervals but irrigation scheduling based on developmental stage has not been studied specially in our region. In this study, we focused trying to reduce irrigation by terminating irrigation in different growth stage in both species and its interaction with plant density. The objective of this study was to investigate the effects of different irrigation regimes and different plant population on seed yield and seed quality in *P.psyllium* and *P.ovata*.

Materials and methods

The experiments were conducted during the 2005 and 2006 growing seasons at the Agriculture research field of Tehran University, Karaj, Iran (Latitude: 35°48'N; longitude: 51°10'E; Elevation: 1316 m). Climate in this region is arid Mediterranean climate. Average annual rainfall is about 265 mm; precipitation falls in winter as snow and mainly occurs between Novembers to April. Long-term annual maximum, minimum and mean temperatures are 40, -18 and 13.5 ºC, respectively. Maximum and minimum temperatures and precipitation of both years of this experiment are shown in Fig. 1. Soil was a silty loam with pH 8.2, containing total N (766 ppm), total P (5.21 ppm), and total K (166 ppm), with an EC of 8 mmhos.cm^{-1}.

Experimental design

Two separate experiments in 2005 and 2006 consisted of two plantago species, Isabgol (*Plantago ovata*) and French psyllium (*P.psyllium*), three different plant density included 40, 70,100 plant per m^2 described as Low, medium and high plant density, respectively. Three irrigation regimes included R1: Irrigation from emergence to harvest at 50% of available soil water in each treatment (control), R2: Irrigation terminated at the start of flowering with a complementary irrigation at the seed formation stage and R3: irrigation terminated at the start of flowering. All treatments repeated three times on field following a factorial form on complete randomized design. Each experimental plot was 5m long and 3m wide with total area of $15m^2$. Irrigation furrows with uniform slopes constructed in each experimental plot, and rows were 25cm apart. In order to prevent the lateral spread of water, plots surrounded by dikes with a distance of 2m between plots. Fertilizer (N: P at a rate of 55:65 kg.ha^{-1}) applied before sowing for both species. Sowing of French psyllium and Isabgol added manually, 0.5cm depth and densities of 40, 70,100 plants per m^{-2}, on 13 April 2005 and 16 April 2006. A one-time irrigation applied immediately after sowing for uniform emergence. Weeds controlled by hand, when required. To record the developmental stages on a weekly basis, $1m^2$ of each plot monitored. The developmental stages were determined when one plant in each plot indicated that stage. The daily meteorological data from the regional meteorological station, located about 4 km from the experimental field, were recorded. Soil water content was measured for each developmental stage weekly across all treatments and was determined on a dry mass basis and converted to a volumetric unit using 1.35 g.cm^{-3} as soil bulk density (Nadjafi, 2001). Based on field capacity (28.5% θ) and wilting point (12% θ) of the study site (Nadjafi, 2001), 50% of available soil water was considered as the water stress threshold (21% θ). For each irrigation treatment, the water uniformly applied with sprinklers. Due to the differences in maturity induced by the different irrigation treatments, there were two harvest dates for both species in both years of the study. Harvesting was done manually by pulling the dry plant out of the soil and removing the roots. Final seed and biological yield were measured from 1 m^2 of each plot. Mucilage percentage of Isabgol and French psyllium measured according to Sharma and Koul (1986).

Measurements

Soil moisture measurements

Soil moisture contents (% θ, weight based) at field capacity (FC) and permanent wilting point were 28.5% and 12%, respectively. Soil water budget was measured using a moisture

Table 2. Effect of planting density on seed and herbage biomass yield, Mucilage percentage, WU and WUE of *P.ovata* and *P.psyllium*

Planting Density	Seed Yield (Kg/ha)		Herbage biomass (Kg/ha)		Mucilage (%)		WU (mm)		WUEs (Kg/mm)		WUE_b (Kg/mm)	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
P.ovata												
Low	832 b	733 b	2954 c	2325 c	26.2 a	26.9 a	197 c	211 b	0.43 a	0.36 a	1.48 b	1.15 b
Medium	909 a	790 a	3415 b	2664 b	26.3 a	27.0 a	207 b	208 b	0.44 a	0.39 a	1.64 a	1.29 a
high	795 b	677 c	3604 a	2774 a	25.0 a	25.6 a	224 a	220 a	0.35 b	0.31 b	1.60 a	1.26 a
P.psyllium												
Low	702 b	541 b	5238 b	4175 c	16.6 a	17.0 a	234 b	202 c	0.30 a	0.27 a	2.27 c	2.10 b
Medium	766 a	594 a	5661 a	4522 b	16.2 a	16.6 a	241 a	211 b	0.32 a	0.28 a	2.34 b	2.17 a
high	632 c	514 c	5765 a	4876 a	16.5 a	16.9 a	246 a	221 a	0.26 b	0.24 b	2.45 a	2.20 a

Means followed by the same letters in each column are not significantly different at the 5% probability

Table 3. Interaction Effect of Plant Density and Irrigation regime on Seed Yield and Herbage biomass of *P.ovata* and *P.psyllium* in 2 year of experiment

	Seed Yield (Kg/ha)			Herbage biomass (Kg/ha)			Mucilage (%)		
	Plant Density ($P.m^{-2}$)			Plant Density ($P.m^{-2}$)			Plant Density ($P.m^{-2}$)		
P.Ovata	40	70	100	40	70	100	40	70	100
2005									
R1	983	1055	1010	3592	4037	4191	21.2	21.2	21.4
R2	872	988	781	3296	3936	4296	31.7	30.7	28.4
R3	641	686	595	1974	2272	2326	25.7	27	25.1
LSR	29.5			23.67			2.5		
2006									
R1	879	900	799	2832	3237	3384	21.7	21.8	22
R2	563	623	560	1641	1902	1996	26.4	27.7	25.7
R3	759	849	673	2502	2854	2942	32.5	31.4	29.1
LSR	20.46			49.70			2.54		
P.psyllium	Plant Density ($P.m^{-2}$)			Plant Density ($P.m^{-2}$)			Plant Density ($P.m^{-2}$)		
2005									
	40	70	100	40	70	100	40	70	100
R1	858	922	720	6034	6284	6505	14.5	14	15.6
R2	760	837	697	5655	6034	6277	19.4	17.9	18.6
R3	488	540	481	4025	4365	4813	15.9	16.6	15.4
LSR	18.69			26.25			2.01		
2006									
R1	628	720	582	5037	5648	6098	14.9	14.4	16
R2	395	419	388	3181	3335	3445	16.3	17	15.8
R3	600	644	573	4307	4584	5085	19.9	18.3	19
LSR	19.65			29.66			1.95		

LSR, Least significant range

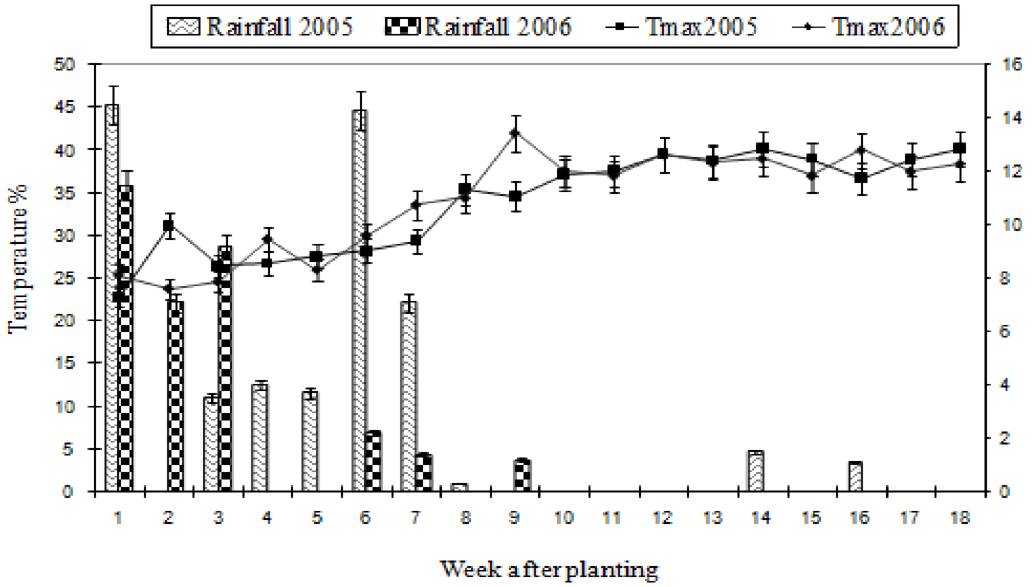

Fig 1. Weekly values of maximum and minimum temperature (ºC) and precipitation (mm) of years 2005 and 2006.

meter (Delta T model 550 British). Polyethylene tubes of 1m length and 20mm diameter installed at the middle of each experimental plot. The depth of soil was 0.6m so that 0.4m of each tube left above the ground. Volumetric soil moisture was measured at 3 depths of 0.10, 0.30 and 0.60 m. To prevent water stress, when mean soil moisture content reached to %21, irrigation was applied. The amount of irrigation water was 450 litters or 30 mm height for each application (calculations not shown). The crop water use or evapotranspiration (ET) calculated from the changes in the storage of soil water, rainfall and irrigation data using the following equation. $\Delta S = (P + I) - (R + D + ET)$, Where ΔS is the change in soil moisture storage, P: precipitation; I: irrigation; R: runoff; D: drainage, ET: evapotranspiration. Moisture storage up to FC applied to the soil with volumetric counter to compensate for water deficiency. Since applied water controlled not to exceed the soil FC, drainage of water was very low and almost negligible. In addition, runoff eliminated by creating ridges around the experimental plots; As a result, the water budget calculated by the following equation:

$\Delta S = P + I - ET$

Therefore $ET = P + I - \Delta S$

Moreover, WUE calculated from below equation

$WUEs = \text{Seed yield}/ET$

$WUE_b = \text{Total dry matter}/ET$

At crop maturity, $1m^2$ of each experimental plot harvested by hand to determine the grain yield and total dry matter production.

Statistical analyses

Seed yield, dry matter, ET, WU, WUEb, and WUEs in the Isabgol and French psyllium were analyzed using analysis of variance (SAS) (2001). Each trial analyzed separately and LSD derived for comparison between seasons within species. A combined analysis undertaken in order to compare grain yield, dry matter, ET, WUEb, and WUEs between Isabgol and French psyllium and the interaction between species and seasons. The LSD derived for comparisons across species. For supplemental irrigation experiments, statistical analysis carried out for individual seasons, and no combined analysis was made.

Results and discussion

Irrigation regime

Seed yield and herbage biomass in two years were significantly affected ($P<0.05$) by irrigation regimes in both species which were the highest in R1 and the lowest in R3. Irrigation regimes also significantly ($P<0.05$) affected mucilage percentage, WU, WUEs and WUE_b of both species in two years (Table 1). Generally seed yield and herbage biomass production of both crops, in both years of experiment reduced, as irrigation was limited especially in R3. Across all irrigation regimes in both years, R1 significantly ($P<0.05$) showed higher seed and biomass yield in both species. However, mucilage percentage in both species was highest in R3 in two years of experiments. Both species produced more seed and biomass yield as well as mucilage percentage in first year. Averaged over both years of experiment, our results showed that herbage biomass and seed yield gradually decreased ($p<0.05$) as irrigation limited more from R1 to R3, however mucilage percentage significantly increased in this condition. Averaged over both years, Isabgol seed yield and mucilage percentage were significantly ($P<0.05$) higher than French psyllium at each type of irrigation because of growth type difference between them. Since there was not

Table 4. Interaction Effect of Plant Density and Irrigation regime on WU, WUEs and WUEb of *P.ovata* and *P.psyllium* in 2 year of experiment

	WU (mm)			WUEs (Kg/mm)			WUEb (Kg/mm)		
	Plant Density (P.m^{-2})			Plant Density (P.m^{-2})			Plant Density (P.m^{-2})		
P.Ovata	40	70	100	40	70	100	40	70	100
2005									
R1	249	264	280	0.4	0.4	0.36	1.44	1.53	1.5
R2	197	205	217	0.44	0.48	0.36	1.67	1.92	1.98
R3	147	154	176	0.44	0.44	0.34	1.34	1.47	1.32
LSR	11.95			0.006			0.014		
2006									
R1	249	264	276	0.35	0.34	0.29	1.14	1.23	1.23
R2	216	148	160	0.29	0.42	0.35	0.84	1.29	1.24
R3	170	212	224	0.45	0.4	0.3	1.48	1.35	1.32
LSR		13.26			0.012			0.027	
	Plant Density (P.m^{-2})			Plant Density (P.m^{-2})			Plant Density (P.m^{-2})		
P.psyllium	40	70	100	40	70	100	40	70	100
2005									
R1	289	297	309	0.3	0.31	0.23	2.09	2.11	2.11
R2	245	256	258	0.31	0.33	0.27	2.31	2.36	2.43
R3	168	172	171	0.29	0.31	0.28	2.4	2.54	2.82
LSR	10.26			0.005			0.021		
2006									
R1	256	267	281	0.25	0.27	0.21	1.98	2.12	2.17
R2	144	150	160	0.28	0.28	0.24	2.22	2.24	2.15
R3	207	217	224	0.29	0.3	0.26	2.1	2.14	2.28
LSR	11.25				0.0041				0.017

LSR, Least significant range

much difference between weather conditions of both years (Fig.1), less seed and herbage biomass production of both crops in year 2 (Table 1) could be due to other factor like different relative humidity in the first year of experiment or allelophatic potential or sensitivity of these crops to continuous planting in same land (Rahimi, 2006). Under full growth period irrigation (R1), in both species WU was significantly higher than R2 and R3 in 2 years of experiments though the more WU accompanied with the less WUEs and WUE_b (Table 1). No WUEs and WUE_b differences were observed between 2 years of experiment in both species. Generally, Isabgol significantly showed higher WUEs and lower WUE_b compared to French Isabgol. It could be due to lower herbage biomass and more seed production compared to French psyllium. There are various studies on the effects of irrigation regimes on production of different crops. Nadjafi (2001) and Tabrizi (2004) applied different irrigation intervals from 7 to 28 days and reported that irrigation regimes did not show any effect on vegetative development in Isabgol, but longer irrigation intervals induced a two weeks earlier maturity. Mirsa and Sircastava (2000) showed that moderate water stress decreased leaf area, herbage biomass and essential oil yield in peppermint (*Mentha piperita*). Our results showed that irrigation intervals significantly affected Mucilage percentage in both crops that were highest in R2 and R3 in Isabgol and French psyllium in year1, respectively (Table 1). There were no considerable differences in mucilage percentage in two years of experiment in both species; however, the highest mucilage percentage for Isabgol obtained at the R2 in both years but for French psyllium, it observed at R2 and R3 in first and second years of experiment, respectively (Table 1). Baher et al. (2002) showed that severe water stress (66% field capacity), decreased yield of savory (*Satureja hortensis*) but essential oil percentage increased. Karamzadeh (2003) also reported that water stress increased the essential oil percentages of lavender (*Lavandula officinalis*) and absinthian (*Artemisia absinthium*).

Planting density

Optimum planting density is a key factor to achieve maximum crop production especially when water is limited. Our results showed that seed yield, herbage biomass, WU, WUEs and WUE_b were significantly ($P<0.05$) affected by planting density in both year of experiments though mucilage percentage was not affected by plant density in both species (Table 2). The highest herbage biomass, WU and WUE_b were obtained at the highest planting density in Isabgol and French psyllium in both years of experiments. The highest seed yield and WUEs observed in medium plant density in both species and mucilage percentage did not affected by planting density in both species (Table 2) which also reported by Nadjafi and Rezvani (2002). It was concluded that the highest seed yield was obtained in medium density in both species, which has been accompanied with highest WUEs. It seems that in suitable and stress condition, Isabgol invest more energy to produce seed compared with biomass, which is probably due to an efficient drought resistant mechanism, or more developed rooting system (Table 1, 2). Such capability considered as a valuable trait for a cash crop in dry land agroecosystems. As mucilage is produced from seed husk, therefore more seed production would lead to more mucilage production in hectare with the economically use of water. Contrary to WUEs, WUE_b in French psyllium was significantly lower than Isabgol due to more herbage biomass production. Contrary to Irrigation regime, planting density did not affect mucilage percentage of both species, however across all planting densities French psyllium recognized as a lower mucilage producer compared to Isabgol (Table 2). Nadjafi and Rezvani (2003) also reported that planting densities did not affect seed quality parameters of Isabgol. Tabrizi (2004) also showed that irrigation intervals and plant density, except for one case, did not affect mucilage percentage of Isabgol but reported that the highest mucilage percentage was under irrigation interval of 30 days. Baghalian (1999) reported that water deficit increased mucilage percentage of Isabgol seeds and concluded that it was a response of the plant to increase water stress tolerance. If plant density is too high, the decrease in the availability of water per plant generates a marked fall in yield per plant that is not offset by the increase in the number of plants (Vega et al., 2001).

Interactive effects of irrigation and planting density

Limited irrigation showed the highest interaction of the two treatments on herbage biomass at the highest planting density in both years of experiments (Table 3). Similar results were obtained when irrigation were more limited from R1 to R3 in two years (Table 3). Interactions of planting densities and irrigation regimes in both years showed a similar direction as interactive effect on herbage biomass. For Isabgol and French psyllium, medium plant density showed the highest seed yield and WUEs in full growth period Irrigation (R1) and the highest plant density caused the lowest seed yield and WUEs in R3 and the highest WUE_b and WU recognized at highest plant density in R1 irrigation regime (Table 4). It seems that the best condition to get the most seed yield and mucilage with minimum WU and maximum WUEs would be 100 $P.m^{-2}$ and 70 $p.m^{-2}$ for Isabgol and French psyllium in irrigation regime R2, respectively. As expected, changing irrigation regime from R1 to R3 will result in less available water in the soil, however, depth of rooting systems and their ability to absorb water would prominently affect the plants access to available water (Hutton et al., 2007).

Conclusion

It is suggested that for both species R2 (Irrigation terminated at the start of flowering with a complementary irrigation at the seed formation stage) in medium plant density would be suitable to get the best seed yield, mucilage percentage, minimum WU and maximum WUEs. The most important result to emerge from this study is that substantial saving in water about 60 mm (20 to 30 % saving) may be achieved by terminating irrigation in flowering with one complementary irrigation in both species, which are adapted to local environments and able to maintain both herbage biomass and mucilage (Table 1). It seems that Isabgol is better than French psyllium in dry land farming system to get more mucilage due to higher WUEs and lower WUE_b compared with French psyllium.

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