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Effect of Pre- and Post-Emergence Herbicides on Weed Control and Yield in Sunflower (*Helianthus annuus* L.)

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Abstract: Weeds are a major cause of yield and quality loss in sunflower (*Helianthus annuus* L.) crops. Therefore, weed control is important in sunflower production. In this context, the study was conducted in 2023 to determine the effectiveness of pre-emergence and post-emergence herbicides with different modes of action on weed population, dry weight of weeds and sunflower yield and yield components in sunflower. Four herbicides with different modes of action, three pre-emergence (aclonifen (A), pendimethalin (P), linuron (L) and one post-emergence (quizalofop-p-ethyl) (Q) and combinations of these herbicides were used in the study. To determine the effects of herbicides on weed populations and species, four different assessments were conducted at regular intervals. As a result of the study, a total of 10 weed species belonging to 5 families were detected in the trial area. The weed species with the highest density were *Sorghum halepense* (L.) Pers., *Xanthium strumarium* L., *Convolvulus arvensis* L. and *Chenopodium album* L. The study found that the effects of herbicides on weed populations and species varied. In the study, the highest rates of weed control were achieved in plots where both pre-emergence and post-emergence herbicides were used together. The highest weed control rate was observed in plots P+Q (96.66%). The highest effect on weed dry weight was obtained in plot L+Q with a rate of 89.63%. The highest weed dry weight was recorded in the weedy control plots. In the study, the highest yield (287.53 kg da^{-1}) was obtained in the weed-free (hoe) control plot. Yield increases of 18% to 45% can be achieved by controlling weeds in sunflowers. As a result, herbicide efficacy on weed population and dry weight of weeds increased when herbicides were used in combination. Some herbicides have been shown to increase yields when used alone. However, it is important to use herbicides in combination to control more weed populations and prevent a potential resistance problem.

Keywords: Herbicide, *Sorghum halepense*, sunflower, weed control, herbicide combinations

1. Introduction

Sunflower (*Helianthus annuus* L.) is a cultivated plant belonging to the Asteraceae family (Meral, 2019). It is an important crop that is grown in many countries of the world (Anonymous, 2023a) and contains high-quality oil in its seeds (Kaya, 2004). The origin of sunflowers (Karkanis et al., 2022), one of today's most important oil crops, is known as North America (Kaya et al., 2012). Sunflower, which first started to be grown in Europe in the 16th century, was used as an ornamental plant at that time. In later times, it became an important plant due to its use in bread making and especially the production of oil from its seeds (Duke, 1983). Sunflower contains abundant carbohydrates, proteins, vitamins and minerals in their structure (González-Pérez and Vereijken, 2007). Among the oilseed plants grown in Türkiye, it ranks first in terms of cultivation area and production amount (Anonymous, 2023b). Its seeds contain 40-50% oil, and its pulp, which is obtained at 40-45% during oil production, contains 30-40% protein and is used as a valuable feed for animal. Oils other than edible oil are used in the soap and paint industries; the stalks after harvest are also used as fuel. Sunflower seeds are also eaten as a snack (Eken, 2004). As sunflower is an important crop in the world and Türkiye, it had 29.5 million hectares of cultivation area in the world in 2021 and 58 million tons were produced. The continents that produce the most sunflowers are Europe (76%), Asia (12%) and the America (8%), respectively. The countries that produced the most sunflower in the world in 2021 are Ukraine (16.3 million tons), Russia (15.6 million tons) and Argentina (3.4 million tons). Türkiye is the 6th country that produces the most sunflower in the world with a production amount of 2.4 million tons (Anonymous, 2023a). In 2022, the sunflower cultivation area in Türkiye was 9.8 million da and the production was 2.5 million tons. In Iğdır province, the area under sunflower cultivation has been increasing in recent years, and in 2022, the area under sunflower cultivation was 1.90 hectare, and 58 tons were produced (Anonymous, 2023b).

The fact that the sunflower plant has an important place in human and animal nutrition, its use in industry for various purposes (Seiler and Gulya, 2016), and its ability to adapt to many different regions of the world has accelerated the increases in its production (Anonymous, 2023a). However, some factors limit grain and oil yield in sunflower. One of the most important of these factors is weeds (Shylaja and Sundari, 2008; Dindar Yay, 2015; Malidža et al., 2016; Kalaisudarson et al., 2020; Kaya et al., 2020; Torun et al., 2021). The degree of damage caused by weeds in different crops varies, and while some weeds cause problems in only one crop, other species cause crop reduction in more than one crop (Güncan and Karaca, 2018; Akelma et al., 2022; Alptekin et al., 2022, 2023; Alptekin and Gürbüz, 2022; Bozhüyük et al., 2022; Tülek et al., 2022; Savcı and Gürbüz, 2023). Sunflower production is threatened by many weed species (Zengin, 1999; Başaran et al., 2017; Karabacak and Uygur, 2017; Tursun et al., 2017; Asav and Serim, 2019; Özkil et al., 2019), and this situation causes significant yield losses (Kaya, 2016). It is necessary to control weeds in sunflower planting areas. Failure to do so may result in serious crop loss if weed control is inadequate (Pannacci et al., 2007). Different control methods are used to control weeds in sunflower cultivation areas (Pannacci and Tei, 2014; Tursun et al., 2017; Kalaisudarson et al., 2020). However, herbicides are used to manage weeds in sunflower due to their easy applicability, cheap and quick results (Pannacci et al., 2007; Sankar and Subramanyam, 2011; Pannacci and Tei, 2014). This method is especially preferred in agricultural areas that have large production areas and where labor is expensive for weed control by hoeing (Kaya et al., 2004). In particular, complex combinations of pre-emergence and post-emergence herbicides, as well as herbicide mixtures, are used to optimize weed control effectiveness and minimize application costs (Pannacci et al., 2007; Alptekin et al., 2023). This strategy can also be an important method for the prevention of herbicide resistance problems (Peterson et al., 2018). The most effective and widespread control of weeds is achieved through the use of herbicides. However, to get the desired results from a herbicide application, the right herbicide needs to be applied at the right time and in the right amount (Mutlu and Üstüner, 2017; Yavuz et al., 2017), and when spraying with the correct method, the damage caused by weeds can be minimized (Mutlu and Üstüner, 2017). This study was carried out to determine the effects of some pre-emergence and one post-emergence herbicides with different active ingredients on weeds, sunflower (*H. annuus*) yield and some yield elements in oil sunflower.

2. Materials and Methods

The research was carried out at Iğdır University Agricultural Application and Research Center (39° 55' 45.6" N 44° 05' 42.3" E). Pioneer P64LP130 oil sunflower (*H. annuus*) variety was used in the study. Climate data for Iğdır province for the months in which the study was carried out and for the long-term period (1941-2023) are presented in Table 1.

Table 1. The weather conditions of the region (Anonymous, 2023c)

Months	Temperature (°C)		Precipitation (mm)		Humidity (%)	
	2022	LTP	2022	LTP	2022	LTP
March	11.7	6.2	27.2	22.1	55.4	52.2
April	13.7	13.0	51.2	33.8	60.1	49.9
May	18.1	17.7	43.2	46.5	53.8	51.5
June	23.0	22.1	48.3	32.0	52.6	47.3
July	26.5	25.9	10.5	13.7	42.2	45.3
August	28.3	25.3	0.8	9.7	39.8	47.1
September	22.0	20.4	7.6	11.5	50.1	46.2
October	15.1	13.1	29.5	26.3	64.7	48.5
Total / Mean	19.8	17.96	218.3	195.6	52.34	48.5

LTP: Long-term period (1941-2022)

Sufficient soil samples were taken from 0-30 cm depth prior to planting for soil analysis of the trial area. In the experimental area, the soil structure class is clay loam, lime ($CaCo_3$) content is 11.3%, total salinity is 2 mmhos cm^{-1}, pH is 7.9, available phosphorus (P_2O_5) content is 0.8 kg da^{-1}, available potassium (K_2O) content is 9 kg da^{-1}, organic matter content is 1.8%.

In the study, 4 herbicides with different modes of action were used: 3 pre-emergence (aclonifen, pendimethalin, linuron) and one post-emergence (quizalofop-p-ethyl) (Table 2).

Table 2. Herbicides used in the study and their general properties

Code	Active ingredients	Formulation	Mode of action	Application time	Dose (ml da^{-1})
A	Aclonifen	SC	S 32	Pre-emergence	125-300
P	Pendimethalin	EC	K1 3	Pre-emergence	500
L	Linuron	SC	C1,2 5	Pre-emergence	250
Q	Quizalofop-p-ethyl	EC	A 1	Post emergence	100
A+Q	Aclonifen+Quizalofop-p-ethyl	SC+EC	S 32 +A 1	Pre-emergence+	125-300+100
P+Q	Pendimethalin Quizalofop-p-ethyl	EC+EC	K1 3+A 1	Post-emergence	500+100
L+Q	Linuron Quizalofop-p-ethyl	SC+EC	C1, 2 +A 1	Pre-emergence+	250+100

SC: Suspension Concentrate, EC: Emulsifiable Concentrate

2.1. Sunflower sowing, maintenance and setting up of trials

Before sowing sunflower seeds, the trial area was plowed with a cultivator and soil preparation was made. Sunflower seeds were planted in the annealed soil on 10.05.2023 at Iğdır University Agricultural Application and Research Center, where the research was carried out, with a 20x70 cm inter- and intra-row spacing. Before planting, 300 kg ha^{-1} of NPK fertilizer was mixed and applied to the soil. After sowing sunflower seeds, a sprinkler irrigation system was installed and the first irrigation was done immediately after planting. Afterward, considering the rainfall and the water needs of the plant, irrigation was carried out as flood irrigation every 2 weeks. In weed-free (hoe) plots, manual weeding and hoeing were carried out as soon as weeds emerged.

The study was conducted according to the randomized complete block trial design with 4 replications and 9 different applications (Aclonifen, Pendimethalin, Linuron as pre-emergence, (Quizalofop-p-ethyl) and Aclonifen+Quizalofop-p-ethyl, Pendimethalin+Quizalofop-p-ethyl, Linuron+Quizalofop-p-ethyl as post-emergence, with weedy check and weed-free checks was established in a total of 36 plots. Parcelization was done before the use of preemergence herbicides. In the study, the parcels were 10 m^2 (4m x 2.5m) and 1 m security strips were left between the parcels and 1 m between the blocks. The trial area was 579.5 m^2 in total. For parcelization, slats were fixed to the ground and ropes were used in strips. In the study, pre-emergence herbicides were applied on 12.05.2023, 2 days after sunflower planting under suitable weather conditions, and post-emergence herbicide was applied on 05.06.2023. The herbicides used in the experiment were applied with a 25-liter tank, a gasoline engine, and a backpack sprayer equipped with flat fan nozzles.

2.2. Determination of weed species and densities in the trial area

In the study, to determine the weed species in the trial area and the density of these species, a 1 m^{-2} (1x1 m) frame was used in the trial area and the weeds in the frame were counted by randomly throwing them. In determining the density of weeds, an evaluation was made based on the arithmetic average. Weed density (plant m^{-2}) was calculated by dividing the total number of plants per m^2 in the surveys by the number of surveys (Odum, 1971).

The density, expressed as the number per square meter, is calculated by dividing the total sample count (B) by the total number of frames that were thrown (M) (Equation 1).

$$\text{Density (number m}^{-2}\text{)} = B/M \quad (1)$$

In addition, according to Üstüner and Güncan (2002), the densities of weed species in the experimental area were graded according to the density scale used as Table 3.

Table 3. Weed density scale

Scale	Density level	Density (plants m^{-2})
A	High density	10+
B	Density	1-10
C	Medium density	0.1-1
D	Low density	0.01-0.1
E	Rare	Less than 0.01

2.3. Determination of the effects of herbicides on weed populations and weed species

In the study, evaluations were made 4 times at regular intervals during the trial period to determine the effects of the herbicides on the weed density and species (Anonymous, 2020) (Table 4).

Table 4. Assessments and assessment times corresponding to the herbicide treatments

Assessments	Time
	Pre-emergence
1. Assessment	After the completion of the cultivation plant emergence in the control plots
2. Assessment	15-20 days after first assessment
3. Assessment	Beginning of flowering
4. Assessment	Before harvest
	Post emergence
1. Assessment	7-10 days after application
2. Assessment	20-30 days after application
3. Assessment	Just before the cultivated plant blooms
4. Assessment	Before harvest

During the evaluation, decreases in weed population and species compared to the control were recorded, expressed as shortening in height or damage. The percentage of reduction in the weed population was determined by comparing the treated plots with the control plots. In the evaluations made in the study, the percentage effect rates of herbicides on weeds were determined according to the Equation 2 (Abbott, 1925). The herbicide effect, expressed as a percentage, is calculated by subtracting the number of weeds in treatments (B) from the number of weeds in control (A), dividing the result by the number of weeds in control (A), and then multiplying by 100.

$$\text{Herbicide effect (\%)} = (A-B)/A \quad (2)$$

In the study, various levels of control, including excellent control (90%-100%), good control (70%-90%), fair control (50%-70%), and poor control, were utilized to assess the impact of herbicides on weed population, weed species, and weed dry weight, with control values below 50% being included in the analysis.

2.4. Determination of the effect of herbicides on weed dry weights

In the study, weeds in each plot were cut with scissors so that they were flush with the soil surface and placed in separate bags. Then they were taken to the herbology laboratory of Iğdır University Faculty of Agriculture, and the weeds were kept in paper bags in an oven at 70 °C for 24 hours, then they were taken, their dry weights were weighed one by one, and the numerical data were recorded. In addition, to determine the percentage effects of the herbicides used in the study on the dry weights of weeds, the percentage effects of the herbicide-applied parcels on weeds were determined based on the weedy control parcels.

2.5. Determination of the effect of herbicides on sunflower yield components and yield

Sunflower harvest was done on 15.09.2023. In order to determine the effects of herbicides with different active ingredients on yield components and yield in sunflower; grain yield (kg ha^{-1}), plant height (cm), head diameter (cm) and 1000 grain weight (g) parameters were evaluated. Yield and yield components of the weedy control and weedless plots were compared.

2.6. Statistical analysis

As a result of four different assessments made in the study, the percentage impact of weeds in the plots, dry weights of weeds and sunflower yield and yield components were evaluated. Relevant data were subjected to a one-way analysis of variance. Means were compared using Duncan's multiple comparison test ($p<0.05$) using Statistical Package for the Social Sciences (SPSS version 20.0, SPSS Inc., Chicago, IL, USA). In addition, a series of statistical analyzes were conducted to correlate the findings of the study. After transformation/normalization of the data; correlation analysis using R and JASP software, heat map clustering (SRplot), principal component analysis (PAST software) and network graph analysis (PAST software) were performed.

3. Results and Discussion

3.1. Species and densities of weeds found in the experimental plots

A total of 10 weed species belonging to 5 families were detected in the study area. Among the weed species detected, 2 are monocotyledonous and 8 are dicotyledonous (Table 5).

Among the families that were identified, Amaranthaceae had the highest number of weed species with 4 species, while Poaceae and Asteraceae had 2 species each. Other families had one weed species each. Of the weed species detected, 4 were perennial and 6 were annual. In the trial area, 6 weed species were detected at a density of 1 or more per m^2. The highest density was in *Sorghum halepense* (L.) Pers. (10.50 number m^{-2}), *Xanthium strumarium* L. (9.75 number m^{-2}), *Convolvulus arvensis* L. (3.50 number m^{-2}) and *Chenopodium album* L. (3.25 number m^{-2}) weed species. In addition, the densities of the weed species detected in the trial area were 1 at high

Table 5. Some systematic features and densities (number m^{-2}) of weeds

Family	Scientific name	Common name	Life cycle	Density (adet m^{-2})	Density scale
		Monocotyledonous			
Poaceae	*Sorghum halepense* (L.) Pers.	Johnson grass	P	10.50	A
	Seteria viridis L.	Green foxtail	A	0.70	C
		Dicotyledonous			
Amaranthaceae	*Amaranthus retroflexus* L.	Redroot pigweed	A	0.50	C
	Chenopodium album L.	Common lambsquarters	A	3.25	B
	Atriplex nitens Schkuhr.	Saltbush	P	1.25	B
	Suaeda altissima (L.) PALL	Seablite	A	0.75	C
Asteraceae	*Cirsium arvense* (L.) Scop.	Canada thistle	P	1.25	B
	Xanthium strumarium L.	Common cocklebur	A	9.75	B
Convolvulaceae	*Convolvulus arvensis* L.	Field bindweed	P	3.50	B
Portulacaceae	*Portulaca oleracea* L.	Purslane	A	0.50	C

Life cycle-A: Annual, P: Perennial; Density scale-A= High density (>10.00 m^2), B= Intensive (1.00-10.00 m^2), C= Medium (0.10-1.00 m^2), Ç= Low density (0.01-0.10 m^2)

density (A:D>10.00 m^{-2}), 5 at density (B:D= 1.00-10.00 m^{-2}) and 4 at medium density (C:D= 0.10-1.00 m^{-2}) (Table 5). Özkil et al. (2019) identified 67 different weed species in 30 families as a result of their surveys in sunflower growing areas. Poaceae (11 species), Asteraceae (9 species), Fabaceae (6 species) and Amaranthaceae (5 species) were the families with the most weed species. The highest density was *Chenopodium album*, (first survey: 6.76 number m^{-2} and second survey: 5.13 number m^{-2}), *Heliotropium europaeum* (first survey: 3.75 number m^{-2} and second survey: 0.66 number m^{-2}), *Convolvulus arvensis* (first survey: 3.05 number m^{-2} and second survey: 1.75 number m^{-2}) and *Sinapis arvensis* (first survey: 1.68 number m^{-2} and second survey: 0.58 number m^{-2}) were detected (Özkil et al., 2019). Karabacak and Uygur (2017) conducted a survey that identified a total of 51 weed species across 23 families. Their findings highlighted that the families Poaceae and Asteraceae each had 10 species, while the family Convolvulaceae had 3 species, making these families the most prevalent among the weeds surveyed. The weed species with the highest density were *Chenopodium album* (3.32 number m^{-2}) and *Convolvulus arvensis* (1.52 number m^{-2}). In another study, they identified 15 weed species belonging to 11 families in the study area. The weed species with the highest density were *Chenopodium album* (41.7 number m^{-2}), *Echinochloa cruss-galli* (8.45 number m^{-2}), *Convolvulus arvensis* (6.5 number m^{-2}) and *A. retroflexus* (5.78 number m^{-2}) (Koç and Işık, 2022). In Štefanić et al. (2021) study, the highest densities in sunflower fields were *Ambrosia artemisiifolia* (first year: 0.64 number m^{-2} and second year: 0.69 number m^{-2}), *S. viridis* (first year: 0.36 number m^{-2} and second year: 0.31 number m^{-2}), *E. crus-galli* (first year: 0.26 number m^{-2} and second year: 0.16 number m^{-2}) and *Chenopodium album* (first year: 0.16 number m^{-2} and second year: 0.36 number m^{-2}) were recorded as weed species. Except for the weed species *A. nitens* and *S. altissima*, which were recorded by Mitkov (2021) in the experimental area, all other weed species were similar. Also, as mentioned above and in Pannacci et al. (2007), Asav and Serim (2019), Bharati et al. (2020) and Tonev et al. (2020), the weed species detected in the studies are mostly similar to the weed species we detected in the experimental area.

3.2. Effect of herbicides on weed population, species and dry weight

In the four assessments made to determine the effects of herbicides on the weed population, there was a statistically significant difference between the applications (columns) at the level of 5% in the first evaluation and at the level of 1% in the other three evaluations. There was a statistically significant difference of 1% in the 4 evaluations (rows) made for each application (Table 6).

In the first evaluation of the study, the effect of herbicides on the weed population was small, but in the second evaluation, there was a large increase. In the evaluations carried out, the first evaluation was generally included in a separate statistical group, while the other three evaluations were included in the same statistical group. In the last assessment, the highest percentage impact rates on the weed population were obtained from the plots where P+Q (96.66%), L+Q (91.66%) and A+Q (88.33%) active substances were used. The greatest effect on the weed population (76.66%) was achieved with Q herbicide used alone after emergence. In the final assessment, A, P and L were in the same statistical group and showed the lowest impact (Table 6). In their study, Pannacci et al. (2007) found that pre-emergence herbicides provided higher weed control (>90%). They reported that the herbicides they used, except for linuron, gave good control of dicotyledonous weeds. They stated that post-

Table 6. Effects of herbicides on weed populations (%)[1]

Applications	1. Assessment	2. Assessment	3. Assessment	4. Assessment	F	P-value
A	25.00±2.88 abC	65.00±2.88 cB	73.33±1.66 bA	73.33±1.66 cA	96.167**	0.000
P	26.66±4.40 abB	66.66±1.66 cA	71.66±1.66 bA	71.66±1.66 cA	68.400**	0.000
L	15.00±2.88 bB	65.00±2.88 cA	70.00±2.88 bA	71.66±4.40 cA	66.063**	0.000
Q	15.00±2.88 bB	70.00±2.88 bcA	71.66±1.66 bA	76.66±4.40 bcA	86.667**	0.000
A+Q	20.00±2.88 bB	80.00±5.77 bA	86.66±8.33 aA	88.33±9.27 abA	21.685**	0.000
P+Q	21.66±6.00 bC	78.33±1.66 abB	93.33±1.66 aA	96.66±1.66 aA	109.083**	0.000
L+Q	35.00±2.88 aB	86.66±1.66 aA	90.00±2.88 aA	91.66±1.66 aA	134.167**	0.000
Mean	22.61±1.87	73.09±2.02	79.52±2.38	81.42±2.58		
F	3.590*	7.722**	7.248**	5.687**		
P-value	0.023	0.001	0.001	0.004		

A= Aclonifen, P= Pendimethalin, L= Linuron, Q= Quizalofop-p-ethyl, A+Q= Aclonifen+Quizalofop-p-ethyl, P+Q= Pendimethalin+Quizalofop-p-ethyl, L+Q= Linuron+Quizalofop-p-ethyl, *: Statistically significant at 5% (p<0.05) level, **: Statistically significant at 1% (p<0.01) level, [1]: The differences between the means with the same letter are not significant at the p<0.05 level.

emergence applications of Aclonife did not provide satisfactory control against dicotyledonous weeds. They stated that the mixture of Aclonifenin and Quizalofop-p-ethyl may be the best option for possible good weed control. Štefanić et al. (2021) controlled the weed density acceptably with the pre-emergence and post-emergence herbicides they used and concluded that better weed control would be achieved with the use of herbicides and higher planting density. Kalaisudarson et al. (2020) stated that pendimethalin is an effective and economically viable alternative to manage weeds in sunflower with pre-emergence use and with intercropping with blackgram. In another study, the herbicides used reduced the density of some weed species and increased the density of others (Tonev et al., 2020). Another study reported that the combination of herbicide use and inter-row hoeing may be the best option for weed control (average 99% of weed control) (Pannacci and Tei, 2014). The results we obtained are parallel to the results of the above-mentioned studies. The differences that occur are due to the time of use of the herbicide with the active ingredient used and the type of weed. As a result, for the best weed control, it is important to choose the right herbicide according to the relevant weed species in the field.

In the four assessments made, the effects of the herbicides used in the study on the weed species *S. halepense*, *S. viridis*, *A. retroflexus* and *Chenopodium album* showed a statistically significant difference between applications at all times. There was a statistically significant difference between the periods, but there was no difference because some herbicides did not affect the weed (Figure 1).

Four of the applications used in the study affected *S. halepense*. However, three of them had no effect. In the last assessment, the highest effect was determined in the plots where P+Q (96.67%) and L+Q (95%) herbicides were applied. All herbicides used in the study affected *S. viridis*. In the last assessment, the effectiveness rate against this weed was 90% and above in 6 applications. The L herbicide had a 25% effect. In the final assessment of the study, an effect of 95% or more on *A. retroflexus* was observed in 4 applications. While an effect of 40% and 46% was observed in the other two applications, no effect was observed in one application. An effect of 95% or more on *Chenopodium album* was observed in 6 applications. No effect was observed with the Q herbicide. In general, there is an increase in the rate of control of these weeds in plots where pre-emergence and post-emergence herbicides have been used together (Figure 1). Pannacci et al. (2007) reported that post-emergence herbicides showed lower effectiveness against *A. retroflexus* compared to pre-emergence herbicides. Tonev et al. (2020) indicate that the herbicides used have limited effectiveness on *Chenopodium album*. In another study, the effect rates of the herbicides used on *Chenopodium album* varied between 60% and 100% in the first year and 65% and 100% in the second year. As for the effect on *S. viridis*, they observed an effect between 0% and 100% in both years. While only one of the herbicides they used on *S. halepense* seeds showed 0% effectiveness, the others showed 100% effectiveness. Effects on rhizomes were observed between 0% and 80%. They observed that the herbicides they used had an effect of 45% to 100% on *A. retroflexus* in both years (Mitkov, 2021).

In the four assessments made, the effects of the herbicides used in the study on the weed species *A. nitens*, *S. altissima*, *Cirsium arvense* and *X. strumarium* showed a statistically significant difference between applications at all times. There was no difference because some herbicides did not affect the weeds, although there was a statistically significant difference between the times (Figure 2).

In the last assessment made in the study, a 98.33% effect on *A. nitens* was determined in the plots where A+Q pre-emergence and post-

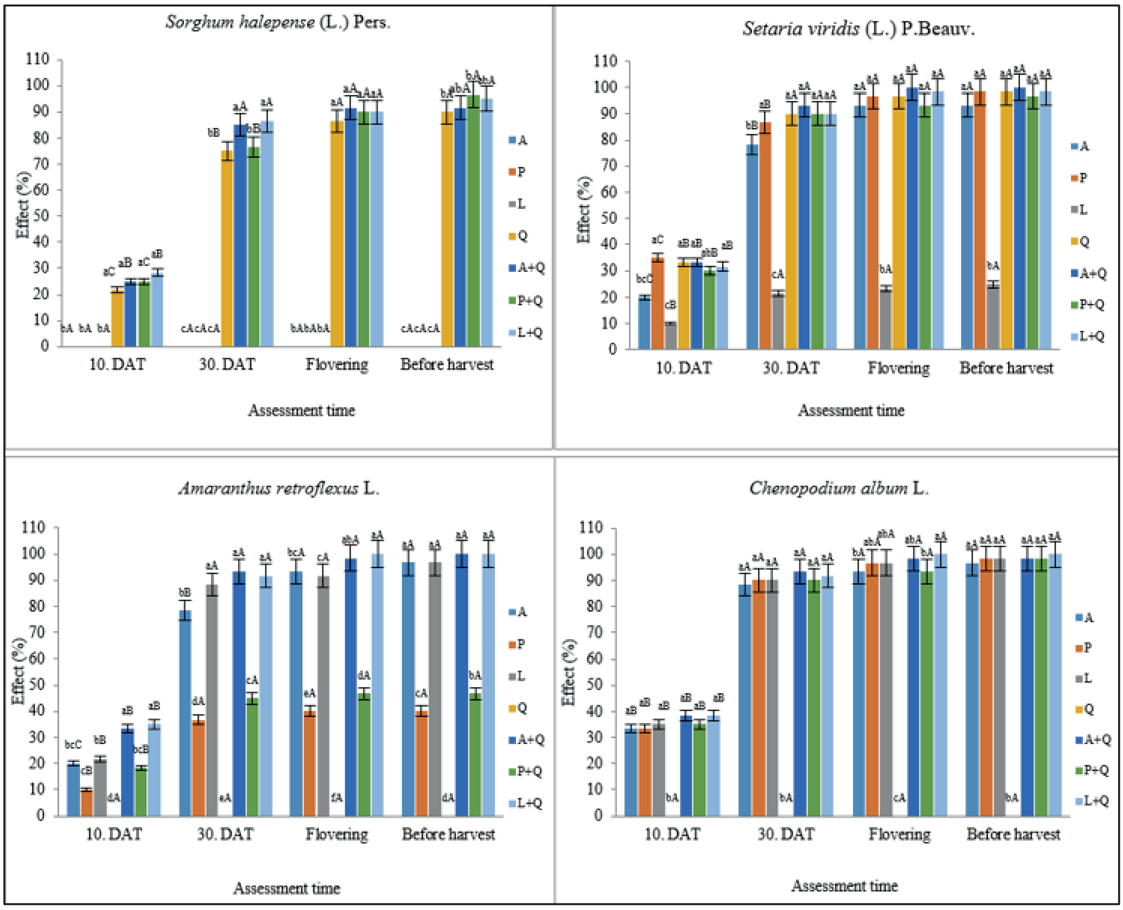

Figure 1. Effect of herbicides on the weeds *Sorghum halepense*, *Setaria viridis*, *Amaranthus retroflexus* and *Chenopodium album**

A= Aclonifen, P= Pendimethalin, L= Linuron, Q= Quizalofop-p-ethyl, A+Q= Aclonifen+Quizalofop-p-ethyl, P+Q= Pendimethalin+Quizalofop-p-ethyl, L+Q= Linuron+Quizalofop-p-ethyl, DAT: Days After Treatment, *: The differences between the mean values marked with the same letter are not significant at the 0.05 level, Lowercase letters indicate the grouping between applications, and uppercase letters indicate the grouping between the assessment times of each application.

emergence herbicides were used. While an effect rate of less than 50% was determined in the other 5 applications, no effect was observed in the plot where Q herbicide was applied. Herbicides had a low effect on *S. altissima*, and the highest effect was obtained in P+Q (40%) plots. The effect rates of herbicides on *Cirsium arvense* were low, and the highest effect rate was determined in L+Q (36.67%) plots. The highest effect on *X. strumarium* was determined in L+Q parcels with a rate of 36.67%. No effects were observed on the weed species *S. altissima, Cirsium arvense* and *X. strumarium* in Q plots (Figure 2). According to Tonev et al. (2020), the herbicides used by them reduced the density and the distribution of *X. strumarium*. Mitkov (2021) found that the herbicides he used were effective between 85% and 95% on *X. strumarium* in both years.

In the four evaluations made, the effects of the herbicides used in the study on the weed species *Convolvulus arvensis and P. oleracea* showed a statistical difference between the applications in all periods. There was a statistical difference between the periods, but there was no difference because some herbicides did not affect the weeds (Figure 3).

In the final assessment of the study, the highest impact rates on *Convolvulus arvensis* were determined in L and L+Q plots. The highest effect on *P. oleracea* was determined with a rate of 98.33% in the plots where A+Q and P+Q pre-emergence and post-emergence herbicides were applied (Figure 3). No effect was observed on these two weed species in the plots where Q herbicide was used Tonev et al. (2020) reported that the herbicides they used had only a limited effect on *P. oleracea*. Tonev et al. (2020) reported that the herbicides they used had only a limited effect on *P. oleracea*. Mitkov (2021) found that the herbicides he used were effective on *P. oleracea* between 0% and 30% in the first year and 0% and 40% in the second year. None of the herbicides they used had any effect on *Convolvulus arvensis*.

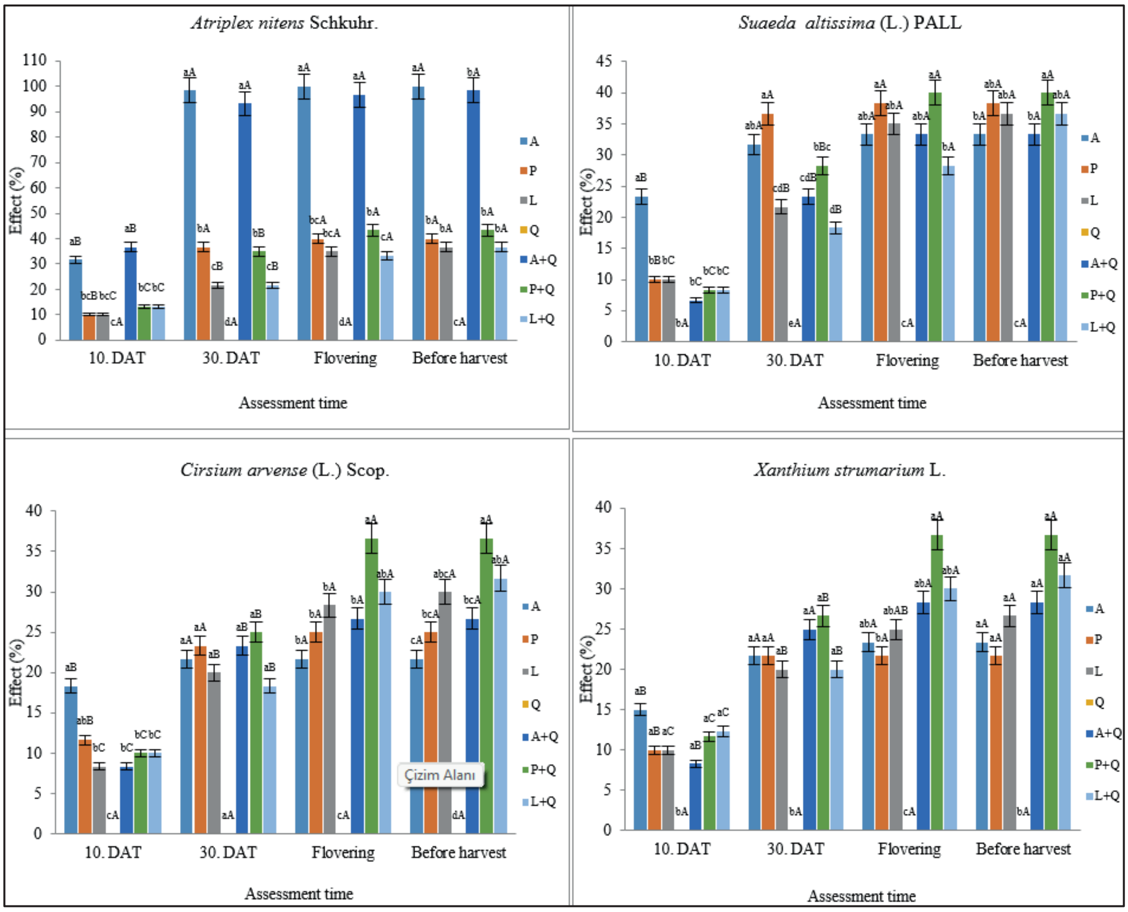

Figure 2. Effects of herbicides on the weeds *Atriplex nitens*, *Suaeda altissima*, *Cirsium arvense* and *Xanthium strumarium**

A= Aclonifen, P= Pendimethalin, L= Linuron, Q= Quizalofop-p-ethyl, A+Q= Aclonifen+Quizalofop-p-ethyl, P+Q= Pendimethalin+Quizalofop-p-ethyl, L+Q= Linuron+Quizalofop-p-ethyl, DAT: Days After Treatment, *: The differences between the mean values marked with the same letter are not significant at the 0.05 level, Lowercase letters indicate the grouping between applications, and uppercase letters indicate the grouping between the assessment times of each application.

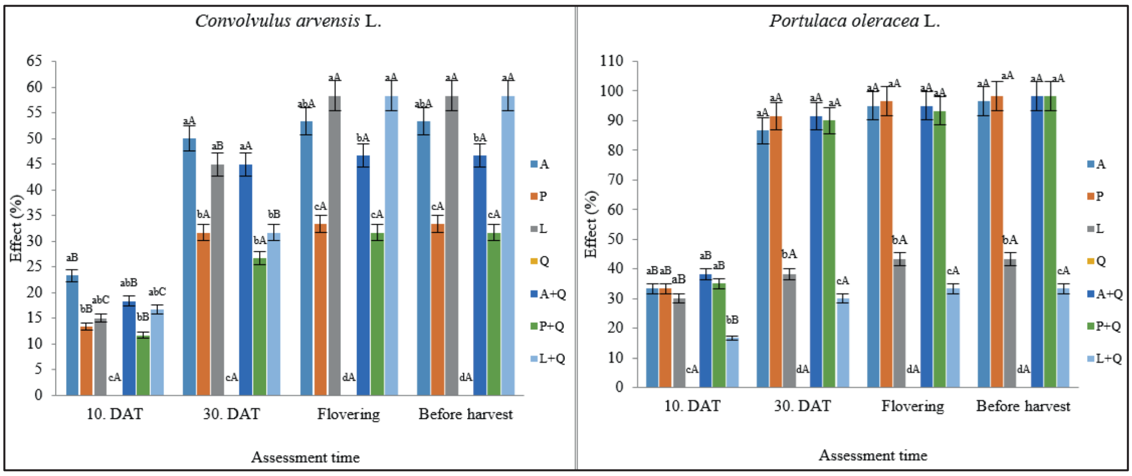

Figure 3. Effects of herbicides on the weeds *Convolvulus arvensis* and *Portulaca oleracea**

A= Aclonifen, P= Pendimethalin, L= Linuron, Q= Quizalofop-p-ethyl, A+Q= Aclonifen+Quizalofop-p-ethyl, P+Q= Pendimethalin+Quizalofop-p-ethyl, L+Q= Linuron+Quizalofop-p-ethyl, DAT: Days After Treatment, *: The differences between the mean values marked with the same letter are not significant at the 0.05 level, Lowercase letters indicate the grouping between applications, and uppercase letters indicate the grouping between the assessment times of each application.

In the study, there was a statistically significant difference in the effects of herbicides on weed dry weight at the 1% level. The effects of herbicides on weed dry weight are given in Table 7.

Table 7. Effects of herbicides on weed dry weight

Applications	Weed dry weight (g m^{-2}) (Mean ± standard error)	Effects (%)
A	89.13±4.59 cd	79.77
P	90.30±5.74 cd	79.50
L	101.90±6.79 c	76.87
Q	285.63±13.33 b	35.17
A+Q	55.46±7.69 cd	87.41
P+Q	50.33±5.71 d	88.58
L+Q	45.66±7.67 de	89.63
Weed free	0.00±0.00 e	100.00
Weedy	440.56±41.65 a	0.00
Mean	128.77±26.54	
F	83.489**	
P-value	0.00	

A= Aclonifen, P= Pendimethalin, L= Linuron, Q= Quizalofop-p-ethyl, A+Q= Aclonifen+Quizalofop-p-ethyl, P+Q= Pendimethalin+Quizalofop-p-ethyl, L+Q= Linuron+Quizalofop-p-ethyl, **: Statistically significant at 1% (p<0.01) level, The differences between the mean values marked with the same letter are not significant at the 0.05 level.

In the study, the highest weed dry weight was obtained in weedy control (440.56 g m^{-2}) plots. The lowest dry weight was obtained in the plot where L+Q (45.66 g m^{-2}), P+Q (50.33 g m^{-2}) and A+Q (55.46 g m^{-2}) herbicides were applied. The highest percentage effect on weed dry weight was obtained in plot L+Q with a rate of 89.63%. In general, lower weed dry weights and therefore higher percentage control rates were achieved in plots where both pre- and post-emergence herbicides were applied (Table 7). Antipova and Chornyy (2021) obtained the highest weed dry weight in the weed control (449 g m^{-2}) parcel, and with their application, a decrease of 86.2% in the weed dry weight occurred. In another study, the highest weed dry weight was determined as 132.10 g m^{-2} and the lowest was 10.45 g m^{-2}. The percentage impact of the herbicides they used on weed dry weight varied between 44.36% and 92.06% (Kalaisudarson et al., 2020). In another study, the highest weed dry weight was obtained in the weedy control (121 g m^{-2}) plot. The lowest weed dry weight was obtained in Pendimethalin+Quizalofop-p-ethyl (21 g m^{-2}) plots. Among the herbicides used, the highest dry weight was determined as 69 g m^{-2}. They also achieved lower weed dry weights by using pre-emergence and post-emergence herbicides together (Mohapatra et al., 2020). Mohapatra et al. (2020) reported that the dry weight of the weed was reduced by 84.1 % to 43.2 % with the combined use of post-emergence herbicides and pre-emergence herbicides. In another study, they obtained the highest weed in the plot, and the percentage effect of the herbicides they used on the weed's dry weight varied between 17.79% and 78.60% (Bharati et al., 2020). The results mentioned above are similar to the results of our study.

Differences may vary depending on the herbicide used and the weed species found in the relevant area. Additionally, in the study, the effectiveness levels of herbicides on weed population, weed species and weed dry weights are presented in Table 8.

Two of the herbicide applications made in the study provided Excellent control (90%-100%) on the weed population, and five applications provided good control (70%-90%). On weed dry weight, six applications provided good control (70%-90%) and one application provided poor control (<50%). When these herbicide applications were examined in terms of the average effect on weed population and dry weight, two applications provided excellent control, four applications provided good control and one application provided fair control. When evaluated in general, there is an increase in the effect rates on the weed population and dry weight in plots where pre-emergence and post-emergence herbicides were used together (Table 8).

The effectiveness levels of herbicide applications on weed species are given in Table 9. In the study, excellent control (90%-100%) of the highest number of weed species was obtained in the plots where A+Q pre-emergence and post-emergence herbicides were used together. This plot provided excellent control of 6 weed species. The fewest weed species were obtained in the parcel where excellent control Q herbicide was applied. In the study, it was determined that all herbicides had poor control of 3 weed species. In the study, the highest excellent control was generally determined in the parcels where pre-emergence and post-emergence herbicides were used together (Table 9).

3.3. The effect of herbicides on the yield and yield components of wheat

In the study, pre-emergence and post-emergence herbicides affected sunflower plant height (F= 26.498 and p<0.00), head diameter (F= 25.342 and p<0.00), 1000 grain weight (F= 9.928 and p<0.00), and their effects on grain yield (F= 38.426 and p<0.00) resulted in a statistically significant difference of 1% (Table 10).

In the study, plant height averages varied between 196.66 and 129.00 cm, and the highest plant height was obtained in the weed-free (hoe) control plot, which was in a single statistical group. After the control parcel, the highest plant height was determined in the P+Q (181.30 cm) parcel (Table 10). Mohapatra et al. (2020), reported the highest plant height in the weed-free control (134.7 cm)

Table 8. Herbicide efficacy on weed population and dry weight

Applications	Weed population (%)	RS	Weed dry biomass (%)	RS	Mean	RS
A	73.33	G	79.77	G	76.55	G
P	71.66	G	79.50	G	75.58	G
L	71.66	G	76.87	G	74.26	G
Q	76.66	G	35.17	P	55.91	F
A+Q	88.33	G	87.41	G	87.87	G
P+Q	96.66	E	88.58	G	92.62	E
L+Q	91.66	E	89.63	G	90.65	E

RS: Rating scala [E= Excellent control (90%-100%), G= Good control (70%-90%), F= Fair control (50%-70%), P= Poor control (<50%)]

Table 9. Efficacy levels of herbicide applications on weed species

Applications	1	RS	2	RS	3	RS	4	RS	5	RS	5	RS	Ca	RS	Xs	RS	Ca	RS	Po	RS
A	0	P	93	E	96	E	96	E	100	E	33	P	21	P	23	P	53	F	96	E
P	0	P	98	E	40	P	98	E	40	P	38	P	25	P	21	P	33	P	98	E
L	0	P	25	P	96	E	98	E	36	P	36	P	30	P	26	P	58	F	43	P
Q	90	E	98	E	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P
A+Q	91	E	100	E	100	E	98	E	98	E	33	P	26	P	28	P	46	P	98	E
P+Q	96	E	96	E	46	P	98	E	43	P	40	P	36	P	36	P	31	P	98	E
L+Q	95	E	98	E	100	E	100	E	36	P	36	P	31	P	31	P	58	F	33	P

RS: Rating scala [E= Excellent control (90%-100%), G= Good control (70%-90%), F= Fair control (50%-70%), P= Poor control (<50%)], Ca: *C. arvense*, Xs: *X. stromonium*, Po: *P. olaracea*

Table 10. Effect of herbicides on sunflower yield and yield components

Applications	Plant height (cm)	Head diameter (cm)	1000 grain weight (g)	Yield (kg da^{-1})
A	173.06±6.19 bc	15.73±.39 cd	58.40±.94 a	254.93±3.27 bc
P	169.56±2.84 bcd	16.56±.46 bc	57.96±1.23 a	255.00±8.96 bc
L	166.93±2.35 cd	16.43±.35 bc	57.16±.93 a	245.23±2.42 bc
Q	158.96±4.45 d	15.00±.11 d	55.90±1.55 a	234.10±12.11 c
A+Q	178.73±1.94 b	17.70±.25 b	57.00±.73 a	246.90±7.91 bc
P+Q	181.30±2.04 b	16.96±.31 bc	60.06±1.31 a	254.30±2.86 bc
L+Q	174.06±1.80 bc	17.53±.40 b	59.66±.53 a	256.60±3.33 b
Weed free	196.66±4.40 a	19.26±.46 a	61.43±3.85 a	287.53±5.95 a
Weedy	129.00±3.78 e	12.16±.60 e	42.20±2.08 b	198.20±4.72 d
Mean	169.81±3.57	16.37±.38	56.42±1.12	242.62±7.69
F	26.498**	25.342**	9.928**	38.426**
P-value	0.000	0.000	0.000	0.000

A= Aclonifen, P= Pendimethalin, L= Linuron, Q= Quizalofop-p-ethyl, A+Q= Aclonifen+Quizalofop-p-ethyl, P+Q= Pendimethalin+Quizalofop-p-ethyl, L+Q= Linuron+Quizalofop-p-ethyl, **: Statistically significant at 1% (p<0.01) level, In the same column, the differences between the mean values marked with the same letter are not significant at the 0.05 level.

parcel and the lowest plant height was obtained in the weedy control (120.4 cm) parcel. Bharati et al. (2020), reported the highest sunflower plant height in the weed-free control (171.06 cm) plots and the lowest plant height was obtained in the weedy control (145.91 cm) plots.

In the study, the highest table diameter was obtained in the weed-free (hoe) control (19.26 cm) parcel, which was in a single statistical group. After this parcel, it was obtained in parcels A+Q (17.70 cm) and L+Q (17.53 cm) (Table 10). Mohapatra et al. (2020), found the highest table diameter in the weed-free control (15.16 cm) plots and the lowest in the weedy control (12.55 cm) plots. Bharati et al. (2020), reported the highest tray diameter in the weed-free control (16.64 cm) plots, and the lowest tray diameter was obtained in the weedy control (9.05 cm) plots.

Mean 1000 grain weight ranged from 61.43 to 42.20 g. Except for the weed control plot, all other treatments were statistically similar in 1000 grain weight.. The highest 1000-grain weight was detected in the weed-free control plot (Table 10). Mohapatra et al. (2020), reported the highest 1000 grain weight in the weed-free control (45.4 g) plots and the lowest in the weedy control (35 g) plots. Bharati et al. (2020), obtained the highest 1000 grain weight in the weedless control (41.9 g) plots and the lowest 1000 grain weight in the weedy control (28.9 g) plots.

In the study, yield averages varied between 287.53 and 198.20 kg da^{-1}. The weed-free control plot achieved the highest yield, forming a single statistical group. The average yield was 242.62 kg da^{-1}. Conversely, the weedy control plots had the lowest sunflower yield and yield components (Table 10). Pannacci et al. (2007) determined that the yield of pre-emergence herbicides was higher than that of post-emergence herbicides. The highest yield was s-metolachlor+linuron in the first two years (487.6 kg da^{-1} in the first year and 468.7 kg da^{-1} in the second year), the highest yield in the third year was s-metolachlor+Aclonifen (479.5 kg da^{-1}), the highest yield low yield was obtained from the weedy control (254.8 kg da^{-1}) parcel. In general, higher yields were obtained with the combined use of pre-emergence and post-emergence herbicides. Štefanić et al. (2021), reported that there was no statistical difference between the herbicides applied. However, they stated that increasing planting density with the herbicides they use is the best alternative strategy in economic terms to reduce weed invasion and obtain better yields. In another study, the highest yield was obtained in the first year from the herbicide application used alone (350.17 kg da^{-1}), and in the second year from the application in which both pre-emergence and post-emergence herbicides were used (401.10 kg da^{-1}) (Mitkov, 2021). Kalaisudarson et al. (2020) suggested that pre-emergence pendimethalin provides an efficient and economically viable approach for weed control in sunflower. Mohapatra et al. (2020), in both years of the study, found the highest efficiency in weedless control (first year; 250 kg da^{-1} and second year; 210 kg da^{-1}), and the lowest efficiency was in weedy control (first year; 170 kg da^{-1} and second year; 210 kg da^{-1}). year; 140 kg da^{-1}) parcels. They also concluded that weed competition caused a 31.3% yield loss in sunflower. In their study, Pannacci and Tei (2014) obtained the highest plant yield in weed-free control and the lowest in weed control in all three years. Bharati et al. (2020) reported the highest yield in weed-free control (225.1 kg da^{-1}) plots and the lowest yield in weedy control (12.78 kg da^{-1}) plots. Our results are consistent with those of the above studies, with differences mainly due to factors such as study location, sunflower variety and growing conditions.

3.4. Multivariate analysis of the parameters and the applications

In addition to one-way ANOVA, mean values were analyzed to visualize size, correlation, and estimated parameters. The relationships of weed dry weight and density with other parameters were examined using correlation coefficients, heat map clustering, network graph analysis, and principal component analysis.

In our study, weed dry weight is negatively related to all agronomic characteristics of sunflower with negative correlation coefficients in the range of -0.907 to -0.943. In the study, weed dry weight, plant height ($r= -0.943$, $P<0.000$), head diameter ($r= -0.938$, $p<0.000$), 1000 grain weight ($r= -0.907$, $P<0.000$) and grain yield ($r= -0.920$, $P<0.000$) showed a negative correlation with the parameters. Sunflower agronomic traits are positively correlated with each other between 0.853 and 0.964 (Figure 4 and 5).

Heatmap clustering clearly distinguished the dependent/independent variables into two main clusters, with a color range (+1.5 to -1.5; red to blue) indicating the resulting values (Figure 6). Among the main clusters, a single cluster included a weed-free control plot and Q herbicide. The results obtained from heat map clustering revealed that it was effective in combating weeds, although the herbicides used in the study differed. In particular, choosing herbicides by considering their impact on the weed species in the relevant area can increase the effectiveness rate.

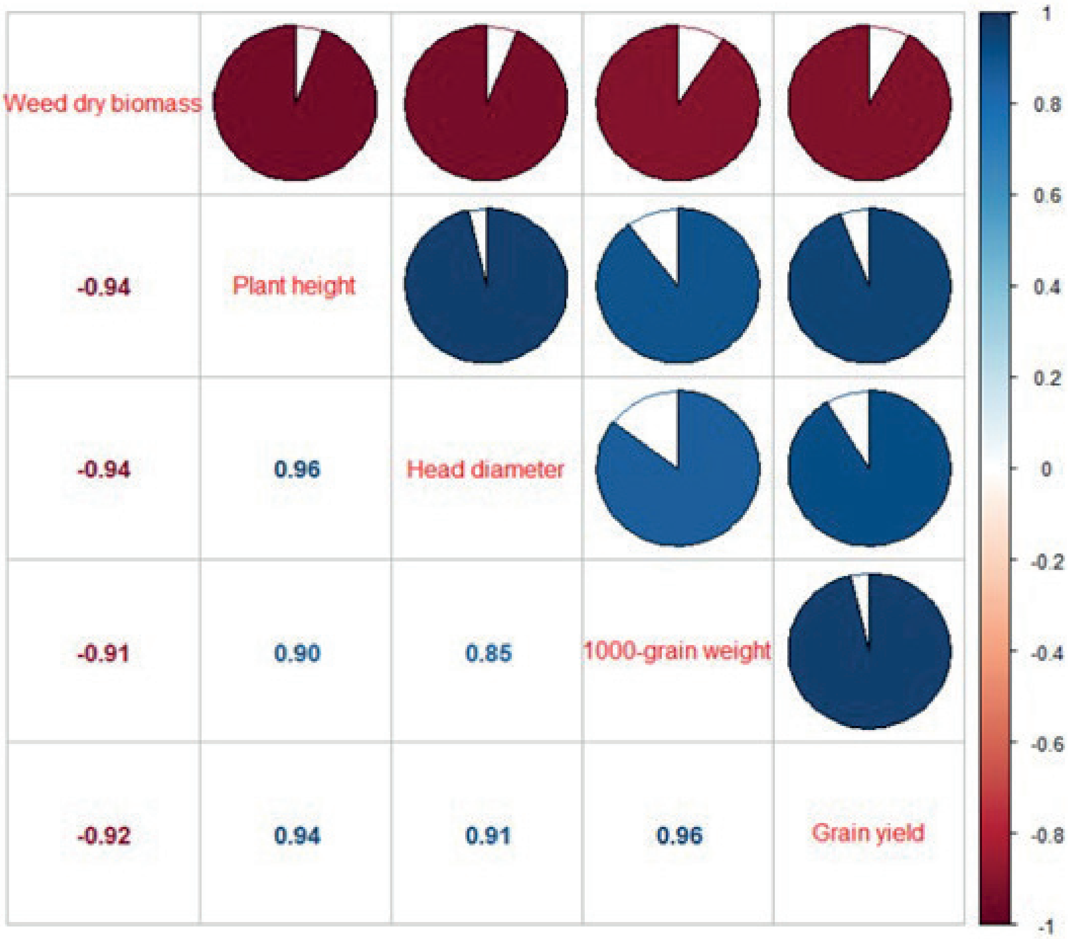

Figure 4. Correlation analysis of estimated parameters

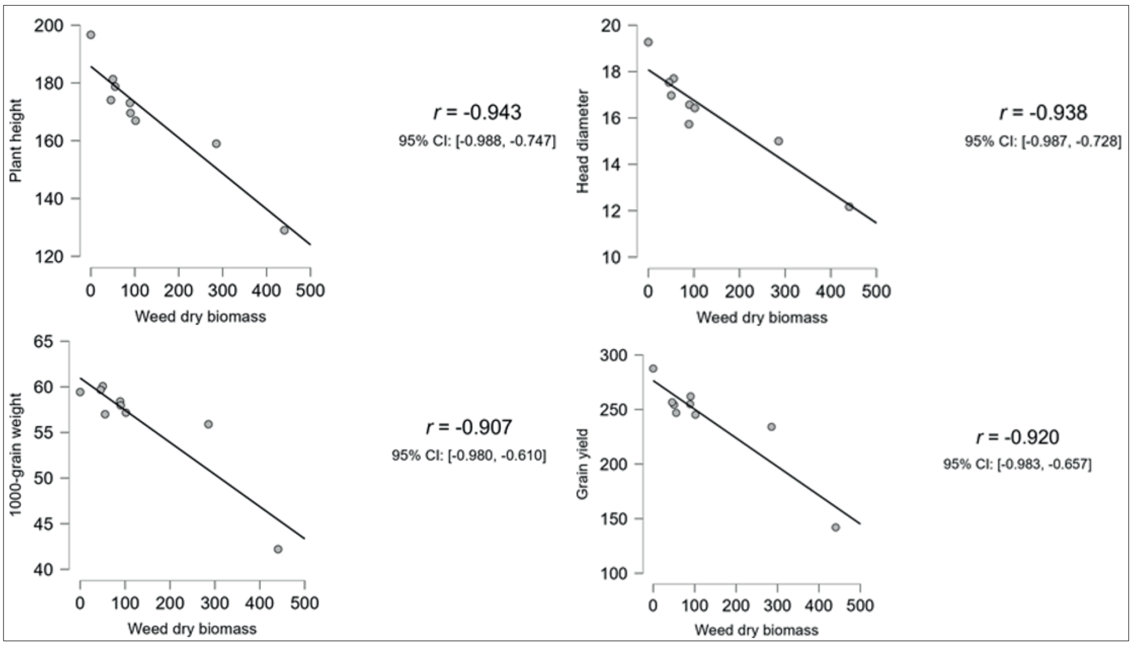

Figure 5. Correlations between weed dry weight and other parameters

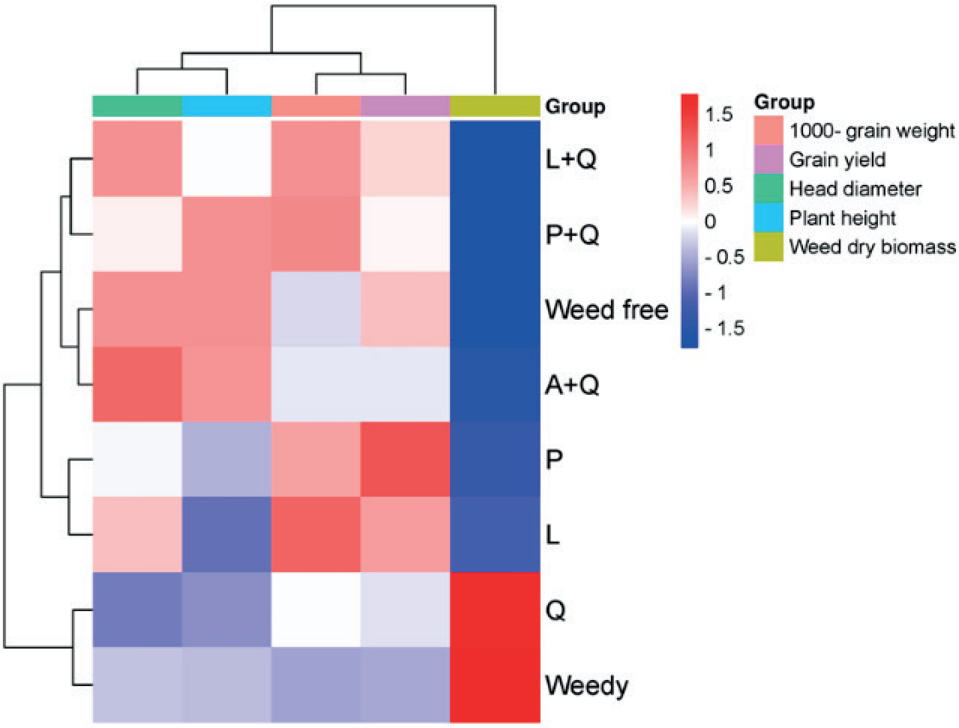

Figure 6. Heat map of parameters corresponding to applications

A=Aclonifen, P= Pendimethalin, L= Linuron, Q= Quizalofop-p-ethyl, A+Q= Aclonifen+Quizalofop-p-ethyl, P+Q= Pendimethalin+Quizalofop-p-ethyl, L+Q= Linuron+Quizalofop-p-ethyl

To consolidate the effects of the trials/treatments on sunflower plants, a network graph analysis was also conducted to identify the relationship between treatments based on their effects/performance on agronomic traits and weed dry weight (Figure 7). The nodes on the lines correspond to the degree of relationships, i.e. the thinner/lighter line indicates weaker relationships with each other and the thicker line indicates stronger relationships. Consistent with heat map clustering, a clear distinction emerged. In this analysis, the weed-free control group did not have a relationship with any treatment. Other practices have been interrelated to a certain degree.

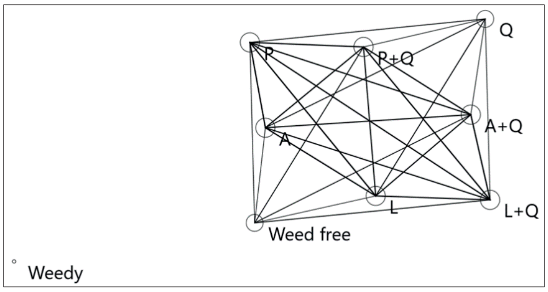

Figure 7. Network graph analysis of applications

A= Aclonifen, P= Pendimethalin, L= Linuron, Q= Quizalofop-p-ethyl, A+Q= Aclonifen+Quizalofop-p-ethyl, P+Q= Pendimethalin + Quizalofop-p-ethyl, L+Q= Linuron + Quizalofop-p-ethyl

In order to describe the rate of variation, the agronomic traits of the sunflower and the weed dry weight were distributed over a pair of biplot plots (Figure 8). Accordingly, the first two components (PC1: 93.93% and PC2: 3.63%) explained 97.56% of the variability of the original data. Such a high explained variance clearly shows that Principal Component Analysis can be successfully used to evaluate the impact of estimated parameters along with applications. The first component (PC1), Q (with a score of -1.20) and weedy control (with a score of -5.17), the groups are negatively correlated. But A (with 0.35 points), P (with 0.49 points), L (with 0.11 points), A+Q (with 0.83 points), P+Q (with 1.08 points), It is positively related to L+Q (with 1.03 points) and weed-free control (with 2.44 points). Additionally, while “weed dry weight” (with a score of -0.44) is negatively related, other agronomic parameters are positively related (Figure 8).

Advanced analyses such as correlation, heat map clustering, network graph analysis, and principal component analysis that we performed on the mean values of the variables in the study support the analysis of variance, and by clustering the results, the effects and relationships between applications and parameters are clearly stated.

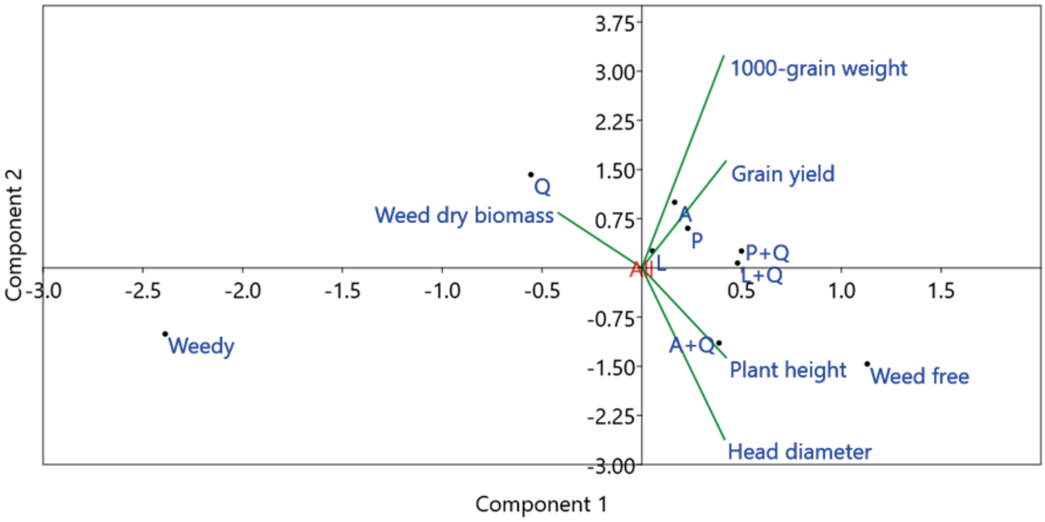

Figure 8. Principal component analysis of parameters and applications

A= Aclonifen, P= Pendimethalin, L= Linuron, Q= Quizalofop-p-ethyl, A+Q= Aclonifen+Quizalofop-p-ethyl, P+Q= Pendimethalin+Quizalofop-p-ethyl, L+Q= Linuron+Quizalofop-p-ethyl

4. Conclusions

In our study evaluating the effects of pre-emergence and post-emergence herbicides with different modes of action on weed control and sunflower yield, we observed significant differences in weed population due to the application of these herbicides. In the study, the highest effect rates on the weed population were obtained in the plots where both pre-emergence and post-emergence herbicides were used together. The highest impact rate was observed in P+Q plots (96.66%). The effects of herbicides on weed species vary, and in the last evaluation it was observed that while herbicides had a high effect on some weeds, they had a very low effect on others. The highest effect on weed dry weight was obtained in plot L+Q with a rate of 89.63%. The highest weed dry weight was recorded in the weedy control plots. In the study, the highest yield (287.53 kg da^{-1}) was obtained in the weed-free (hoe) control plot. The study found no statistical difference in yield between plots treated with both pre-emergence and post-emergence herbicides and those treated with each herbicide alone. Weed control in sunflowers can increase yields by 18% to 45%. As a result, the combined use of herbicides increased their effectiveness on weed population and dry weight. It has been determined that yield increases occur when some herbicides are used alone. However, it is important to use herbicides in combination to control a broader range of weed populations and prevent the potential development of resistance. Additionally, selecting the appropriate herbicide for the specific target weed species is crucial.

Ethical Statement

The authors declare that ethical approval is not required for this research.

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Declaration of Author Contributions

The authors declare that they have contributed equally to the article. All authors declare that they have seen/read and approved the final version of the article ready for publication.

Declaration of Conflicts of Interest

All authors declare that there is no conflict of interest related to this article.

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