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Effect of Mechanical and Herbicide Treatments on Weed Densities and Biomass in Two Potato Cultivars

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Abstract: The effect of potato cultivar and mechanical or herbicide treatments on weed densities and biomass was determined in a research study on a field, conducted from 2007 to 2009 at the Institute of Plant Breeding and Acclimatization. Included in the study were two cultivars and different weed control treatments, including a mechanical method and metribuzin combined with various herbicides and application timings. Chemical methods of controlling weeds were more effective than mechanical methods to reduce weed densities and biomass. The combination of metribuzin with rimsulfuron + SN oil, applied before potato emergence (PRE), was more effective than the other metribuzin combinations. The weed infestation of potato cv. "Irga" was greater than that of cultivar "Fianna" due to differences in the type of growth.

Keywords: potato; cultivars; biodiversity of weeds; mechanical method; chemical method; monocotyledonous weeds; dicotyledonous weeds

1. Introduction

Weeds compete with crops for water, light, and nutrients. Due to the long period from planting to covering inter-rows, potatoes are not as competitive as some other crops. In addition, weeds can reduce air circulation in the potato crop and contribute to favorable conditions for potato infection by pathogens. Effective weed control can eliminate the competitive effects of weeds and should be based on detailed knowledge, including factors impacting performance [1–4]. For example, the same herbicide may have varying efficacy depending on the environmental conditions at and after the application time. Other factors include absorption, translocation, and degradation in the plant [5–7]. Selection of herbicides, herbicide combinations, rates, and application timings should be suited to the degree of weed infestation, the optimal date for using agrochemicals, and the combination of herbicides required to eliminate a wide spectrum of weeds [3–8]. Earlier, Pawlonka [8] used metribuzin pre- and postemergence on potato plants, combined with mechanical treatments, in order to minimize the adverse effect of monoculture on potato yields. However, no publications by other authors concerning the use of metribuzin in mixtures with other herbicides were found. Hence, research was undertaken on the use of metribuzin in combination with other active substances of herbicides, with a different spectrum of action to eliminate both dicotyledonous and monocotyledonous weeds.

The main aim of the research is to develop innovative, effective methods of weed control under the conditions of weed threat, which will provide a larger spectrum of chemical agent action and result in weed control efficiency, costs, rate reductions, and impact on the environment. Hence, the intention of the work is use metribuzin (pre- and post-emergence) and the chosen herbicide mixtures (metribuzin + rimsulfuron + ethoxylated isodecyl alcohol; metribuzin + fluazifop-P-butyl; metribuzin + sulfosulfuron + SN oil) for the control of weeds in the cultivation of two potato cultivars, which will provide a wider spectrum of action of the active substance compared to the mechanical method of combating weeds. This will result in better weed control, a reduction in the dose of herbicides, a reduction in their negative impact on the environment, and a reduction in costs. The selection of these herbicides results from their availability, spectrum of action, and their prices, which is important for farmers, who will make the most economical decision. This research can add value to existing methods. A comparison of chemical weed control methods with mechanical methods that are rarely used today would make it possible to move away from such mechanical methods.

The paper verifies the alternative hypothesis that the use of herbicides and their mixtures, namely, (a) metribuzin—PRE; (b) metribuzin + rimsulfuron + ethoxylated isodecyl alcohol—PRE; (c) metribuzin—POST; (d) metribuzin + rimsulfuron + isodecyl alcohol ethoxylate—PRE; (e) metribuzin + fluazifop-P butyl—POST; (f) metribuzin + sulfosulfuron + SN oil—POST-emergence in potato cultivation will

(a) provide a broader spectrum of action of herbicide chemistry and greater weed control than no weed control and mechanical weed control;
(b) reduce environmental pollution and ensure better effectiveness of chemical treatments, due to the use of lower doses of herbicides, against the null hypothesis that there are no differences between the variants with herbicides and their mixtures and the variant without weed protection and the variant with mechanical weed infestation control in potatoes.

2. Material and Methods

Field trials were carried out for three years, from 2007 to 2009, at the Institute of Plant Breeding and Acclimatization—National Research Institute in Jadwisin (52°29′ N, 21°03′ E). The soil each year was a sandy loam [9]. The experimental design was randomized sub-blocks in a dependent, split-plot system, with three replications. Two factors were examined in the experiment: the first-order factor was potato cultivars ("Irga", an edible, medium-early, stem-type cultivar, and "Fianna", a medium-late, edible, leaf-like cultivar). The second-order factors were weed control methods, including extensive mechanical treatments (every 2 weeks) from planting until row closure and several metribuzin combinations and application timings. Table 1 shows the combinations, rates, and application timings of herbicide treatments. A nontreated control was included for comparison. Herbicides were applied in 400 dm^3 ha^{-1} of water with a backpack sprayer with flat-spray nozzles and a flow rate of 0.35–0.65 $dm.min^{-1}$ and a pressure of 0.1–0.2 MPa. The plot area for treatments was 31.0 m^2, of which 25 m^2 was harvested for tuber yields and quality.

2.1. Agrotechnical Treatments

The previous crops were winter wheat, and white mustard green manure was plowed the fall before potato planting. The type and timing of tillage for field preparation, fertilizer rates and timing, as well as nutrients provided by the white mustard, are shown in Table 2. After harvesting wheat, nitrogen fertilization was applied in an amount of 50 kg N ha^{-1}, followed by stubble cultivation and the sowing of white mustard in an amount of 20 kg·ha^{-1}. White mustard, as a green fertilizer for plowing, brings macro- and micronutrients annually in the amount presented in Table 2.

In addition, in autumn each year, preceding planting, mineral phosphorus–potassium fertilization was applied in the amount of 39.3 kg P·ha^{-1} and 116.2 kg K·ha^{-1} during prewinter plowing. Nitrogen fertilizers were sown in spring, in the amount of 100 kg N ha^{-1}, mixing them with the soil using a tilling set (cultivator + string roller). The fertilizer doses were determined on the basis of the abundance. Potato tubers were planted by hand in the third decade of April, with a spacing of

75 × 33 cm. The propagating material was in Class C/A. Herbicide spraying was done manually using a backpack sprayer. Nursing treatments were performed in accordance with the requirements of good agricultural practice and the methodological assumptions of the experiment. They consisted of covering ridges and ridging. Herbicides in the following combinations were applied to the freshly formed soil, just before the emergence of the potato (metribuzin 1 kg ha^{-1}; metribuzin1 kg ha^{-1} + rimsulfuron 40 g ha^{-1} + ethoxylated isodecyl alcohol 0.1%). After potato emergence, the following preparations were used in reduced doses after prior ridging: metribuzin 0.5 kg ha^{-1}; metribuzin 0.3 kg ha^{-1} + rimsulfuron 30 g ha + ethoxylated isodecyl alcohol 0.1%; metribuzin 0.3 kg ha^{-1} + fluazyfop-P butyl 2 L ha^{-1}; metribuzin 0.3 kg ha^{-1} + sulfosulfuron 26.5 g ha^{-1} + SN oil 1 L ha^{-1} (Table 3). In addition, 400 L ha^{-1} of water was used for spraying with the herbicides.

Potato protection against diseases and insects (Table 4) was used in accordance with the recommendations of the Institute of Plant Protection, National Research Institute, Poland [11].

Table 1. Characteristics of the herbicides and adjuvants used in the experiment.

Trade Names	Common Names	Formulation	Dosage	Utility Forms and Application Date	Grace ***
			Herbicides		
Apyros 75WG	Sulfosulfuron	75%	26.5 g·ha^{-1}	granules for water suspension (POST)	Not applicable
Fusilade Forte 150 EC	Fluazyfop-P butyl	150 g in 1 L of measure	2 L ha^{-1}	(POST) concentrate for water suspension	Not applicable
Sencor 70 WG	Metribuzin	70%	0.5 (PRE *) or 0.3 kg ha^{-1} (POST **)	granules for water suspension	42 days
Titus 25 WG	Rimsulfuron	25%	40 g ha^{-1}	granules for water suspension (POST)	Not applicable
			Adjuvants (boosters)		
Atpolan 80 SC	SN oil	76%	1 L ha^{-1}	concentrate for water suspension (POST)	Not applicable
Trend 90 EC	ethoxylated isodecil alcohol	90%	0.1%	concentrate for water suspension (PRE)	Not applicable

Sources: [10,11]; * before potato emergence (PRE); ** after emergence (POST); *** the period from the day of the last treatment to the day of harvesting plants intended for consumption

Table 2. Chemical composition of white mustard as a green fertilizer.

Specification	DM (g kg^{-1})	Ash (g kg^{-1} DM)	N Total (g kg^{-1}DM)	N Miner. (g kg^{-1} DM)	P (g kg^{-1} DM)	K (g kg^{-1} DM)	Mg (g kg^{-1} DM)	Ca (g kg^{-1} DM)	Na (g kg^{-1} DM)	Cu (mg kg^{-1} DM)	Zn (mg kg^{-1} DM)	Mn (mg kg^{-1} DM)	Fe (mg kg^{-1} DM)	Ni (mg kg^{-1} DM)
White mustard biomass	454	55.1	19.2	0.8	3.1	31.6	4.5	1.2	0.8	0.4	35.4	36.0	63.4	7.05

Table 3. The agricultural treatments in the experiment in the years 2006–2009.

Autumn 2006–2008		
Nitrogen fertilization (50 kg ha^{-1})—ammonium nitrate Tillage Sowing and plowing under the forecrop white mustard sowing (20 kg ha^{-1}) disking of white mustard fertilization with phosphorus (39.3 kg P ha^{-1} in the form of granulated superphosphate) and potassium (116.2 kg K ha^{-1} in the form of 60% potassium salt) winter plowing to a depth of about 27 cm		
Spring 2007	Spring 2008	Spring 2009
Tillage and agricultural treatments		
Harrowing fertilization of N (100 kg ha^{-1}—salmag) Cultivation with an aggregate planting of potato seeds—manually Earthing 2 times; in mechanical treatment, earthing and weeding 3 times Herbicide spraying PRE andPOST with atomic knapsack sprayerHarvest with potato elevator digger	Harrowing fertilization of N (100 kg ha^{-1}—salmag) Cultivation with an aggregate planting of potato seeds—manually Earthing 2 times; in mechanical treatment, earthing and weeding 4 times Herbicide spraying PRE and POST with atomic knapsack sprayer Harvest with potato elevator digger	Harrowing fertilization of N (100 kg ha^{-1}—salmag) Cultivation with an aggregate planting of potato seeds—manually Earthing 2 times; in mechanical treatment, earthing and weeding 4 times Herbicide spraying PRE and POST with atomic knapsack sprayer Harvest with potato elevator digger

Source: own research.

Table 4. Potato protection against diseases and insects.

Pesticides	**Years**		
	2007	**2008**	**2009**
Fungicides	chlorothalonil propamocarb hydrochloride SC—2.5 dm^3 ha^{-1} fluazynam—0.4 L ha^{-1}fenamidon + mankozeb—1.25 kg ha^{-1} metalaxyl − M + mancozeb—2.5 kg ha^{-1}	metalaxyl − M + mancozeb—2.5 kg ha^{-1} chlorothalonil (tetrachloroisophthalonitrile)—2 L ha^{-1} propamocarb hydrochloride, fenamidone—2 L ha^{-1}	metalaxyl − M + mancozeb—2.5 kg ha^{-1} mancozeb + cymoxanil/2-cyano-*N*-[(ethylamino) carbonyl]-2-(methoxyimino) acetamide—2 kg ha^{-1} propamocarb hydrochloride, fenamidone—2 L ha^{-1}
Insecticides	thiamethoxam—0.04 kg ha^{-1} acetamiprid—0.08 kg ha^{-1}	thiamethoxam—0.04 kg ha^{-1} thiacloprid—0.75 L ha^{-1} acetamiprid—0.08 kg ha^{-1}	imidacloprid—0.25 L ha^{-1} thiacloprid—0.75 L ha^{-1}

Source: [10,11].

2.2. Assessment of Weeds

The assessment of weed infestation was carried out using the quadrat method, quantitatively and qualitatively, on three randomly selected 1-m^2 areas in each plot, after row closure and just before harvest. Weed species were determined, and before potato harvest, when weed plants entered Stage 97 based on the BBCH scale (BBCH abbreviation comes from the German Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie), fresh biomass from three randomly selected 1.0 m^2 quadrats per plot [11,12] was collected. After measuring fresh weight, samples were dried, and the dry weight was recorded.

A weed species list was established. The number of weeds present in each 1 m^2 quadrat was calculated according to the formula

$$\mathrm{Nw} = \frac{(\mathrm{N1} + \mathrm{N2} + \mathrm{N3})}{(\mathrm{Nm} \times \mathrm{Qa})} \quad (1)$$

where

Nw—number of weeds of a given species growing on an area of 1 m^2,
N1, N2, N3—number of plants in the quadrat in subsequent measurements (pcs),
Nm—number of measurements,
Qa—quadrat of area (m^2) [11].

Plants were uprooted from soil, segregated by species, and the fresh weight of each species was determined. The weight of a given species was averaged across the three randomly selected quadrats. After drying, the dry weight of weeds was weighed for each species separately, and the weighing results were recorded in an evaluation card. Weed samples were placed in a ventilated room until a constant mass was obtained [11].

2.3. Meteorological Conditions

To characterize thermal and humidity conditions in the years of research, data from the meteorological station located at the Institute of Plant Breeding and Acclimatization, National Research Institute, Jadwisin, were used. The conditions of the growing season in 2007–2009 were characterized by varying air temperatures and rainfall (Figure 1, Table 5).

The 2007 and 2008 growing seasons can be described as relatively dry, while 2009 could be characterized as the year with the most favorable humidity and thermal conditions for potato development. Weather data is included in Table 5.

In 2007, the average temperature of the April–September period was 13.7 °C, and this was lower than the long-term average of this period by 0.6 °C. The sum of precipitation was 165.3% of the norm. Weather conditions in May and August of 2008 exceeded the multiyear norm, and, in the remaining months, there was a noticeable water shortage. The average air temperature in the April–September period was 14.2 °C, and this was lower than the multiyear average by 0.3 °C. The meteorological conditions of the 2009 growing season were varied, but their common feature was a drought period at the beginning of the potato-growing season (Figure 1, Table 5).

Table 5. Precipitation and the hydrothermal coefficient of Sielianinov during the potato vegetation period in 2007–2009 according to the meteorological station of the Plant Breeding and Acclimatization Institute, National Research Institute, Jadwisin.

Year	Month	The Sum of Precipitation in the Month (mm)				% of the Long-Term Norm (1971–1995)	Sielianinov Hydrothermal Coefficient	Evaluation of the Month **
		Decade			Month			
		1	2	3				
2007	April	12.0	4.0	0.3	16.3	<25	0.69	Extremely dry
	May	11.6	28.7	38.1	78.4	75–125	1.93	Quite humid
	June	30.4	13.6	65.6	109.6	75–125	2.32	Humid
	July	30.1	6.4	17.6	54.1	50–74	0.99	Dry
	August	43.8	17.2	13.3	74.3	50–74	1.34	Optimum
	September	42.5	49.0	12.2	103.7	75–125	3.20	Extremely moist
	Total	170.4	118.9	146.8	436.4	-	-	-
2008	April	11.4	12.9	5.0	29.3	25–49	1.36	Optimum
	May	36.8	12.8	13.3	62.9	50–74	1.64	Quite humid
	June	0.0	21.0	22.5	43.5	25–49	0.84	Dry
	July	20.2	38.2	10.4	68.8	50–74	1.22	Quite dry
	August	26.8	37.8	16.3	80.9	75–125	1.48	Optimum
	September	21.6	10.3	16.9	48.9	25–49	1.40	Optimum
	Total	116.8	133.0	84.4	334.3	-	-	-
2009	April	0.0	0.0	0.0	0.0	<25	0.0	Extremely dry
	May	8.8	13.3	58.7	80.8	75–125	2.12	Humid
	June	30.2	17.5	24.7	72.4	50–74	1.38	Optimum
	July	36.8	20.5	28.3	85.6	75–125	1.28	Quite dry
	August	12.5	48.5	22.1	83.1	75–125	1.54	Optimum
	September	8.2	4.7	5.9	18.8	<25	0.44	Very dry
	Total	96.5	104.5	139.7	340.7	-	-	-

** Hydrothermal coefficient according to Sielianinov: extremely dry (ed)→k ≤ 0.4; very dry (vd) → 0.4 < k ≤ 0.7; dry (d) → 0.7 < k ≤ 1.0; quite dry (Qd) → 1.0 < k ≤ 1.3; optimum (o) → 1.3 < k ≤ 1.6; quite humid (pd) → 1.6 < k ≤ 2.0; humid (w) → 2.0 < k ≤ 2.5; very humid (vh) → 2.5 < k ≤ 3.0; extremely moist (em) → k > 3.0.

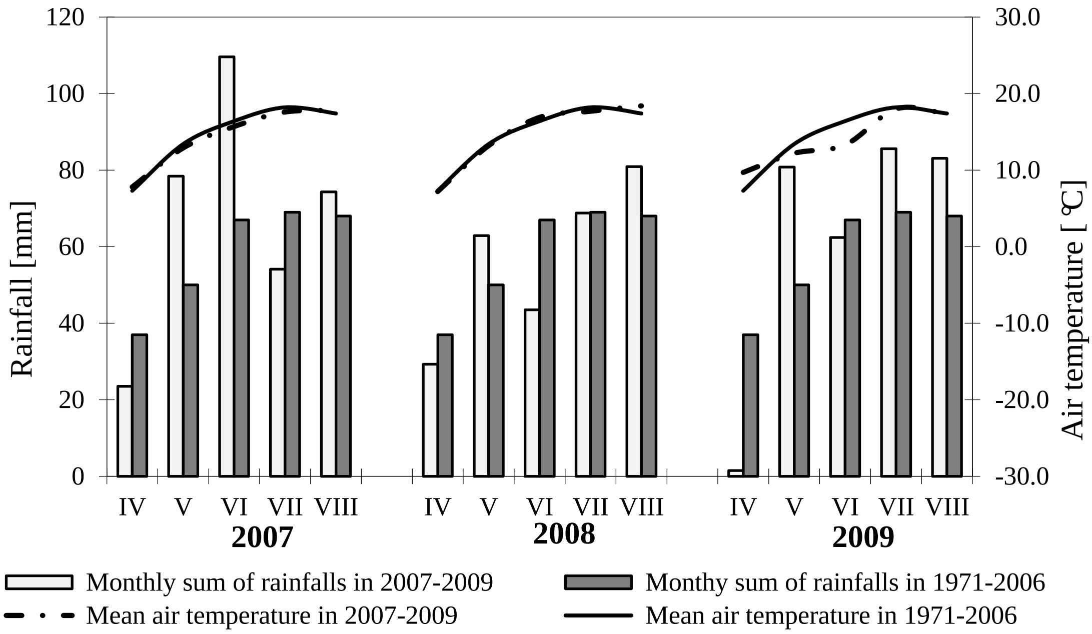

Figure 1. Precipitation and air temperature during the potato-growing season according to the meteorological station of the Institute of Plant Breeding and Seed Production, National Research Institute, Jadwisin (2007–2009), against the background of the long-term average.

2.4. *Statistical Analyses*

SAS v.9.2 software was used for statistical analyses [13]. The factors for the models were (years × cultivars × weed control treatment), and variance and multiple Tukey's *t*-tests were determined at significance level $p_{0.05}$. The significance of sources of variation was tested using the Fischer–Snedecor F-test [14].

The averaged data are given: for cultivars—means for treatments, years, and repetitions; in the case of care treatments—averages for cultivars, years, and repetitions; in the case of years—averages for treatments, cultivars, and repetitions.

3. Results

3.1. *Soil Conditions*

Information on the value of soils, on which research with potato are presented in Tables 6 and 7.

Table 6. The granulometric composition of the soil (%).

Years	Percentage of Fraction with Diameter (mm Diameter)			Grain Size Subgroup	Soil–Agricultural Complex
	2.0–0.05	0.05–0.002	<0.002		
2007	72.0	24.0	4.0	Sandy loam	Rye complex
2008	71.0	26.0	3.0	Sandy loam	Rye complex
2009	72.0	24.0	4.0	Sandy loam	Rye complex

Source: Results were determined at the Chemical and Agricultural Station in Wesoła, near Warsaw. The determinations were made according to the applicable methods and standards [9,15,16].

Table 7. Physicochemical properties of soil in Jadwisin (2007–2009).

Years	Content of Available Forms (mg·100 g^{-1} DM of Soil)			pH (1M KCl)	Content of Organic Substance (%)
	P_2O_5	K_2O	Mg		
2007	23.9	22.2	20.0	4.7	0.73
2008	9.9	16.8	15.5	5.4	0.68
2009	3.9	7.3	6.0	5.0	0.70

Source: Results were made at the Chemical and Agricultural Station in Wesoła. The determinations were made according to the applicable methods and standards [15–22].

3.2. Weed Species

In the plantation, before the row closure of plants, only two species of monocotyledonous weeds (*Echinochloa crus-galli*—cockspur grass or barnyard grass (ECHCG) and *Agropyron repens*—quackgrass (*AGRRE*)) and four species of dicotyledonous weeds (*Chenopodium album*—common lambsquarters (CHEAL); *Convolvulus arvensis*—bindweed (*CONAR*); *Erodium cicutarium*—redstem filaree (*EROCI*); *Viola arvensis*—field violet (*VIOAR*)) were recorded. Both the cultivars and methods of weed control, as well as meteorological conditions in the years of research, shaped the floristic composition of weeds that were recorded (Table 8). Weed control methods, cultivars, and years of research differentiated the composition and number of weeds found on the potato plantation. The dominant monocotyledonous species was ECHCG, while the main dicotyledonous species was VIOAR. The least ECHCG was recorded on variants with the application of the mixture of herbicides metribuzin + sulfosulfuron + SN oil POST (Variant 8) and preparations metribuzin + rimsulfuron + ethoxylated isodecyl alcohol, used before crop emergence (Variant 4), compared to the control variant and with the mechanical weed control method (Variant 2). AGRRE was dominant in the variant where the metribuzin and metribuzin + rimsulfuron + ethoxylated isodecyl alcohol mixture was used to control weeds, applied PRE. The least dominance of this weed species was recorded after the application of the mixture of metribuzin + fluazyfop-P butyl (variant 7) and metribuzin + sulfosulfuron + SN oil (Variant 8). CHEAL was best destroyed by a mixture of metribuzin + rimsulfuron + ethoxylated isodecyl alcohol preparations, applied before the potato emerges (Variant 4). Field bindweed was best limited by metribuzin applied after crop emergence. EROCI was best removed when metribuzin + rimsulfuron + ethoxylated isodecyl alcohol was applied PRE and with metribuzin applied after potatoes emergence. VIOAR was the least numerous when applying the mixture of metribuzin + sulfosulfuron + SN oil.

Higher weed infestation before row closure was recorded in the medium-early "Irga" cultivar than the medium-late "Fianna", but only in the case of ECHCG. In the case of EROCI, on the other hand, the "Fianna" cultivar was more weeded. Weed infestation with species such as AGRRE, CHEAL, CONAR, and *VIOAR* did not differentiate the potato cultivars (Table 8).

ECHCG turned out to be the relatively dominant weed species in the years 2007 and 2008; in 2009, the dominating weed was VIOAR, which could possibly be associated with the used forecrop of potato. AGRRE was not present at row closure in the fairly humid conditions of 2008, and CONAR was not present in 2007 and 2008. CHEAL, VIOAR, and CONAR were most frequently recorded in the potato canopy in the quite-dry conditions of 2009. Only the size of *EROCI* did not significantly depend on growing-season conditions (Table 8).

Species composition of weeds before potato harvest was of little variation. The state and structure of weed infestation in variants with chemical plant protection, compared to mechanical cultivation and the control variant, were similar to the weed infestation determined before shorting the rows. In the species composition of weeds, determined before harvesting, monocotyledons taxa species predominated, with *ECHCG* dominating (Table 9).

Table 8. Species composition and the number of monocotyledonous and dicotyledonous weeds before the closure of potato rows, depending on cultivar, weed control method, and year (pcs m^2).

Experiment Factors		Species According WSSA ***					
		ECHCG	AGRRE	CHEAL	CONAR	EROCI	VIOAR
Cultivar	"Irga"	6.6	0.8	1.1	0.4	0.0	3.6
	"Fianna"	5.4	0.7	1.3	0.3	0.5	3.1
	$LSD_{p0.05}$	1.0	ns **	ns	ns	0.2	ns
Weed control methods *	1	14.9	0.9	5.4	1.2	1.8	9.3
	2	6.5	0.7	2.7	0.6	0.2	5.9
	3	5.3	0.7	0.2	0.3	0.1	3.8
	4	3.0	0.7	0.0	0.2	0.0	1.8
	5	5.4	1.0	0.2	0.0	0.0	1.6
	6	5.6	1.1	1.0	0.1	0.1	1.8
	7	4.5	0.5	0.2	0.2	0.2	1.6
	8	3.0	0.6	0.2	0.2	0.2	0.7
	$LSD_{p0.05}$	3.3	ns	1.5	0.8	0.8	2.7
Years	2007	5.1	1.7	0.1	0.0	0.5	1.6
	2008	10.1	0.0	0.6	0.0	0.4	0.4
	2009	2.8	0.5	2.9	0.9	0.0	8.0
	$LSD_{p0.05}$	1.5	0.5	0.7	0.4	ns	1.2
Mean		6.0	0.7	1.2	0.3	0.3	3.3

Source: own research; * (1) Control variant—without chemical protection; (2) extensive mechanical weeding (every 2 weeks) from planting to closure of the rows; (3) metribuzin 1 kg ha^{-1}—PRE; (4) metribuzin 0.3 kg ha^{-1} + rimsulfuron 40 gha^{-1} + ethoxylated isodecyl alcohol 0.1%—PRE; (5) metribuzin 0.5 kg ha^{-1}—POST; (6) metribuzin 0.3 kg ha^{-1} + rimsulfuron 30 g ha^{-1} + ethoxylated isodecyl alcohol 0.1%—PRE; (7) metribuzin 0.3 kg ha^{-1} + fluazifop-P butyl 2 L ha^{-1}—POST; (8) metribuzin 0.3 kg ha^{-1} + ulfosulfuron 26.5 g ha^{-1} + SN oil 1 L ha^{-1}—POST; ns **—not significant at the level $p_{0.05}$; *** AGRRE—*Agropyron repens*; ECHCG—*Echinochloa crus-galli*; CHEAL—*Chenopodium album*; CONAR—*Convolvulus arvensis*; EROCI—*Erodium cicutarium*; VIOAR—*Viola arvensis* [23].

The morphological and physiological features of the studied cultivars differentiated only in the number of ECHCG, VIOAR, and EROCI. The first two were more numerous in the cultivar "Irga" than "Fianna", while, in the last cultivar, it was the opposite. The monocotyledonous weed community was most effectively limited by the following treatments: variant 4 (metribuzin + rimsulfuron + ethoxylated isodecyl alcohol), variant 7 (metribuzin + fluazifop-P butyl), variant 8 (metribuzin + sulfosulfuron + SN oil) (Table 4), limiting their occurrence in comparison with mechanical treatments and the control variant. Dicotyledonous species were eliminated to the greatest extent on Sites 5 (metribuzin) and vriant 8 (metribuzin + sulfosulfuron). Homologous in terms of this feature turned out to be Variant 6 (metribuzin + rimsulfuron + ethoxylated isodecyl alcohol), Variant 7 (metribuzin + fluazifop-P butyl), Variant 5 (Sencor), and Variant 8 (metribuzin + sulfosulfuran + SN oil), on which these herbicides were used after potato emergence. Potato vegetation conditions also significantly differentiated the number and species composition of weeds. Higher numbers of ECHCG were recorded in 2008, with high rainfall in the period of July–August preceding the potato harvest, while there were high numbers of CHEAL, CONAR, and VIOAR in 2009, as it was quite a dry year (Table 9).

The fresh matter of weeds before harvest was 254.1 g on average, whereas their average air-dry matter was 102.8 g·m^{-2}. The weed mass at the end of the growing season was differentiated by cultivars, weed control methods, and years of research (Table 10).

Among the compared cultivars, the medium-early "Irga" was more weeded, the shoots of which dried up earlier and ended the growing season earlier than the medium-late cultivar "Fianna". The best herbicidal effect was achieved using mixtures of the metribuzin + rimsulfuron + ethoxylated isodecyl alcohol (Variant 4) and Sencor + Apyros + Atpolan (Variant 8). Variants 4 and 8 proved to be homologous in terms of this feature. Both fresh and air-dry matter of weeds were the highest in the fairly humid conditions of 2008 and the lowest in 2009, a fairly dry year (Table 10).

Table 9. Species composition and number of mono- and dicotyledonous weeds before potato harvest, depending on cultivar, weed control method, and year (pcs. m^{-2}).

Experiment Factors		ECHCG	AGRRE	CAPBP	CHEAL	CONAR	EROCI	SONAR	VIOAR
Cultivars	"Irga"	8.3	1.4	0.3	2.4	1.6	0.0	0.04	4.7
	"Fianna"	6.4	1.5	0.0	2.0	1.2	0.5	0.01	3.4
	$LSD_{p0.05}$	1.3	ns **	ns	ns	ns	0.1	ns	1.2
Weed control methods *	1	16.2	1.8	1.6	7.4	2.5	1.0	0.10	8.6
	2	8.4	2.0	0.0	4.3	1.8	0.3	0.05	6.6
	3	7.6	1.3	0.0	1.5	1.8	0.2	0.00	6.5
	4	4.8	1.7	0.0	0.6	1.0	0.0	0.00	2.8
	5	6.0	2.1	0.0	0.7	1.0	0.0	0.00	1.5
	6	6.7	1.2	0.0	1.1	1.0	0.2	0.00	2.8
	7	5.7	0.8	0.0	1.3	1.3	0.3	0.00	2.2
	8	3.2	1.0	0.0	0.7	0.8	0.0	0.00	1.4
	$LSD_{p0.05}$	4.0	ns	ns	1.8	ns	0.6	ns	4.2
Years	2007	4.3	3.5	0.0	0.8	0.6	0.4	0.00	0.6
	2008	12.4	0.1	0.0	1.6	0.5	0.4	0.00	0.5
	2009	5.4	0.8	0.6	4.2	3.2	0.0	0.08	11.0
	$LSD_{p0.05}$	1.8	0.8	ns	0.8	0.9	Ns	ns	1.9
Mean		7.3	1.4	0.2	2.2	1.4	0.2	0.02	4.0

Source: own research; * explanations as in Table 8; ** not significant at the level $p_{0.05}$.

Table 10. Fresh and air-dry matter of weeds and their number before potato harvest, depending on cultivar, weed control method, and year.

Experiment Factors		Weed Matter (g·m^{-2})		The Number of Weeds (pcs m^{-2})	
		Fresh Matter	Air-Dry Matter	Monocotyledonous	Dicotyledonous
Cultivars	"Irga"	286.7	116.9	9.7	9.0
	"Fianna"	221.5	88.7	7.9	7.1
	$LSD_{p0.05}$	38.6	16.1	ns **	1.6
Weed control methods *	1	576.9	236.7	18.0	21.2
	2	321.1	142.7	10.4	13.0
	3	231.7	76.7	8.9	10.0
	4	111.4	55.8	6.5	4.4
	5	260.6	90.1	8.1	3.2
	6	227.5	94.5	7.9	5.1
	7	142.5	63.1	6.5	5.1
	8	141.1	62.9	4.2	2.9
	$LSD_{p0.05}$	120.6	50.4	4.3	4.9
Years	2007	276.7	114.0	7.8	2.4
	2008	295.3	132.2	12.5	3.0
	2009	190.3	62.2	6.2	19.0
	$LSD_{p0.05}$	56.7	23.7	2.0	2.3
Mean		254,1	102.8	8.8	8.1

Source: own research; * explanations as in Table 7; ** not significant at the level $p_{0.05}$.

In the case of the fresh mass of weeds assessed before the rows were closed, a significant interaction of cultivars × years was found. The medium-early cultivar "Irga" showed a significantly higher weed weight than the medium-late cultivar "Fianna", but only in 2009, which were characterized by lower humidity in May–June than in 2007. Before the harvest, however, both cultivars showed a similar response to the conditions in the years of research (Table 11).

Table 11. Fresh matter of weeds depending on the cultivar and year (average for weed control methods).

Cultivars	Years		
	2007	2008	2009
Before row closing			
"Irga"	283.1	310.8	265.0
"Fianna"	270.2	279.7	114.3
$LSD_{p0.05}$		36.6	
Before tuber harvest			
"Irga"	125.4	142.1	83.2
"Fianna"	102.7	122.3	41.0
$LSD_{p0.05}$		15.3	

In the experiment, the number of monocotyledonous weeds before the potato harvest was 8.8 pcs·m^{-2}; for dicotyledonous weeds, it was 8.1 pcs·m^{-2}. The reduction in the number of monocotyledonous and dicotyledonous weeds was higher in the case of mechanical and chemical care using various herbicides than in mechanical weed control alone. The lowest number of these species, for both classes, was recorded after using the mixture of herbicides Sencor + Apyros + Atpolan (Variant 8) to regulate weed infestation. In the case of the number of monocotyledonous weeds, Variants 4, 7, and 6, and, in the case of dicotyledonous weeds, the combinations of 4, 5, 6, and 7 proved to be homologous in terms of this characteristic. The highest number of monocotyledonous and dicotyledonous weeds was recorded in 2008 and 2009, respectively, while the smallest number was in 2009 and 2007, respectively, as a result of the weather conditions prevailing during the potato growing season (Table 9). In 2009, the cultivar "Irga", with a stem habit, reacted with more weed infestation than the leaf cultivar "Fianna", both before closing the inter-rows and before harvesting the tubers (Table 12).

Table 12. The number weeds per 1 m^2, depending on the cultivar and year (average for weed control methods).

Cultivars	Years		
	2007	2008	2009
Before row closing			
"Irga"	8.7	11.9	17.0
"Fianna"	9.6	11.7	13.2
$LSD_{p0.05}$		3.5	
Before tuber harvest			
"Irga"	10.7	15.2	31.0
"Fianna"	10.4	15.7	19.7
$LSD_{p0.05}$		6.8	

4. Discussion

The size of potato yields is largely determined by weeds, and the number, size of the air-dried matter of weeds, and their species composition play a significant role [23–28]. The lowest number of weeds in the tests, regardless of the date of weed infestation measurement timing, was recorded after using the mixture of metribuzin + sulfosulfuran + SN oil, and the highest number of weeds found in the tests was after the application of metribuzin before the emergence of the crop. Mechanical weed control reduced the number of weeds by twice as much as the control variant. These results were confirmed in the studies of Ciesielska and Wysmułek [29]. In their opinion, metribuzin, regardless of the date of use, is characterized by a wide spectrum of weed control, while the addition of rimsulfuron and the ethoxylated isodecyl alcohol adjuvant caused the majority of weeds present in the potato crop to be destroyed by 87–100%. Nowak et al. [30] and Ilić et al. [31] confirmed the improvement of herbicide effectiveness due to the addition of adjuvants to the working liquid. These are chemical substances of organic or inorganic origin, which directly or indirectly affect the herbicidal activity of the herbicide's active substance or change the usable properties of the formulation and application liquid [31–33]. In addition, adjuvants prevent the crystallization of the utilized liquid on the surface of plants and delay its drying, causing an increase in the adhesion and solubility of the herbicide and better hydration of the leaf epidermis [24,31,34–39].

The effect of herbicides is largely dependent on the thermal conditions during the application of the herbicide and a few days after the procedure. This was also confirmed by other authors [3,40,41]. According to Gugała et al. [40], a higher temperature promotes increased herbicide adsorption and translocation. Air humidity is also positively correlated with herbicide effects. In conditions of higher humidity, herbicide uptake increases because the used liquid evaporates more slowly from the leaf surface, and, as a consequence, there is a greater amount of agent that can penetrate plant tissues [1,42]. In addition, in conditions of high humidity, the movement of the herbicide in the plant from its penetration to the site of action is much faster than in the case of low humidity [43–46]. However, as suggested by Lavlesh et al. [5], with excessive humidity, there may be a danger of greater herbicide leaching, faster root uptake, and, therefore, increased plant toxicity. Toxicity and degradation rate of biocides, according to Awasthi et al. [45] and Jezierska and Frąc [47], depend primarily on their dose and the structure of the active substance that is the basic plant protection product, which can also be a cause of the inhibition and growth of microorganisms.

With Zarzecka et al. [48], the smallest number of weeds were observed on variants sprayed with metribuzin, while the number was significantly higher after using flurochloridon and purely mechanical treatments. Additionally, Tomczak et al. [49] demonstrated the high effectiveness of metribuzin and mixtures of prosulfocarb and metribuzin in weed control in potato cultivation. Pszczółkowski and Sawicka [50] obtained the best results of eliminating monocotyledonous weeds after applying linuron, and they limited dicotyledonous weeds after using a mixture of linuron + clomazone. In the study of Wichrowska [51], the most effective chemical in controlling weeds was linuron, reducing the population size by 80.3%, especially of dicotyledonous weeds. The least effective in weed control was promethrin used before potato plant emergence.

ECHCG and AGRRE were the most abundant among the monocotyledonous weed species, while CHEAL was the most abundant of the dicotyledonous species. Similar results were also obtained by Gugała et al. [40] and Baranowska et al. [52]. During the vegetation period, these authors showed the dominance of taxa of the following weed species: AGRRE—19.8%, ECHCG—13.2%, VIOAR—12.1%, and CHEAL—11.2%. A similar tendency also appeared before potato tuber harvesting. AGRRE was the most frequently encountered weed (25.9%), followed by ECHCG (14.7%) and CHEAL (20.3%).

Cultivars were another factor that differentiated potato weed infestation. The difference in weed infestation observed between the two examined potato cultivars may be determined by such features as volume of foliage, plant growth rate, morphological and anatomical type, and resistance to abiotic stress. The highest fresh and dry mass of weeds was found in the medium-early cultivar, with a stalk habit, as well as a shorter vegetation period. A medium-late cultivar turned out to be significantly less weedy, with a leaf habit. These results show that potato cultivars with a strong, erect shoot growth habit (shorter stems, more branching, and a denser and taller canopy in the early stages of plant vegetation) may be less susceptible to weed interference than cultivars with lofty plant habit. Similar observations were made by Zarzecka et al. [50] and Baranowska et al. [52]. The optimal time for weed management and the formation of the physiological age of tubers have not been thoroughly investigated and probably vary by cultivar. These dependencies should be established in future research.

The varied response of the studied cultivars to the meteorological conditions of the growing season, in the case of both the number and fresh mass of weeds, could be explained by a different plant habit, as well as by the length of the vegetation period. The medium-early "Irga" cultivar is characterized by a stem habit that is more favorable to weed infestation, while the middle-late "Fianna" leaf type cultivar shaded the soil more and thus prevented strong weed infestation. Other authors shared similar observations [48–50,53]. In the Polish register of cultivars, and, currently, in the EU register, there is a very large assortment of potato cultivars with different physiological and morphological types and different production possibilities. Therefore, it is necessary to determine not only the potential of the potato cultivars and lines currently grown in Poland but also to test them with biotic and abiotic stresses, including the response to herbicides.

Weed management in the conditions of the changing climate in recent years requires the integration of methods and strategies and a change in the way they are perceived. Weeds in potato crops must be combated in a comprehensive, targeted, and proactive manner. Understanding the interactions between weed control methods and the weed spectrum, as well as managing the crop system to prevent and discourage weeds and keep the level of weed seed in the soil low, is essential for effective weed management in all crop systems [50,53]. Good agricultural and tillage practices, including well-planned crop rotation, planting of cover crops, as well as good sanitary practices [10], optimal row spacing, and early planting dates are important aspects of weed management not only in organic systems but also in other cultivation systems [54,55]. Timely mechanical weed control, before the rows of potato plants close, can eliminate many early weed species. In this regard, the selection of appropriate potato cultivars that have a fast initial growth rate and create a leaf canopy capable of controlling weeds can help to reduce weed infestation and, thereby, increase yield. For this purpose, further research, with the participation of potato breeders, is needed on new creations of cultivars that will allow the reduction of primary weed infestation in potato cultivation.

Thanks to the conducted research, for the first time, a broader spectrum of chemical activity of the active substance metribuzin was obtained, with better weed control than mechanical treatments alone. The use of lower doses of metribuzin will contribute to reducing the pollution of the natural environment. Moreover, it was proven that the deciduous cultivar "Fianna" contributed to less weed infestation of potato stalks by creating a larger canopy of leaves than the stalk cultivar "Irga".

5. Conclusions

The fresh and air-dry matter of weeds were most limited by the combination of the mixture of metribuzin + rimsulfuron and ethoxylated isodecyl alcohol adjuvant used before potato emergence (PRE). The best effect of reducing the number of monocotyledonous and dicotyledonous weeds was obtained in the potato field with the following preparations: metribuzin + sulfosulfuron + SN oil applied POST emergence of the potato plants.

The best way to reduce the number of monocotyledonous weeds in the crop of tested cultivars was to use a mixture of herbicides and an adjuvant (metribuzin + sulfosulfuron + SN oil).

The combination of metribuzin + sulfosulfuron + SN oil eliminated CONAR, VIOAR, and mostly limited the number of CHEAL weeds. In turn, the number of EROCI was best reduced by metribuzin applied after potato emergence and a mixture of herbicides, metribuzin + rimsulfuron + ethoxylated isodecyl alcohol, used before the emergence of the plants, while the numbers of SONAR and CAPBP were successfully eliminated by all herbicides.

The leaf-type cultivar "Fianna" (shorter stems, more branched, and denser and taller leaf canopy) proved to be less susceptible to weed infestation than the stem-type cultivar "Irga".

Selecting cultivars with a fast initial growth rate and a leaf crown capable of controlling weeds can help to reduce weed infestation in potato crops.

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Abbreviation

AGRRE	*Agropyron repens* (L). *P. Beauv.*
ECHCG	*Echinochloa crus-galli* (L.) *P. Beauv*
CAPBP	*Capsella bursa-pastoris* (L.) *Medik.*
CHEAL	*Chenopodium album* (L.)
CONAR	*Convolvulus arvensis* (L.)
EROCI	*Erodium cicutarium* (L.) *L'H R*
SONAR	*Sonchus arvensis* (L.)
VIOAR	*Viola arvenis* Murray
BBCH	Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie
PRE	before potato emergence
POST	after potato emergence

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