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Seed yield and water use efficiency of canola (*Brassica napus* L.) as affected by high temperature stress and supplemental irrigation

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ABSTRACT

The effects of high temperature stress and supplemental irrigation on seed yield and water use efficiency (WUE) of canola (*Brassica napus* L.) were studied in a field experiment conducted for 2 years. The experiment was a randomized complete block design arranged in split plot, conducted at Agricultural Research Station of Gonbad, Iran. It was arranged in two conditions, i.e. supplemental irrigation and rainfed. Two cultivars of canola (Hyola401 and RGS003) as subplots were grown at five sowing dates as main plots. The sowing dates were 9 November, 6 December, 5 January, 4 February and 6 March in 2005–2006 and 6 November, 6 December, 5 January, 4 February and 6 March in 2006–2007, to have a wide range of environmental conditions around flowering and seed filling periods, and to coincide reproductive stages of the crop with high temperature stress. Seed yield was improved due to field management practices, such as supplemental irrigation and optimum sowing date. Supplemental irrigation was an efficient practice to mitigate water stress, and to increase aboveground dry matter and seed yield. There was a strongly negative relationship between seed yield and air temperature during reproductive stages. Delay in sowing led to more rapid developmental of canola, decreased aboveground dry matter, leaf area index (LAI), harvest index (HI), WUE, and seed yield. Achieving a high aboveground dry matter was an essential prerequisite for high reproductive growth and a high seed yield. Greater seed yield and WUE at first sowing date were associated with greater LAI and aboveground dry matter, and lower temperatures during reproductive stages. The results support the view that WUE can be used as an indirect selection criterion for seed yield in genotypic selection.

1. Introduction

A field-grown crop is under temperature stress for much of the growing season (Mahan et al., 1995). Severe stress reduces photosynthetic resources (Morrison, 1993) and decreases the duration of reproductive growth (Hall, 1992). Water stress and high temperature can reduce crop yield by affecting both source and sink for assimilates (Mendham and Salsbury, 1995). Canola response to stress depends on the developmental stage, and seed yield in canola depends on the events occurring prior to and during flowering stage (Mendham and Salsbury, 1995; Angadi et al., 1999). Heat stress during

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flowering of canola can prematurely end flowering, resulting in limited seed set (Angadi et al., 1999). Nuttal et al. (1992) reported that a 3 °C (21–24 °C) rise in maximum daily temperature during flowering resulted in a 430 kg ha^{-1} decline in canola seed yield. Gan et al. (2004) resulted temperature stress of 28/18 and 35/18 °C reduced seed yield of canola as 54 and 87%, respectively, while water stress had no effect on seed yield. Brandt and McGregor (1997) showed that for each degree rise in mean daily temperature, seed yield of canola declined by 188 kg ha^{-1}. Similar negative effects on seed yield have been observed with water stress during flowering and seed filling (Stoker and Carter, 1984; Nielsen, 1997). In Australia, seed yield of canola was reduced by 35% for a May sowing and by 67% for a July sowing, compared with an April sowing (Hocking and Stapper, 2001). Si and Walton (2004) suggested that a combination of an early sowing date with an early flowering cultivar would be essential for the production of high seed yield in the lower rainfall area. Johnston et al. (2002) reported once the minimum water use of approximately 127 mm was achieved, seed yield of canola increased at a rate of 6.9–7.2 kg ha^{-1} mm^{-1}. Water stress at flowering negatively influenced the formation of pods and seed size, resulting in lower final seed yield.

The relationship between water use efficiency (WUE) and seed yield have been a major focus of agricultural research in the semiarid and Mediterranean regions and have been reviewed for many species (Nielsen, 1997; Craufurd et al., 1999; Johnston et al., 2002; Condon et al., 2004; Blum, 2005; Fan et al., 2005). However, one of the greatest challenges for agriculture is to develop technology or agronomic options to improve WUE (Turner, 2004). WUE was partially a function of canola adaptation to environmental conditions, so favorable agronomic managements are of great importance (Nielsen, 1997). In the sub humid regions of Canada, canola has been shown to have WUE, from 8.3 to 11.4 kg ha^{-1} mm^{-1} (Johnston et al., 1996). Blum (2005) concluded that when water use was the same for both cultivars, WUE was higher for high-yielding variety than the other, due to relative differences in dry matter production.

Although the importance of sowing date and water and high temperature stress on canola have been investigated (Mogensen et al., 1997; Nielsen, 1997; Chongo and McVetty, 2000; Morrison and Stewart, 2002; Ozer, 2003; Gan et al., 2004), but little information is available on the interactive effects of temperature and supplemental irrigation on seed yield and WUE. Therefore, as part of a broader project, we investigated seed yield and WUE of canola in a Mediterranean-type region with terminal drought and high temperature stresses.

2. Materials and methods

The study was conducted at Agricultural Research Station of Gonbad, Golestan province, Iran (45 m a.s.l., 37°N, 55°E) over two conditions (supplemental irrigation and rainfed) and 2 years (2005–2006 and 2006–2007). The experiment was a randomized complete block design arranged in split plot with three replications. Two cultivars of spring canola (Hyola401, a hybrid cultivar and RGS003, an open pollinated one) as subplots were grown at five sowing dates as main plots. The sowing dates were 9 November, 6 December, 5 January, 4 February and 6 March in 2005–2006 and 6 November, 6 December, 5 January, 4 February and 6 Mar in 2006–2007. The best sowing date of canola in the area is mid November, but late sowing dates were selected to coincide reproductive stages of the crop with high temperature stress, and to have a wide range of environmental conditions around flowering and seed filling periods.

Based on Coupen classification the region could be classified as warm and semiarid Mediterranean climate. The soil was a deep silty loam (fine-silty, mixed, active, thermic, typic calcixerolls) with a pH of 8.1, a bulk density of 1.4 g cm^{-3}, an EC of 0.73 dS/m, 12 g kg^{-1} of organic matter, 9.5 mg P kg^{-1} and 640 mg K kg^{-1}. Water content at field capacity and at permanent wilting point was, respectively, 25 and 13% in volume. Prior to sowing, soil samples were taken at depth of 0–30 and 3–60 cm, and according to soil test data, P and K were preplant-incorporated to supply 50 kg P_2O_5 ha^{-1} and 50 kg K_2O ha^{-1} from triple super phosphate and potassium sulphate, respectively. N was applied at 75 kg N (as urea) ha^{-1}, that a third of this amount was applied preplant, a third of that was side-dressed at beginning of stem elongation and the rest at the beginning of flowering. An overview of the experiment conditions is given in Tables 1 and 2.

Plots were over planted and after seedling establishment, the plants were thinned to the desired spacing between plants of 5 cm (1,000,000-plant ha^{-1}). Each subplot consisted of eight 5-m long rows. Main plots and subplots were 2 and 0.4 m apart, respectively. A 3-m pathway separated replicates. From each plot, aboveground dry matter, leaf area index (LAI) and other

Table 1 – Rainfall and average monthly temperatures and radiation in 2 years

Month	2005–2006				2006–2007			
	T_{max} (°C)	T_{min} (°C)	Rainfall (mm)	Radiation (MJ m^{-2} d^{-1})	T_{max} (°C)	T_{min} (°C)	Rainfall (mm)	Radiation (MJ m^{-2} d^{-1})
November	19.2	8.0	136.7	7.3	20.0	9.0	63.9	6.8
December	16.7	6.2	38.6	6.1	12.1	3.7	63.2	5.0
January	10.3	0.5	47.3	6.1	16.0	3.6	10.6	6.8
February	16.7	4.3	34.5	8.0	15.3	3.5	35.8	8.2
March	19.3	6.9	22.6	9.9	15.8	5.4	148.1	8.7
April	23.4	11.7	52.8	11.6	19.6	10.1	56.2	9.3
May	29.2	15.8	22.3	13.2	29.1	14.5	25.0	15.1
June	37.5	21.7	8.1	17.2	34.1	20.7	14.9	17.0

Table 2 – Water amount applied (mm) in supplemental irrigation site

Sowing dates	Stem elongation	Flowering	Seed filling
2005–2006			
9 November	15	30	30
6 December	14	30	39
5 January	15	35	42
4 February	25	35	46
6 March	21	37	57
2006–2007			
6 November	12	14	14
6 December	10	19	22
5 January	13	23	23
4 February	14	24	32
6 March	16	38	46

necessary samples during growth season were taken from 10 plants of rows of 2 and 3. The area of leaves (one side lamina) was measured using a leaf-area meter (DIAS, Delta-T Devices). Yellow and senescent tissues were not included in the measurements. In harvested time (2 days after physiological maturity) rows of 5, 6 and 7 were harvested for seed yield determination. Phenological observations were made on a regular basis with Harper and Berkenkamp (1975) growth stage key. Flowering and seed filling periods were considered as the number of days between the beginning of flowering to the end of flowering, and between the beginning of seed filling to the end of seed filling, respectively. Temperature was calculated as the sum of the daily temperatures divided by the number of days during the period.

At the irrigated site, flood-irrigation was provided three times, stem elongation, flowering and seed filling stages, to replenish soil water in the root zone to field capacity. Two days before irrigation times, soil samples were dried for 24 h at 105 °C and weighed. Then soil water content was measured and plots were reached to field capacity with irrigation, using a flow meter to measure the amount of water applied. Total water use was identified from initial soil water content minus final soil water content, precipitation, runoff, drainage, capillary rise and irrigation using the following equation (Zhang et al., 1999): $TWU = P + I + \Delta W - R - D + CR$, where TWU = total water use during duration of crop growth (mm), P = precipitation or rainfall (mm), I = irrigation (mm), ΔW = soil water content when the crop is sown minus that of at harvest for the 1.2-m depth (mm), R = runoff (mm), D = drainage from the root zone (mm) and CR = capillary rise to the root zone (mm). As runoff was never observed in the field, and drainage and capillary rise were consider negligible, thus $TWU = -P + I + \Delta W$ was used under our experimental conditions (Zhang et al., 1999). Therefore, WUE = Y/TWU, where Y = seed yield (kg ha^{-1}) and WUE = water use efficiency (kg ha^{-1} mm^{-1}). Also harvest index (HI) was obtained from following equation: HI = Y/DM, where DM = aboveground dry matter at physiological maturity (kg ha^{-1}). The regression functions fitted to the data of each cultivar and each condition, over years and sowing dates (SAS Institute Inc., 1996). Data were tested by analysis of variance using SAS (SAS Institute, 1996).

3. Results

Seed yield of canola was influenced by growing season rainfall, radiation and temperature, as suggested by the significant effect of year (Y) in the combined ANOVA (Table 3), therefore each year data was analyzed separately. Seed yield of canola in 2005–2006 was more than that of in 2006–2007, across sowing dates, irrigation conditions and cultivars (Table 4). The mean seed yield of canola in 2005–2006 and 2006–2007 was 2332 and 2110 kg ha^{-1}, respectively (Table 4). Seed yield was significantly higher in supplemental irrigation, compared to rainfed conditions in both years (Table 4). Supplemental irrigation

Table 3 – Analysis of variance for some traits of canola in the combined ANOVA

Source of variation	d.f.	Seed yield	Days to flowering	Days to maturity	Aboveground dry matter at maturity	WUE	Harvest index
Year (Y)	1	*	***	***	*	***	ns
Irrigation (IR)	1	ns	ns	ns	ns	ns	ns
Y × IR	1	ns	ns	ns	ns	ns	ns
Error 1	8	–	–	–	–	–	–
Sowing date (SD)	4	***	***	***	***	***	**
Y × SD	4	ns	***	***	**	ns	**
IR × SD	4	ns	ns	ns	ns	ns	ns
Y × IR × SD	4	ns	*	ns	ns	ns	ns
Error 2	32	–	–	–	–	–	–
Cultivar (C)	1	ns	ns	ns	ns	ns	ns
Y × C	1	*	*	***	*	**	ns
IR × C	1	ns	ns	ns	ns	ns	ns
Y × IR × C	1	ns	ns	ns	ns	ns	ns
SD × C	4	ns	ns	ns	ns	ns	ns
Y × SD × C	4	ns	***	***	ns	ns	ns
IR × SD × C	4	ns	ns	ns	ns	ns	ns
Y × IR × SD × C	4	ns	ns	ns	ns	ns	ns
Error 3	40	–	–	–	–	–	–

ns: Non significant and *, **, *** significant at 5, 1 and 0.1% level, respectively.

Table 4 – Means of some traits of canola during 2 years in the experiment

	Seed yield ($kg\ ha^{-1}$)	Days to flowering	Days to maturity	Aboveground dry matter at maturity ($kg\ ha^{-1}$)	WUE ($kg\ ha^{-1}\ mm^{-1}$)	Harvest index (%)
2005–2006						
Irrigated	2567 a	70 a	119 a	9587 a	7.5 b	25.5 a
Rainfed	2095 b	69 a	117 b	7511 b	8.5 a	25.6 a
Sowing dates						
9 November	3780 a	103 a	160 a	12263 a	11.7 a	30.9 a
6 December	3106 b	89 b	141 b	10195 b	10.4 b	30.9 a
5 January	2460 c	58 c	110 c	8848 c	9.0 c	27.6 b
4 February	1724 d	54 d	94 d	6442 d	6.5 d	26.3 b
6 March	582 e	45 e	85 e	4996 e	2.3 e	12.2 c
Cultivars						
Hyola401	2678 a	68 b	117 b	8968 a	9.3 a	28.7 a
RGS003	1984 b	71 a	119 a	8130 b	6.7 b	22.5 b
2006–2007						
Irrigated	2233 a	76 a	131 a	8683 a	6.0 a	22.9 a
Rainfed	1987 b	75 b	130 b	7134 b	6.0 a	25.2 a
Sowing dates						
6 November	3543 a	105 a	177 a	12719 a	9.0 a	27.8 a
6 December	2896 b	92 b	150 b	10260 b	8.2 ab	28.7 a
5 January	2362 c	72 c	121 c	7815 c	7.6 b	30.6 a
4 February	1588 d	63 d	108 d	5186 d	5.0 c	28.5 a
6 March	162 e	45 e	96 e	3563 e	0.5 d	4.7 b
Cultivars						
Hyola401	2332 a	75 b	130 b	8127 a	6.7 a	25.7 a
RGS003	1888 b	76 a	131 a	7690 b	5.4 b	22.4 b

Means followed by the same letter within each column are not significantly different according to the LSD ($P = 0.05$).

increased seed yield of canola each year, but the amount of increase varied between 2 years (Table 4), that was 472 and 246 $kg\ ha^{-1}$ for first and second year of the experiment, respectively. The combined analysis also revealed statistical significant effect of sowing date on seed yield (Table 3). In each year, with a delay in sowing date, seed yield of canola decreased, ranging from 3780 to 582 $kg\ ha^{-1}$ in 2005–2006, and from 3543 to 162 $kg\ ha^{-1}$ in 2006–2007, respectively (Table 4). In both years, the highest seed yields were achieved when canola was sown in early November (Table 4).

Factors, such as temperature, LAI and aboveground dry matter influenced seed yield of canola. When we evaluated the relationships between seed yield with mean temperature from flowering to seed filling and seed filling period, it was obvious that there was a strong negative relationship between them (Fig. 1), explaining 74 and 87% of the variation for Hyola401 and 82 and 69% of that for RGS003, respectively. For an each degree increase in mean daily temperature from flowering to seed filling, seed yield of Hyola401 and RGS003 decreased 338 and 303 $kg\ ha^{-1}$, respectively (Fig. 1). In addition, for an each degree increase in mean daily temperature during seed filling period, seed yield of Hyola401 and RGS003 decreased 337 and 284 $kg\ ha^{-1}$, respectively (Fig. 1). This was confirmed by the strong negative relationship of seed yield with temperature from flowering to seed filling and seed filling period for irrigated and rainfed conditions (Fig. 2), explaining 70 and 76% of the variation for irrigated conditions, and 84 and 90% of that for rainfed one, respectively. Also, seed yield responded linearly to increase in LAI at the beginning of seed filling and aboveground dry matter at physiological maturity in the cultivars (Fig. 3).

In both years, the seed yield of Hyola401 was more than that of RGS003, over sowing dates and irrigation conditions. The seed yield of Hyola401 and RGS003 was 2678 and 1984 $kg\ ha^{-1}$ in 2005–2006, and 2332 and 1888 $kg\ ha^{-1}$ in 2006–2007, respectively. The higher seed yield of Hyola401, compared to RGS003, was associated with lower days to maturity, greater aboveground dry matter at maturity and higher HI (Table 4).

Two-year ANOVA revealed that WUE was significantly influenced by year, sowing date and year × irrigation interaction (Table 3). In overall, the WUE of canola in 2005–2006 (8.0 $kg\ ha^{-1}\ mm^{-1}$) was more than that of 2006–2007 (6.0 $kg\ ha^{-1}\ mm^{-1}$), due to favorable weather conditions, and better distribution of rainfall during crop growth season in 2005–2006 (Tables 1 and 4). There was a different trend for WUE at irrigated and rainfed conditions in each year. In 2005–2006, supplemental irrigation decreased WUE, while there was not any significant difference between WUE of irrigated and rainfed conditions in 2006–2007. The increase of WUE was particularly due to increase in LAI and aboveground dry matter, as presented in Table 4 and Fig. 3, and to some extent due to production and translocation of dry matter to seeds, i.e. HI (Table 4).

With a delay in sowing date, WUE was obviously reduced due to increase in terminal temperature stress (Table 5), ranging from 11.7 to 2.3 $kg\ ha^{-1}\ mm^{-1}$ in 2005–2006, and from 9.0 to 0.5 $kg\ ha^{-1}\ mm^{-1}$ in 2006–2007 (Table 4), respectively,

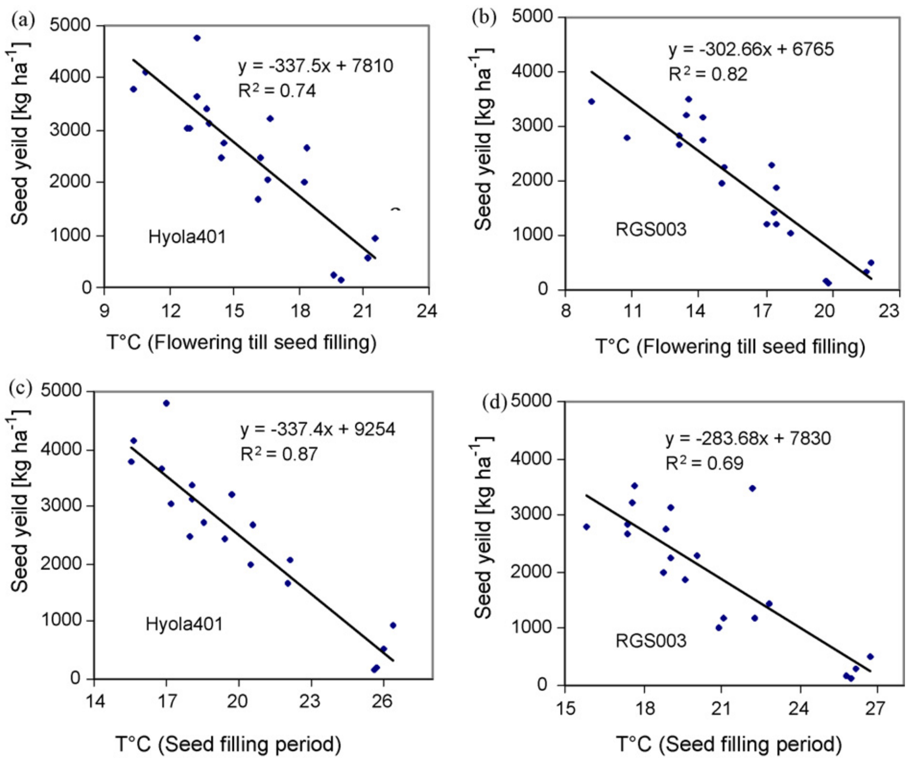

Fig. 1 – Relationships between seed yield of canola and mean air temperature during flowering till seed filling (a and b) and seed filling period (c and d) in two cultivars.

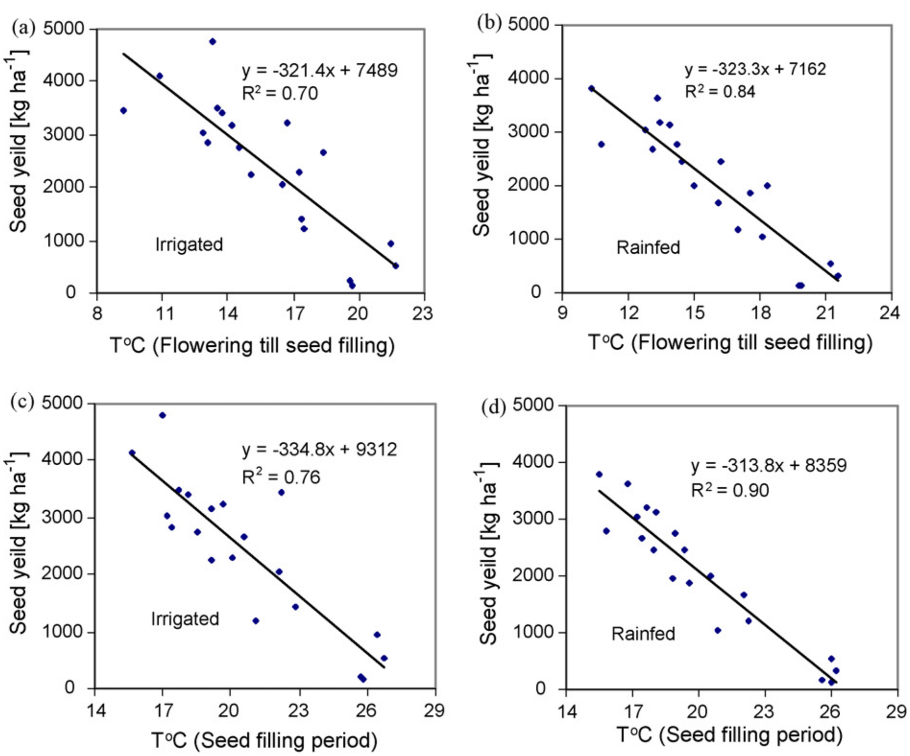

Fig. 2 – Relationship between seed yield of canola with mean air temperature during flowering till seed filling (a and b) and seed filling period (c and d) at irrigated and rainfed conditions.

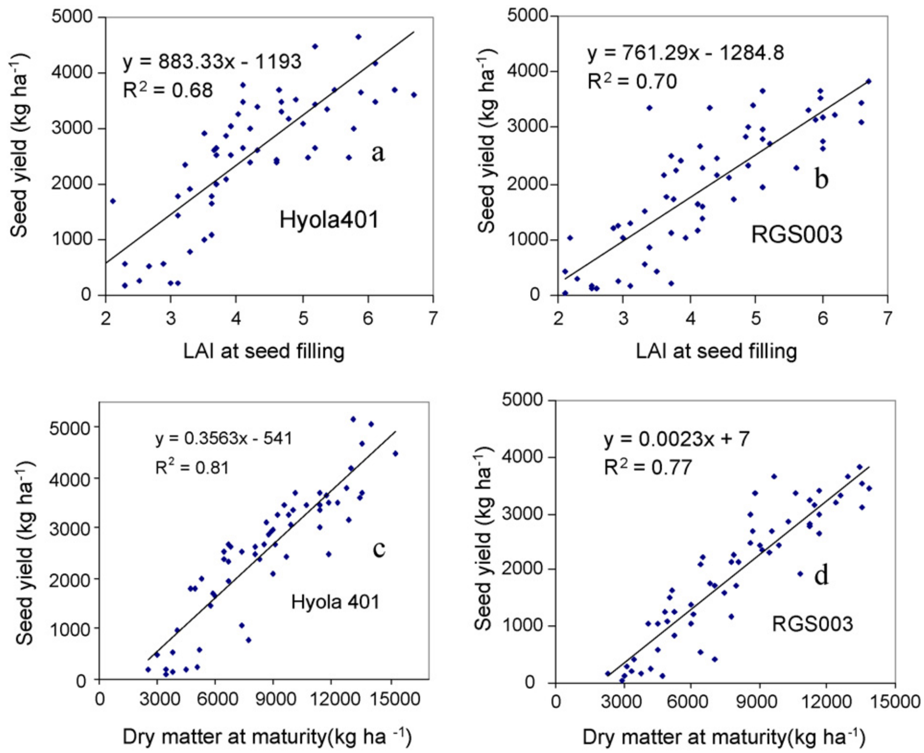

Fig. 3 – Relationships between seed yield of canola with LAI at the beginning of seed filling (a and b), and aboveground dry matter at physiological maturity (c and d).

reflecting the lower air temperatures and moisture deficits at first sowing date (Table 5). In both years, WUE of Hyola401 was more than that of RGS003 (Table 4). The superiority of Hyola401 compare to RGS003 was considerable over irrigation conditions and sowing dates. WUE of Hyola401 and RGS003 were 9.3 and 6.7 kg ha^{-1} mm^{-1} in 2005–2006 and 6.7 and 5.4 kg ha^{-1} mm^{-1} in 2006–2007 (Table 4). The ranking of cultivars for WUE remained constant across years, sowing dates and irrigation conditions (Table 4, some data not shown).

Table 5 – The mean max. temperature (°C) during flowering and seed filling periods

Sowing dates	Flowering period		Seed filling period	
	Hyola401	RGS003	Hyola401	RGS003
2005–2006				
9 November	20.0	20.9	22.3	23.1
6 December	20.6	21.5	23.5	24.9
5 January	22.3	23.3	25.2	25.3
4 February	24.5	23.5	26.1	26.8
6 March	28.2	29.1	35.7	36.1
2006–2007				
6 November	16.8	17.1	20.4	20.9
6 December	18.0	18.5	22.0	22.9
5 January	19.8	19.2	24.1	24.9
4 February	22.5	23.2	29.7	30.6
6 March	28.6	29.4	33.9	34.5

4. Discussion

The duration of crop growth season in 2006–2007 was more than that of in 2005–2006 (Table 4), due to prolonged vegetative growth period, as affected by lower temperatures, particularly during December, in 2006–2007 compared to 2005–2006 (Table 1). However the aboveground dry matter, WUE and HI of canola in 2005–2006 were more than those of in 2006–2007, led to higher seed yield in 2005–2006 (Table 4). That was particularly due to better distribution of rainfall and radiation in 2005–2006 compared to 2006–2007 (Table 1). Seed yield and WUE of canola were improved due to field management practices, such as supplemental irrigation, optimum sowing date and selecting high-yielding cultivar. Supplemental irrigation using a small amount of water at the critical times was an efficient practice to mitigate water stress, and to increase yield. Generally, it appears that the benefit of supplemental irrigation in 2005–2006 was more than that of in 2006–2007. The cumulative rainfall from November to June in 2005–2006 and 2006–2007 was 363 and 418 mm, respectively (Table 1), so supplemental irrigation amount was higher in the first year of the experiment (Table 2). When we compared the amount of rainfall from March to May, that was flowering and seed filling periods of canola at normal sowing date, the difference between 2 years was even higher. The cumulative rainfall from March to May in 2005–2006 and 2006–2007 was 98 and 229 mm, respectively (Table 1). Under Mediterranean conditions, there are some years with not enough rainfall, particularly during critical periods of reproductive stages, to achieve seed yield potential, led to dramatic decrease in seed

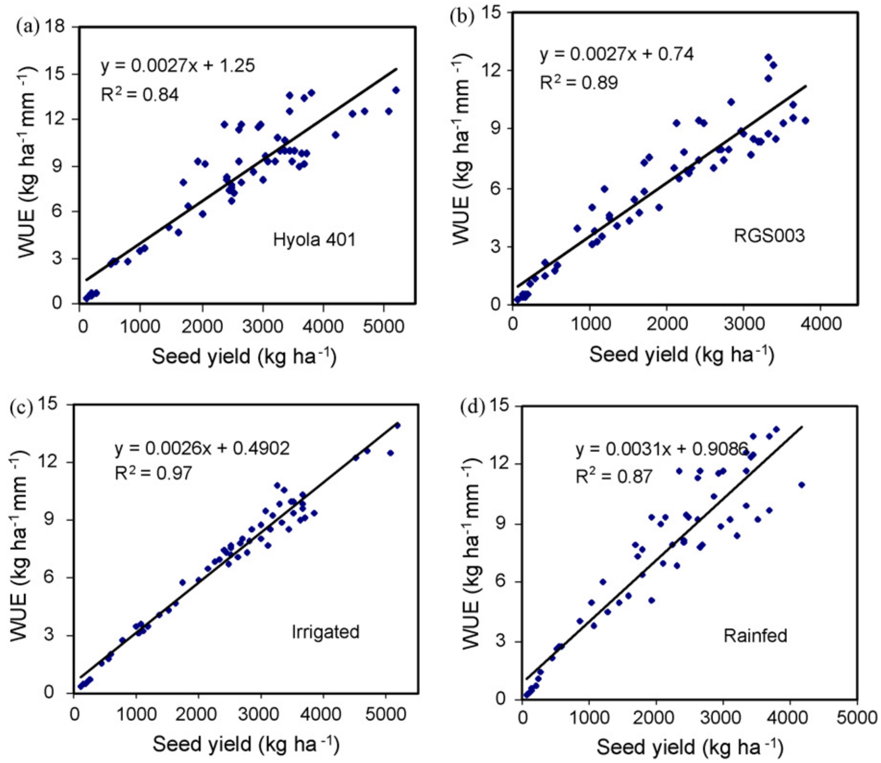

Fig. 4 – Relationship between seed yield of canola and WUE in the cultivars (a and b), and irrigation conditions (c and d).

yield. During these years, supplemental irrigation is an important tool to increase seed yield (Oweis et al., 2004).

Delay in sowing led to more rapid development of the crop, decreased the days from emergence to flowering and to physiological maturity, duration of flowering and seed filling, aboveground dry matter, LAI, seed number per unit area and seed yield (Table 4, some data not shown). Earlier sowing more closely matched incoming rainfall, and reduced terminal heat and drought stress (Table 5), led to increase in WUE and seed yield (Table 4), as could be seen in some literature (Habekotte, 1997; Morrison and Stewart, 2002; Turner, 2004; Gunasekera et al., 2006). Therefore, the ability to match key phenological growth period of the crop to a less stressful growth period in the growing season was an effective means of avoiding the negative impact of heat and drought stress, as pointed out by Ludlow and Muchow (1990). Seed yield of canola was closely related to temperature during flowering and early seed development, and increased by minimizing the crop exposure to high temperature and water stress, as showed by Gan et al. (2004). In this study, sowing date was a very important management tool in minimizing the negative impact of high temperature and moisture stress during the critical flowering and seed filling periods (Table 4).

The significant relationship between seed yield with LAI and aboveground dry matter at reproductive stages over environmental conditions, sowing dates and cultivars, showed these variables to be generally applicable. Both seed yield and WUE increased with higher post-flowering available water (i.e. irrigation and rainfall) and lower post-flowering temperatures (Tables 2, 4 and 5). In each year, greater WUE under first sowing date was associated with greater aboveground dry matter, longer duration of flowering and seed filling periods (some data not shown), and higher seed yield (Table 4). There was a strong positive relation between WUE and seed yield of canola, accounting for 84 and 89% of the variation for Hyola401 and RGS003, and 97 and 87% of that for irrigated and rainfed conditions, respectively (Fig. 4), indicating that WUE can be used as an indirect selection criterion for seed yield in genotypic selection. Reduction in WUE due to last sowing date compared to first sowing date was 80% in 2005–2006 and 96% in 2006–2007 (Table 4), that was highly considerable.

In contrast with the results of Condon et al. (2002), in our study, genotypic variations in seed yield and WUE were driven mainly by variations in HI, plant production or assimilation per given amount of used water, rather than by variations in used water. For an each unit increase in LAI at the beginning of seed filling, seed yield of Hyola401 and RGS003 increased 883 and 761 kg ha^{-1}, respectively (Fig. 3). In addition, for an each kg ha^{-1} increase in aboveground dry matter at physiological maturity, seed yield of Hyola401 and RGS003 increased 0.366 and 0.002 kg ha^{-1}, respectively, showing more response of Hyola4o1 to assimilate supply during reproductive stages (Fig. 3). The superiority of Hyola401 to RGS003 for WUE was due to higher HI. The HI of Hyola401 and RGS003 was 28.7 and 22.5% in 2005–2006 and 25.7 and 22.4% in 2006–2007, respectively (Table 4).

This study is an agreement with what is well established in the literature (Habekotte, 1997; Morrison and Stewart, 2002; Gan et al., 2004; Oweis et al., 2004; Turner, 2004; Gunasekera et al., 2006). In the present study, seed yield increased as LAI and aboveground dry matter at reproductive stages increased (Fig. 3). This implies that agronomic management and environmental conditions that increased LAI and aboveground dry matter at reproductive stages, increased seed yield (Table 4). This emphasizes that the contribution of assimilates supply was very significant source for increasing seed yield. The present study shows that optimum environmental conditions around reproductive stages, as such we can see in early sowing dates (Tables 1 and 5), not only accumulated more aboveground dry matter but also produced more seed yield and WUE than those of late sowing dates (Table 4). This result in part agrees with Specht et al. (1986) who stated that achieving a high total dry matter through adequate vegetative growth is an essential prerequisite for high reproductive growth and a high yield in soybean. In this study, higher LAI in early sowing dates, and supplemental irrigation probably increased the interception of solar radiation, and thus a greater CO_2-fixing ability of the canola plants resulted in accumulation of more assimilates, led to higher seed yield. Temperature around flowering and seed filling periods was good indicator of canola seed yield potential, so the production success was due to avoidance of high temperature stress, and by the crop management to take advantage of optimum environmental conditions for reproductive stages.

5. Conclusion

In Gonbad area, like other Mediterranean type environments, rainfall and temperature are the most important factors affected crop production. Seed yield and WUE are primarily limited by the relatively soil moisture deficit and high temperature stress during the latter phases of reproductive development.

In this study, a great proportion of the variation in seed yield and WUE of canola were related to environmental conditions during the critical periods that were flowering and seed filling. Growing season rainfall and air temperature were good indicators of canola WUE and seed yield potential.

Under warm and semiarid Mediterranean conditions, like Gonbad area, weather conditions during vegetative growth is usually favorable and produces large amount of dry matter. Therefore, the occurrence of terminal temperature and drought stress can reduce seed formation, HI, WUE and seed yield. Under these conditions, optimum sowing dates and supplemental irrigation at reproductive stages, i.e. flowering and seed filling periods could be very good management options to coincide these critical periods with favorable weather conditions, and to decrease negative aspects of temperature and drought stress.

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