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ARTICLE

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Supplemental irrigation impact on yield and yield quality parameters of rapeseed

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Abstract

Dryland winter rapeseed (*Brassica napus* L.) produced in the semi-arid regions of Turkey has variable yields. Supplemental irrigation alleviates the adverse effects of soil moisture stress on yield during drought periods. To determine the influence of irrigation timing on yield stability, a 3-yr, on-farm irrigation experiment was conducted to determine the effects of supplemental irrigation on rapeseed yield and yield components in a semi-arid environment. The field experiment considered the influence of six irrigation quantities applied at three growth stages (vegetative, flowering, and early ripening) on rapeseed yield and quality. Supplemental irrigation improved rapeseed yield compared with cultivation under rainfed conditions throughout the three experimental years. Although the greatest seasonal evapotranspiration and rapeseed yields were observed with full irrigation, the highest economic rate and most efficient irrigation rate were for the optimum level to be applied at flowering. Protein content, oil content, and fatty acids increased with irrigation and were highest for the full-irrigation treatment. Irrigation should be applied when 50% of available soil moisture has been consumed in the effective root zone at the early flowering stage. This timing enhances the water use efficiency and yield potential of rapeseed without reducing quality and could be highly beneficial for semi-arid regions.

1 | INTRODUCTION

Water supplies are vital for agriculture and sustainable food production. They should be clean, reliable, and available for various purposes. Today, more than a billion people live in water-scarce regions, and as many as 3.5 billion could experience water scarcity by the year 2025. Moreover, current global warming and climate change have shifted precipitation patterns and produced floods in some regions and droughts in others (WRI, 2015). To prepare for an uncertain future, we need to understand the consequences of and how to manage extreme climate conditions.

Grains and industrial crops are the primary source of human nutrition and play a complementary and balancing role in human diets. Rapeseed (*Brassica napus* L.) is an important oil crop and is cultivated worldwide. It is categorized among the industrial crops and is used for the production of edible oil, biodiesel, and other oleochemical industrial materials. Because it has low saturated fatty acids (≤7%) and high oleic acid (>60%), it has many beneficial impacts on human health (CCC, 2017). According to data from the Food and Agriculture Organization (FAO, 2017), rapeseed has been cultivated worldwide on 34.7 million ha, with an annual production of 76 MG; it is the

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Abbreviations: DOY, day of year; ET, evapotranspiration; IWUE, irrigation water use efficiency; WUE, water use efficiency.

Core Ideas

- Irrigation improved rapeseed yield and quality in a semi-arid environment.
- Irrigation during the flowering period is suggested with a higher WUE and net income.
- Line-source sprinkler irrigation is suggested for field crops at small- to medium-scale farms.

second most produced oilseed after soybean. However, rapeseed production ranks first in many European countries such as France, Germany, and Poland. In Turkey, rapeseed is cultivated on 37,000 ha, with an annual production of approximately 125,000 Mg (Turkish Statistical Institute, 2018).

One objective for agricultural irrigation is to produce more yield with less water, obtaining maximum benefit from each unit of water and thus increasing per capita income. To this end, the first option is to increase water efficiency in agriculture. The choice of water source, the accuracy of the plant pattern in the basin, irrigation programs, and the irrigation methods directly affect the efficiency of water used in agriculture. The second option is to improve the efficiency of what is applied. Supplemental irrigation, especially during critical growth stages, can improve crop yield, improve water productivity, and stabilize yields when rainfall fails to provide sufficient moisture for normal plant growth (Nangia, Oweis, Kemeze, & Schnetzer, 2018). Although rapeseed is generally cultivated under rainfed conditions, the increasing occurrence of extreme weather events necessitates that we expand our knowledge (Bauder, 2019).

The main objective of this study was to determine the effects of supplemental irrigation timing on yield, oil content, fatty acid composition, protein content, 1,000-seed weight, and dry matter.

2 | MATERIALS AND METHODS

2.1 | Experimental site and treatments

A 3-yr field experiment was conducted in Tekirdağ province in northwestern Turkey during the 2009/2010, 2010/2011, and 2011/2012 growing seasons. The study site was located at 41°02′ N and 27°39′ E (148 m asl). The area has a semi-arid climat that is a transition climate between the Mediterranean climate and both the Black Sea and more continental Balkans Peninsula climates. The long-term (1939–2011) average temperature is 13.9 °C, sunshine duration is 6.3 h d^{-1}, wind speed is 2.7 m s^{-1}, and relative humidity is 78%. Long-term yearly average precipitation is 585 mm (TSMS, 2012). Some climatic factors, such as maximum and minimum temperatures and rainfall for experimental years recorded by an automatic weather station (Model WS-STD 1′, Delta-T Devices), are graphed in Figure 1.

The soil texture was 240, 460, and 30 g kg^{-1} sand, silt, and clay, respectively, and was classified as a clay loam. The bulk density values varied between 1.48 and 1.69 g cm^{-3}. The available water holding capacity within 0.90 m of the soil profile was about 160 mm. The water content at field capacity and permanent wilting point in effective root depth of rapeseed (0.90 m) were about 400 and 245 mm, respectively. Infiltration rate of the experimental soils was about 20 mm h^{-1}. Irrigation water quality was classified as C_2S_1, with electrical conductivity of 0.4 dS m^{-1} according to the principles of U.S. Salinity Laboratory (USDA, 1954).

A line-source sprinkler irrigation system was used to irrigate ES Hydromel (Tat Seed Production Inc.) rapeseed

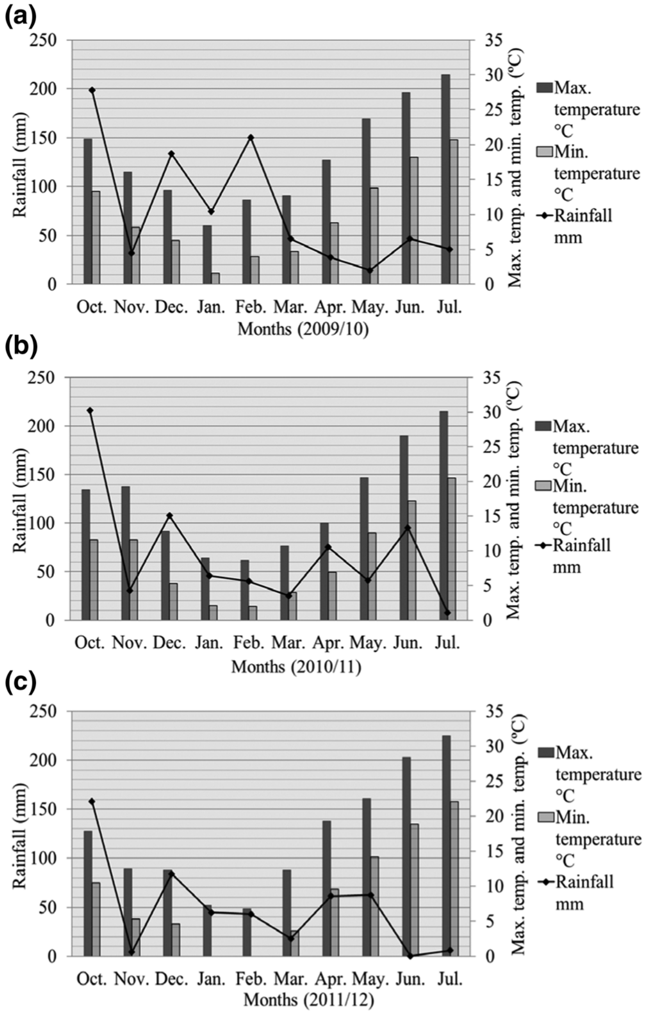

FIGURE 1 Monthly averages of maximum and minimum temperatures and rainfall for (a) Year 1, (b) Year 2, and (c) Year 3

TABLE 1 Length of the growth periods by year

Growth stage	Growth event/start date	Growth event/end date	Stage length	Day of planting
Germination and emergence	Sowing	Plant has a few leaves		
	26 Oct. 2009	24 Nov. 2009	30	30
	9 Oct. 2010	5 Nov. 2010	27	27
	8 Oct. 2011	7 Nov. 2011	30	30
Vegetative growth	Several plant leaves formed	First flowers seen		
	24 Nov. 2009	15 Apr. 2010	141	171
	5 Nov. 2010	18 Apr. 2011	164	191
	7 Nov. 2011	13 Apr. 2012	158	188
Flowering	First flowers seen	Pods formation completed		
	15 Apr. 2010	14 May 2010	29	200
	18 Apr. 2011	11 May 2011	23	214
	13 Apr. 2012	12 May 2012	29	217
Yield formation	Pods formation completed	Pods dried		
	14 May 2010	28 May 2010	14	214
	11 May 2011	28 May 2011	17	231
	12 May 2012	25 May 2012	13	230
Physiological maturity	Pods dried	Harvest		
	28 May 2010	14 July 2010	47	261
	28 May 2011	10 July 2011	43	274
	25 May 2012	5 July 2012	41	271
Totals	Sowing	Harvest		
2009–2010	26 Oct. 2009	14 July 2010	261	261
2010–2011	9 Oct. 2010	10 July 2011	274	274
2011–2012	8 Oct. 2011	5 July 2012	271	271

cultivar, which was preferred due to its high germination rate, disease and insect resistance, and high oil content. Lateral pipelines were set up according to the principles of Hanks, Keller, Rasmussen, and Wilson (1976). In this layout, irrigation treatments included different irrigation quantities and crop development periods, which together influence irrigation timing. Irrigation was applied with a line source that decreased the rate of irrigation as distance from the irrigation treatment increased. The experimental design was a split-block replicated four times based on Hanks, Sisson, Hurst, and Hubbard (1980). For ANOVA, irrigation timing was considered the main plot, and irrigation quantity was considered the subplot. The total experimental area was about 1.0 ha (75 × 120 m). Each plot covered an area of 15 m^2 (3 × 5 m), and harvest was carried out on the harvest plot of 2 × 3 m to avoid the horizontal movement of soil water from one plot to another.

Rapeseed was planted at the end of October for 3 yr and harvested on 14 July 2010 (day of year [DOY] 195), 10 July 2011 (DOY 191), and 5 July 2012 (DOY 187). The start and end dates of each growth period in experimental years are identified based on the Canola Council of Canada database and on phenological observations (Table 1). Irrigation treatments were established for each main plot (Figure 2) and were set up as (a) irrigation timing (III, full irrigation in all three growth periods; I00 irrigation during the vegetative growth period; 0I0, irrigation during the flowering period; 00I, irrigation during the early ripening period) and (b) six different irrigation quantities (100, 80, 60, 40, 20, and 0% of water requirement designated as I_{100}, I_{80}, I_{60}, I_{40}, I_{20}, and I_0, respectively).

To maintain the amount of irrigation water needed for treatments, a fully irrigated treatment (III-I_{100}), designed to receive 100% soil water depletion, was considered. At the beginning of each growing period, soil moisture content at 90 cm root depth was at field capacity. The irrigation was stopped when the amount of water accumulating in the relevant container reached the amount of water applied by irrigation. Containers were 10.5 cm in diameter and 22 cm in height and were placed at varying heights, depending on plant growth.

After irrigation, the depth of applied water was determined for each subtreatment by measuring the amount of water accumulated in each container. The average amount of water accumulated in each container refers to 100, 80,

TABLE 2 The total amount of irrigation water applied to the treatments, the seasonal water consumption (ET), irrigation water use efficiency (IWUE), and water use efficiency (WUE)

Irrigation timing[a]	Irrigation quantity[b]	Irrigation water			Total ET			WUE			IWUE		
		2009/2010	2010/2011	2011/2012	2009/2010	2010/2011	2011/2012	2009/2010	2010/2011	2011/2012	2009/2010	2010/2011	2011/2012
		mm						kg m^{-3}					
III	I_{100}	364	362	250	941	923	730	0.51	0.53	0.65	0.47	0.43	0.48
	I_{80}	290	295	192	867	858	676	0.51	0.53	0.67	0.44	0.41	0.48
	I_{60}	246	237	146	853	813	630	0.51	0.55	0.65	0.49	0.46	0.38
	I_{40}	179	164	81	784	733	571	0.54	0.54	0.67	0.60	0.38	0.30
	I_{20}	59	74	24	738	727	494	0.50	0.53	0.74	0.94	0.65	0.33
I00	I_{100}	102	105	–	766	768	–	0.52	0.54	–	0.82	0.75	–
	I_{80}	80	92	–	754	753	–	0.51	0.50	–	0.85	0.39	–
	I_{60}	66	69	–	745	729	–	0.48	0.49	–	0.61	0.28	–
	I_{40}	45	57	–	739	710	–	0.49	0.50	–	1.13	0.32	–
	I_{20}	23	24	–	722	712	–	0.47	0.47	–	1.08	–	–
0I0	I_{100}	124	123	116	833	771	641	0.55	0.61	0.68	1.15	1.09	0.69
	I_{80}	102	97	81	811	735	571	0.49	0.49	0.68	0.85	0.25	0.37
	I_{60}	91	84	60	790	731	555	0.51	0.49	0.68	0.97	0.24	0.37
	I_{40}	70	50	35	774	704	505	0.49	0.36	0.74	0.90	–	0.51
	I_{20}	22	36	14	726	704	479	0.46	0.34	0.60	0.77	–	–
00I	I_{100}	139	134	135	838	737	599	0.54	0.61	0.65	1.01	0.86	0.29
	I_{80}	109	107	112	808	710	586	0.51	0.63	0.68	0.94	1.06	0.43
	I_{60}	90	84	87	789	707	561	0.46	0.59	0.75	0.58	1.00	0.33
	I_{40}	64	57	46	763	700	511	0.44	0.56	0.75	0.30	0.94	0.61
	I_{20}	14	14	11	713	682	476	0.45	0.51	0.76	0.71	0.64	0.64
	I_0				699	698	465	0.45	0.48	0.77			

[a] III, full irrigation in all three growth periods; I00, irrigation during the vegetative growth period; 0I0, irrigation during the flowering period; 00I, irrigation during the early ripening period.

[b] Irrigation at 100, 80, 60, 40, 20, and 0% of water requirement designated as I_{100}, I_{80}, I_{60}, I_{40}, I_{20}, and I_0, respectively.

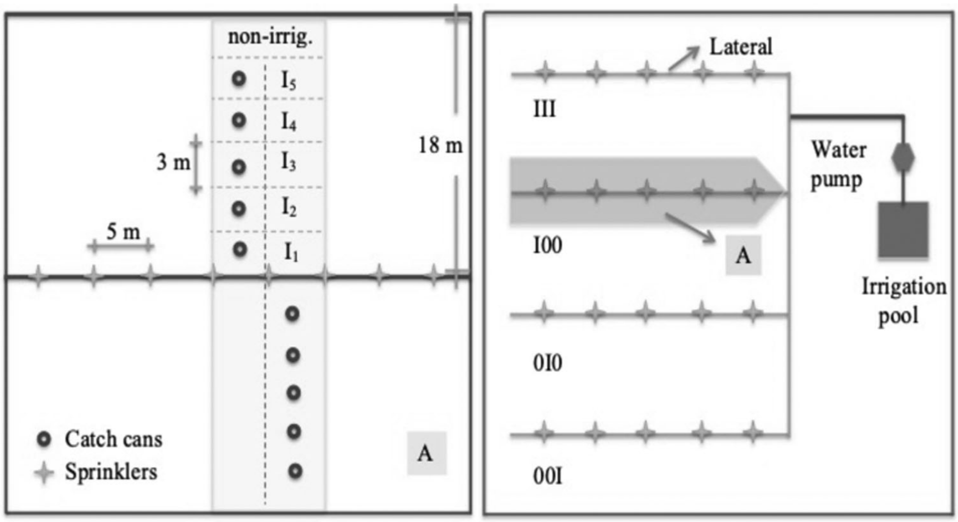

FIGURE 2 Layout of the line source sprinkler system and parcel detail

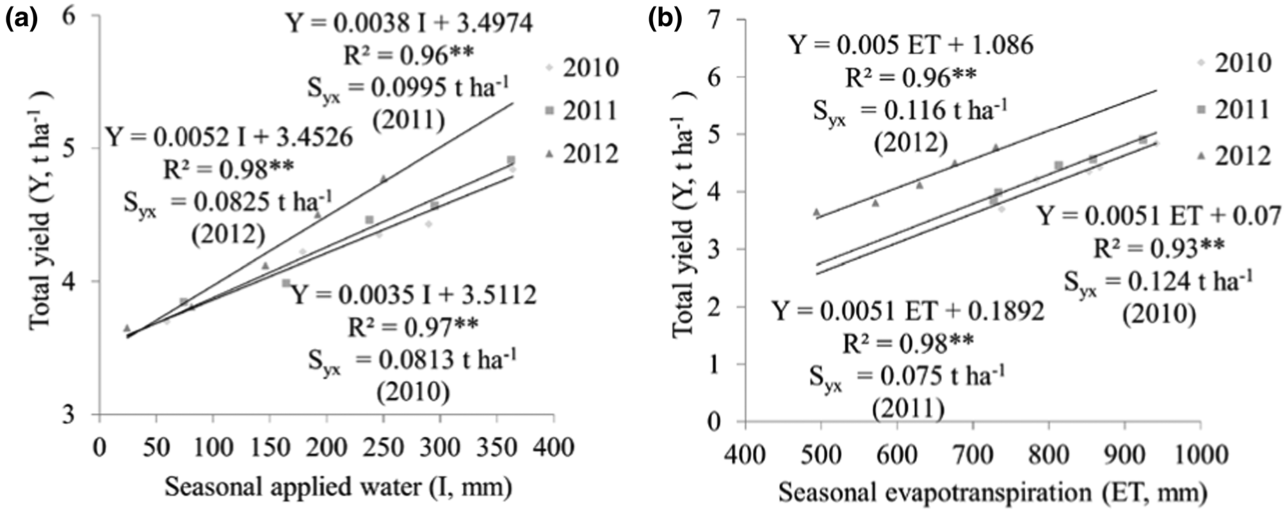

FIGURE 3 (a) Total yield vs. seasonal applied water and (b) total yield vs. evapotranspiration for 2010, 2011, and 2012

60, 40, 20, and 0% (I_{100}, I_{80}, I_{60}, I_{40}, I_{20}, and I_0) of total irrigation water.

In the experimental layout, each plot contains a single lateral line. There were eight impact sprinklers located on single line, and each sprinkler was affected by the others. In this experiment, an impact sprinkler (5035 G, NaanDan Jain Irrigation Co.) was used. Flow rates of the sprinklers vary between 2.5 and 2.8 m^3 h^{-1} at 3.0 atm operational pressures.

2.2 | Water production functions

Although the amount of water applied was calculated for 90 cm effective root depth, plant water consumption rates were calculated according to water budget approach, taking 120 cm soil depth into account for deep percolation (Rao, Regar, Tanwar, & Singh, 2013). The following equation was used for this purpose:

$$\text{ET} = I + P + C_p - D_p \pm R_f \pm \Delta S \quad (1)$$

where ET is evapotranspiration (mm), I is irrigation water (mm), P is effective rainfall (mm), C_p is capillary flow (considered to be zero because no groundwater was observed), ΔS is change in the soil water storage in 120 cm depth of soil profile (mm), DP is deep percolation (mm), and R_f is the amount of runoff assumed to be zero (mm).

The irrigation water use efficiency (IWUE) and water use efficiency (WUE), both on a yield basis, were

TABLE 3 Yield and yield quality parameters of rapeseed for all treatments, 2009/2010

Irrigation timing[a]	Irrigation quantity[b]	Yield	1,000-seed weight	Dry matter	Protein content	Oil content	Mean values of fatty acids: Oleic acid C18:1	Linoleic acid C18:2	Erucic acid C22:1
		t ha^{-1}	g	%					
III	I_{100}	4.84	4.39	90.0	23.0	38.0	62.0	21.0	0.2
	I_{80}	4.43	4.28	90.0	23.0	38.0	62.0	21.0	0.1
	I_{60}	4.35	4.34	90.0	23.0	37.0	62.0	21.0	0.2
	I_{40}	4.22	4.06	90.0	23.0	36.0	61.0	21.0	0.3
	I_{20}	3.70	3.91	91.0	23.0	37.0	62.0	22.0	0.2
I00	I_{100}	3.98	3.58	90.0	20.0	37.0	63.0	21.0	0.2
	I_{80}	3.82	3.70	90.0	20.0	38.0	63.0	21.0	0.5
	I_{60}	3.54	3.73	91.0	19.0	38.0	63.0	21.0	0.5
	I_{40}	3.65	3.72	91.0	19.0	39.0	61.0	21.0	0.1
	I_{20}	3.39	3.63	90.0	19.0	38.0	63.0	21.0	0.2
0I0	I_{100}	4.56	3.88	90.0	29.0	40.0	64.0	21.0	0.1
	I_{80}	4.01	3.67	90.0	28.0	39.0	63.0	22.0	0.0
	I_{60}	4.02	3.90	91.0	28.0	39.0	64.0	22.0	0.1
	I_{40}	3.77	3.65	91.0	29.0	39.0	64.0	22.0	0.0
	I_{20}	3.31	3.68	90.0	29.0	39.0	63.0	22.0	0.1
00I	I_{100}	4.54	3.89	91.0	21.0	42.0	63.0	22.0	0.1
	I_{80}	4.16	4.01	91.0	22.0	41.0	63.0	21.0	0.1
	I_{60}	3.66	4.03	92.0	22.0	41.0	63.0	22.0	0.1
	I_{40}	3.33	3.67	92.0	21.0	39.0	63.0	21.0	0.1
	I_{20}	3.24	3.62	91.0	22.0	39.0	63.0	22.0	0.1
III		4.11a[c]**	4.4a**	90.3 ns	22.2b**	37.6c**	61.8b*	21.0ab*	0.2 ns
I00		3.59b	3.6c	90.4	19.3d	38.3b	62.5ab	21.0b	0.2
0I0		3.80ab	3.9bc	90.6	26.8a	39.1ab	63.3a	22.0a	0.1
00I		3.68b	3.9b	91.3	21.0c	40.1a	62.6a	22.0ab	0.1
	I_{100}	4.48a**	4.0a**	90.1b**	23.4a**	39.2a**	62.8a**	21.8a*	0.2 ns
	I_{80}	4.10ab	4.0a	90.1b	23.1ab	39.0a	62.8a	21.3ab	0.3
	I_{60}	3.89b	4.0a	90.9ab	22.6b	38.9ab	62.9a	21.3b	0.2
	I_{40}	3.74b	3.8ab	91.1a	22.6b	38.3c	62.2bc	21.6ab	0.1
	I_{20}	3.41b	3.7b	90.6ab	23.2ab	38.3bc	62.6ac	21.4ab	0.1
	I_0	3.14c	3.7b	91.0a	19.0c	39.0a	62.0c	21.6ab	0.1
Irrigation timing × irrigation quantity		ns	ns	ns	**	**	**	ns	ns

[a] III, full irrigation in all three growth periods; I00, irrigation during the vegetative growth period; 0I0, irrigation during the flowering period; 00I, irrigation during the early ripening period.

[b] Irrigation at 100, 80, 60, 40, 20, and 0% of water requirement designated as I_{100}, I_{80}, I_{60}, I_{40}, I_{20}, and I_0, respectively.

[c] Different letters following numbers indicate significant difference. ns, nonsignificant.

*Significant at the .05 probability level.

**Significant at the .01 probability level.

calculated using Equations 2 and 3 (Sadras, Grassini, & Steduto, 2011; Zhang, Wang, You, & Liu, 1999):

$$\mathrm{IWUE} = (Y_\mathrm{I} - Y_0)/I \tag{2}$$

$$\mathrm{WUE} = Y_\mathrm{I}/\mathrm{ET} \tag{3}$$

where Y_I is the yield (kg ha^{-1}), Y_0 is the yield of the control plots (kg ha^{-1}), I is the irrigation water (mm), and ET is the evapotranspiration (mm). To determine the effect of water stress during growing season on yield, the Stewart's model was used (Doorenbos & Kassam, 1979; Villalobos & Fereres, 2016) (Equation 4):

TABLE 4 Yield and yield quality parameters of rapeseed for all treatments, 2010/2011

							Mean values of fatty acids		
Irrigation timing[a]	**Irrigation quantity**[b]	**Yield**	**1,000-seed weight**	**Dry matter**	**Protein content**	**Oil content**	**Oleic acid C18:1**	**Linoleic acid C18:2**	**Erucic acid C22:1**
		t ha^{-1}	g	%					
III	I_{100}	4.91	3.69	92.0	23.0	38.0	61.0	21.0	0.0
	I_{80}	4.57	3.73	92.0	23.0	37.0	61.0	21.0	0.0
	I_{60}	4.46	3.69	92.0	24.0	38.0	61.0	22.0	0.0
	I_{40}	3.99	3.72	92.0	24.0	39.0	61.0	22.0	0.0
	I_{20}	3.85	3.70	93.0	23.0	38.0	62.0	22.0	0.1
I00	I_{100}	4.16	3.55	90.0	22.0	38.0	61.0	22.0	0.1
	I_{80}	3.73	3.56	89.0	21.0	38.0	61.0	21.0	0.0
	I_{60}	3.56	3.61	91.0	21.0	38.0	61.0	21.0	0.1
	I_{40}	3.55	3.56	91.0	21.0	38.0	61.0	21.0	0.0
	I_{20}	3.32	3.62	89.0	22.0	38.0	61.0	22.0	0.3
0I0	I_{100}	4.71	3.59	91.0	25.0	39.0	61.0	21.0	0.1
	I_{80}	3.61	3.63	92.0	25.0	38.0	62.0	22.0	0.0
	I_{60}	3.57	3.61	93.0	25.0	39.0	61.0	21.0	0.1
	I_{40}	2.55	3.60	93.0	25.0	37.0	61.0	21.0	0.1
	I_{20}	2.36	3.58	92.0	25.0	38.0	62.0	22.0	0.1
00I	I_{100}	4.52	3.65	90.0	22.0	38.0	61.0	21.0	0.1
	I_{80}	4.50	3.73	90.0	21.0	38.0	61.0	21.0	0.1
	I_{60}	4.21	3.70	90.0	22.0	38.0	63.0	21.0	0.1
	I_{40}	3.91	3.75	90.0	22.0	38.0	62.0	21.0	0.1
	I_{20}	3.46	3.72	91.0	21.0	39.0	63.0	21.0	0.1
III		4.19a*[c]	3.70 ns	90.2b*	23.0b**	37.9 ns	61.3b*	21.0 ns	0.0 ns
I00		3.61ab	3.60	90.3b	21.4c	38.1	61.2b	22.0	0.1
0I0		3.36b	3.60	91.9ab	24.3a	38.3	61.5ab	21.0	0.1
00I		4.00ab	3.70	92.8a	21.5c	38.3	62.1a	21.0	0.1
	I_{100}	4.58a**	3.7 ns	90.8 ns	22.7 ns	37.9b**	61.1c**	21.3b*	0.2 ns
	I_{80}	4.10ab	3.70	90.9	22.6	37.8b	61.3c	21.3b	0.1
	I_{60}	3.95b	3.70	91.6	22.8	38.1b	61.6ab	21.4ab	0.2
	I_{40}	3.50c	3.70	92.1	22.8	37.8b	61.4c	21.4ab	0.1
	I_{20}	3.24c	3.60	91.3	22.7	38.3ab	61.9ab	21.5ab	0.1
	I_0	3.37c	3.70	91.0	21.8	39.0a	62.0a	22.0a	0.1
Irrigation timing × irrigation quantity		**	ns	*	**	**	**	ns	ns

[a] III, full irrigation in all three growth periods; I00, irrigation during the vegetative growth period; 0I0, irrigation during the flowering period; 00I, irrigation during the early ripening period.

[b] Irrigation at 100, 80, 60, 40, 20, and 0% of water requirement designated as I_{100}, I_{80}, I_{60}, I_{40}, I_{20}, and I_0, respectively.

[c] Different letters following numbers indicate significant difference. ns, nonsignificant.

*Significant at the .05 probability level.

**Significant at the .01 probability level.

$$\left(1-\frac{Y_a}{Y_m}\right)=k_y\left(1-\frac{ET_a}{ET_m}\right) \tag{4}$$

where Y_a is actual harvested yield (t ha^{-1}), Y_m is maximum harvested yield (t ha^{-1}), k_y is yield response factor, ET_a is actual evapotranspiration (mm), ET_m is maximum evapotranspiration (mm) corresponding to Y_m, $1-(Y_a/Y_m)$ is relative yield decrease, and $1-(ET_a/ET_m)$ is relative ET deficit.

TABLE 5 Yield and yield quality parameters of rapeseed for all treatments, 2011/2012

Irrigation timing[a]	Irrigation quantity[b]	Yield	1,000-seed weight	Dry matter	Oil content	Mean values of fatty acids		
						Oleic acid C18:1	Linoleic Acid C18:2	Erucic acid C22:1
		t ha^{-1}	g	%				
III	I_{100}	4.77	4.1	92.0	39.0	64.0	22.0	0.1
	I_{80}	4.50	4.1	92.0	37.0	64.0	22.0	0.1
	I_{60}	4.12	4.2	92.0	38.0	64.0	21.0	0.1
	I_{40}	3.81	4.1	92.0	38.0	63.0	22.0	0.1
	I_{20}	3.65	4.2	93.0	38.0	64.0	21.0	0.1
0I0	I_{100}	4.37	4.0	90.0	38.0	64.0	21.0	0.1
	I_{80}	3.87	3.9	89.0	37.0	63.0	21.0	0.1
	I_{60}	3.79	3.9	91.0	37.0	64.0	22.0	0.1
	I_{40}	3.57	3.9	91.0	38.0	63.0	22.0	0.1
	I_{20}	2.88	4.0	89.0	38.0	63.0	21.0	0.1
00I	I_{100}	3.95	4.1	91.0	38.0	63.0	22.0	0.1
	I_{80}	4.03	3.9	92.0	38.0	64.0	21.0	0.1
	I_{60}	3.84	4.0	93.0	39.0	63.0	22.0	0.1
	I_{40}	3.85	4.0	93.0	39.0	63.0	22.0	0.1
	I_{20}	3.62	4.3	92.0	39.0	63.0	22.0	0.1
III		4.07ns	4.1ns	90.0	37.9ab**	63.8ns	22.0ns	0.1ns
0I0		3.67	4.0	90.0	37.7b	63.4	21.0	0.1
00I		3.81	4.1	90.0	38.3a	63.1	22.0	0.1
	I_{100}	4.36a$^{c\,**}$	4.1ns	91.0	38.0ns	63.6ab**	21.4ab*	0.1ns
	I_{80}	4.13ab	4.0	90.2b*	37.4	63.4abc	21.3b	0.0
	I_{60}	3.91bc	4.1	90.3b	38.1	64.0a	21.8ab	0.2
	I_{40}	3.74cd	4.0	91.9ab	38.1	62.9c	21.8ab	0.1
	I_{20}	3.38d	4.2	92.8a	38.3	63.7ab	21.8ab	0.1
	I_0	3.55d	3.9	90.8ns	38.0	63.0bc	22.0a	0.1
Irrigation timing × irrigation quantity		ns	ns	*ns		*	ns	ns

[a] III, full irrigation in all three growth periods; I00, irrigation during the vegetative growth period; 0I0, irrigation during the flowering period; 00I, irrigation during the early ripening period.

[b] Irrigation at 100, 80, 60, 40, 20, and 0% of water requirement designated as I_{100}, I_{80}, I_{60}, I_{40}, I_{20}, and I_0, respectively.

[c] Different letters following numbers indicate significant difference. ns, nonsignificant.

*Significant at the .05 probability level.

**Significant at the .01 probability level.

2.3 | Yield and quality parameters

The harvest plot yield (t ha^{-1}) and the 1,000-grain weight (g) were obtained separately from the experimental plots. To determine dry matter content, vegetative parts of plant were separated and dried at 65 °C in a forced-air oven (Daun, Eskin, & Hickling, 2011). Seed crude oil content (%) was determined with the aid of IUPAC method Item 122 (IUPAC, 1987). Total N content in the dry matter of seed was analyzed by the Kjeldahl method, and the resultant N content was multiplied by 6.25 to determine the crude protein content (%) of the seeds (AOAC, 2000; Daun et al., 2011). To determine the concentrations of fatty acids (erucic acid, C22-1; oleic acid, C18-1n9; linoleic acid, C18-2n6), the studied oil samples were transformed into methyl esters of fatty acids by using BF3-methanol in accordance with the Ce 2-66 method of AOCS (AOCS, 1993).

2.4 | Statistical and economic analysis

Experimental data were subjected to ANOVA with SPSS 18.0 (SPSS Inc.) and Excel (Microsoft) software. Significant means were compared with the aid of Duncan's multiple range tests at $p < .01$ and $p < .05$ (Gomez & Gomez, 1984).

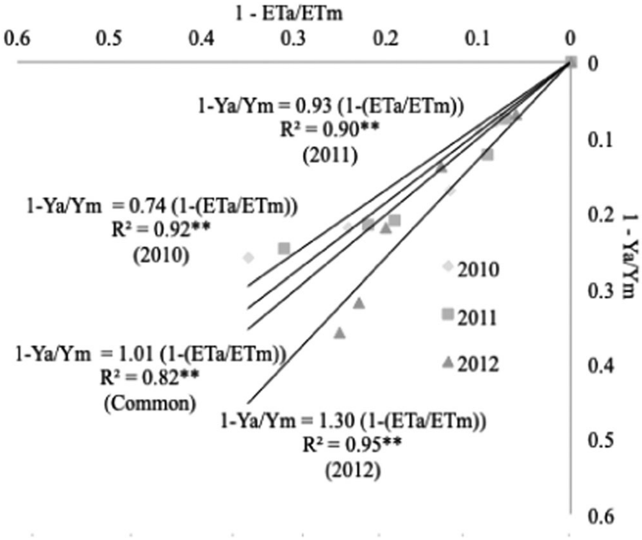

FIGURE 4 Relative yield decrease to relative evapotranspiration deficit, yield response factor (k_y) by years

The experimental results were analyzed with a split block design, which is a variation of the time modification of the split-plot design for the line source irrigation method based on Hanks et al. (1980) and Sezen and Yazar (2006).

Net income of irrigation treatments, irrigation system cost, investment cost, fixed cost, operating cost, repair and maintenance costs, and irrigation labor costs were calculated according to principles given in Letey, Dinar, Woodring, and Oster (1990). Total costs and net income were compared to determined which irrigation treatment would be more economical.

3 | RESULTS AND DISCUSSION

3.1 | Irrigation water and evapotranspiration

The total amounts of irrigation water applied in experimental treatments, the seasonal water consumption of rapeseed (ET, mm), the yield obtained from experimental plots, and the calculated IWUE and WUE values for each year are provided in Table 2. These differences were attributed to annual climatic differences. The amount of irrigation water applied in full irrigation (III-I_{100}) was 364 mm in Year 1, 362 mm in Year 2, and 250 mm in Year 3. Seasonal cumulative rainfall was 583 mm in Year 1, 694 mm in Year 2, and 369 mm in Year 3. In the last year of the research, irrigation of I00 could not be conducted due to climatic conditions. Total rainfall was 427, 312, and 246 mm during the vegetative growth stage; 20, 49, and 10 mm during the flowering stage; and 60, 102, and 20 mm during the yield formation stage for 2009/2010, 2010/2011, and 2011/2012, respectively.

The nearest treatment (I_{100}) to the lateral line received the greatest amount of water (100%), and the amount applied decreased with distance from the lateral line (Table 2). In 2010, the amount of irrigation water collected in containers was approximately 100% for the full irrigation (I_{100}) nearest to the lateral and 17% for the I_{20} furthest from the lateral. The same tendency was seen in 2011 and 2012. The differences in the amounts of irrigation water are mostly attributed to long growing periods and differences in soil water storage and to differences in winter and spring precipitation. These irrigation amounts were similar to others (Doğan, Copur, Kahraman, Kırnak, & Guldur, 2011; İstanbulluoğlu, Arslan, Göçmen, Gezer, & Paşa, 2010).

The seasonal evapotranspiration values reached a maximum in the III-I100 treatments (Table 2). Nominal values were 941 mm in Year 1, 923 mm in Year 2, and 730 mm in Year 3. In the other treatments, evapotranspiration values varied with irrigation water quantity. In nonirrigated treatments (I_0), minimum evapotranspiration values were 699, 698, and 465 mm in Years 1, 2, and 3, respectively. In all treatments, evapotranspiration values were slightly greater than other rapeseed studies (400–700 mm) (Banuelos, Bryla, & Cook, 2002; Bilibio, Carvalho, Hensel, & Richter, 2011; Majnooni-Heris et al., 2012, 2014; Rahnema & Bakhshandeh, 2006; Tesfamariam, 2004). This phenomenon is thought to be due to climate conditions and application differences. İstanbulluoğlu et al. (2010) calculated evapotranspiration to be between 465 and 715 mm the northwestern portion of Turkey, whereas Doğan et al. (2011) reported that values ranged from 275 to 316 mm in the southeastern portion of Turkey. The researchers confirm that there may be differences in evapotranspiration results depending on local conditions.

In all years of the study, WUE values were calculated between 0.44 and 0.77 kg m^{-3}, respectively. Water use efficiency values increased with decreasing irrigation water quantities in 2012. The greater WUE of 2012 was due to less total ET. Values of IWUE with full irrigation at all growing periods (III-I_{100}) were 0.47 kg m^{-3} in 2010, 0.43 kg m^{-3} in 2011, and 0.48 kg m^{-3} in 2012. Buttar, Thind, and Aujla (2006) reported WUE values of rapeseed irrigation treatments of 0.14–0.31 kg m^{-3}; İstanbulluoğlu et al. (2010) reported WUE values of 0.62–0.77 kg m^{-3} and IWUE values of 1.91–7.16 kg m^{-3}. In other experiments, WUE values ranged from 0.10 to 3.13 kg m^{-3} (Banuelos et al., 2002; Kar, Kumar, & Martha, 2007; Sinaki, Heravan, Rad, Noormohammadi, & Zarei, 2007), and IWUE values ranged from 1.48 to 4.11 kg m^{-3} (Djaman et al., 2018; Doğan et al., 2011, Majnooni-Heris, Nazemi, & Sadraddini, 2014).

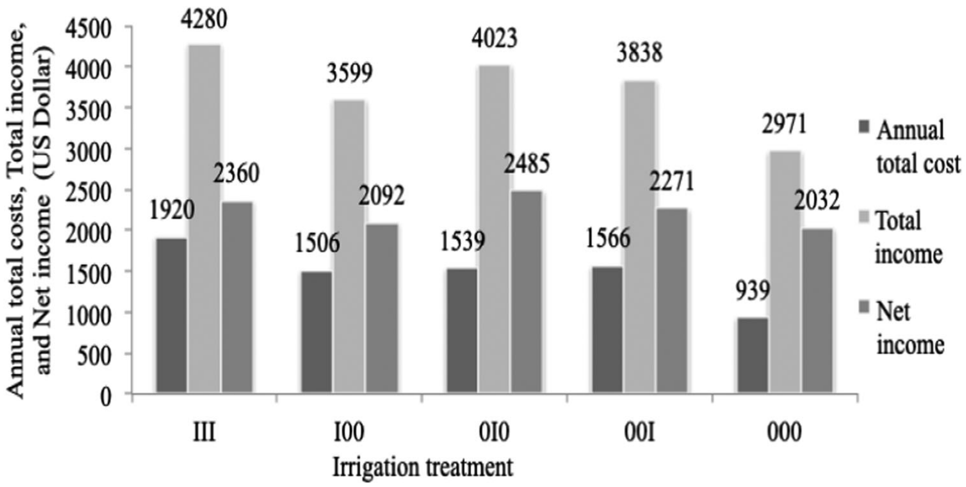

FIGURE 5 Variation of total cost, total income, and net income for rapeseed cultivar based on irrigation timing treatments

Throughout the growing season, there was a strong positive correlation between seasonal plant water consumption and yield (Figure 3). In 2010, 2011, and 2012, higher yields of 54, 46, and 34%, respectively, were obtained from full irrigation (III-I_{100}) as compared to the control (nonirrigated) treatments. Linear relationships between water consumption and yield were also reported in previous studies (Banuelos et al., 2002; Bilibio et al., 2011; Doğan et al., 2011; Shabani, Sepaskhah, & Kamgar-Haghighi, 2013).

Yield response factors, expressed as the ratio of relative yield decrease $[1 - (Y_a/Y_m)]$ to relative ET deficit $[1 - (ET_a/ET_m)]$, calculated with the aid of maximum yield (Y_m), actual yield (Y_a), ET_m, and ET_a, are plotted in Figure 4. The relative yield decrease increased linearly with relative ET deficit ($p < .01$). According to the regression equations, seasonal yield response factor, k_y, was 0.74, 0.93, and 1.30 for Years 1, 2, and 3, respectively, and was 1.01 for all years. İstanbulluoğlu et al. (2010) obtained a seasonal k_y value of 0.87 under the same conditions. According to the yield response factor equations for total growing period, it can be said that a 53% yield reduction will be seen if a 50% water deficit occurred throughout the entire growing season.

3.2 | Yield and yield quality parameters

Average yield and quality parameters obtained from each treatment are provided in Tables 3, 4, and 5 for 2009/2010, 2010/2011, and 2011/2012, respectively. As seen in the tables, in each of the three growing seasons, the greatest yields (4.84, 4.91, and 4.77 t ha^{-1}, respectively) were obtained from III-I_{100}, and the lowest yields were obtained from nonirrigated control treatments. The interaction between the irrigation timing and irrigation quantity on total yield was not statistically significant in Years 1 and 3. Differences in yields of irrigation treatments were found to be significant at the .01 and .05 confidence level in Years 1 and 2, respectively (Tables 3 and 4). In general, III and I_{100} treatments were placed in the first group, and this treatment could be recommended for high yields.

Statistical analysis revealed that some yield quality parameters, such as protein content, oil content, and some fatty acids, were affected by irrigation quantity, but treatment had little or no effect on 1,000-seed weight, linoleic acid, or erucic acid. The greatest 1,000-seed weights in Years 1, 2, and 3 were 4.4, 3.7, and 4.1 g, respectively, with the greatest value from III treatments. These values were similar to others (Ahmadi & Bahrani, 2009; Bilibio et al., 2011; Doğan et al., 2011; Moaveni, Ebrahimi, & Farahani, 2010; Shabani et al., 2013). According to the ANOVA, although differences in 1,000-seed weight of irrigation timing and quantity for Year 1 were significant, they were insignificant for Years 2 and 3.

Dry matter contents varied between 90 and 92% in Year 1 and between 89 and 93% in the Years 2 and 3 (Tables 3–5). Crude protein contents varied between 19 and 29% in Year 1 and between 21 and 25% in Year 2. In Year 2, protein contents could not be determined due to equipment failure. Shabani et al. (2013) conducted deficit irrigation research that consisted of full irrigation (FI), 0.75 FI, and 0.50 FI in Year 1 and FI, 0.65 FI, and 0.35 FI in Year 2 and reported crude protein contents between 17.8 and 21.3%. Tahir, Ali, Nadeem, Tanveer, and Sabir (2007) reported that, in Pakistan, protein contents varied from 20.02 to 20.48% among irrigation levels, whereas in Iran protein was not affected by time or the number of irrigations (Sinaki et al., 2007). The greatest crude protein content was obtained from the 0I0 treatment, and the lowest crude protein content was obtained from the control treatment in both years. These results show that irrigation applied during the flowering period increased crude protein contents.

Oil content is an important quality parameter for rapeseed. Previous studies reported that oil content in rapeseed ranged from 35 to 50% (CCC, 2013; İstanbulluoğlu et al., 2010; Maleki & Mirsheraki, 2011; Onemli, 2014; Shabani et al., 2013; Sinaki et al., 2007). In our study, oil contents varied between 36 and 42% in 2010 and between 37 and 39% in 2011 and 2012.

Oleic acid was the major fatty acid, and oleic contents varied between 61 and 64% (Tables 3–5). Fatty acid composition of irrigated rapeseed was not previously reported. The Canola Council of Canada (CCC, 2013) declared that the oleic acid content of rapeseed should be 60–65%. Maximum values were observed when irrigation was applied during the flowering and ripening periods. As with the other yield parameters, irrigation applied during these periods increased oleic acid contents. The effects of irrigation timing on linoleic acid contents were significant only in the 2009/2010 growing season ($p < .05$). However, the effects of irrigation quantities on linoleic acid contents were significant in all 3 yr ($p < .05$). Erucic acid contents varied between 0.1 and 0.5%. Erucic acid is an important control parameter that must be contained in the seed. High ratios of erucic acid can have negative effects on human health; therefore, it is stated in the international standards that the levels should not exceed 3%.

The annual total cost, total income, and net income based on irrigation treatments are summarized in Figure 5. The highest net income was $2,485 per hectare from the 0I0 treatment irrigated only in the flowering period. It was $2,360 for the III treatment and $2,032 for the nonirrigated treatment. The total costs varied depending on the annual operating costs. The total cost in the III treatment was 20% higher than the irrigated treatment during the flowering period treatment (0I0) and 52% higher than the nonirrigated treatment, but the net income was highest in the 0I0 treatment. Net income was also relatively high in the nonirrigated treatment, with only a 19% difference from the highest net income, which is attributed to high total rainfall observed during the growing period compared with long-term averages.

4 | CONCLUSION

Full irrigation had remarkable yields in all 3 yr of the study and thus could be recommended for acieving high yields. The highest IWUE and net income were obtained when irrigation was applied during flowering. At this time, the net income was $2,485 ha^{-1} yr^{-1}. Supplemental irrigation was very beneficial during years with insufficient precipitation.

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REFERENCES

Ahmadi, M., & Bahrani, M. J. (2009). Yield and yield components of rapeseed as ınfluenced by water stress at different growth stages and nitrogen levels. *American-Eurasian Journal of Agricultural & Environmental Sciences*, *5*(6), 755–761.

AOAC. (2000). *Official methods of analysis of the association of official analytical chemists*. Rockville, MD: AOAC.

AOCS. (1993). *Official methods and recommended practices of the American Oil Chemists Society* (3rd ed.).Urbana, IL: AOCS.

Banuelos, G. S., Bryla, D. R., & Cook, C. G. (2002). Vegetative production of kenaf and canola under irrigation in central California. *Industrial Crops and Products*, *15*, 237–245. http://doi.org/10.1016/S0926-6690(01)00119-4

Bauder, J. W. (2019). The right strategy for your irrigated canola crop. Retrieved from http://waterquality.montana.edu/farm-ranch/irrigation/

Bilibio, C., Carvalho, J.A., Hensel, O., & Richter, U. (2011). Effect of different levels of water deficit on rapeseed (*Brassica napus* L.) crop. *Ciência e Agrotecnologia*, *35*(4), 672–684. http://doi.org/10.1590/S1413-70542011000400005

Buttar, G. S., Thind, H. S., & Aujla, M. S. (2006). Methods of planting and irrigation at various levels of nitrogen affect the seed yield and water use efficiency in transplanted oilseed rape (*Brassica napus* L.). *Agricultural Water Management*, *85*, 253–260. http://doi.org/10.1016/j.agwat.2006.05.008

CCC. (2013). Canola Council of Canada annual reports of 2012. Retrieved from https://www.canolacouncil.org/what-we-do/annual-reports/

CCC. (2017). Canola growth stages. Retrieved from https://www.canolacouncil.org/canola-encyclopedia/crop-development/growth-stages/

Daun, J. K., Michael Eskin, N. A., & Hickling, D. (2011). *Canola; chemistry, production, processing and, utilization*.Urbana, OH: AOCS Press.

Djaman, K., O'Neill, M., Owen, C., Smeal, D., West, M., Dallen, B., … Lombard, K. (2018). Seed yield and water productivity of irrigated winter canola (*Brassica napus* L.) under semiarid climate and high elevation. *Agronomy*, *8*(90), 1–14.

Doğan, E., Copur, O., Kahraman, A., Kırnak, H., & Guldur, M. E. (2011). Supplemental irrigation effects on canola yield components under semiarid climatic conditions. *Agricultural Water Management*, *98*, 1403–1408. http://doi.org/10.1016/j.agwat.2011.04.006

Doorenbos, J., & Kassam, A. H. (1979). *Yield response to water*. Rome: FAO.

FAO. (2017). Production databases 20 February 2018. Retrieved from http://faostat.fao.org

Gomez, K. A., & Gomez, A. A. (1984). *Statistical procedures for agricultural research*. New York: John Wiley & Sons.

Hanks, R. J., Keller, J., Rasmussen, V. P., & Wilson, G. D. (1976). Line source sprinkler for continuous variable irrigation-crop production studies. *Soil Science Society of America Journal*, *40*(3), 426–429. http://doi.org/10.2136/sssaj1976.03615995004000030033x

Hanks, R. J., Sisson, D. V., Hurst, R. L., & Hubbard, K. G. (1980). Statistical analysis results from irrigation experiments using the line-source sprinkler system. *Soil Science Society of*

America Journal, *44*(4), 886–888. http://doi.org/10.2136/sssaj1980.03615995004400040048x

IUPAC. (1987). *Standard methods for the analysis of oils, fats and derivatives*. Research Triangle Park, NC: IUPAC.

İstanbulluoğlu, A., Arslan, B., Göçmen, E., Gezer, E., & Paşa, C. (2010). Effects of deficit irrigation regimes on the yield and growth of oilseed rape (*Brassica napus* L.). *Biosystems Engineering*, *105*, 388–394. http://doi.org/10.1016/j.biosystemseng.2009.12.010

Kar, G., Kumar, A., & Martha, M. (2007). Water use efficiency and crop coefficients of dry season oilseed crops. *Agricultural Water Management*, *87*, 73–82. http://doi.org/10.1016/j.agwat.2006.06.002

Letey, J., Dinar, A., Woodring, C., & Oster, J. D. (1990). An economic analysis of irrigation systems. *Irrigation Science*, *11*, 37–43. http://doi.org/10.1007/BF00189993

Majnooni-Heris, A., Sadraddini, A. A., Nazemi, A. H., Shakiba, M. R., Neyshaburi, M. R., & Tuzel, I. H. (2012). Determination of single and dual crop coefficients, ratio of transpiration to evapotranspiration for canola. *Annals of Biological Research*, *3*(4), 1885–1894.

Majnooni-Heris, A., Nazemi, A. H., & Sadraddini, A. A. (2014). Effects of deficit irrigation on the yield, yield components, water and irrigation water use efficiency of spring canola. *Journal of Biodiversity and Environmental Sciences*, *5*(2), 44–53.

Maleki, S. H., & Mirsheraki, B. (2011). Irrigation period in three rapeseed cultivars influences crop phenology and yield. *Journal of Food, Agriculture and Environment*, *9*(2), 446–448.

Moaveni, P., Ebrahimi, A., & Farahani, H. A. (2010). Studying of oil yield variations in winter rapeseed (*Brassica napus* L.) cultivars under drought stress conditions. *Journal of Agricultural Biotechnology and Sustainable Development*, *2*(5), 71–75.

Nangia, V., Oweis, T., Kemeze, F. H., & Schnetzer, J. (2018). *Supplemental irrigation: A promising climate-smart practise for dryland agriculture. Practise briefs on climate-smart agriculture*. Rome: FAO Publications.

Onemli, F. (2014). Fatty acid content of seed at different development stages in canola on different soil types with low organic matter. *Plant Production Science*, *17*(3), 253–259. http://doi.org/10.1626/pps.17.253

Rao, S. S., Regar, P. L., Tanwar, S. P. S., & Singh, Y. V. (2013). Wheat yield response to line source sprinkler irrigation and soil management practices on medium-textured shallow soils of arid environment. *Irrigation Science*, *31*, 1185–1197. http://doi.org/10.1007/s00271-012-0398-1

Rahnema, A. A., & Bakhshandeh, A. M. (2006). Determination of optimum irrigation level and compatible oilseed rape varieties in the Mediterranean environment. *Asian Journal of Plant Sciences*, *5*(3), 543–546.

Sadras, V. O., Grassini, P., & Steduto, P. (2011). *Status of water use efficiency of main crops*. Rome: FAO.

Sezen, S. M., & Yazar, A. (2006). Wheat yield response to line-source sprinkler irrigation in the arid Southeast Anatolia region of Turkey. *Agricultural Water Management*, *81*, 59–76. http://doi.org/10.1016/j.agwat.2005.04.011

Shabani, A., Sepaskhah, A. R., & Kamgar-Haghighi, A. A. (2013). Responses of agronomic components of rapeseed (*Brassica napus* L.) as influenced by deficit irrigation, water salinity and planting method. *International Journal of Plant Production*, *7*(2), 313–340.

Sinaki, J. F., Heravan, E. M., Rad, A. H. S., Noormohammadi, G., & Zarei, G. (2007). The effects of water deficit during growth stages of Canola (*Brassica napus* L.). *American-Eurasian Journal of Agricultural & Environmental Sciences*, *2*(4), 417–422.

Tahir, M., Ali, A., Nadeem, M. A., Tanveer, A., & Sabir, Q. M. (2007). Performance of canola (*Brassica napus* L.) under different irrigation levels. *Pakistan Journal of Botany*, *39*(3), 739–746.

Tesfamariam, E. H. (2004). *Modeling the soil water balance of canola Brassica napus L. (Hyola 60)* (Doctoral dissertation, University of Pretoria). Retrieved from https://repository.up.ac.za/bitstream/handle/2263/28069/00dissertation.pdf?sequence=1&isAllowed=y

Turkish Statistical Institute. (2015). Production databases. Retrieved from http://www.turkstat.gov.tr/PreTabloArama.do?metod=search&araType=vt

TSMS. (2012). Turkish State Meteorological Service database. Retrieved from https://www.mgm.gov.tr/tahmin/il-ve-ilceler.aspx?il=Tekirdag

USDA. (1954). *Diagnosis and improvement of saline and alkali soils*. Washington, DC: USDA Agricultural Research Service.

Villalobos, F. J., & Fereres, E. (2016). *Principles of agronomy for sustainable agriculture*. Retrieved from http://doi.org/10.1007/978-3-319-46116-8

WRI. (2015). Water: Mapping, measuring, and mitigating global water challenges. Retrieved from http://www.wri.org/our-work/topics/water

Zhang, H., Wang, X., You, M., & Liu, C. (1999). Water-yield relations and water-use efficiency of winter wheat in the North China Plain. *Irrigation Science*, *19*, 37–45. http://doi.org/10.1007/s002710050069

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