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Investigation of the Effectiveness of Different Weed Control Methods Used for Potato (*Solanum tuberosum* L.) Cultivation

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Abstract

Potato (*Solanum tuberosum* L.) is the fourth most common food in the world, after wheat, rice, and maize, and it is cultivated in almost all countries around the world. Weeds are one of the most critical factors affecting the yield and quality of potato. An appropriate weed management strategy must be developed and applied on time to enhance its efficacy against the weeds of potatoes. This research evaluated the effectiveness of different herbicides and mechanical weed management methods, applied alone and in combination, in potato (cv. Marabel). This study was conducted in the Melikgazi district, which has critical potato-growing areas in Kayseri, Türkiye. In the trial, 1 and 2 tractor hoe operations were conducted alone and in combination with the herbicides 600 g/L metribuzin (Sencor SC 600), 330 g/L pendimethalin (Herbimat 330 EC), 450 g/L linuron (Aries), and 150 g/L fluazifop-P-butyl (Fusilade Forte). A weedy check plot with no control measure was also included for comparison. The results revealed that the most effective application against weeds in potato crops was the combined application of pendimethalin + metribuzin + fluazifop-P-butyl, where the highest (39,575 kg ha^{-1}) potato yield was achieved compared to the weedy check plot where only 22,945 kg $ha^{-1}$of potatoes were harvested. Similarly, the highest net income of 4633.91 USD (United States Dollar) ha^{-1} was calculated for the plots treated with pendimethalin PRE + metribuzin POST + fluazifop-P-butyl POST, parallel to the highest yield. These findings underscore the importance of integrating selective herbicide combinations with mechanical weed control as part of a holistic, sustainable weed management framework. Such an approach not only enhances potato yield and economic efficiency but also supports long-term agroecosystem resilience by reducing herbicide dependence, minimizing environmental impacts, and promoting region-specific adaptation in future potato production systems. Further, studies are suggesting to test the dose responses of herbicides in addition to mechanical tools for searching an eco-friendly weed control solution with minimum herbicidal exposure in potatoes.

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Keywords Herbicides · Mechanical weed control · Net income · Potatoes · Weed management

Introduction

The potato (*Solanum tuberosum* L.) originates from the Andes in South America and has been cultivated for at least 8000 years (Spooner et al. 2005). Spanish explorers brought it to Europe from Peru in the sixteenth century and it spread from there to other continents (Calıskan et al. 2022; Shepherd 2024). Today, it is cultivated in about 150 countries worldwide (Calıskan et al. 2022). According to 2022 data, potato ranks fourth in global production after wheat, maize, and rice, with an annual yield of approximately 374 million tons cultivated on around 18 million hectares (FAOSTAT 2024). In Türkiye, data from 2023 show that potatoes are grown on 150,926 hectares, with a total production of 5.7 million tons (TUIK 2023).

The world population is growing by about ~ 200,000 people per day (United Nations 2023), and the need for agricultural production is increasing at the same rate. Recent studies indicate that the expansion of arable land is highly limited, emphasizing the need to enhance productivity and adopt sustainable land management rather than relying on further land conversion (Čengić et al. 2023; Liu et al. 2024). It is clear that current agricultural production is insufficient to feed the current population and that the new agricultural land being developed will not be able to fill this gap (Maja and Ayano 2021). It also follows from this situation that the losses in the existing areas due to diseases, pests, and weeds must be minimized using various control methods that do not harm the environment for sustainable agriculture (Oerke 2006).

Among the numerous factors hindering potato growth, weeds remain one of the most critical, often leading to considerable economic damage (Isik et al. 2015; Ganie et al.2023). They engage in direct competition with the crop for essential elements such as sunlight, moisture, nutrients, and growing space. Additionally, some weed species commonly found in potato fields, such as *Chenopodium album* L., *Amaranthus retroflexus* L., and *Cyperus rotundus* L., are known to release allelopathic compounds (e.g., phenolic acids, terpenoids) that can inhibit tuber formation and reduce photosynthetic efficiency in potato plants (Singh et al.2003; Dhima et al.2016; Shams et al.2023). Severe weed pressure has been shown to adversely affect potato production, resulting in yield losses of up to 33% in tuber output (Bhullar et al. 2015). However, the extent of yield reduction can vary widely depending on local environmental conditions and management practices. The magnitude of this loss is largely determined by the species composition of the weed population, their density, and how long they compete with the crop. In addition to depleting vital resources, weeds can interfere with plant physiological processes andact as alternate hosts or shelter for insect pests, thereby indirectly increasing pest incidence and activity in potato crops (Yadav et al. 2015; Haldhar et al. 2017). If weed management is not carried out in time, it causes significant product losses (Isik et al. 2023). This loss caused by weeds is about 12–61% for potato (Ganie et al. 2023). In a potato growing area, 100 kg of green weed parts cause a product loss of 400 kg

(Siddiqui et al.2024). Although, the potato is a fast-growing and developing crop, it is regarded as a weak competitor against weeds (Kumar and Aulakh 2022). The timing of weed management in potato cultivation significantly influences crop growth, with variations in yield ranging from 93 to 216% depending on the control period (Isik et al. 2015). For the crops grown worldwide (maize, wheat, potato, sugar beet, rice, soybeans, and cotton), the product loss caused by diseases, pests, and weeds is around 67.15% (Oerke 2006). Of this crop loss, 21.75% is due to pests, 13.78% to diseases, and 31.62% to weeds (Oerke 2006). The interaction between potato and weeds involves water, plant nutrients, and light (Chandel et al. 2022). Therefore, yield directly depends on utilizing these resources as much as possible during the production season (Isik et al. 2015).

In potato cultivation, weed management can be achieved by integrating cultural measures and chemical control (Abdallah et al. 2021). Cultural measures can be summarized under four headings: protective measures, tillage, crop rotation, and mowing (Karadoğan and Şanlı 2019). Pre-sowing tillage is one of the most effective methods of weed management. Hoeing is an effective means of weed management for potatoes. Aeration and slurry application can be used when the plants reach the soil surface and have 2–4 leaves (Karadoğan and Şanlı 2019). In chemical management, herbicides are applied at three different times: pre-planting, post-planting, and post-emergence (Karadoğan and Şanlı 2019). Weeds are a significant problem in agricultural areas, found in almost every environment in our country and the world (Faraj et al. 2023). Effective weed management is necessary to minimize the problems caused by weeds and to increase yield and quality.

Comprehensive weed control approach is crucial in potato production, and recent research emphasizes the importance of integrated approaches combining chemical, mechanical, and ecological methods. Studies have shown that in specific regional potato production systems, the use of pre- and post-emergence herbicides such as metribuzin, pendimethalin, paraquat, and linuron can achieve over 90% reduction in weed density when applied at optimal timing, leading to significant improvements in tuber yield and quality (Abdallah et al. 2021; Mondani et al. 2011; Yadav et al. 2015).

In potato cultivation, effective weed management is commonly achieved through the combined use of herbicides and mechanical interventions; however, integrating these approaches with ecological and cultural practices such as crop rotation, mulching, and optimized planting density provides a more sustainable framework on integrated weed management. However, the rising costs associated with herbicide applications driven by both the price of the chemicals and the growing reliance on selective herbicides aimed at specific weed families have placed an economic burden on producers (Siddiqui et al. 2024). Additionally, increasing societal concerns over pesticide use in agriculture have prompted a surge in research focused on minimizing herbicide dependence and exploring alternative strategies for sustainable weed control in potato production.

In Türkiye and in different parts of the world, farmers tend to use different herbicides separately or in tank mixtures for weed control in potato. However, it is not clear whether this will be effective against weeds or whether it will be economical. Therefore, studies on this subject are needed. This study tested different control

Table 1 Monthly climate data for the experimental area, 2015–2016

Months	Monthly total rainfall average (kg m^{-2})			Monthly average temperature (°C)			Monthly average relative humidity (%)		
	2015	2016	L.Y.A*	2015	2016	L.Y.A	2015	2016	L.Y.A
January	40.4	52.4	35.2	−0.9	−1.6	−1.7	78.8	78.2	75.5
February	56.6	53.7	36.2	2.3	4.4	0.1	70.7	74.1	71.9
March	122.4	13.6	41.8	6.0	7.3	4.8	69.7	56.1	64.7
April	45.4	8.6	52.1	8.9	13.5	10.7	59.9	46.5	59.0
May	24.8	105.8	51.8	14.8	14.7	15.2	57.5	64.8	59.2
June	39.8	26.2	39.5	18.0	20.2	19.3	66.2	56.1	54.2
July	2.0	9.9	9.5	22.0	22.8	22.6	48.4	45.9	48.0
August	8.9	0.0	6.8	23.8	24.6	22.2	48.5	43.2	47.6
September	0.2	18.4	13.9	21.4	16.8	17.3	43.2	51.9	52.3
October	14.7	4.0	28.0	13.4	12.2	11.6	66.4	52.0	63.1
November	14.5	5.0	32.4	6.2	4.9	5.3	62.3	53.0	70.1
December	15.0	28.8	37.4	−1.7	−1.2	0.5	79.8	73.5	75.2

**L.Y.A.* long year average. Climate data were obtained from the general directorate of meteorology

Table 2 Chemical and physical properties of soil from 2015 and 2016 experimental plots

Properties	2015	2016
pH	8.20	8.19
EC (mmhos cm^{-1})	0.253	0.254
Lime (%)	15.2	27.2
Phosphorus (P_2O_5) (kg ha^{-1})	91.33	72.98
Organic matter (%)	3.55	0.93
Texture	Clay loam	Clay loam

methods and combinations against weeds that cause significant product losses in potato cultivation. The aim was to identify the most effective weed management method to maximize economic returns for growers.

Materials and Methods

Experimental Area

The study was conducted in the province of Kayseri, which is located between 37° 45′ and 38° 18′ north latitude and 34° 56′ and 36° 58′ east longitude. Table 1 presents the climatic data corresponding to the years during which the study was conducted. The soil analysis data for the experimental plot are shown in Table 2. According to the analysis results, the 2015 trial plot belongs to the classes of strongly alkaline reaction with a pH of 8.20, slightly saline with 0.253 EC mmhos cm^{-1}, and

rich calcareous (problematic) with 15.2% lime. It was found to have a high organic matter content of 3.55% and a medium phosphorus content of 91.33 kg ha^{-1}. The experimental plots 2016 belong to the classes of strongly alkaline reaction with a pH of 8.19, slightly saline with 0.254 EC mmhos cm^{-1}, and abundantly calcareous (problematic) with a lime value of 27.2%. In terms of organic matter, it was found to have a very low organic matter content of 0.93% and a medium phosphorus content of 72.98 kg ha^{-1}.

Field Trials

The trial was designed following the randomized block design principle and included four replicates with 13 treatments. Each plot was 15 m^2 in size, arranged in four rows of 3 × 5 m. There was a 1 m space between the plots and a 2.5 m distance between the blocks. The same experimental design was used in both years. The potato variety used for the trials was Marabel which was registered in the Netherlands in 1993. Marabel is a yellow-fleshed potato known for its taste and smooth skin, commonly cultivated in Türkiye and nearby regions. For the 2015 and 2016 trial periods, the trial area was deeply ploughed, with a plough in the previous year's fall in October. The land was left untouched until it was suitable for planting. On 10 May in the 2015 trial and 21 April in the 2016 trial, a 15-15-15 compound NPK fertilizer was applied to the soil surface at a rate of 800 kg ha^{-1}. The fertilizer was immediately mixed into the soil as the tractor passed.

Before planting, the seed potato was treated against root neck necrosis, black scurf (*Rhizoctonia solani* Kühn), and the Colorado potato beetle [*Leptinotarsa decemlineata* Say (Coleoptera: Chrysomelidae)]. For every ton of seed, 0.5 kg of Guacho FS 600 with 600 g l^{-1} imidacloprid and 1.5 kg of Serenade SC fungicide with 1.34% *Bacillus subtilis* QST 713 were used.

After applying the fertilizer, the treated potato tubers were planted, and ridges were created with a planting machine on 14 May in the 2015 trial and 25 April in the 2016 trial. Each plot was planted with 75 seed potatoes, using a row spacing of 0.70 m and 0.25 m between plants within the row. In the 2015 trial, sowing could only occur in May, as the necessary soil moisture was lacking due to rainfall. 100 kg ha^{-1} of urea was used for top dressing. In the trial area, annual potato water consumption is 5850 tons per hectare. Irrigation was adjusted to provide this amount. Once the potato plants had emerged and reached a height of 25–30 cm, the first irrigation was performed, lasting for 5 h. Following the initial irrigation, water was applied weekly for 4 h until 1 month prior to harvest. During the final month before harvest, irrigation continued at weekly intervals but was shortened to 2 h per application.

Herbicide Applications

Various treatments were used in the field trials to investigate how to manage weeds in potato (Table 3). In the trials, 600 g/L metribuzin (Sencor SC 600 – BAYER from Germany), 330 g/L pendimethalin (Herbimat 330 EC—HEKTAS

Table 3 Applications made in the field according to the trial plan

Order of applications	Applications made
1. Application	1 time hoeing with a tractor
2. Application	2 times hoeing with a tractor
3. Application	Pendimethalin (pre-emergence)
4. Application	Linuron (pre-emergence)
5. Application	Metribuzin (post-emergence)
6. Application	Pendimethalin (pre-emergence) + 1 time hoeing with a tractor
7. Application	Linuron (pre-emergence) + 1 time hoeing with a tractor
8. Application	Pendimethalin (pre-emergence) + Metribuzin (post-emergence)
9. Application	Linuron (pre-emergence) + Metribuzin (post-emergence)
10. Application	Metribuzin (post-emergence) + 1 time hoeing with a tractor
11. Application	Pendimethalin (pre-emergence) + Metribuzin (post-emergence) + Fluazifop – P – Butyl (post-emergence)
12. Application	Linuron (pre-emergence) + Metribuzin (post-emergence) + Fluazifop – P – Butyl (post-emergence)
13. Application	Weedy Control Plot

from Türkiye), 450 g/L linuron (Aries— HEKTAS from Türkiye), and 150 g/L fluazifop-P-butyl (Fusilade Forte—Syngentha from Switzerland) were used as herbicides. Calibration was carried out before herbicide application, and it was calculated that 300 L ha^{-1} of water would be used. Pre-emergence herbicide applications were performed on the same day after sowing, with pendimethalin applied at a rate of 5000 mL ha^{-1} (equivalent to 1650 g ha^{-1} active ingredient) and linuron at 2500 mL ha^{-1} (1125 g ha^{-1} active ingredient). These applications took place on May 16, 2015, and April 28, 2016.

The post-emergence herbicide application took place on June 20, 2015, and June 10, 2016, when the first emerging potatoes were 10 cm long and the emerging weeds were 10–15 cm long. After the calibration adjustment, the herbicide was applied post-emergence with herbicide doses of 800 mL ha^{-1} (360 g ha^{-1} ai) for 600 g/L metribuzin and 1000 mL ha^{-1} (150 g ha^{-1} ai) for 150 g/L fluazifop-P-butyl. In addition to the herbicides, 1 hoeing plot, 2 hoeing plots, and control plots (weed-covered and weed-free plots) were established in the experimental blocks. The herbicides were applied with a portable sprayer loaded with Palmera SX-MD 18E (Chinese origin). The portable sprayer was fitted with four 110° flat fan nozzles (model 11002) and operated over a working width of 2 m. Applications were conducted at a constant pressure of 303.97 kPa, delivering a spray volume of 300 L ha^{-1}.

A Grimme milling machine was used as a tractor hoe for weed management in the hoe plots. The machine destroyed the weeds between the potato rows without damaging the green parts of the plants, thereby improving the plants' ability to absorb nutrients and water from the soil. In 2015, the 1st tractor hoeing was performed on June 3, followed by the second hoeing on June 17. In 2016, the first and second hoeings were carried out on June 14 and June 28, respectively.

Determination of the Effects of Applications on Weeds

The weed species in the experimental plots were counted in 0.25 m^2 frames. Phytotoxicity was assessed on the 7th, 14th, and 28th days after herbicide application using a scale of 0–100, where 0% indicates no effect on the potato plant, and 100% indicates plant death. Weed observations were conducted on the 7th, 14th, 28th, and 56th days after application, and samples of weed biomass were collected. For this purpose, 50 × 50 cm quadrats were randomly placed at four locations within each experimental plot. All weed species within each quadrat were identified to the species level, and the number of individuals per species was recorded to determine weed density and species composition. After counting the weeds in the quadrats, the weeds that were within the frame were harvested from the soil, bagged, and shifted to the laboratory for biomass measurement. The weeds were dried in an oven at 70 °C for 48 h to determine the dry biomass and then weighed.

Statistical Analysis

The results obtained in the trial were compared with the control, and the effects of applications and weed biomass on potato yield were analyzed. Statistical analyses were performed using R software (version 4.2.2; Core Team R 2022). An analysis of variance (ANOVA) was conducted using the "aov()" function from the stats package to evaluate the effects of treatments on the measured parameters. When significant differences were detected, treatment means were separated by the Least Significant Difference (LSD) test using the "LSD.test()" function from the agricolae package at the 0.05 probability level.

Prior to conducting ANOVA, the assumptions of normality and homogeneity of variances were examined. Normality of residuals was assessed using the Shapiro–Wilk test, and homogeneity of variances was verified using the Levene test. All statistical procedures followed standard experimental design principles to ensure the validity and reproducibility of the results.

Economic Analysis of Applications

The costs of tillage, seedbed preparation, planting, weed management, irrigation, fertilization, harvesting, and tractor fuel were calculated for all applications (Yaldiz et al. 1993). The total profit (Erenstein 2009) and the fixed and variable costs were calculated with the following formula:

$$\text{Profit}\left(\text{USD ha}^{-1}\right) = \left[\text{Yield}\left(\text{kg ha}^{-1}\right)\text{x Unit Price USD kg}^{-1}\right] - \left[\text{Herbicide Cost}\left(\text{USD ha}^{-1}\right) + \text{Fixed and Variable Costs}\left(\text{USD ha}^{-1}\right)\right]$$

Variable costs: Include land preparation, planting (seeds and labour), fertilization (fertilizer and labour), spraying (cost of pesticides and application), irrigation (labour and energy), hoeing, crop marketing (packaging, transport), and 25% interest on capital. Fixed costs consist of land rent, general expenses, and product insurance costs.

Results

Weed Species Densities

After data analysis for both the years, the general density of weeds observed in the experimental plot is given in Table 4. Weed densities were calculated and expressed as the number of individuals per square metre (plants m^{-2}). When reviewing the field observations from 2015 and 2016 in the table, it was found that the most common species were *Convolvulus arvensis* L. (field bindweed), *Amaranthus albus* L. (tumble pigweed), and *Amaranthus retroflexus* L. (redroot pigweed).

Effects of Applications on Weed Dry Weight (g 0.25 m^{-2}) on Day 28

The study results indicate statistically significant differences between years and applications. Weed dry biomass data are presented as annual averages in Table 5. The highest average weed dry weight was recorded with the weedy control at 69.50 g 0.25 m^{-2}, while the lowest weed dry weight was observed with the application of metribuzin + 1 hoe at 8.07 g 0.25 m^{-2}. In the annual evaluation, the highest weed dry biomass of 113.50 g 0.25 m^{-2} was recorded in 2015 in the Weedy Control plots. The lowest weed dry biomass was observed under the Metribuzin POST + 1

Table 4 Weeds and their densities

		Density (plant m^{-2})	
Family	**Scientific name**	**2015**	**2016**
Convolvulaceae	*Convolvulus arvensis* L.	1.853	1.692
Amaranthaceae	*Amaranthus albus* L.	1.400	1.615
Amaranthaceae	*Amaranthus retroflexus* L.	0.900	1.076
Poaceae	*Cynodon dactylon* (L.) Pers	1.380	1.000
Brassicaceae (Cruciferae)	*Sinapis arvensis* L.	1.00	0.980
Chenopodiaceae	*Chenopodium album* L.	0.890	0.384
Chenopodiaceae	*Salsola kali* L.	1.0	0.346
Asteraceae	*Tragopogon dubius* Scop	0.780	0.192
Rubiaceae	*Galium aperina* L.	0.34	0.120
Asteraceae	*Centaurea cyanus* L.	0.18	0.115
Boraginaceae	*Heliotropium europaeum* L.	0.10	0.076
Poaceae	*Avena sterilis* L.	-	0.018
Papaveraceae	*Papaver rhoeas* L.	-	0.010

Table 5 Effects of weed control applications on weed dry weight (g 0.25 m^{-2}) and reduction compared to weedy control (%)

Applications	2015		2016		Average	
	Dry weight	Reduction	Dry weight	Reduction	Dry weight	Reduction
1 Tractor hoeing	43.25 bc*	61.89**	24.50 a	3.92	33.87 B	51.27
2 Tractor hoeing	35.50 bc	68.72	13.75 b	46.08	24.62 BC	64.58
Pendimethalin PRE	37.00 bc	67.40	3.61 c	85.84	20.30 BC	70.79
Linuron PRE	32.00 bc	71.81	1.82 c	92.86	16.91 BC	75.67
Metribuzin POST	29.25 bc	74.23	4.77 c	81.29	17.01 BC	75.53
Pendimethalin + 1 hoeing	23.50 bc	79.30	7.51 bc	70.55	15.50 BC	77.70
Linuron + 1 hoeing	50.50 bc	55.51	7.45 bc	70.78	28.97 BC	58.32
Pendimethalin PRE + Metribuzin POST	56.25 b	50.44	3.65 c	85.69	29.95 BC	56.91
Linuron PRE + Metribuzin POST	20.25 bc	82.16	4.50 c	82.35	12.37 BC	82.20
Metribuzin POST + 1 hoeing	11.75 c	89.65	4.39 c	82.78	8.07 C	88.39
Pendimethalin PRE + Metribuzin POST + Fluazifop-P-butyl POST	49.25 bc	56.61	4.55 c	82.16	26.90 BC	61.29
Linuron PRE + Metribuzin POST + Fluazifop-P-butyl POST	49.25 bc	56.61	2.74 c	89.25	22.49 BC	67.64
Weedy control	113.50 a	–	25.50 a	–	69.50 A	–

*There was no significant difference between applications indicated with the same letter on a column basis ($p \leq 0.01$)

**Reduction (%) values were calculated relative to the weedy control and were not subjected to statistical analysis

hoe application in the same year. The minimum overall value of 2.74 g 0.25 m^{-2} was obtained in 2016 under the Linuron PRE + Metribuzin POST + Fluazifop-P-Butyl POST application.

The dry weight of the weeds was compared with that of the control, and the decreases compared to the weed control were expressed as percentages. The highest reduction in weed dry weight on the 28th day after planting date was achieved with the 10th application of metribuzin + 1 hoeing in the 1st year with 89.65% and the 4th application of linuron in the 2nd year with 92.86%. On average, over the two years, the highest reduction was achieved with the 10th application, with 88.39% (Table 5).

Biological Effects of Applications on Weeds

The biological effects of the applications on the four most common weeds in the trial area were visually recorded as a percentage effect on the 7th, 14th, 28th, and 56th day. The data for the 28th day were recorded as a percentage effect. The biological effects of the applications on weeds are listed in Table 6. In the study, the highest

Table 6 The biological effect of applications on weeds, %

Applications	*A. retroflexus*	*A. albus*	*S. arvensis*	*C. album*
3 Pendimethalin PRE	96.5 ab*	93.0 b	96.5 b	96.5 ab
4 Linuron PRE	94.75 bc	92.0 b	4.75 bc	94.75 bc
5 Metribuzin POST	96.75 ab	93.0 b	93.5 bc	95.25 bc
6 Pendimethalin + 1 hoeing	94.25 bc	92.0 b	93.0 c	96.25 b
7 Linuron + 1 hoeing	94.25 bc	93.0 c	94.25 bc	93.0 bc
8 Pendimethalin PRE + Metribuzin POST	100.0 a	100.0 a	100.0 a	100.0 a
9 Linuron PRE + Metribuzin POST	100.0 a	100.0 a	100.0 a	100.0 a
10 Metribuzin POST + 1 hoeing	92.5 c	93.25 b	92.5 c	92.5 c
11 Pendimethalin PRE + Metribuzin POST + Fluazifop – P – Butyl POST	100.0 a	100.0 a	100.0 a	100.0 a
12 Linuron PRE + Metribuzin POST + Fluazifop – P – Butyl POST	96.5 ab	93.75 b	96.25 b	96.5 ab
13 Weedy Control	0.0 d	0.0 c	0.0 d	0.0 d

*There was no significant difference between applications indicated with the same letter on a column basis

biological activity value was found in pendimethalin PRE + metribuzin POST, linuron PRE + metribuzin POST, and pendimethalin PRE + metribuzin POST + fluazifop-p-butyl POST applications. When the results obtained from the study were examined, it was observed that the lowest biological activity value, excluding weedy control, was obtained from metribuzin POST + 1 hoe application for *A. retroflexus* and *Chenopodium album* L. (common lambs quarters). The biological activity value for *Sinapis arvensis* L. (wild mustard) was observed to be at the lowest level in pendimethalin PRE + 1 hoe application and metribuzin POST + 1 hoe application. When the data for A. albus were examined, it was observed that the lowest biological activity value was obtained from linuron PRE + 1 hoe application.

Yield (kg ha^{-1})

In 2015 and 2016, the middle two rows of each four-row plot were harvested at 119 and 149 days after planting, respectively, to determine the application yields. The yield data obtained underwent analysis of variance (ANOVA), and treatment means were compared using the LSD multiple comparison test. The results indicated statistically significant differences between years and applications. The application yield data are presented in Table 7 as average values on an annual basis. The highest average yield was achieved in application number 11, where pendimethalin PRE + metribuzin POST + fluazifop-p-butyl POST was applied at 39,574 kg ha^{-1}. In contrast, the lowest average yield was recorded in the weedy control at 22,945 kg ha^{-1}. When evaluating by year, the highest yield in 2015 was obtained in the 1 st application with 44,959 kg ha^{-1}, and the lowest yield in the weedy control with 26,054 kg ha^{-1}.

Table 7 Average potato yield values for 2015–2016

Application	Yield		Average
	2015	2016	
1 1 Tractor hoeing	44,959 a*	19,785 f	32,372 BD
2 2 Tractor hoeing	30,981 de	21,235 ef	26,108 EF
3 Pendimethalin PRE	32,981 be	28,700 be	30,840 CE
4 Linuron PRE	41,882 ab	25,335 cf	33,609 BD
5 Metribuzin POST	36,606 ad	32,021 ac	34,314 AD
6 Pendimethalin + 1 hoeing	31,409 ce	26,271 cf	28,840 DE
7 Linuron + 1 hoeing	40,828 ab	26,135 cf	33,482 BD
8 Pendimethalin PRE + Metribuzin POST	36,371 ad	31,128 ad	33,750 AD
9 Linuron PRE + Metribuzin POST	36,697 ad	35,028 ab	35,862 AC
10 Metribuzin POST + 1 hoeing	44,826 a	23,835 df	34,330 AD
11 Pendimethalin PRE + Metribuzin POST + Fluazifop – P – Butyl POST	40,420 ac	38,728 a	39,574 A
12 Linuron PRE + Metribuzin POST + Fluazifop – P – Butyl POST	41,320 ab	32,078 ac	36,699 AB
13 Weedy Control	26,054 e	19,835 f	22,945 F
Application	**	**	**

*There was no significant difference between applications indicated with the same letter on a column basis

**$p \leq 0.01$: significant at 1% level. PD: not significant

In 2016, the highest yield was observed in the 11th application with 38,728 kg ha^{-1}, while the lowest yield was in the 1 st application with 19,785 kg ha^{-1}.

Economic Analysis of Applications

The costs of tillage, seedbed preparation, planting, weed management, irrigation, fertilization, harvesting, and tractor energy were calculated for all applications (Yaldiz et al. 1993). The total profit (Erenstein 2009) and the fixed and variable costs were calculated. By comparing the average yield values of the applications, the highest yield and also the highest profit were achieved with application number 11 (pendimethalin + metribuzin + fluazifop-p-butyl) at 4633.91 USD ha^{-1}. The application with the lowest yield and the lowest profit was the application for weedy control (13) with 1105.79 USD ha^{-1}.

When examining the applications in terms of cost per unit area, the highest yielding application, pendimethalin + metribuzin + fluazifop-p-butyl, had a cost of 4468.25 USD ha^{-1}, while the lowest yielding application, weed control, had a cost of 4171.56 USD ha^{-1}. In contrast to the 296.69 USD overspent between the highest and lowest yielding applications, the 11th application generated a net return of 4633.91 USD ha^{-1}. The economic analysis of the applications can be found in Table 8.

Table 8 Economic Analysis of Applications in USD per Hectare for Potato Production in Kayseri Province (2016)

		1 time hoeing	2 times hoeing	Pendimetalin	Linuron	Metribuzin	Pendimethalin Hoeing	Linuron Hoeing	Pendimethalin Metribuzin	Linuron Metribuzin	Metribuzin Hoeing	Pendimethalin Metribuzin Fluazifop—P—Butyl	Linuron Metribuzin Fluazifop-P—Butyl	Control
A	Inputs													
1	Seed, fertilizer, irrigation, and energy	2356.01	2356.01	2356.01	2356.01	2356.01	2356.01	2356.01	2356.01	2356.01	2356.01	2356.01	2356.01	2356.01
2	Pesticide	100.63	100.63	150.94	147.35	131.68	150.94	147.35	182	178.4	131.68	205	201.4	100.63
	Total	2456.64	2456.64	2506.95	2503.36	2487.69	2506.95	2503.36	2538.01	2534.41	2487.69	2561.01	2557.41	2456.64
B	Maintenance and labor expences													
1	Tillage	166.75	166.75	166.75	166.75	166.75	166.75	166.75	166.75	166.75	166.75	166.75	166.75	166.75
2	Planting and fertilization work	97.75	97.75	97.75	97.75	97.75	97.75	97.75	97.75	97.75	97.75	97.75	97.75	97.75
7	Machine hoeing	43.12	86.24	0	0	0	43.12	43.12	0	0	43.12	0	0	0
8	Irrigation work	201.25	201.25	201.25	201.25	201.25	201.25	201.25	201.25	201.25	201.25	201.25	201.25	201.25
9	Other (pesticide applicationl work)	86.25	86.25	115	115	115	115	115	143.75	143.75	115	172.6	172.6	0
	Total	595.12	638.24	580.75	580.75	580.75	623.87	623.87	609.5	609.5	623.87	638.35	638.35	465.75
C	Harvesting and marketing													
1	Harvest, transportation, packaging	569.28	569.28	569.28	569.28	569.28	569.28	569.28	569.28	569.28	569.28	569.28	569.28	569.28
	Total	569.28	569.28	569.28	569.28	569.28	569.28	569.28	569.28	569.28	569.28	569.28	569.28	569.28
D	Sum of variable expenses (A + B + C) + Interest on variable expenses (%4)	3.765.88	3.810.73	3.803.26	3.799.53	3.783.23	3.848.10	3.844.37	3.865.46	3.861.72	3.828.07	3.919.39	3.915.64	3.631.34

Table 8 (continued)

		1 time hoeing	2 times hoeing	Pendimetalin	Linuron	Metribuzin	Pendimethalin Hoeing	Linuron Hoeing	Pendimethalin Metribuzin	Linuron Metribuzin	Metribuzin Hoeing	Pendimethalin Metribuzin Fluazifop—P—Butyl	Linuron Metribuzin Fluazifop-P—Butyl	Control
E	Total fixed costs (General administrive expenses + Land rent)	544.2564	545.601.792	545.3778	545.2658	544.7769	546.7231	546.6111	547.2438	547.1315	546.1222	548.8616	548.7492	540.2201
F	Total production costs (D + E)	4.310.14	4.356.33	4.348.64	4.344.79	4.328.01	4.394.83	4.390.98	4.412.71	4.408.85	4.374.20	4.468.25	4.464.39	4.171.56
G	Avarage yield (kg/Ha)	32,372.50	26,108.70	30,840.50	33,609.20	34,314.10	28,840.50	33,482.30	33,750.00	35,862.00	34,330.80	39,574.60	36,699.60	22,945.00
H	Average sales price kg/dollar)	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
I	Main product revenue (G*H)	7445.675	6005.001	7093.315	7730.116	7892.243	6633.315	7700.929	7762.5	8248.26	7896.084	9102.158	8440.908	5277.35
J	Total expenses made for main product	4.310.14	4.356.33	4.348.64	4.344.79	4.328.01	4.394.83	4.390.98	4.412.71	4.408.85	4.374.20	4.468.25	4.464.39	4.171.56
K	Net income (I–J)	3.135.54	1.648.67	2.744.68	3.385.32	3.564.24	2.238.49	3.309.95	3.349.79	3.839.41	3.521.89	4.633.91	3.976.52	1.105.79

Discussion

Weed infestation is a critical limiting factor in potato production systems; as it significantly reduces both the quality and quantity of yield. The presence of weeds during the initial growth stages is particularly detrimental, as favourable environmental conditions combined with the limited competitive capacity of emerging potato seedlings lead to pronounced yield reductions. Extended durations of early-season weed interference have been shown to impair germination and, subsequently, result in notable declines in critical agronomic parameters, including plant height, tuber count, tuber size, tuber biomass, and total yield (Siddiqui et al. 2024).al.2024

Among the various constraints affecting potato cultivation, weed presence ranks as one of the most critical, leading to significant economic losses. Weeds not only compete with potato plants for essential resources such as light, water, space, and nutrients but may also release allelopathic substances that hinder crop development. Heavily infested fields are often associated with reduced yields and compromised tuber quality (Zarzecka et al. 2020).

In present study, a total of 14 weed species were identified across the 2015–2016 application period. The identified species are *S. arvensis*, *Galium aperina* L. (cleavers herb), *C. album*, *A. albus*, *A. retroflexus*, *Cynodon dactylon* (L.) Pers. (bermuda grass), *Tragopogon dubius* Scop (yellow goatsbeard), *Heliotropium europaeum* L. (common heliotrope), *Salsola kali* L. (tumbleweed), *C. arvensis*, and *Centaurea cyanus* L. (cornflower). The weeds observed in the field were found to be largely similar in occurrence and density to those identified in previous surveys conducted in the Kayseri region (Tursun et al. 2003; Akca and Isik 2016; Esitmez and Isik 2016; Ozdemir and Isik 2020).

The most abundant weed species in the experimental area was *C. arvensis* with a density of 1.69 plants m^{-2}. Following this species, the next most abundant species were *A. albus* with a density of 1.61 plants m^{-2}, *A. retroflexus* with a density of 1.07 plants m^{-2}, *C. dactylon* with a density of 1.00 plants m^{-2}, *S. arvensis* with a density of 0.98 plants m^{-2}, *C. album* with 0.38 plants m^{-2}, *S. kali* with 0.34 plants m^{-2}, *T. dubius* with 0.19 plants m^{-2}, *G. aperina* with 0.12 plants m^{-2}, *C. cyanus* with 0.11 plants m^{-2}, and *H. europaeum* with 0.07 plants m^{-2}. Additionally, there were 0.01 *Avena sterilis* L. (sterile oat) and 0.01 *Papaver rhoeas* L. (corn poppy). The species composition on the experimental plot is similar to studies conducted in Türkiye by Uremis et al. 2009) and Kilic (2016). The extent of yield reduction is influenced by the composition of weed species, their population density, and the duration of competition with crops. Weeds not only compete for essential growth resources, but can also alter plant physiology making them more susceptible to pests and insect infestations (Yadav et al. 2015).

In the 2015 trial, the dry weights on day 28 and the yield values obtained from the applications were higher than in the 2016 trial. This difference may be attributed to the soil's organic matter content, which was 3.55% in the 2015 trial and 0.95% in the 2016 trial. Khan et al. (2009) reported that the presence of weeds in potato fields throughout the growing season significantly reduced the number of leaves and fresh biomass per plant compared to weed-free conditions. Similarly, Mondani et al.

(2011) found that weed interference negatively impacted various agro-physiological traits in potatoes, such as leaf area per plant, leaf area index, crop growth rate, net assimilation rate, and overall dry matter production.

The yield of the 3rd application of pendimethalin was 30,840.50 kg ha^{-1}, while the yield of the 8th application of pendimethalin + metribuzin was 33,750 kg ha^{-1}, resulting in a yield difference of 2909.60 kg ha^{-1} between the two applications. This difference may be due to the suppression of early-emerging weeds by the pre-emergence application of pendimethalin in the 3rd application, while later emerging weeds were not affected. In contrast, the post-emergence application of metribuzin after pendimethalin in the pendimethalin + metribuzin application suppressed emerging weeds. The effects of pre- and post-emergence herbicide combinations on yield align with studies by Singh et al. (2016) and Gitsopoulos et al. (2014). Effective weed suppression during the initial growth phase is crucial, as maintaining a weed-free environment before potato plants exceed 20 cm in height significantly mitigated yield reductions (Ciuberkis et al. 2007).

Previous studies have consistently demonstrated that the effectiveness of herbicide-based weed management in potato production varies depending on weed species, environmental conditions, and application strategies. Bailey et al. (2001) reported that the combination of metribuzin and metolachlor provided high control of yellow nutsedge ($\geq 81\%$), indicating the strong efficacy of this mixture against sedge species. However, the considerably lower control of common lambsquarters observed in 1996 compared with 1995 highlights the sensitivity of metribuzin-based treatments to post-application rainfall, which likely reduced herbicide persistence and availability in the soil. Similarly, effective control of common ragweed ($\geq 73\%$) with linuron across both years suggests that herbicide selectivity and weed biology play a crucial role in determining control success. The corresponding increase in potato yield across seasons further supports the close relationship between effective weed suppression and yield improvement.

Comparable findings were reported by Sharshar et al. (2015), who demonstrated that integrated herbicide strategies were more effective than single-product applications. In particular, the combination of metribuzin (Sencor) and fluazifop-p-butyl (Fusilade Forte) resulted in superior weed control and yield performance, emphasizing the advantage of combining broadleaf and grass-specific herbicides. These results reinforce the concept that diversified chemical strategies enhance the weed control spectrum and reduce competition throughout critical growth stages of potato.

The positive yield response to metribuzin application observed in the present study is also consistent with the findings of Hermeziu et al. (2018), who reported significant yield increases over two consecutive seasons following metribuzin treatment. The substantial reduction in weed density, particularly of dominant species such as *A. retroflexus*, *C. album*, and *G. aparine*, likely contributed to improved resource availability for potato plants. Moreover, the higher yields recorded in the second year of their study suggest that favourable environmental conditions and improved weed suppression can further enhance the benefits of chemical weed control.

Overall, these findings indicate that metribuzin-based weed management, especially when integrated with complementary herbicides, provides effective weed suppression and contributes to stable yield improvements in potato production.

However, the variability observed among years underscores the importance of considering environmental factors, such as rainfall patterns, when selecting and timing herbicide applications.

Herbicides either alone or in combination with other applications have been found to significantly impact weed populations, biomass, and yield. The study revealed that using 1 or 2 tractor hoe operations alone did not effectively manage weeds without pre- or post-emergence herbicide applications. Comparing the weed dry weight of weeds after applying 1 hoe operation with that of the control, there was a decrease of 61.89% in 2015 and 3.92% in 2016. It is believed that the reduction in the dry weight of weeds has a positive effect on the yield of this application to a certain extent, but irrigating the potatoes weekly after emergence created a conducive environment for weeds, affecting yield. In 2015 and 2016,

While an average yield of 30,840.50 kg ha^{-1} was achieved with the pre-emergence application of pendimethalin (3) in 2015 and 2016, a yield of 28,840.50 kg ha^{-1} was achieved with pendimethalin + hoe (6), 33,609.20 kg ha^{-1} with the application of linuron (4) and 33,482.30 kg ha^{-1} with the application of linuron + hoe (7). It is assumed that the pre-emergence herbicide application suppresses the weeds, including during hoeing, suggesting little impact on yield. Post-emergence metribuzin (5) application yielded 34,314.10 kg ha−1, similar to metribuzin + hoe (10) at 34,330.80 kg ha−1. Comparing average yield, 34,314.10 kg ha^{-1} was obtained by applying metribuzin (5) post-emergence in 2015 and 2016, while an average yield of 34,330.80 kg ha^{-1} was obtained by applying metribuzin + hoe (10). It is believed that there is almost no difference between the two applications because, in the pre-emergence + tractor hoe application, the effect of metribuzin application exerts pressure on the weeds during the hoeing period.

Comparing herbicide combinations of pendimethalin + metribuzin (8) and linuron + metribuzin (9) pre- and post-emergence with the control showed an average yield of 33,750 kg ha^{-1} for the 8. Compared to the weedy control, the yield was increased by 47.09% with pendimethalin + metribuzin (8) and by 56.30% with linuron + metribuzin (9). It is assumed that this is because the wild mustard (*S. arvensis*), which was densely present on the experimental plot in the years tested, was controlled with the pre-emergence application of linuron. The later emerging wild mustard was controlled with the post-emergence application of metribuzin. The results are similar to the studies conducted by Kahramanoglu (2014).

The highest yield was obtained with application No. 11, which included pendimethalin + metribuzin + fluazifop-p-butyl, while the lowest yield was observed in the weedy control group. This is likely due to the effective control of weeds by pendimethalin in the early stages, followed by the control of narrow and broadleaf weeds with metribuzin and fluazifop-p-butyl, reducing competition with the potato crop. These results are consistent with previous studies conducted by Ginter et al. (2022).

Analysis of the economic yield revealed that weed management applications significantly impacted the final yield. Application No. 11 (pendimethalin + metribuzin + fluazifop-p-butyl) was the most profitable, with a net yield of 4633.91 USD per hectare, while the weedy control group had the lowest net yield of 1105.79 USD per hectare.

Conclusion

This study clearly demonstrated that weed management strategies significantly influenced both yield and economic returns in potato production under the conditions of Kayseri, Türkiye. Among the tested treatments, the integrated application of pendimethalin (PRE) + metribuzin (POST) + fluazifop-P-butyl (POST) provided the most effective weed control, resulting in the highest tuber yield (39,574.60 kg ha^{-1}) and net income (4,633.91 USD ha^{-1}), markedly outperforming the weedy control (22,945 kg ha^{-1}). In contrast, treatments relying solely on mechanical control or single herbicide applications were less effective, highlighting the advantage of combining chemical and mechanical approaches.

These findings indicate that integrated weed management practices, particularly those combining pre- and post-emergence herbicides with complementary modes of action, can substantially enhance both productivity and profitability in potato cultivation. The superior performance of the combined treatment also suggests improved control of a broader weed spectrum throughout the growing season.

Future research should focus on optimizing herbicide dose combinations and application timing in conjunction with mechanical methods to further improve efficacy while reducing chemical inputs. Additionally, long-term studies are needed to evaluate the environmental sustainability and potential resistance risks associated with repeated herbicide use under similar production systems.

Author Contribution O.G.: collected data, performed experiments, did data analysis, and reviewed the manuscript, assigned in computational analysis. E.S.C.: reviewed the manuscript, assigned in computational analysis. D.I.: conceptualized and supervised the study, did data analysis, assigned computational analysis, proofread, and edited the manuscript.

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Data Availability The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of Interest The authors declare no competing interests.

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