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ARTICLE

Effects of partial rootzone drying on yield, yield components, and irrigation water use efficiency of canola (*Brassica napus* L.)

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Abstract Effect of PRD (partial rootzone drying) on yield and yield components of canola (*Brassica napus* L.) was investigated in greenhouse conditions. The treatments were: T_1, full watering of both sides of roots; T_2, alternate irrigation on both sides; T_3, half of irrigation water in T_1 was given to one side; T_4, same as T_3 but without plate; T_5, same as T_2 but without plate. In T_1, T_2, and T_3 treatments, the boxes were evenly separated into two compartments with thin plates. The results showed that grain yield of T_1 to T_5 treatments was 18.11, 16.38, 12.44, 9.29, and 8.66 g plant^{-1}. T_2 treatment increased plant height by 46.9% and 1000-seed weight by 17.8%, but reduced lateral branches by 16.7% and number of pods by 24%, over T_1 treatment. T_2 treatment was the most efficient (irrigation water use efficiency = 0.679 kg m^{-3}) and treatment T_5 was the least efficient (0.359 kg m^{-3}). The difference between irrigation water use efficiency (IWUE) of T_2 and T_5, and T_3 and T_4 treatments, was significant ($p < 0.05$). Therefore, halving the amount of applied irrigation water and applying this water alternatively on both sides of the root zone will produce the highest IWUE. This study showed that PRD irrigation management has high influence on rooting system of canola. This phenomenon could affect nutrients uptake and consequently all aspects of plant growth and development.

Keywords PRD · Deficit irrigation · Alternate irrigation · Root system · Canola

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Introduction

Water scarcity and soil salinity are two important limitations for agricultural production in arid regions. In recent years, one of the strategies for crop production with maximum income under water scarcity conditions is deficit irrigation (Sepaskhah et al. 2006). One method of deficit irrigation is partial rootzone drying (PRD). PRD is a deficit irrigation technique in which the plant is tricked into a continual state of water retaining activity by drying part of the plant's root system and keeping the remaining roots well irrigated. Thereby, the amount of applied irrigation water is reduced (Zegbe et al. 2004, Kirda et al. 2004, Tang et al. 2005). The wetted and dry sides are interchanged in the subsequent irrigations according to the kind of crop, growth stage, and soil water balance (Dry et al. 2000).

The expectation from PRD is that any yield reduction will be insignificant compared with the benefits gained through diverting the saved water to irrigate other crops. If deficit irrigation is properly practiced, it may increase crop quality. PRD has been found to be promising in several crops. For example, the protein content and baking quality of wheat, the length and strength of cotton fibers, and the sucrose concentration of sugarbeet and grape all increase under deficit irrigation.

This technique has been tested on several horticultural crops and fruit trees, including grapevine (Dry et al. 2000, Gu et al. 2000), pear (Kang et al. 2003), olive tree (Wahbi et al. 2005), cotton (Tang et al. 2005), tomato (Kirda et al. 2004), and potato (Liu et al. 2006).

According to Kang et al. (1998) when the two halves of a maize root system were alternately exposed to drying and wetting, water use was reduced by 34.4–36.8% and total biomass production was reduced by only 6–11%, as compared with well-watered plants.

Liu et al. (2006) compared the effect of PRD with full irrigation (FI) and deficit irrigation (DI), on morphological and physiological characteristics of potato (*Solanum tuberosum* L.) at tuber initiation stage. Compared to FI, both DI and PRD significantly decreased leaf area and biomass. Irrigation water use efficiency (IWUE; plant total biomass production divided by the plant water use during the growing period) and transpiration efficiency (ratio between photosynthetic rate and transpiration) were similar for PRD and FI plants, and were significantly less than those of DI plants.

Kang et al. (2000) also found that alternate furrow irrigation of maize maintained high grain yield with up to 50% reduction in irrigation amount. Gencoglan et al. (2006) compared conventional (SDI) and alternating subsurface drip irrigation (SPRD) for water use efficiency (WUE), IWUE, and yield of green bean (*P. vulgaris* L.). The results showed that SPRD technique increased IWUE, WUE, and slope of water-yield relationships. The overall irrigation water saving was found to be 16% for SPRD as compared to SDI treatments.

The effects of PRD, applied through furrow and drip irrigation, on plant water relations, yield and fruit quality of processing tomato (*Lycopersicon esculentum* Mill.) were studied by Zegbe et al. (2004). Number of fruit, mean fruit mass, and harvest index were the same among treatments, but PRD treatments improved irrigation WUE by 70%. In studying the responses of cotton (*Gossypium hirsutum* L.) to PRD irrigation, Tang et al. (2005) reported that alternate furrow irrigation is an effective water-saving method in arid areas and plant vegetative growth can be controlled such that cotton seed yield can be maintained with less water but higher quality fibers.

Kang et al. (2003) studied the effect of PRD practice on soil water distribution, water consumption of pear trees, and water balance for 3 months in an irrigated orchard with a shallow ground water table. The irrigation treatments included: conventional flooded irrigation (CFI), fixed partial rootzone drying (FPRD), and alternate partial rootzone drying (APRD). The results showed that the total irrigation amount was greatly reduced (43.64 and 45.84%), respectively, for APRD and FPRD. On the average, both APRD and FPRD reduced plant daily water consumption by 9.96 and 17.97%, respectively, when compared to CFI during the PRD period.

Regulated deficit irrigation (RDI) and PRD were evaluated for their effect on yield and quality of ‘Chok Anan’ mango fruits (Spreer et al. 2007). Under PRD, fruit size was increased and fruits had a higher fraction of edible parts. It is concluded that in areas where water is a limiting factor, PRD may be the key for a sustainable increase in mango production. According to Wahbi et al. (2005), yield reduction of olive trees, irrigated by PRD, was 15–20% with a 50% reduction in the total amount of water applied.

Davies and Hartung (2004) proposed that PRD could simulate root growth and maintain a constant Abscisic acid signaling to regulate shoot physiology. Early works have shown that by withholding water from half of the root system, stomatal conductance, photosynthesis, and growth rate are reduced when compared with plants with all their root system fully irrigated (Dry et al. 2000). Abscisic acid derived from drying roots is thought to be responsible for the physiological changes to the plant as well as the inhibition of the plant hormones cytokinins that affect stomatal aperture and lateral shoot development.

World water supplies are limited and water-saving irrigation practices, such as deficit irrigation and PRD should be explored. It seems that PRD has the potential to be used in arid regions with limited water sources.

Since there is not much data on the effects of PRD irrigation practice on yield, yield components, rooting system, and IWUE of canola (*Brassica napus* L.), the objective of this research was to assess comparative yield responses and IWUE of greenhouse-grown canola under PRD and regular irrigation practices.

Materials and methods

This research was carried out on winter canola (*Brassica napus* L., cv. Zarfam) under greenhouse at Agriculture and Natural Resources Research Center of Yazd city (latitude 54° 16′ N, longitude 31° 55′ E, 1,230 m above mean sea level), Iran, in 2006–2007. The area has desert conditions, with average annual rainfall of about 106 mm and average annual temperature of 19.2°C.

The experimental design was a randomized block design with three replicates for each treatment. The experiment was performed in five treatments: T_1, full watering of both sides of the root system at every irrigation (control treatment); T_2, alternate irrigation at right and left sides of the boxes; T_3, half of irrigation water volume in T_1 was given only to one side of the boxes at every irrigation; T_4, same as T_3 but without a thin plate in the middle of the boxes; T_5, same as T_2 but without the plate. In T_1, T_2 and T_3 treatments, each box (70 × 70 × 45 cm and made of thin wooden plates) was evenly separated into two compartments with a thin plate such that water exchange between the two sections was prevented (Fig. 1).

In each irrigation event, the amount of applied water for each pot was determined based on the difference between the weight of the pot at field capacity with the weight of the pot at the time of irrigation.

The soil was sandy loam and poor in organic matter, with bulk density of 1.43 g cm^{-3}, moisture content at field capacity of 25% and at permanent wilting point of 5% by weight. Some of the physical and chemical properties of

Fig. 1 Wooden box and the thin plate inside it for PRD experiments

the soil are given in Table 1. On the basis of N, P, and K content of the soil, 150 kg ha^{-1} of N, 50 kg ha^{-1} of P and 150 kg ha^{-1} of K was applied to the boxes prior to the cultivation of canola seeds.

Seeds were sown on Oct. 15, 2006 over the upper edge of the plate in each box. When germinated and had 5 leaves, 4 seedlings were kept in each box. Up to this point, irrigation was normal and equal amount of water was applied to all treatments. PRD treatments started on November 5, 2006. After 189 days of the growing season, plants were harvested (on April 21, 2007) and the yield, yield components and IWUE were calculated. After harvest, roots were washed carefully to see if there is any difference in their shape due to PRD irrigation practice.

Salinity of irrigation water was 6.56 dS m^{-1} and irrigation water was applied after 50% soil moisture depletion. Soil moisture depletion was determined by time domain reflectometry (TDR) method. Chemical characteristics of irrigation water are given in Table 2.

The data were statistically analyzed with SAS software and means were compared using LSD test.

Results and discussion

Grain yield

The grain yield per plant was measured. ANOVA showed that PRD has significant effect on seed yield ($p < 0.01$). Table 3 shows that with 50% reduction in irrigation water of treatment T_2 with respect to treatment T_1, the grain yield decreased only 9.56% (16.38 vs. 18.11 g $plant^{-1}$). With change of irrigation management (T_3 treatment instead of T_2), grain yield was reduced to 12.44 g $plant^{-1}$

Table 1 Physical and chemical characteristics of soil

(A) Physical characteristics

Bulk density (g cm^{-3})	Sand (%)	Silt (%)	Clay (%)	$CaCO_3$ (g kg^{-1})	Ca_2SO_4 (mg kg^{-1})	Texture
1.43	77	9	14	242	111.5	Sandy loam

(B) Chemical characteristics

Zn (ppm)	Cu (ppm)	Mn (ppm)	Fe (ppm)	Na^+ (meq/l)	Mg^{2+} (meq/l)	Ca^{2+} (meq/l)	Cl^- (meq/l)	HCO_3^- (meq/l)	K (mg kg^{-1})	P (mg kg^{-1})	N (mg kg^{-1})	C (mg kg^{-1})	pH	EC (dS/m)
0.662	0.43	2.33	7.126	28	15.3	39.9	24.5	3.0	176	60	50	580	7.17	7.5

EC electrical conductivity, *pH* acidity, *Cl^-* chloride, *HCO_3^-* bicarbonate, *Na^+* sodium, *Ca^{2+}* calcium, *Mg^{2+}* magnesium

Table 2 Chemical characteristics of irrigation water

EC (dS/m)	pH	Cl^- (meq/l)	HCO_3^- (meq/l)	Na^+ (meq/l)	Ca^{2+} (meq/l)	Mg^{2+} (meq/l)
6.56	7.68	62	1.15	45	25.3	1

Table 3 Mean yield and yield components of canola in PRD experiments

Component	Treatment*				
	T_1	T_2	T_3	T_4	T_5
Grain yield (g plant^{-1})	18.11 a**	16.38 a	12.44 b	9.29 c	8.66 c
Plant height (cm)	61.8 c	90.8 a	76.6 b	74.9 b	85.5 a
Pod length (cm)	4.4 ab	4.4 ab	4.5 a	4.5 a	4.2 b
No. of pods per plant	69.7 a	53 ab	36.7 b	38 b	48.7 b
No. of seeds per pod	20.3 a	20 a	16.7 b	20.3 a	18.7 ab
1000-seed weight (g)	2.47 ab	2.91 a	2.25 bc	2.14 bc	1.97 c
No. of lateral branches	3.6 a	3 ab	2 bc	2 bc	0.7 c
Plant dry matter (g)	27.4 a	24.33 ab	20.37 ab	18.43 b	21.37 ab
Irrigation water use efficiency (kg m^{-3})	0.376 c	0.679 a	0.516 b	0.385 c	0.359 c

* T_1 full watering with plate, T_2 alternate partial root-zone drying (APRD) with plate, T_3 half of irrigation water in T_1 to one side with plate, T_4 same as T3 but without plate, and T_5 APRD without plate

** In each row, means followed by the same letter are not significantly different at 5% level

Fig. 2 Root system in T_1 treatment (full watering of both sides of the root system in each irrigation)

Fig. 3 Root system in T_2 treatment (alternate irrigation at right and left sides of the box)

while the amount of applied irrigation water was the same in these two treatments. Hence, alternate irrigation is preferable to irrigation of one-side of the boxes.

Treatments T_1, T_2, and T_3 showed that PRD practice has affected the rooting system (Figs. 2, 3 and 4, respectively) and as a result, the grain yield and yield components.

Comparison of grain yield in T3 and T4 treatments (Table 3) showed that although the amount of applied irrigation water in these treatments was the same, but the grain yield of T_4 treatment was significantly less than T_3 treatment (25.3% less). The reason is the existence of the thin plate in the middle of the box, such that all the water is limited to one-half of the soil in the box. But, in T_4 treatment, there is no plate in the box and some of the water was unavailable to the plants. Therefore, placing a barrier between the two soil sections helped to have more yield.

Grain yield in T_5 treatment was 47.1% less than T_2 treatment (8.66 vs. 16.38 g plant^{-1}), although the amount of applied irrigation water was the same in both. Again, placing the barrier in T_2 treatment was very effective in increasing the grain yield. The rooting pattern in T_5 treatment was similar to the T_2 treatment (Fig. 3), but smaller in dimensions.

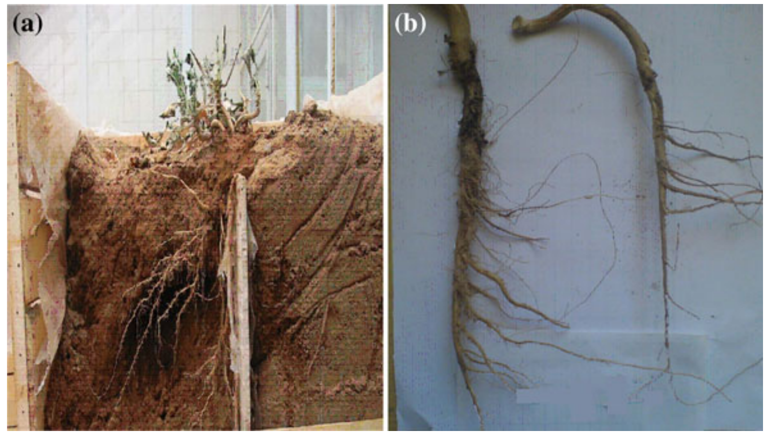

Fig. 4 Two examples of root systems in T_3 treatment (in each irrigation, half of the volume of irrigation water applied to T_1 treatment was given only to one side of the box); **a** roots in the box and **b** washed-out roots

Richards (1978) and Palomo et al. (1999) showed that water stress decreases canola seed yield.

In comparison of the results with Kang et al. (2003), it can be stated that (1) in Kang et al. (2003), the amount of applied water was different for APRD and FPRD. But in our experiment the amount of water was the same; (2) in Kang et al. (2003) the plant was pear and in our experiment the plant was canola; (3) root expansion and water uptake in pear is different from canola; (4) shallow water table existed in Kang et al. (2003) experiment, but we did our experiment in pots without any water table. Therefore, based on the above statements, our results are different from Kang et al. (2003).

Plant height

Partial rootzone drying treatment affected plant height significantly ($p < 0.01$). According to Table 3, the tallest plants (90.8 cm) were observed in T_2 treatment and the shortest plants were in T_1 treatment (61.8 cm). Average plant height in all the treatments was 77.9 cm. Therefore, alternate PRD irrigation of the canola plants produced the tallest plants. The difference between T_2 and T_5, and T_3 and T_4 treatments was not statistically significant.

Pod length

Mean pod length in each plant was determined with averaging the length of 30 pods. Pods were selected randomly from different branches of the plant. PRD practice (T_2 treatment) did not have significant effect on pod length and this parameter was almost equal in all the experimental treatments (Table 3). Mean pod length of all treatments (T_1 to T_5) was 4.4 cm.

No. of pods per plant

No. of pods in each plant is an important yield component accounted in final yield estimating. PRD irrigation practice has significant effect on number of pods per plant (Table 3). According to this table, with 50% reduction in irrigation water of T_2 treatment with respect to T_1 treatment, no. of pods decreased from 69.7 to 53.0 (23.9% reduction). Average no. of pods per plant was 49.2, with lowest in T_3 treatment (36.7 pods per plant) and highest in T_1 treatment (69.7 pods per plant).

No. of seeds per pod

For determination of no. of seeds per pod, the seeds in 30 pods were counted. These pods were selected randomly in one plant. PRD has significant effect on no. of seeds per pod. Table 3 shows that with 50% reduction in irrigation water of T_1 treatment as compared to T_2 treatment, no. of seeds per pod decreased only 1.62%. No. of seeds per pod in T_2 is more than T_3 treatment, although the amount of irrigation water was equal. Average no. of seeds per pod in all the treatments was 19.2.

1000-seed weight

According to Table 3, PRD irrigation practice has significant effect ($p < 0.05$) on 1000-seed weight. With management change of T_2 to T_3 treatment, 1000-seed weight decreased 22.7%. The highest 1000-seed weight (2.91 g) was obtained in T_2 treatment. Comparison of 1000-seed weight in T_3 and T_4 treatments showed that this parameter is less in T_4, but the difference is not statistically significant. 1000-seed weight in T_2 treatment is much greater than T_5 treatment and so is the grain yield. Therefore, putting a barrier helped to increase the weight of canola seeds. Average 1000-seed weight in all the treatments was 2.3 g.

No. of lateral branches

Number of lateral branches could affect yield, because with more lateral branches we may have more pods on the plant.

Table 3 shows that the highest number of lateral branches was observed in T_1 treatment (3.6) and the lowest was in T_5 treatment (0.7). PRD did not affect the number of lateral branches significantly. Average number of lateral branches in all the treatments was 2.27.

Plant dry matter

PRD irrigation practice has significant effect ($p < 0.05$) on plant dry matter (Table 3). According to this table, plant dry matter was decreased from 24.33 g plant^{-1} in T_2 to 20.37 g plant^{-1} in T_3, although the amount of applied irrigation water was equal. Also, dry matter of plants in T_3 treatment is less that T_4 treatment. The difference could be attributed to the placement of the barrier. Average plant dry matter of all treatments was 21.57 g plant^{-1}. Shoot dry matter reduction was reported under deficit irrigation in canola by Moradshahi et al. (2004).

Irrigation water use efficiency

Irrigation water use efficiency (IWUE, in kg m^{-3}) is the ratio of grain yield by the amount of water applied during the growing season. ANOVA showed that PRD irrigation practice affected significantly ($p < 0.01$) the IWUE. According to Table 3, treatment T_2 was the most efficient (IWUE = 0.679 kg m^{-3}) and treatment T_5 was the least efficient (IWUE = 0.359 kg m^{-3}). The difference between IWUE of T_2 and T_5, and T_3 and T_4 treatments is significant ($p < 0.05$). This means that halving the amount of applied irrigation water and applying this water alternatively on both sides of the root zone will produce the highest IWUE. Comparison of T_2 and T_3 treatments showed that irrigation of both sides of the boxes is better than one side. This conclusion is true even if there is no plate in the middle of the boxes (comparison of T4 and T5 treatments).

Kirda (2000) states that with a 25% water deficit under deficit irrigation, WUE was 1.2 times that achieved under normal irrigation practice. Zegbe et al. (2004) reported that PRD irrigation improved WUE by 70%. PRD has the potential to be used for processing tomatoes, especially in environments with limited water.

Conclusions

PRD irrigation practice was applied in an arid region to study its effect on yield, yield components, rooting system, and IWUE of canola under greenhouse conditions. PRD is an irrigation technique that improves IWUE, while minimizing adverse effects on yield. The wet roots, however, keep the plant healthy and productive. The results of PRD treatments showed that halving the amount of irrigation water reduced grain yield by less than 10% as compared to full irrigation. IWUE of control treatment (full irrigation) was less than that of PRD treatment. Yield components of the PRD treatments in which a thin plate was placed in the boxes were better than treatments with no plate. Alternate PRD irrigation is also more efficient than irrigating only one side of the rootzone. The previous studies did not show the effects of PRD on root distribution pattern, especially for canola. This study showed that PRD irrigation management has high influence on rooting system of canola. This phenomenon could affect nutrients uptake and consequently all aspects of plant growth and development. Further studies about this subject are recommended.

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