

Effects of Weed-Control Treatments and Plant Density on Root Yield and Sugar Content of Sugar Beet

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Abstract This study was conducted to investigate the effects of weed-control treatments and plant densities on root yield and sugar content of sugar beet in the 2015, 2016, and 2017 growing seasons in Eskişehir, Türkiye. Weed-control treatments were designed considering the applications of sugar beet farmers and non-weed management (T_0), pre-emergence herbicide (T_1), post-emergence herbicide (T_2), $T_1 + T_2$ (T_3), T_1 + hand-hoeing (T_4), and weed-free (T_5) with continuous hand-hoeing. Five plant densities were arranged in different row spacings of 30 (D_1), 35 (D_2), 40 (D_3), 45 (D_4), and 50 (D_5) cm. Root yield, sugar content, yield reduction, weed-control efficiency, weed density, weed frequency, weed fresh weight, and weed dry weight were investigated. The results showed that the highest root yield and sugar content were obtained from T_5 with 117.1 ton ha⁻¹ and 15.17%, respectively. The lowest weed density and weed fresh and dry weights were measured in T_4 and T_3 . Depending on the year, the root yield decreased by 100% when there was no weed management. Among the plant densities, D_1 gave the highest sugar content with 13.22%, while the highest root yield (63.9 ton ha⁻¹) was observed in D_3 . The most common weed, *Amaranthus retroflexus* L., had an 85% frequency. The most intense weed was *Chenopodium album* L., with 38.86 plant m⁻². Weed-control treatments significantly enhanced sugar beet root yield and sugar content; furthermore, T_4 produced yields similar to weed-free treatment (T_5). To suppress weeds in sugar beet production, higher plant

densities (30, 35, and 40 cm) are suggested if mechanization facilities are available.

Keywords *Beta vulgaris* L. · Weed control · Plant density · Yield · Quality

Introduction

Sugar, humans' most important source of metabolic energy, is obtained mainly from plants such as sugar cane and sugar beet. In 2021 and 2022, a total of 170.5 million tons of sugar (37.4 million tons of sugar beet and 133.1 million tons of sugar cane) were produced in 110 countries. Sugar cane has several advantages; it is a perennial plant with high yields and low labor requirements. With 2.5 million tons of sugar production from sugar beet (Anonymous 2022), Türkiye is 5 worldwide and 4th in Europe. However, sugar beet production requires intensive labor and sophisticated mechanization.

The primary obstacle to high-yield sugar beet production is weeds from sowing to harvesting. Weeds compete with sugar beet plants for water, nutrients, and sunlight, resulting in a dramatic decline in sugar content and sugar beet yield. Without weed control, sugar content and beet yield losses range from 6 to 40% (Soroka and Gadzhieva 2006; Sabancı 2013). Roland et al. (2017) reported that competitive weeds such as *C. album* and *A. retroflexus* cause a higher than an 80% loss in sugar beet yield. Bezhin et al. (2015) stated that sugar beet yield loss reached close to 100% unless weeds were controlled before reaching the 4–6 leaf stage. In Türkiye, mechanical and chemical weed management are the first choices for sugar beet cultivation (Buzluk and Acar 2002). Hoeing by hand or tractor can be applied to control weeds that emerge in row spacing (Schwizer and May

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1993); however, sugar beet roots and leaves may be damaged during hoeing. Recently, herbicides have been shown to provide several important advantages for efficient weed control due to their low cost, reduced labor requirements, and time-saving application during the vegetation period (Cioni and Maines 2010). Commonly used pre- and post-emergence herbicides include chloridazone, ethofumesate, desmedipham, and phenmedipham (Cioni and Maines 2010). Desmedipham controls *A. retroflexus* and phenmedipham controls other weeds except for *A. retroflexus*, while chloridazone controls broad-leaved weeds in sugar beet farming (Vencill 2002; Odero et al. 2010; Jursik et al. 2011).

The number and distribution of plants per unit area greatly affect the yield and quality of sugar beet as well as agronomic practices such as fertilization and irrigation (Söğüt and Arıoğlu 2004; Ghaly and Salem 2016). As plant density increases, sodium, potassium, and amino nitrogen decrease, and sugar content, dry matter, and juice purity increase (Çakmakçı and Oral 1998; Shalaby et al. 2011; Leilah et al. 2017). Çakmakçı and Oral (1998) found that 80,000–100,000 plants per hectare are optimal in Türkiye, and Bee and Jaggard (1996) recommended this in the UK. Lower plant density led to an increase in free space in the field and resulted in greater weed growth (Tharp and Kells 2001). In previous research, different plant densities have been advised for sugar beet including 100,000–150,000 (Yonts and Smith 1997), 108,000–118,000 (Kristek et al. 2012), and 88,000 (Safina et al. 2012) plants per hectare. In general, row spacing of 45 cm is considered optimal because of mechanization (Er and Uranbey 1998; Arıoğlu 2000), but narrower or wider spacings have not been tested for weed control. In the present study, the effectiveness of pre- and post-emergence herbicides and plant densities was investigated for weed control in sugar beet.

Material and Methods

Description of Field Sites and Experimental Design

Field experiments for this study were conducted during the 2015, 2016, and 2017 growing seasons at the Eskişehir

Osmangazi University, Faculty of Agriculture, Eskişehir, Türkiye (39°45'N, 30°28'E). The soil in the experimental area had a loamy texture, good drainage, and no groundwater problems. It was less calcareous in 2016 and 2017 compared to 2015. In terms of soil reaction, it is slightly alkaline and has a harmless total sand level and an enriched potassium level. The plant-available phosphorus was sufficient in 2015 and 2016, and moderate in 2017, and organic matter was low in all three years. Some physical and chemical properties are summarized in Table 1.

The mean temperatures were recorded as 15.8 °C over the long term, and 16.4 °C, 16.8 °C, and 16.2 °C in 2015, 2016, and 2017, respectively. The amount of total precipitation over the long term (180 mm) was lower in 2015 (299.8 mm) and 2017 (258.6 mm) but higher in 2016 (169.7 mm), when the summer (especially June) was wet and unfavorable for sugar beet growth. However, the situation was reversed for weed development, and the amount of total precipitation was about 200% higher in 2015 than in 2016. The conditions were adverse for effective hand-weeding. September in 2015 and 2017 was less wet compared to the long term and to 2016. Average temperatures for the summer and autumn were similar and above 10 °C in all three years after April. During the growing period, the meteorological conditions were close to the long-term average except for the summer of 2015 (Table 2).

In the experiment, chloridazone + triallate (Zoekon Super®) was used as a pre-emergence and ethofumesate + phenmedipham + desmedipham (Betanal Progress OF®) as a post-emergence herbicide (Table 3). Weeds were sprayed with chloridazone + triallate after sowing sugar beet, and with ethofumesate + phenmedipham + desmedipham when weeds had 2–6 leaves. The study included six weed-control treatments (T_0 , T_1 , T_2 , T_3 , T_4 , and T_5) with a combination of five plant densities (D_1 , D_2 , D_3 , D_4 , and D_5) (Table 4).

Crop Management

The experimental setting was a fallow area in crop rotation. In general, *A. retroflexus*, *C. album*, and

Table 1 Some physical and chemical properties of the experimental soils

Year	Depth cm	pH	CaCO ₃ %	Total sand %	Organic matter %	Available contents (kg ha ⁻¹)		Textural
						P ₂ O	K ₂ O	
2015	0–20	7.52	8.50	0.02	1.79	41	2540	Loam
	20–40	7.59	8.30	0.02	1.57	60	2420	Clay-Loam
2016	0–20	7.50	4.49	0.04	1.85	55	3750	Loam
	20–40	7.64	4.61	0.02	1.92	69	3660	Loam
2017	0–20	7.87	1.30	0.02	1.92	82	2620	Loam
	20–40	7.79	1.20	0.01	2.28	145	2160	Loam

Table 2 Meteorological conditions during the sugar beet growing seasons

Month	1970–2014		2015		2016		2017	
	°C	mm	°C	mm	°C	mm	°C	mm
April	9.6	43.1	7.9	26.6	12.9	36.7	9.7	58.7
May	14.9	40.0	15.5	47.8	14.2	44.7	14.3	55.2
June	19.1	23.7	17.1	151.1	20.9	6.3	19.1	46.3
July	22.1	13.1	22.1	0.0	22.0	14.5	22.9	11.6
August	21.8	9.2	22.7	37.2	22.7	27.7	22.0	35.2
September	16.7	18.1	20.9	3.1	17.7	31.7	19.6	5.1
October	11.7	32.8	13.1	34.0	12.1	8.1	10.7	46.5
Mean	15.8	27.5	16.4	39.5	16.8	25.6	16.2	37.9
Total	–	180	–	299.8	–	169.7	–	258.6

Table 3 Explanation of the herbicides

	Pre-emergence herbicide	Post-emergence herbicide
Trade name	Zoekon super®	Betanal progress OF®
Active ingredients	244 g L ⁻¹ chloridazone (5*) + 150 g L ⁻¹ triallate (15*)	112 g L ⁻¹ ethofumesate (15*) + 91 g L ⁻¹ phenmedipham (5*) + 71 g L ⁻¹ desmedipham (5*)
Formulation	SE	EC
IUPAC name	5-Amino-4-chloro-2-phenylpyridazin-3(2H)-one + S-2,3,3-trichloroallyl diisopropyl (thiocarbamate)	(RS)-2-ethoxy-2,3-dihydro-3,3-dimethylbenzofuran-5-yl methanesulfonate + Methyl 3-(3-methylcarbaniloyloxy) carbanilate or 3-methoxycarbonylamino phenyl 3-Methylcarbanilate + ethyl 3-phenylcarbamoyloxy carbanilate

*: WSSA code (WSSA 2022)

Solanum nigrum L. were the dominant weeds in the experimental areas, and standard soil-tillage methods were used. The experimental areas were deeply tilled with a standard moldboard plow in the fall and cultivated by a vertical spring cultivator in early spring. After that, nitrogen and phosphorus fertilizer was applied at the rate of 250 kg ha⁻¹ (18–46–0% N–P–K) for basal fertilization as a calculated 45 kg N ha⁻¹ and 115 kg P ha⁻¹. In this study, ‘Valentina’—a genetic monogerm, hybrid, root beard, and powdery mildew tolerant sugar beet variety—was used. Each subplot was arranged as 4 rows, each 4-m long, and seeds were manually sown at 2-cm depth with intra-row spacing of 22 cm on May 7, 2015; April 19, 2016; and April 20, 2017. Following sowing, subplots were sprayed

with pre-emergence herbicide. After emergence was completed, the thinning process was conducted. A post-emergence herbicide application was performed using a back sprayer when the weeds were at the 2–6 leaf stage. Ammonium sulfate (21% N) was applied using a spreader in two doses as top fertilization. The first dose was applied at the rate of 200 kg ha⁻¹ with the first irrigation, and the second dose was at the rate of 300 kg ha⁻¹ during the second half of July. Irrigation was performed by sprinklers placed at 15 × 10 m and spraying 2.0832 m³ of water per hour. The total amount of water applied at each irrigation was 50 mm. The weeds were identified, counted, and recorded using quadrat sampling (0.5 × 0.5 m = 0.25 m²) randomly at two places in each subplot a week before

Table 4 Explanation of the weed control treatments and code

Code	Treatment	Description
<i>Weed control treatments</i>		
T_0	Control	Non-weed control
T_1	Pre-emergence herbicide	244 g L ⁻¹ chloridazone + 150 g L ⁻¹ triallate
T_2	Post-emergence herbicide	112 g L ⁻¹ ethofumesate + 91 g L ⁻¹ phenmedipham + 71 g L ⁻¹ desmedipham
T_3	$T_1 + T_2$	244 g L ⁻¹ chloridazone + 150 g L ⁻¹ triallate + 112 g L ⁻¹ ethofumesate + 91 g L ⁻¹ phenmedipham + 71 g L ⁻¹ desmedipham
T_4	T_1 + hand-hoeing	244 g L ⁻¹ chloridazone + 150 g L ⁻¹ triallate + two time hand-hoeing
T_5	Weed-free	Repeated hand-hoeing, no chemical treatment
Code	Row spacing (cm) × Intra-row spacing (cm)	Number of plant (plant ha ⁻¹)
<i>Code</i>		
D_1	30 × 22	151,510
D_2	35 × 22	129,870
D_3	40 × 22	113,640
D_4	45 × 22	101,010
D_5	50 × 22	90,900

Table 5 The dates of the observation and agricultural operations carried out in the field in 2015, 2016 and 2017

Observation and agricultural operations	2015	2016	2017
Basal fertilization	03.15	03.16	03.22
Pre-emergence herbicide	05.06	04.19	04.20
Sowing	05.07	04.19	04.20
Emergence	05.28	05.10	05.05
Thinning	06.15	05.30	05.15
Post-emergence herbicide	06.16	05.30	05.15
1. Top fertilization	07.09	07.07	06.29
2. Top fertilization	07.21	07.21	07.21
Irrigation	05.07	06.23	06.29
	05.13	06.30	07.05
	05.18	07.07	07.13
	05.20	07.14	07.21
	05.25	07.21	07.29
	07.21	07.28	08.08
	07.28	08.04	08.18
	08.04	08.11	08.28
	08.18	08.18	09.08
	08.27	08.25	09.22
	–	09.01	–
Determination of weeds	10.23	10.17	10.10
Harvest	11.02	10.25	10.17

harvest (Chinnusamy et al. 2013). Harvesting was performed on November 2, 2015; October 25, 2016; and October 17, 2017 (Table 5).

Measurements and Calculations

At harvest, 10 plants were randomly selected from each subplot and pulled out. Their leaves were separated and cleaned; then the weights of the sugar beet roots were recorded. The root yield was calculated at the rate of a ton h⁻¹ as described by Cooke and Scott (1993). After that, 26 g of the sample were mixed with a 3% solution of 178.2 mL AlSO₄ (ICUMSA 1994) for 10 min, and the sugar content was determined by a portable digital saccharimeter with automatic reading (Autopol 589). The rotation of plane-polarized light was measured by a solution of a sample (Desai et al. 2013). The yield reduction (Eq. 1) was calculated using the following formula.

$$\text{Yield reduction (\%)} = \frac{T_{0,1,2,3,4} (\text{kg ha}^{-1})}{T_5 (\text{kg ha}^{-1})} \times 100 \quad (1)$$

Weed-control efficiency (Eq. 2) was modified by Chinnusamy et al. (2013) and calculated using the following formula.

$$\text{Weed control efficiency (\%)} = \frac{\text{Weed density of } T_0 (\text{number m}^{-2}) - \text{Weed density of } T_{1,2,3,4,5} (\text{number m}^{-2})}{\text{Weed density of } T_0 (\text{number m}^{-2})} \times 100 \quad (2)$$

Weed frequency (Eq. 3) and density (Eq. 4) were calculated using the following formulas by Günçan (2014).

$$\text{Weed frequency (\%)} = \frac{\text{Weed species number in the plot}}{\text{Total plots number (120)}} \times 100 \tag{3}$$

$$\text{Weed density (number m}^{-2}\text{)} = \frac{\text{Weed species number at the rate of m}^2}{\text{Total plots number (120)}} \tag{4}$$

Fresh weed samples were collected and weighted by quadrat sampling, and dry weight was determined after the samples were dried in an oven at 80 °C for 48 h.

Statistical Analysis

Weed-control treatments were placed in main plots, and plant densities were placed in subplots. The experiment

was designed using a split-plot, randomized, complete block design with four replicates. After arcsine square root transformation, all data collected from different experiments (both separately and together every year) were subjected to analysis of variance (ANOVA), but actual percentages are

presented in Table 6. Means were compared with Duncan’s Multiple Range Test using the MSTAT-C statistical package program (Michigan State Univ. v. 2.10). The level of significance was determined at a probability level of 0.05 (Düzgüneş et al. 1987). The relationship between root yield and sugar content and weed fresh and dry weight was determined by the correlation coefficient values (*r*) at the 5% level of significance.

Table 6 ANOVA table showing means and *p* values for the main effects of year, weed control treatments, and plant densities on examined characters in sugar beet

	Root yield (ton ha ⁻¹)	Sugar content (%)	Weed fresh weight (g m ⁻²)	Weed dry weight (g m ⁻²)
<i>Years (A)</i>				
2015	52.4 ^b	11.58 ^c	1539 ^a	1048 ^{a†}
2016	54.2 ^b	13.12 ^b	1138 ^b	552 ^b
2017	80.6 ^a	14.66 ^a	720 ^c	359 ^c
<i>Weed control treatments (B)</i>				
T ₀	2.4 ^e	7.52 ^d	2008 ^a	1158 ^a
T ₁	42.9 ^c	13.67 ^c	1575 ^c	936 ^b
T ₂	31.9 ^d	13.23 ^c	1863 ^b	1059 ^a
T ₃	69.9 ^b	14.52 ^b	1029 ^d	635 ^c
T ₄	110.2 ^a	14.62 ^b	317 ^e	129 ^d
T ₅	117.1 ^a	15.17 ^a	– ^f	– ^e
<i>Plant densities (C)</i>				
D ₁	59.95	13.22	1073 ^{cd}	645 ^b
D ₂	63.96	13.19	1000 ^d	541 ^c
D ₃	64.99	13.10	1119 ^{bc}	591 ^{bc}
D ₄	60.05	13.00	1261 ^a	748 ^a
D ₅	63.08	13.08	1207 ^{ab}	740 ^a
<i>Analysis of variance</i>				
A	<0.01**	<0.01**	<0.01**	<0.01**
B	<0.01**	<0.01**	<0.01**	<0.01**
C	0.07 ns	>0.50 ns	<0.01**	<0.01**
A×B	<0.01**	<0.01**	<0.01**	<0.01**
A×C	<0.01**	0.13 ns	<0.01**	<0.01**
B×C	<0.01**	0.34 ns	<0.01**	<0.01**
A×B×C	<0.01**	0.04*	<0.01**	<0.01**

*, **: show significance level at *p* < 0.05 and *p* < 0.01, respectively; ns: non-significant; †: means followed by same letter(s) are not significant

Results and Discussion

Main Effects of Year, Weed-Control Treatments, and Plant Densities

A significant difference was determined between the years for all the investigated characteristics. The highest root yield (80.6 ton ha⁻¹) and sugar content (14.66%) were observed in 2017 due to better climatic conditions for sugar beet growth. In 2015, the highest weed fresh and dry weights (1539 g m⁻² and 1048 g m⁻²) were confirmed due to excessive and irregular precipitation. The highest root yield (117.1 ton ha⁻¹) and sugar content (15.17%) were obtained in T_5 . However, there were no significant differences between T_4 and T_5 in terms of root yield. Although weed fresh and dry weights increased when row spacing was enlarged, insignificant differences in root yield and sugar content were determined among plant densities (Table 6).

Weed Frequency and Density

There were 3 narrow-leaved (monocotyledon) and 13 broad-leaved (dicotyledon) weeds from 10 families in the experimental areas (Table 7). According to the pooled results of all years, the most common weeds were *A. retroflexus* at 85%, *C. album* at 64%, *S. nigrum* at 41%, *Echinochloa crus-galli* L. at 17%, and *Xanthium strumarium* L. at 14% frequency. Similar results were reported by Buzluk and Acar (2002) and Sabancı (2013) in Türkiye, Salehi et al. (2006) in Iran, Deveikyte and Seibutis (2008) in Lithuania, Jursik et al. (2008) in the Czech Republic, who both found that

the most-frequent weed species in sugar beet fields were *A. retroflexus*, *C. album*, *S. nigrum*, and *E. crus-galli*. They reported that the density of *C. album* was 38.86 plant m⁻², followed by *A. retroflexus* (29.84 plant m⁻²), *S. nigrum* (16.87 plant m⁻²), and *E. crus-galli* (6.04 plant m⁻²). These results are in line with the findings of Kunz et al. (2015), who found that *C. album*, *A. retroflexus*, and *S. nigrum* were dominant weeds.

Weed-control treatments significantly affected the density of *A. retroflexus*, *C. album*, and *S. nigrum*. The lowest density of weeds was in T_4 . A means comparison showed that T_1 and T_3 controlled *C. album* and *S. nigrum*, but T_0 and T_2 had no effect on weeds all year (Table 8).

Root Yield and Sugar Content

The interaction effect of weed-control treatments and plant densities on root yield was significant (Fig. 1a). The highest yield was obtained from $T_4 \times D_5$ (116.6 ton ha⁻¹) and $T_4 \times D_3$ (114.5 ton ha⁻¹) in 2015. When row spacing in T_4 was increased, root yield improved. Lower root yield was obtained from T_5 than from T_4 , which resulted from abnormal precipitation throughout the year and prevented mechanical treatment (T_5). In 2016, T_5 was superior to other weed-control treatments, and the highest root yield was determined in D_2 (176.2 ton ha⁻¹), D_4 , and D_5 . The results were reflected in mean values; the highest root yield was obtained with T_5 (158.2 ton ha⁻¹) and D_5 (59.2 ton ha⁻¹). In 2017, weed-control treatments and plant-density interactions did not positively affect root yield. The highest root yield was obtained from the combination of $T_4 \times D_2$ with 133.2 ton ha⁻¹. T_4 produced the highest yield (120.2 ton ha⁻¹) followed by T_3 and

Table 7 The frequency (%) and density (plant m⁻²) of weeds observed in sugar beet cultivation areas of all years

Latin name	English name	Frequency (%)	Density (plant m ⁻²)
<i>Amaranthus retroflexus</i> L	Redroot pigweed	85	29.84
<i>Chenopodium album</i> L	Lambsquarters	64	38.86
<i>Solanum nigrum</i> L	Black night shade	41	16.87
<i>Echinochloa crus-galli</i> L	Cockspur grass	17	6.04
<i>Xanthium strumarium</i> L	Rough cocklebur	14	0.88
<i>Cirsium arvense</i> L	Canada thistle	8	1.60
<i>Alopecurus myosuroides</i> L	Black grass	7	0.61
<i>Acroptilon repens</i> L	Russian knapweed	2	0.17
<i>Convolvulus arvensis</i> L	Bindweed	1	0.29
<i>Capsella bursa-pastoris</i> L	Shepherd's purse	1	0.16
<i>Scolymus maculatus</i> L	Spotted golden thistle	1	<0.10
<i>Setaria verticillata</i> L	Bristly foxtail	1	<0.10
<i>Hibiscus trionum</i> L	Venice mallow	1	<0.10
<i>Malva neglecta</i> L	Round leaf mallow	1	<0.10
<i>Carex acutiformis</i> L	Lesser pond sedge	1	<0.10
<i>Cuscuta</i> spp.	Dodder	1	<0.10

Table 8 ANOVA table showing means and *p* values for the main effects of year, weed control treatments, and plant densities on some weeds densities in sugar beet

	Redroot pigweed (plant m ⁻²)	Lambsquarters (plant m ⁻²)	Black nightshade (plant m ⁻²)
<i>Years (A)</i>			
2015	49.64 ^a	24.94 ^b	46.26 ^a
2016	27.86 ^b	75.70 ^a	4.32 ^b
2017	12.01 ^c	15.96 ^c	0.04 ^c
<i>Weed control treatments (B)</i>			
T ₀	43.53 ^a	85.03 ^a	38.73 ^a
T ₁	31.73 ^b	33.57 ^c	3.47 ^b
T ₂	41.37 ^a	51.90 ^b	37.37 ^a
T ₃	28.58 ^b	22.77 ^d	2.67 ^b
T ₄	3.97 ^c	1.07 ^c	2.13 ^b
<i>Plant densities (C)</i>			
D ₁	31.93 ^a	40.43 ^a	12.67 ^c
D ₂	32.38 ^a	42.07 ^a	11.97 ^c
D ₃	29.63 ^{ab}	41.70 ^a	18.87 ^b
D ₄	27.82 ^b	34.77 ^b	23.40 ^a
D ₅	27.42 ^b	35.37 ^b	17.47 ^b
<i>Analysis of variance</i>			
A	<0.01**	<0.01**	<0.01**
B	<0.01**	<0.01**	<0.01**
C	<0.01**	<0.01**	<0.01**
A×B	<0.01**	<0.01**	<0.01**
A×C	0.04*	<0.01**	<0.01**
B×C	<0.01**	<0.01**	<0.01**
A×B×C	<0.01**	<0.01**	<0.01**

*, **: show significance level at *p* < 0.05 and *p* < 0.01, respectively; ns: non-significant; †: means followed by same letter(s) are not significant

T₅. Although there were no significant differences in plant densities, narrow row spacings resulted in higher root yields. Root yields varied between 59.9 and 64.9 (ton ha⁻¹). Higher root yields were achieved with row spacings D₂ and D₃. As a result, a pre-emergence herbicide with application-hoeing (T₄) showed a significant increase in root yield. Similar results were reported by Campagna et al. (2000), and high lenacil dosages under pre-emergence and post-emergence herbicide applications caused severe reductions in root yield. Using a planetary tractor-hoeing application, Buzluk and Acar (2002) reached the maximum root yield (59.5 ton ha⁻¹) with three times low-dose post-emergence herbicide combinations (phenmedipham + desmedipham + ethofumesat (1200 mL ha⁻¹), chloridazone (1000 mL ha⁻¹), ethofumesat (700 mL ha⁻¹), and clopyralid (500 mL ha⁻¹). Alaoui et al. (2003) discovered that hand-hoeing a total of four times (38.1–49.8 ton ha⁻¹) and post-emergence herbicide (phenmedipham (0.80 kg ai ha⁻¹) + sethoxydim

(0.25 kg ai ha⁻¹) + two hand-hoeings (42.0–43.0 ton ha⁻¹) produced the highest root yield. Çakmakçı and Oral (1998) determined that root yield increased with increased plant densities (90,000–110,000 plant ha⁻¹); however, Kristek et al. (2012) (118,000–139,000 plant ha⁻¹), Safina et al. (2012) (188,000 plant ha⁻¹), Zargar et al. (2017) (twin row spaced 60 cm apart under 100,000 plant ha⁻¹) and Armstrong and Sprague (2010) (76 cm row width under 77,000 plant ha⁻¹) determined that root yield decreased with increasing plant densities depending on sugar beet varieties, sowing time, herbicide treatments and environmental conditions.

Sugar content varied according to weed-control treatments in 2015 (Fig. 1b), and the highest sugar content was reached by T₅ with 15.21%, followed by T₄, T₃, and T₁. In 2016, the interaction effect was significant, and the sugar content ranged from 10.08% (T₀×D₂) – 15.18% (T₅×D₂). The highest sugar content was determined at T₂, T₄, and T₅ had higher sugar contents than with other weed-control treatments. Plant density in 2016 had an insignificant effect on the sugar content. In 2017, the combination of T₅×D₂ produced the highest sugar content at 17.04%. There were no significant differences in weed-control treatments and plant densities, but the lowest sugar content was obtained in T₀, and the highest sugar content was obtained in D₁ (14.84%) and D₂ (15.14%). In our study, the sugar content was significantly affected by weed-control treatments. T₄ produced the highest root yield, and sugar content was higher than with other weed-control treatments. The sugar content was negatively affected by weed density, and increased weed density caused a reduction in sugar content. Our results confirmed the findings of Bosak and Mod (2000), Devėikyte and Seibutis (2006), Mirshekari et al. (2010), Odero et al. (2010), Bakhshkandi et al. (2013), and Bezhin et al. (2015). Similarly, Yonts and Smith (1997) and Kristek et al. (2012) reported the highest sugar content at plant densities of 100,000–150,000, and 108,000–118,000 plants per hectare, respectively.

Yield Reduction and Weed Control Efficiency

The root yield reduction reached the peak level in T₂ at 89%, followed by T₁ at 49% and T₃ at 23% in 2015 (Fig. 2a). In addition, weed competition in T₀ caused a decrease in root yield by up to 100% in the same year. An increase in root yield was observed in D₁×T₃ and all plant densities of T₄ (17%). In 2016, yield reduction was observed for all weed-control treatments, and this rate was above 90% in T₀, T₁, and T₂. The minimum yield reduction was recorded in T₄ at 31%. In the last year (2017), root yield diminished in T₀, T₁, and T₂, while it increased with T₃ and T₄ (15%) treatments. Wallgren (1980) identified the beneficial effect of chloridazone treatment on root and sugar

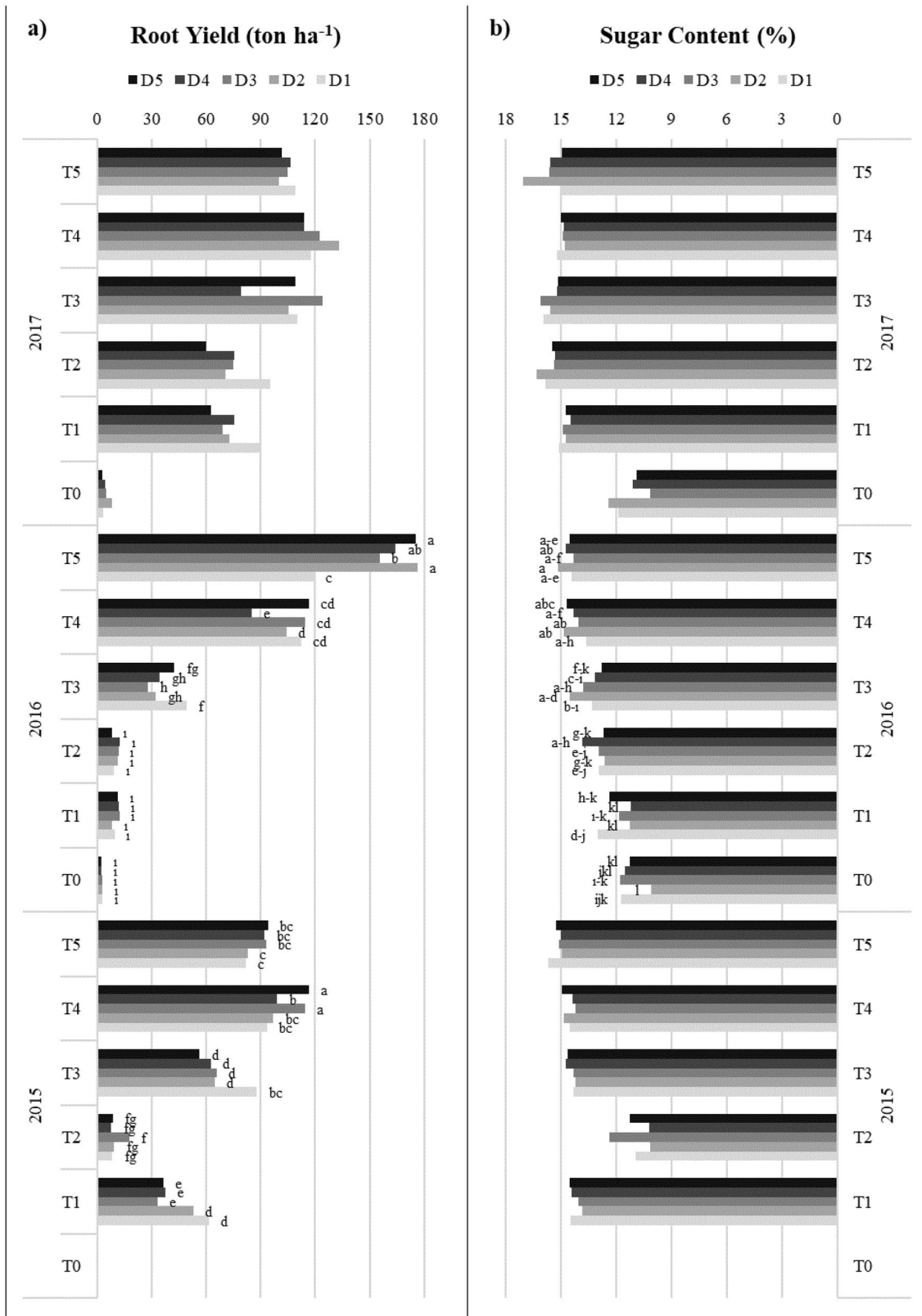


Fig. 1 The interaction effect of weed control treatments and plant densities on root yield (ton ha⁻¹) (a) and sugar content (%) (b) of sugar beet in 2015, 2016, and 2017. Means on the each bar followed by the same letter(s) are not significant at $p < 0.05$

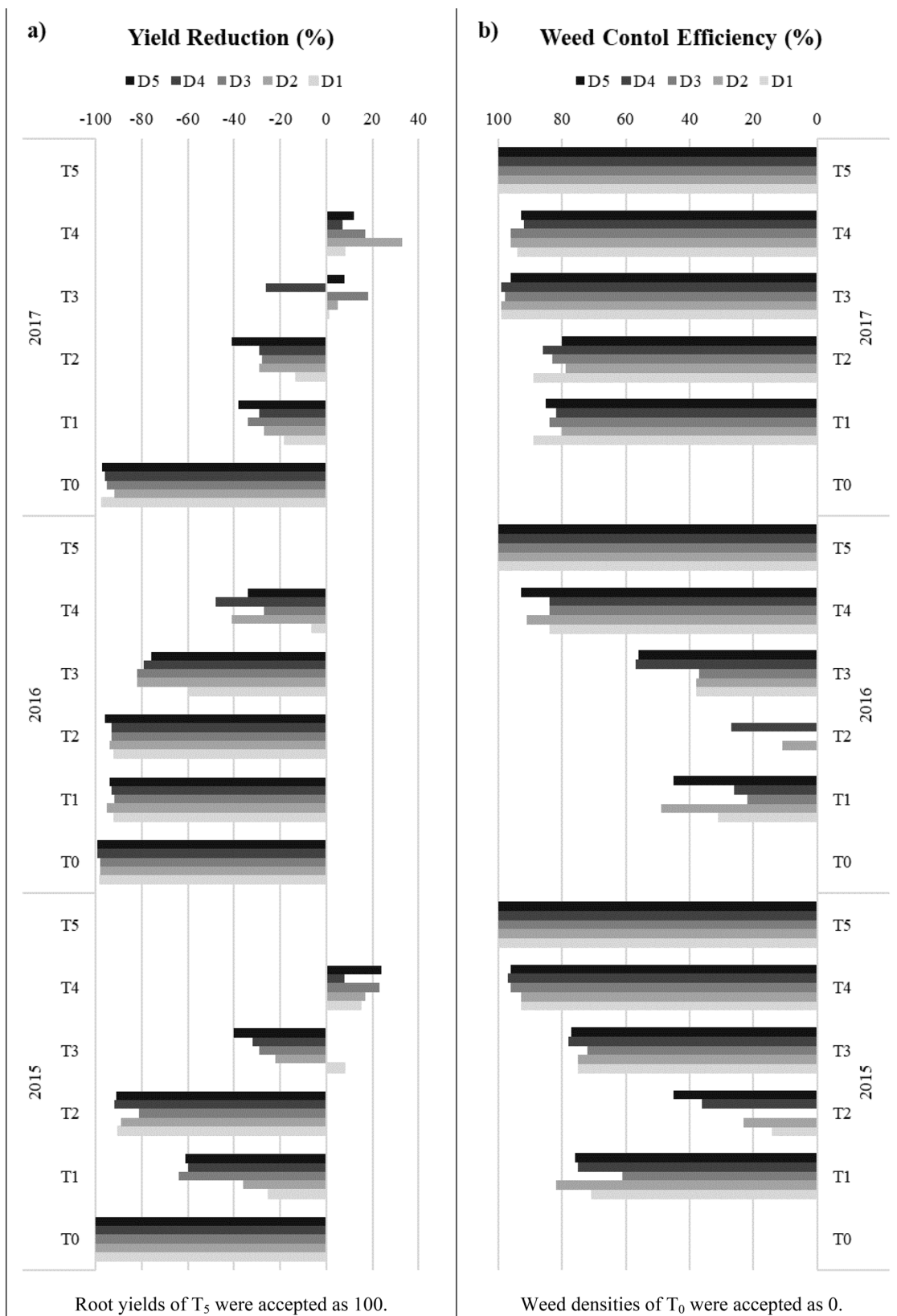


Fig. 2 Yield reduction (%) (a) and weed control efficiency (%) (b) means of sugar beet within 2015, 2016, and 2017 according to weed control treatments and plant densities

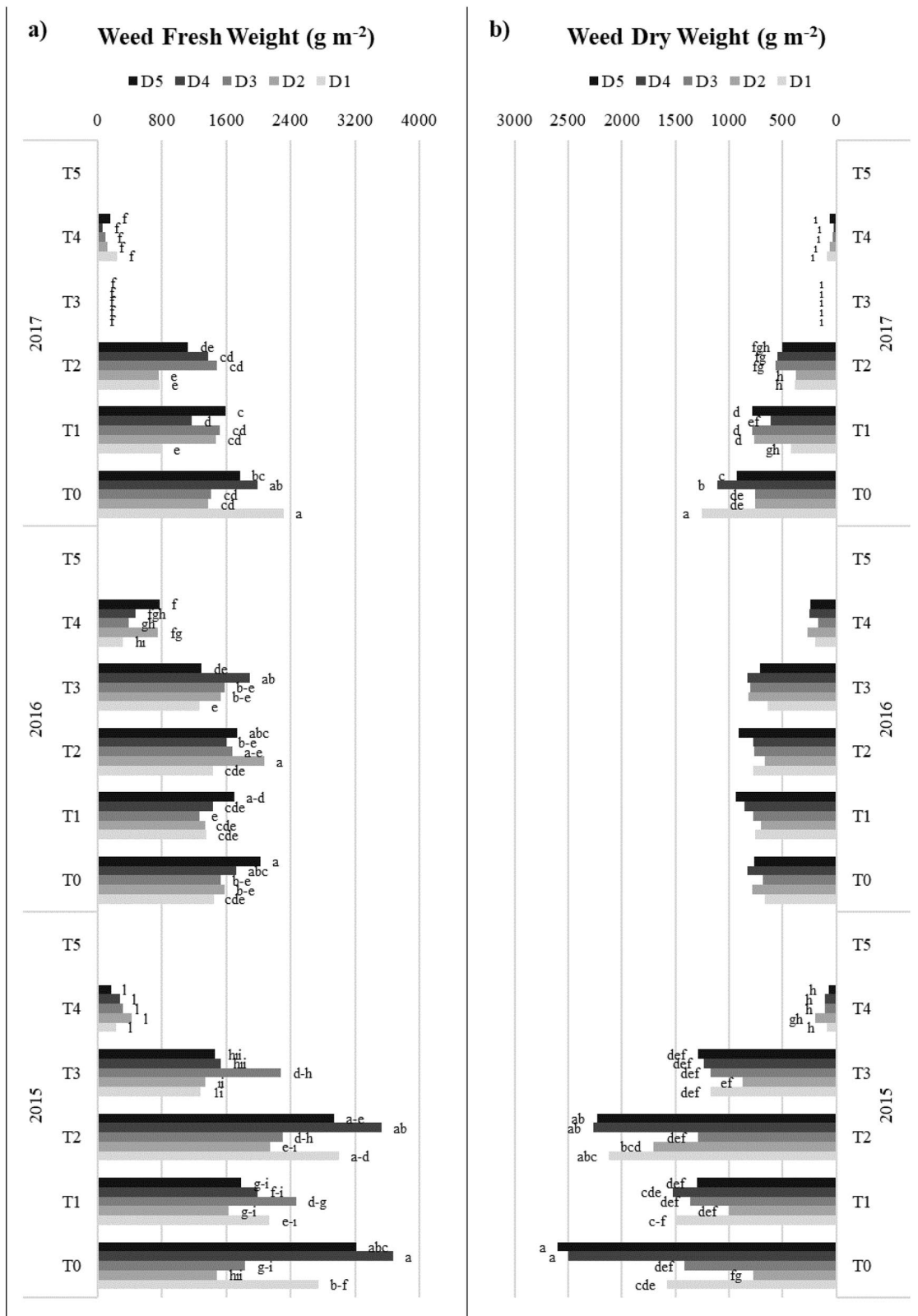


Fig. 3 The interaction effect of weed control treatments and plant densities on weed fresh weight (g m⁻²) (a) and weed dry weight (g m⁻²) (b) in 2015, 2016, and 2017. Means on the each bar followed by the same letter(s) are not significant at *p* < 0.05

Table 9 Correlation coefficients of root yield and sugar content with weed fresh weight and weed dry weight in 2015, 2016, and 2017

	Root yield (ton ha ⁻¹)			Sugar content (%)		
	2015	2016	2017	2015	2016	2017
Weed fresh weight (g m ⁻²)	-0.789**	-0.874**	-0.737**	-0.527**	-0.551**	-0.537**
Weed dry weight (g m ⁻²)	-0.758**	-0.899**	-0.731**	-0.502**	-0.560**	-0.595**

** : significant at the 1%

yield, and Gürsoy (2002) detected the necessity of hoeing. Jursik et al. (2008) reported a reduction in root yield by 80–93% without weed control, while Majidi et al. (2011) determined root yields of 4.33 ton ha⁻¹ with the treatment of chloridazone + desmedipham and 12.4 tons ha⁻¹ with desmedipham + trisulfuron-methyl.

Weed-control efficiency demonstrated that weed density significantly declined with herbicide use. In all three years, the weed control efficiency of T_4 was similar to that of T_5 (weed-free). The weed-control efficiency of T_4 treatment was 95% in 2015, 87% in 2016, and 94% in 2017. Similarly, Buzluk and Acar (2002) determined that the application of herbicide + hoeing reduced weed density by 93.8% and provided the best weed-control method. Gürsoy (2002) reported that weed control was achieved by herbicide application alone, but hoeing was necessary for sugar beet root development. More-effective weed control was conducted in sugar beet with hoeing and herbicide applications, as reported by Wiltshire et al. (2003) and Zargar et al. (2010). Deveikyte and Seibutis (2006), Odero et al. (2008), and Armstrong and Sprague (2010) found that, as the number of herbicide applications increased, weeds could be better controlled and sugar beet yield increased. In addition, the herbicide combination of desmedipham + phenmedipham + ethofumesate controlled *C. album*, *A. retroflexus*, and *S. nigrum*, and it was more effective than chloridazone and clopyralid, as reported by Chitband et al. (2014).

Weed Fresh Weight and Weed Dry Weight

In general, the highest and lowest weights were obtained by T_0 and T_4 , respectively, in all three years (Fig. 3a). However, it is noteworthy that T_3 was extremely low in 2017 compared to other years. The pre-emergence herbicide + post-emergence herbicide application (T_3) exhibited superior weed control; therefore, weed fresh weights decreased. Additionally, row spacing affected weed fresh weight, which decreased in D_1 and D_2 . Majidi et al. (2011) detected a significant decrease in the weight and density of the *C. album* and *A. retroflexus* with hoeing and herbicide application. According to Deveikyte et al. (2015), all pre-emergence herbicide combinations significantly reduced the number and weight of weeds.

Weed dry weight changed depending on weed fresh weight and had a similar statistical trend (Fig. 3b). Majidi

et al. (2011) reported that the highest and lowest dry weights of *A. retroflexus* were obtained from the control plots (T_0) and clopyralid (250 mL ha⁻¹) + desmedipham (3 L ha⁻¹) herbicide mixture, respectively. Also, the lowest dry weight of *A. retroflexus* was obtained by metamitron application.

Correlation Coefficients and Regression Analysis

The correlation coefficients of root yield and sugar content with weed fresh and dry weight are presented in Table 9. All the correlations were found to be negatively significant. However, root yield was more significantly affected than weed fresh and dry weights.

Regression analysis showed that a significantly negative relationship ($p < 0.01$) was recorded between root yield and weed fresh and dry weight during the experimental years (Fig. 4). Root yield increased linearly as weed weight decreased. A similar trend was determined in all three years. The highest coefficient of determination between root yield and weed fresh and dry weight was obtained at $R^2 = 0.865$ and $R^2 = 0.911$ in 2016, respectively. According to the results of the regression analysis conducted with the combined data of all years, a significantly negative relationship was determined between root yield with weed fresh and dry weight (Fig. 5). There was a significant decrease in root yield due to the increased weed weight. The coefficients of determination between root yield and weed fresh and dry weight were calculated at $R^2 = 0.682$ and $R^2 = 0.548$, respectively. Similarly, Schweizer (1983) stated that the biomass weight of sugar beet decreased as the density of common lambsquarters increased. At densities of 6, 12, 18, and 24 weeds/30 m of the row, sugar beet root yields declined by 13%, 29%, 38%, and 48%, respectively. The coefficient of determination between sugar beet root yields and densities of common lambsquarters was calculated at $R^2 = 0.79$ and $R^2 = 0.96$ in two respective years.

According to the three-year results, higher sugar beet root yield and sugar content were obtained in 2017. It was also found that the fresh and dry weights of weeds were lower in 2017. The precipitation regime in 2017 contributed significantly to the development and yield of sugar beet, when regular precipitation of 58.7, 55.2, and 46.3 mm in April, May, and June, respectively, increased root yield. In 2015, late sowing and total precipitation of

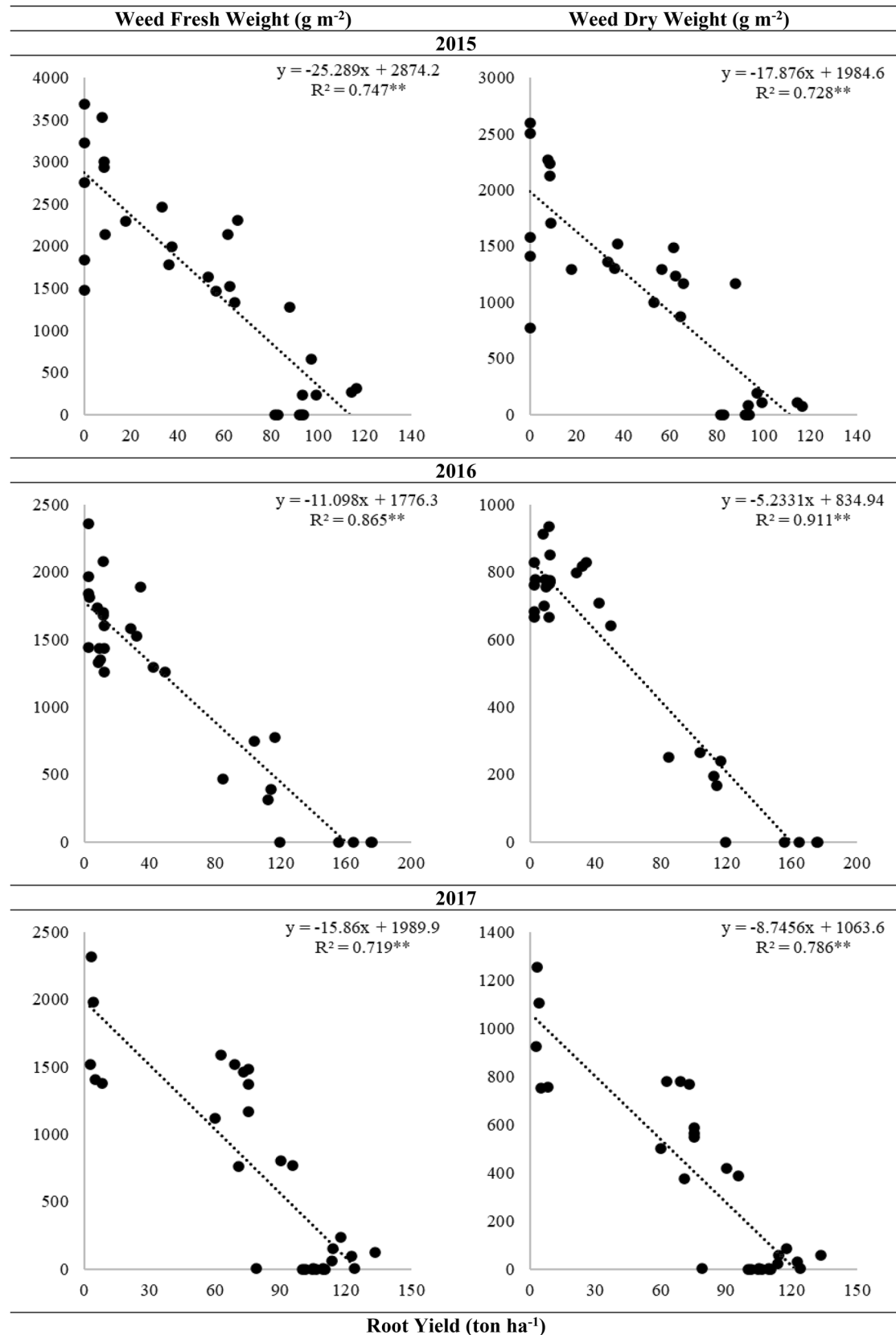


Fig. 4 Linear regression analysis between weed fresh and dry weight with root yield in 2015, 2016, and 2017

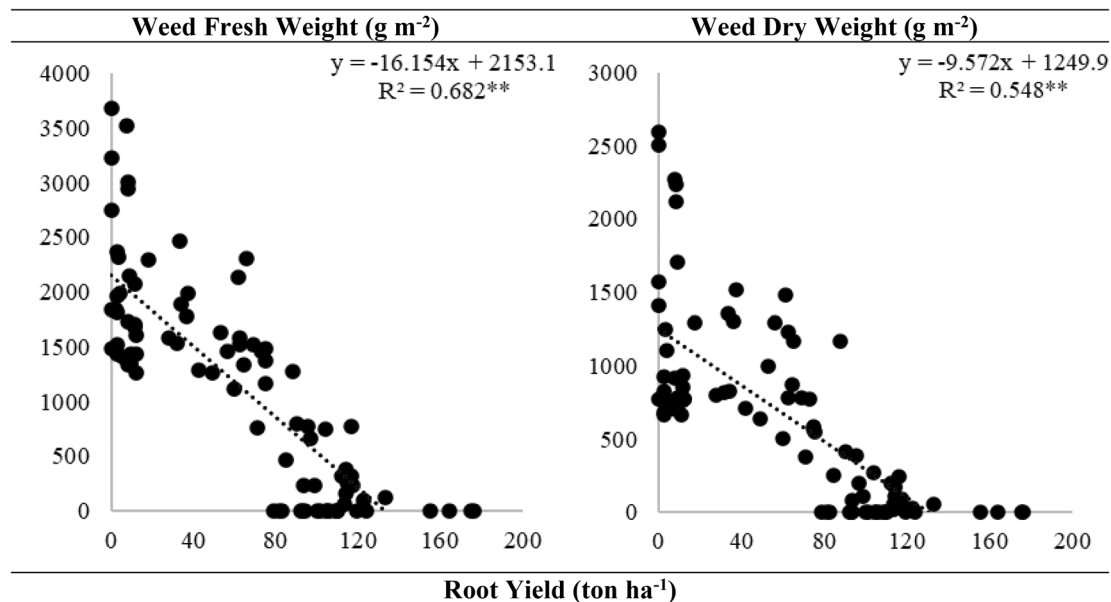


Fig. 5 Linear regression analysis between weed fresh and dry weight with root yield in combined years

151.1 mm in June adversely affected plants and increased weed growth. Herbicide (pre or post) applications provide an important advantage in weed control. Pre- and post-emergence herbicides are necessary for a considerable root yield. However, a single herbicide application is not enough to control weeds. Hand-hoeing was determined to be important for encouraging plant growth by aerating the soil in addition to controlling weeds in sugar beet. A minimum of at least one hoeing should be applied, taking into account labor costs and requirements. In addition, sowing in sugar beet is performed at 45-cm row spacing by a classical or pneumatic sowing machine. However, sugar beet can be sown at intervals ranging from 50 to 35 cm with some modifications depending on the sowing machine. Sugar beet has recently been sown by a pneumatic sowing machine with 70-cm row spacing, used in corn and sunflower as a two-time sowing for dividing each row space into 35 cm, to control weeds and increase the number of plants per unit area in Eskişehir and nearby provinces. In conclusion, weed density can be reduced by increasing plant density. However, increased root yield can only be achieved if weed control is done well. To achieve effective weed control in sugar beet production, pre-emergence herbicide is more effective than post-emergence, and investigating pre-emergence herbicide + hand-hoeing application, and narrow row spacing of less than 45 cm in sowing are recommended.

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Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

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