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Weed Competition Periods Affect Grain Yield and Nutrient Uptake of Black Seed (*Nigella Sativa* L.)

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Abstract

The combination of the relatively open plant canopy and slow growth, especially at early growth stages, results in lower competitiveness of black seed (*Nigella sativa* L.) than weeds. Thus, weed interference is known as an important factor affecting black seed yield. Therefore, to determine the critical period of weed control and its effects on nutrients uptake of black seed field experiments were conducted in 2011 and 2012. Two quantitative series of weed removal treatments including weed-infested and weed-free treatments were implemented from black seed emergence to maturity harvest. To determine critical period of weed control, plots were weed-infested or weed-free for 0, 14, 28, 42, 56, 70 days after emergence, in weed-infested and weed-free treatments, respectively. The results revealed that N, P and K contents in weed tissues significantly increased with increasing weed-infested periods during both years of the experiment. The reduction in grain and oil yield due to longer periods of weed-infested conditions or shorter periods of weed-free conditions were accompanied by simultaneous reduction of N, P and K uptake in black seed grains and tissues. Overall, N, P and K contents in weed tissue were found to be 1.8 to 2 times higher than that of black seed. It was concluded that 58 or 49 days weed-free periods are required to avoid yield loss (above 5% or 10%) in black seed.

Keywords: *Nigella sativa*; nitrogen; nutrient competition; oil yield; phosphorus; weed-free period; weed-infested period

1. Introduction

Black seed (*Nigella sativa* L.) is a short-lived annual plant belonging to the Ranunculaceae family which is grown in arid and semi-arid regions of Iran (D'Antuono et al., 2002; Ghamarnia et al., 2010). Black seed is considered as a multi-purpose crop (D'Antuono et al., 2002). It is a spicy and aromatic plant and used for seasoning in cooking and other foodstuffs (Nergiz and Otles, 1993; Mehta et al., 2009). In addition, black seed seeds are used in traditional and industrial pharmacology especially in the Middle East for the treatment of asthma, bronchitis, fever, influenza and eczema (Burits and Bucar, 2000; Ali and Blunden, 2003; Mehta et al., 2009). It has been reported that the black seed contains a number of pharmacologically active ingredients including antioxidant (Erkan et al., 2008; Mariod et al., 2009), anti-inflammatory and analgesic components (Al-Ghamdi, 2001; Gholamnezhad et al., 2015). Black seed seeds contain up to 21% crude protein and 34% oil (AI-Jassir, 1992; Seyyedi et al., 2015).

The combination of the relatively open plant canopy and slow growth, especially at early growth stages, results in lower competitiveness of black seed than weeds. Thus, weed interference is known as an important factor affecting nutrient uptake, growth and seed yield of black seed (Nadeem et al., 2013). It has been reported that weed competition through growth periods would decrease black seed yield by 69% (Hussain et al., 2009).

Chemical weed control in black seed fields in turn increases production cost, and more, due to adverse impacts of herbicides on the environment and human health (Chikowo et al., 2009; Swanton et al., 2010) and especially on secondary metabolites and pharmacological values of medicinal plants (Tekel et al., 1997; Abou-Arab et al., 1999), non-chemical weed control is considered as an important agronomic practice for black seed production.

Integrated weed management strategies are introduced as an approach for reducing herbicide use (Swanton and Weise, 1991; Swanton et al., 2010). On the other hand, critical period of weed control is well known as a main component of integrated weed

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Table 1 Monthly rainfall and average temperature during both years of the experiment

Month	Rainfall/mm		Average temperature/°C	
	2011	2012	2011	2012
March	15.8	54.2	9.8	8.5
April	2.6	43.2	18.0	17.8
May	15.4	18.4	23.8	21.2
June	6.4	9.5	28.0	26.1
July	0	0	28.8	28.8
Total	40.2	125.3	—	—
Average	—	—	21.7	20.5

management programs (Swanton and Weise, 1991; Knezevic et al., 2002). According to Knezevic et al. (2002), critical period of weed control is defined as "the time interval between two separately measured crop–weed competition components: (1) the critical timing for weed removal or the maximum amount of time early season weed competition can be tolerated by the crop before it suffers irrevocable yield reduction; (2) the critical weed-free period or the minimum weed-free period required from the time of planting to prevent unacceptable yield reductions". The beginning and end of the critical period of weed control are determined by the critical timing of weed removal and the critical weed-free period, respectively (Everman et al., 2008; Cardoso et al., 2011).

The critical period of weed control indicates the optimum time for applying the weed control measure (Cardoso et al., 2011). Therefore, information on these periods can be effective to improve the efficiency of weed management practices (Hall et al., 1992; Amador-Ramírez, 2002; Bukun, 2004). However, information on critical timing of weed removal and critical weed-free periods in black seed is rare. Nadeem et al. (2013) reported that the critical weed competition period of black seed is located within 40 days after emergence. Therefore, the main objective of the present study was to determine the beginning and end of critical period of weed control in black seed in a semi-arid region of Iran. To better understand the black seed–weed interference, the effects of weed competition periods on nutrients uptake by black seed and the companion weeds were also determined. The knowledge of the critical timing of weed removal, critical weed-free period, and subsequently the critical period of weed control in black seed could help producers to improve their weed management strategies and to prevent yield loss resulting from weed interference while reducing the amount of herbicide use.

2. Materials and methods

2.1. Site description

Field studies were conducted in 2011 and 2012 at the experimental station at College of Agriculture, Ferdowsi University of Mashhad, Iran (latitude: 36°15′N; longitude: 59°28′E; elevation: 985 m above sea level). Experimental site was located in semi-arid region with mean annual precipitation and temperature of 252 mm and 15 °C, respectively. Monthly rainfall and average temperature during these years are presented in Table 1.

Soil samples were taken randomly from 0–30 cm depth in both years. The soil texture was clay, pH 8.1, electrical conductivity (EC) 0.90 dS · m^{-1} and 0.38% organic matter (average of two years). The available N, P and K contents of the soil were 11, 10.5 and 143 mg · kg^{-1}, respectively.

2.2. Experimental design

A randomized complete block design with 12 treatments and three replicates was used. Two quantitative series of weed removal treatments including weed-infested (WI) and weed-free (WF) treatments (Tursun et al., 2007) were implemented from black seed emergence to maturity harvest (Fig. 1). The first series was intended to determine the beginning of the critical period of weed control. Black seed plants competed with weeds for 0 (WI 0), 14 (WI 14), 28 (WI 28), 42 (WI 42), 56 (WI 56), 70 (WI 70) days after emergence (Fig. 1, A). The second series was used to determine the end of critical period of weed control. Experimental plots were kept weed-free for 0 (WF 0), 14 (WF 14), 28 (WF 28), 42 (WF 42), 56 (WF 56), 70 (WF 70) days after emergence (Fig. 1, B). There were 8 days intervals from seed sowing until seedlings emergence.

2.3. Agronomic practices

The experimental field was prepared according to the local practice for black seed production. The primary tillage was performed after applying cattle manure at 25 t · ha^{-1} in autumn and followed by two harrowing before seed sowing. Seeds were sown

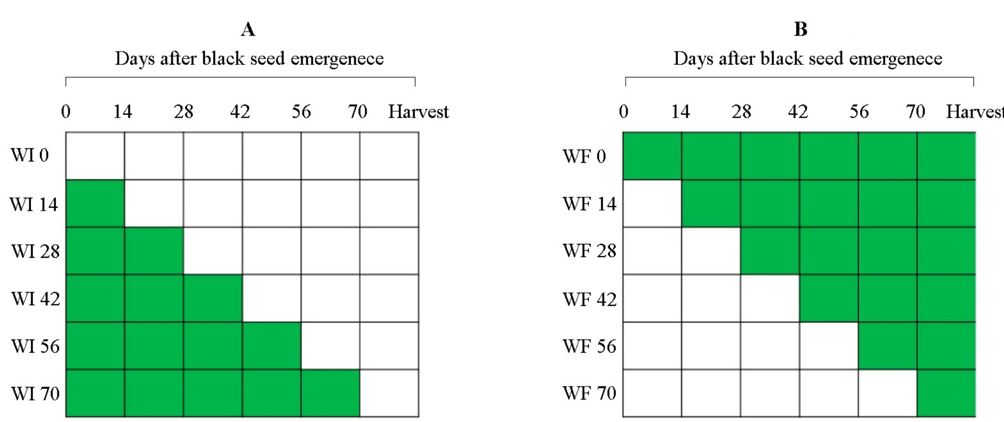

Fig. 1 Weed-infested (A) and weed-free (B) treatments (based on day after emergence)
Green square indicates the weed interference. WI: weed-infested periods; WF: weed-free periods.

on March 12th in 2011 and March 24th in 2012 in 10 m^2 plots (2 m long × 5 m width) with 0.5 m row spacing. These plots were arranged randomly. Final crop density was fixed at 150 plants · m^{-2}.

The first irrigation was done immediately after seed sowing and repeated weekly until physiological maturity of black seed. No chemical fertilizers, herbicides or pesticides were used throughout the growing seasons. Weed management was carried out by removing with a hoe and pulling by hand.

2.4. Weed and crop measurements

Composition, density, leaf area index and dry weight of weed species were determined using a 0.5 m × 0.5 m quadrate at the end of weeding time and harvest stage of black seed in WI and WF treatments. In order to determine the leaf area index and dry weight, weed species were cut at the soil surface and dried at 75 °C for 48 h.

At flowering stage, leaf area index of the crop was measured in a 0.25 m × 0.5 m quadrate per plot. Grain and oil yields and harvest index of black seed were estimated at the end of growing season (June 30th in 2011 and July 6th in 2012). Harvest index was calculated by dividing the grain weight by the total aboveground dry weight at harvesting time (Pedersen and Lauer, 2004). Before harvesting, plant height, number of follicles per plant and 1000-seed weight were measured on 12 randomly selected plants.

2.5. Determination of nutrient content

Nutrient content in dried aerial parts of all weed species as a sample in each plot, as well as in grain and aerial part of black seed were determined by using dried ground material. The N, P and K contents were determined using Kjeltec Auto 1030 Analyzer, Spectero photometer (UNICO S- 2100-Vis) and a flame photometer (Jenway, PFP-7), respectively (Murphy and Riley, 1962; Miller, 1998; AOAC, 2000).

2.6. Determination of nutrient content

A base temperature (T_b) of 5 °C was used as the minimum temperature for black seed growth (Ghaderi et al., 2008). Growing degree days (GDD, °C d) was calculated from Eq. (1) for each day:

$$GDD = \sum[(T_{max} + T_{min})/2 - T_b] \quad (1)$$

The Gompertz equation (Ratkowsky, 1990) was used to describe the effects of WF periods on grain yield of black seed (Eq. 2):

$$Y = A \times \exp[-B \times \exp(-K \times GDD)] \quad (2)$$

where Y is the yield as a percentage of the WF control, A is the upper asymptote, B and K are parameters which determine the shape of the curve, and GDD is for the length of WF or WI periods after crop emergence.

A Logistic equation (Ratkowsky, 1990) was used to determine the effects of WI periods on the grain yield of black seed (Eq. 3):

$$Y = A + B/[1 + C \times \exp(D \times GDD)] \quad (3)$$

where Y is the yield as a percentage of the WF control, A and B are parameters that determine the shape of the curve, C is the lower asymptote, D is the difference between the upper and lower asymptotes, and GDD for the length of WF or WI periods after crop emergence.

Determination of the beginning (critical timing of weed removal) and end (critical weed-free period) of critical period of weed control in this study was on the basis of acceptable grain yield loss levels of 5% and 10% (Tursun et al., 2007).

Statistical analysis was performed using SAS software version 9.3 (SAS Institute Inc., Cary, NC, USA). The data were analyzed using an analysis of variance (ANOVA). Statistically significant mean values were separated by the least significant difference (LSD) tests at the 5% probability level.

3. Results

3.1. Weeds community characteristics

The natural weed community was composed of 12 and 7 different species in 2011 and 2012, respectively. In contrast to the first year, no spring weed species were found in the second year (Table 2).

Differences in weed composition between two years might be due to difference between experimental sites and relatively late sowing date in 2012 (March 24th), compared with 2011 (March 12th). In other words, it seems that the late soil preparation and sowing lead to a disorder in weeds growth cycle that start to germinate and emerge in late winter to early spring. So that in the second year, annual weeds such as *Descurainia sophia* and *Capsella bursa-pastoris* were not observed. In this regards, Tursun et al. (2007) have stated that different experimental sites, year and management practices can affect weed community in leek (*Allium porrum* L.) field. The similar results were also reported by other researchers on different crops (Ngouajio et al., 1997; Amador-Ramírez, 2002; Tepe et al., 2005).

In both years of the experiment, the highest weed densities were observed 42 days after emergence (WI 42) and then declined. On 42nd days after seedling emergence, total weed density was found to be higher in the first year (384 plants · m^{-2}) than in the second year (312 plants · m^{-2}). However, during both years, dominant weed species were very similar (Tables 3 and 4).

Table 2 Weed composition of black seed field in two years of the experiment

Common name	Scientific name	2011	2012
Redroot pigweed	*Amaranthus retroflexus* L.	+	+
Shepherd's-purse	*Capsella bursa-pastoris* L.	+	−
Common lambs quarters	*Chenopodium album* L.	+	+
Field bindweed	*Convolvulus arvensis* L.	−	+
Flixweed	*Descurainia sophia* L.	+	−
Barnyardgrass	*Echinochloa cruss-galli* L.	+	+
Common fumitory or earth smoke	*Fumaria officinalis* L.	+	−
Knotgrass	*Polygonum aviculare* L.	+	−
Little hogweed	*Portulaca oleracea* L.	+	+
European black nightshade	*Solanum nigrum* L.	+	+
Corn sow thistle	*Sonchus arvensis* L.	+	+
Grass leaf starwort	*Stellaria graminea* L.	+	−
Persian speedwell	*Veronica persica* L.	+	−

Note: +: present, −: absent.

Table 3 Effects of weed-free (WF) and weed infested (WI) periods (days after emergence) on plant density, plant height and dry weight of weed species in black seed field (2011)

Scientific name	Plant density/m^2											
	WF0	WF14	WF28	WF42	WF56	WF70	WI0	WI14	WI28	WI42	WI56	WI70
Amaranthus retroflexus L.	36.0 ± 14.2	32.0 ± 12.8	33.3 ± 12.7	41.3 ± 13.4	42.3 ± 15.4	—	—	—	28.0 ± 9.4	141.3 ± 30.7	56.0 ± 12.6	45.3 ± 18.2
Capsella bursa-pastoris L.	—	—	—	—	—	—	—	1.3 ± 1.2	1.3 ± 0.9	2.7 ± 1.3	—	—
Chenopodium album L.	12.0 ± 5.0	13.3 ± 6.5	13.3 ± 3.1	14.7 ± 14.3	—	—	—	34.7 ± 7.1	118.7 ± 23.3	69.3 ± 21.6	41.3 ± 16.0	12.0 ± 3.3
Descurainia sophia L.	—	—	—	—	—	—	—	1.3 ± 0.9	1.3 ± 0.4	2.7 ± 0.5	1.0 ± 0.8	—
Echinochloa cruss-galli L.	33.3 ± 17.3	30.7 ± 12.4	32.0 ± 11.6	29.3 ± 10.3	22.3 ± 4.1	—	—	141.3 ± 37.1	126.7 ± 19.6	142.7 ± 32.1	60.0 ± 16.9	36.0 ± 15.5
Fumaria officinalis L.	—	—	—	—	—	—	—	10.7 ± 1.9	8.0 ± 5.4	2.7 ± 1.3	—	—
Polygonum aviculare L.	—	—	—	—	—	—	—	1.3 ± 0.4	2.7 ± 1.3	1.3 ± 0.4	4.0 ± 2.2	4.0 ± 2.2
Portulaca oleracea L.	4.0 ± 3.3	4.0 ± 3.3	4.0 ± 2.4	4.0 ± 3.6	4.0 ± 2.9	4.0 ± 3.3	—	—	—	—	4.0 ± 2.9	4.0 ± 0.8
Solanum nigrum L.	14.7 ± 4.8	14.7 ± 9.9	13.3 ± 4.9	13.3 ± 6.8	13.3 ± 1.9	—	—	—	—	—	17.0 ± 3.7	17.3 ± 2.7
Sonchus arvensis L.	2.7 ± 2.4	1.3 ± 1.2	1.3 ± 1.2	—	—	—	—	—	—	1.3 ± 1.2	2.7 ± 2.5	1.3 ± 0.4
Stellaria graminea L.	—	—	—	—	—	—	—	25.3 ± 12.6	20.0 ± 3.3	16.0 ± 8.6	10.7 ± 1.9	—
Veronica persica L.	—	—	—	—	—	—	—	8.0 ± 3.3	14.7 ± 5.0	4.0 ± 2.4	4.0 ± 2.2	—
Total	102.7	96.0	97.3	102.7	82.0	4.0	—	223.9	321.3	384.0	200.7	120.0

Scientific name	Plant height/cm											
	WF0	WF14	WF28	WF42	WF56	WF70	WI0	WI14	WI28	WI42	WI56	WI70
Amaranthus retroflexus L.	43.0 ± 5.7	41.9 ± 2.5	39.7 ± 7.0	17.4 ± 5.3	12.2 ± 3.0	—	—	—	3.9 ± 1.5	13.8 ± 2.2	29.4 ± 3.1	44.7 ± 4.9
Capsella bursa-pastoris L.	—	—	—	—	—	—	—	13.8 ± 1.3	42.0 ± 4.3	36.5 ± 5.3	—	—
Chenopodium album L.	95.9 ± 16.4	98.1 ± 7.5	60.9 ± 4.2	21.8 ± 4.3	—	—	—	4.7 ± 1.2	7.6 ± 1.8	47.2 ± 5.1	49.4 ± 3.3	94.2 ± 11.1
Descurainia sophia L.	—	—	—	—	—	—	—	25.1 ± 6.6	54.0 ± 12.4	72.4 ± 15.1	80.0 ± 11.4	—
Echinochloa cruss-galli L.	70.8 ± 7.0	73.9 ± 5.9	71.4 ± 6.3	61.5 ± 4.6	18.0 ± 2.9	—	—	3.3 ± 1.3	11.3 ± 2.3	27.4 ± 3.9	45.2 ± 4.5	71.7 ± 13.2
Fumaria officinalis L.	—	—	—	—	—	—	—	9.7 ± 1.7	24.1 ± 2.3	39.0 ± 9.1	—	—
Polygonum aviculare L.	—	—	—	—	—	—	—	12.1 ± 1.3	16.3 ± 2.3	29.4 ± 6.0	47.0 ± 10.0	45.4 ± 6.9
Portulaca oleracea L.	19.3 ± 1.3	18.5 ± 2.5	16.6 ± 1.8	13.5 ± 1.8	13.8 ± 3.7	9.9 ± 2.1	—	—	—	—	8.0 ± 2.2	16.4 ± 2.6
Solanum nigrum L.	24.8 ± 3.5	22.0 ± 2.2	23.9 ± 2.5	18.1 ± 2.1	13.9 ± 1.5	—	—	—	—	—	6.4 ± 2.0	21.4 ± 3.3
Sonchus arvensis L.	41.2 ± 3.5	42.7 ± 2.5	30.1 ± 3.3	—	—	—	—	—	—	29.3 ± 3.3	34.5 ± 4.5	36.2 ± 3.8
Stellaria graminea L.	—	—	—	—	—	—	—	13.4 ± 1.8	44.6 ± 4.7	70.3 ± 7.6	68.6 ± 10.0	—
Veronica persica L.	—	—	—	—	—	—	—	3.4 ± 1.2	10.3 ± 2.6	32.2 ± 5.8	26.5 ± 4.1	—

Scientific name	Dry weight/(g·m^{-2})											
	WF0	WF14	WF28	WF42	WF56	WF70	WI0	WI14	WI28	WI42	WI56	WI70
Amaranthus retroflexus L.	72.8 ± 26.9	70.4 ± 11.0	60.4 ± 5.1	28.9 ± 7.1	16.8 ± 3.8	—	—	—	10.5 ± 4.0	26.2 ± 5.5	69.6 ± 7.9	80.0 ± 16.8
Capsella bursa-pastoris L.	—	—	—	—	—	—	—	1.4 ± 1.1	1.5 ± 1.1	1.6 ± 0.2	—	—
Chenopodium album L.	200.0 ± 29.0	175.6 ± 16.4	120.0 ± 7.8	36.7 ± 28.3	—	—	—	7.5 ± 1.7	26.4 ± 4.8	47.0 ± 9.6	112.5 ± 19.0	206.7 ± 21.4
Descurainia sophia L.	—	—	—	—	—	—	—	16.0 ± 12.7	20.4 ± 4.9	28.7 ± 2.3	7.5 ± 5.5	—
Echinochloa cruss-galli L.	70.0 ± 16.3	73.6 ± 8.0	60.5 ± 6.0	31.6 ± 9.4	70.6 ± 13.6	—	—	2.9 ± 0.7	3.8 ± 0.8	13.6 ± 3.1	52.8 ± 12.1	68.6 ± 8.0
Fumaria officinalis L.	—	—	—	—	—	—	—	7.3 ± 1.7	22.4 ± 13.4	6.1 ± 2.1	—	—
Polygonum aviculare L.	—	—	—	—	—	—	—	1.5 ± 0.2	3.3 ± 1.9	12.9 ± 4.0	27.7 ± 6.9	23.3 ± 4.6
Portulaca oleracea L.	12.0 ± 9.1	12.4 ± 9.0	11.7 ± 3.2	12.5 ± 4.9	11.6 ± 6.4	3.6 ± 2.8	—	—	—	—	10.0 ± 2.9	10.5 ± 3.0
Solanum nigrum L.	39.9 ± 9.7	40.8 ± 10.6	32.5 ± 9.4	31.6 ± 7.3	14.0 ± 5.6	—	—	—	—	—	19.2 ± 5.8	30.2 ± 6.1
Sonchus arvensis L.	4.1 ± 1.9	3.6 ± 2.5	4.2 ± 3.0	—	—	—	—	—	—	1.9 ± 1.4	4.7 ± 3.6	2.8 ± 1.2
Stellaria graminea L.	—	—	—	—	—	—	—	26.7 ± 3.3	67.4 ± 5.1	62.7 ± 17.5	60.5 ± 4.3	—
Veronica persica L.	—	—	—	—	—	—	—	1.9 ± 0.7	4.8 ± 0.8	6.6 ± 2.6	4.1 ± 1.0	—
Total	398.8	376.4	289.3	141.3	50.0	3.6	—	65.1	160.6	207.3	368.6	422.1

Table 4 Effects of weed-free (WF) and weed infested (WI) periods (days after emergence) on plant density, plant height and dry weight of weed composition in black seed field (2012)

Scientific name	Plant density/m²										
	WF0	WF14	WF28	WF42	WF56	WF70	WI0	WI14	WI28	WI42	WI56	WI70
Amaranthus retroflexus L.	28.0 ± 3.3	26.7 ± 1.9	17.3 ± 1.9	29.3 ± 1.9	26.7 ± 6.8	—	—	1.3 ± 1.9	26.7 ± 3.8	125.3 ± 13.2	25.3 ± 8.2	36.0 ± 9.8
Chenopodium album L.	12.0 ± 3.3	12.0 ± 5.7	10.7 ± 3.8	13.3 ± 1.9	5.3 ± 1.9	1.3 ± 1.9	—	125.3 ± 13.6	90.7 ± 13.2	46.7 ± 8.2	32.0 ± 6.5	10.7 ± 1.9
Convolvulus arvensis L.	1.3 ± 1.9	2.7 ± 1.9	2.7 ± 1.9	—	2.7 ± 3.8	2.7 ± 1.9	—	—	4.0 ± 0.8	4.0 ± 0.8	2.7 ± 3.8	—
Echinochloa cruss-galli L.	21.3 ± 1.9	20.0 ± 3.3	26.7 ± 3.8	25.3 ± 3.8	28.0 ± 5.7	—	—	102.7 ± 15.4	133.3 ± 5.0	126.7 ± 10.0	45.3 ± 8.2	44.0 ± 3.3
Portulaca oleracea L.	4.0 ± 3.3	1.3 ± 1.9	4.0 ± 3.3	2.7 ± 3.8	1.3 ± 1.9	1.3 ± 1.9	—	—	1.3 ± 1.9	6.7 ± 1.9	5.3 ± 1.9	8.0 ± 0.0
Solanum nigrum L.	12.0 ± 3.3	10.7 ± 1.9	12.0 ± 3.3	9.3 ± 1.9	1.3 ± 1.9	—	—	—	4.0 ± 3.3	2.7 ± 1.9	10.7 ± 3.8	13.3 ± 1.9
Sonchus arvensis L.	1.3 ± 1.9	1.3 ± 1.9	2.7 ± 1.9	—	—	—	—	—	1.3 ± 1.9	—	5.3 ± 0.5	5.3 ± 3.8
Total	80.0	74.7	76.0	80.0	65.3	5.3	—	229.3	261.3	312.0	126.7	117.3

Scientific name	Plant height/cm										
	WF0	WF14	WF28	WF42	WF56	WF70	WI0	WI14	WI28	WI42	WI56	WI70
Amaranthus retroflexus L.	51.2 ± 10.8	53.2 ± 6.2	43.1 ± 6.8	30.1 ± 7.1	9.3 ± 2.3		—		11.3 ± 1.7	16.7 ± 4.2	29.3 ± 4.1	54.2 ± 5.6
Chenopodium album L.	90.1 ± 11.3	92.5 ± 20.0	72.4 ± 5.8	61.3 ± 7.1	21.2 ± 4.7	10.9 ± 2.5	—	3.9 ± 1.2	11.9 ± 2.8	32.1 ± 4.2	61.9 ± 4.0	81.9 ± 12.4
Convolvulus arvensis L.	21.3 ± 4.9	30.7 ± 5.0	26.1 ± 6.2	—	16.9 ± 2.7	17.6 ± 3.5	—	—	16.4 ± 3.2	31.4 ± 8.4	19.6 ± 4.5	—
Echinochloa cruss-galli L.	73.9 ± 25.9	68.9 ± 15.4	58.6 ± 12.5	53.3 ± 6.7	28.9 ± 6.0	—	—	2.9 ± 1.0	16.7 ± 6.9	31.9 ± 6.6	61.8 ± 7.0	74.2 ± 5.5
Portulaca oleracea L.	21.6 ± 2.4	16.5 ± 2.5	17.8 ± 4.7	14.5 ± 2.2	10.8 ± 3.3	7.7 ± 1.4	—	—	10.0 ± 3.0	14.9 ± 2.1	16.1 ± 4.2	14.7 ± 2.2
Solanum nigrum L.	33.9 ± 6.2	32.1 ± 5.2	29.0 ± 7.5	17.6 ± 5.2	14.3 ± 4.2	—	—	—	14.5 ± 4.3	21.3 ± 3.5	24.3 ± 3.9	26.4 ± 3.7
Sonchus arvensis L.	36.5 ± 4.5	37.6 ± 6.6	29.6 ± 7.7	—	—	—	—	—	16.9 ± 5.9	—	30.6 ± 7.4	25.5 ± 4.7

Scientific name	Dry weight/(g · m⁻²)										
	WF0	WF14	WF28	WF42	WF56	WF70	WI0	WI14	WI28	WI42	WI56	WI70
Amaranthus retroflexus L.	64.6 ± 3.4	55.4 ± 3.3	57.1 ± 3.4	42.4 ± 0.7	23.4 ± 4.3	—	—	1.3 ± 1.8	25.6 ± 4.9	64.6 ± 3.1	70.0 ± 2.1	70.4 ± 11.3
Chenopodium album L.	178.0 ± 9.8	165.6 ± 5.3	152.6 ± 2.9	109.4 ± 2.5	58.6 ± 1.7	6.7 ± 0.9	—	9.4 ± 0.8	30.0 ± 1.7	95.7 ± 4.5	155.1 ± 4.3	167.9 ± 5.8
Convolvulus arvensis L.	3.7 ± 5.2	5.9 ± 4.2	4.7 ± 3.4	—	1.5 ± 2.2	2.0 ± 1.6	—	—	4.1 ± 0.3	7.7 ± 0.6	4.5 ± 6.4	—
Echinochloa cruss-galli L.	65.6 ± 4.5	56.0 ± 2.6	61.8 ± 1.5	70.3 ± 1.6	37.8 ± 1.0	—	—	8.4 ± 0.5	10.4 ± 0.9	41.0 ± 2.5	76.9 ± 3.3	79.3 ± 2.4
Portulaca oleracea L.	12.9 ± 1.0	13.1 ± 1.3	12.2 ± 1.0	9.9 ± 1.0	9.6 ± 0.6	7.5 ± 0.6	—	—	11.5 ± 0.9	9.8 ± 1.1	12.3 ± 1.6	13.0 ± 1.2
Solanum nigrum L.	34.9 ± 1.4	32.7 ± 1.4	33.6 ± 2.1	28.0 ± 1.2	11.0 ± 1.2	—	—	—	8.4 ± 0.7	14.3 ± 1.6	18.3 ± 2.9	26.3 ± 1.6
Sonchus arvensis L.	3.4 ± 0.2	4.0 ± 0.3	3.8 ± 0.3	—	—	—	—	—	2.9 ± 0.2	—	3.8 ± 0.3	3.7 ± 0.8
Total	363.1	332.7	325.9	260.0	141.9	16.2	—	19.1	92.9	233.2	340.9	360.6

Table 5 Effects of weed-free (WF) and weed infested (WI) periods (days after emergence) on some nutrient content in weed composition tissues

Weed competition periods (W)	Content/(g · kg^{-1})		
	Nitrogen	Phosphorus	Potassium
WF 0	36.7	4.5	5.4
WF 14	36.7	3.9	5.4
WF 28	37.2	4.7	5.7
WF 42	36.0	4.3	6.4
WF 56	35.4	5.5	6.5
WF 70	34.5	4.1	4.4
WI 0	0	0	0
WI 14	33.6	3.5	3.9
WI 28	34.4	4.0	4.1
WI 42	36.3	5.8	4.2
WI 56	36.1	6.0	4.8
WI 70	38.8	5.0	5.5
LSD (P = 0.05)	0.36	0.07	0.05
Year (Y)	*	*	*
W	**	**	**
Y × W	NS	NS	NS

Note: NS, non-significant. *Statistical differences at $P \leq 0.05$. ** Statistical differences at $P \leq 0.01$.

In 2011, dry weight of *Stellaria graminea* at the beginning of the growing season was higher than other weed species. However, *Amaranthus retroflexus*, *Chenopodium album* and *Echinochloa cruss-galli* at the mid and end of growing season were dominant species (Table 3). In 2012, the major weed species were also *E. cruss-galli*, *A. retroflexus* and *C. album* accounting comprising 26.6%, 35% and 15% of total density; together these weed species represented 84.9% of total dry weight of weed composition at the end of growing season (WF 0) (Table 4).

In both years, weeds total dry weight increased with increasing duration of the WI and decreased as duration of the WF increased (Tables 3 and 4). In addition, N, P and K uptake by weed species significantly increased with increasing the WI periods (Table 5). This phenomenon is in agreement with Karkanis et al. (2012) and Stagnari and Pisante (2011) who observed an increase in total weed biomass with increasing weed competition duration.

3.2. Crop response to WF and WI periods

The results indicated that black seed height was strongly affected by different WF and WI periods. Interestingly, weed interference for entire growing season (WF 0) caused an increase in black seed height by 30.3%, compared with the treatment that was WF throughout the growing season (WI 0) (Table 6).

These results could be attributed to higher weed height, especially *C. album*, *E. cruss-galli* and *A. retroflexus* compared with black seed plants (approximately 1.2 to 2.6 times); therefore, probably there was more competition between black seed and weed community over light absorption.

The results showed that grain and oil yields of black seed significantly affected by WF and WI periods (Table 6). Weed competition for total growing season (WF 0) reduced the grain yield of black seed by 87%, compared with entire weed-free treatment (WI 0). It appears that oil yield is directly related to the grain yield as there was no difference between WF and WI treatments on oil percentage (Table 6).

The reduction in grain and oil yields due to increased length of WI and decreased length of WF periods were accompanied by simultaneous reduction in leaf area index, number of follicles per plant and harvest index (Table 6). The results of the current study mirror Hussain et al. (2009) findings. They have reported that follicle number per plant, seed yield and harvest index of black seed were significantly influenced by weed interference. Amador-Ramírez (2002) stated that reduction in fruit number per plant and yield of chili pepper (*Capsicum annum* L.) is attributed to weed pressure measured by weed dry weight and density. From the results, significant reduction in grain and oil yield confirms this fact that black seed has weak competitiveness compared with weed populations.

N, P and K contents in black seed grains and tissues significantly decreased as the weed-black seed competition increased during WI periods (Table 7). Overall, N, P and K contents in

Table 6 Effects of weed-free (WF) and weed infested (WI) periods (days after emergence) on some studied characteristics of black seed

Weed competition periods (W)	Plant height/cm	Leaf area index	Number of follicles per plant	Grain yield/(kg · hm^{-2})	Harvest index/%	Oil/%	Oil yield/(kg · hm^{-2})
WF 0	42.95	0.12	3.73	87.33	15.73	31.04	27.34
WF 14	42.72	0.16	4.25	88.46	15.99	30.33	27.01
WF 28	38.65	0.29	4.17	125.11	16.21	30.27	37.72
WF 42	33.60	0.43	10.96	313.13	29.13	31.46	99.30
WF 56	31.87	0.45	10.83	601.61	30.74	30.14	182.98
WF 70	32.88	0.46	11.23	712.38	31.94	31.13	222.45
WI 0	32.97	0.43	11.33	686.40	31.06	31.04	213.95
WI 14	33.17	0.36	10.77	681.33	31.55	30.07	205.29
WI 28	39.13	0.28	10.25	481.95	27.30	30.66	147.29
WI 42	42.53	0.12	5.08	161.05	20.44	30.84	49.37
WI 56	43.70	0.12	3.84	149.95	18.98	31.31	46.75
WI 70	44.05	0.12	3.96	94.78	16.29	31.47	29.97
LSD (P = 0.05)	*2.10*	*0.03*	*1.11*	*40.03*	*2.29*	*2.61*	*14.47*
Year (Y)	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
W	**	**	**	**	**	*NS*	**
Y × W	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*

Note: NS, non-significant. *Statistical differences at $P \leq 0.05$. **Statistical differences at $P \leq 0.01$.

Table 7 Effects of weed-free (WF) and weed infested (WI) periods (days after emergence) on some nutrient content and contents of black seed $g \cdot kg^{-1}$

Weed competition periods (W)	Grain			Tissue		
	Nitrogen	Phosphorus	Potassium	Nitrogen	Phosphorus	Potassium
WF 0	33.5	3.5	3.8	15.1	2.1	1.2
WF 14	33.9	3.5	3.5	17.0	2.2	1.2
WF 28	33.1	4.6	4.3	16.0	2.5	1.5
WF 42	34.6	5.0	4.2	18.4	3.2	1.8
WF 56	35.2	6.0	6.8	19.3	2.7	2.5
WF 70	36.2	7.5	7.2	19.5	3.5	2.7
WI 0	36.4	7.7	7.0	20.2	3.6	2.8
WI 14	36.5	7.8	7.4	20.0	3.6	2.8
WI 28	35.9	6.5	4.5	19.7	3.4	2.0
WI 42	35.2	6.0	4.2	19.1	3.0	1.8
WI 56	35.7	3.8	3.7	17.3	2.3	1.4
WI 70	33.8	3.5	3.4	16.4	2.5	1.2
LSD ($P = 0.05$)	0.21	0.09	0.08	0.16	0.05	0.03
Year (Y)	NS	NS	NS	*	NS	NS
W	**	**	**	**	**	**
Y × W	NS	NS	NS	NS	NS	NS

Note: NS, non-significant. *Statistical differences at $P \leq 0.05$. **Statistical differences at $P \leq 0.01$.

weed species tissue were found to be 1.8 to 2 times higher those that of black seed (Table 7). These results are in line with Mehriya et al. (2007) who observed a high uptake of N, P and K by weeds under weed-cumin (*Cuminum cyminum*) competition.

Evaluation of the nutrients absorption such as N and P affecting the crop–weed competition can be effective in developing better weed management decision (Blackshaw and Brandt, 2009; Lindquist et al., 2010; Ghasemi-Fasaei and Mansoorpoor, 2015; Tursun et al., 2015). A significant decrease in N, P and K contents in black seed tissue emphasize the poor absorption ability of nutrients by black seed in competition with weed species. Therefore, by considering the significant influence of soil fertility on crop–weed competition (Blackshaw et al., 2004, 2005; Ghasemi-Fasaei and Mansoorpoor, 2015), the timely and appropriate nutrients management in black seed can be effective in reducing the adverse effects of weed interference on soil nutrient resources.

3.3. *Critical period of weed control*

Black seed growth period length in 2011 (111 days) was slightly longer than that in 2012 (105 days). According to 5% and 10% acceptable grain yield loss levels, beginning of the critical period in black seed was estimated at 13 and 17 days after seedling emergence (108 and 149 GDD) in 2011 and 11 and 14 days (87 and 130 GDD) after seedling emergence in 2012 (Fig. 2 and Table 8). In addition, based on 5% and 10% acceptable grain yield loss levels, the end of critical period of weed control was determined 75 and 71 days (960 and 883 GDD) after seedling emergence in 2011 and 64 and 57 days (922 and 783 GDD) after seedling emergence in 2012.

Based on 5% and 10% acceptable grain yield loss levels, critical period of weed control in 2011 was longer than that in 2012. These might be attributed to lower weed density and weed dry weight and delayed sowing date in 2012 compared with 2011. This shows that in terms of a higher density of weeds, farmers should pay more attention to critical timing of weed removal, so that any delay at the beginning of weed control can cause further reduction in black seed yield. In this regards, Tursun et al. (2007) have reported that the temporal differences between the beginning and end of critical period of weed control in leek can be due to different weed densities between the studied years of experiment. Swanton et al. (2010) observed that delay in planting can reduce

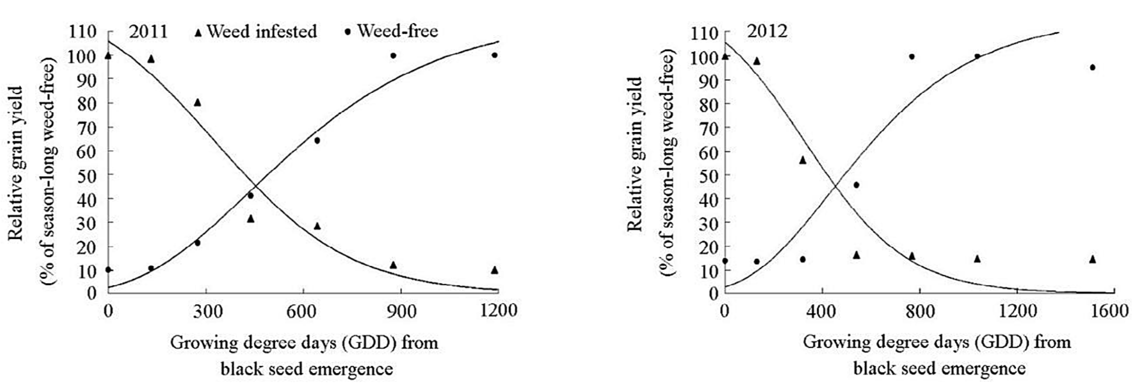

Fig. 2 Effect of weed-free and infested periods on relative grain yield of black seed in 2011 and 2012
Increasing duration of weed infested (triangles) and fitted curves as calculated by the logistic equation; increasing weed-free period (circles) and fitted curves as calculated by the Gompertz equation.

Table 8 Details of critical period of weed control in black seed for two acceptable grain yield loss levels based on growth degree days (GDD) and days after emergence

Year	Acceptable grain yield loss level/%	Critical timing of weed removal (beginning of period)		Minimum weed-free period (end of period)		Critical period of weed control	
		Day	GDD	Day	GDD	Day	GDD
First	5	13	108	75	960	62	852
(2011)	10	17	149	71	883	54	734
Second	5	11	87	64	922	53	835
(2012)	10	14	130	57	783	43	653

the duration of critical period of weed control in carrot (*Daucus carota*). In general, the beginning and end of critical period of weed control in crops can be affected by year, location, plant density, cultivar and arbitrary levels of yield loss (Ngouajio et al., 1997; Martin et al., 2001; Ahmadvand et al., 2009).

4. Conclusions

Annual weed species presence during the growing season of black seed is considered a serious problem which causes severe grain and oil yields losses. According to practical implication, it was concluded that 58 or 49 days weed-free periods are required to avoid yield loss (above 5% or 10%) in black seed. Considering a low reliance on chemical herbicides for long-term weed management, results of this study provide basis information for black seed producers to choose an appropriate time to control weeds. However, further field experiments should be carried out to study the critical period of weed control in black seed fields in different locations with different weed communities and climate conditions.

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