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Efficiency assessment of weed control and soybean productivity depending on herbicide selection and timing of application

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Abstract. Herbicide protection affects the health and plants conditions of soybean and is influenced by the weather. Due to the increase in weed infestation in the initial period of plant growth, agrotechnical solutions are sought to enhance protection of plants against excessive weed infestation, taking into account the weather at sowing time. These solutions, however, are not always effective. The aim of the study was to compare the plant morphology, seed yield and weed infestation of soybean crop, cultivar 'Merlin', depending on the weed management and weather conditions. A two-factor field experiment was set up at the Bayer Crops Experimental Station in Chechło, Poland. The timing of application of herbicides (post-sowing and pre-emergence) and combinations of herbicides were compared. The study showed that application of herbicides immediately after sowing effectively regulates weed infestation of a soybean plantation and shows low phytotoxicity. In years with a high water deficit, herbicides should be applied immediately after sowing. The field experiment confirmed the positive effect of herbicide protection applied immediately after sowing on the habit of soybean plants and the crop yield. The choice of the broad-spectrum mixtures of herbicides Bandur 600 SC (aclonifen) and Sencor Liquid 600 SC (metribuzin) guarantees high efficacy with low or no phytotoxicity. To obtain high soybean yield, however, the application of the herbicide Artist (as a mixture of flufenacet and metribuzin) is recommended.

Keywords: *Glycine max* (L.) Merr., phytotoxicity, seed yield, plant habit, weed infestation

INTRODUCTION

The importance of soybean around the world is systematically growing, together with the increase in demand for protein and oil. Soybean has a pivotal position in agricultural sector due to multiple uses in nutrition, fodder production, and industrial processes. Soybeans contain valuable substances for human health, such as protein, fat, dietary fibre, lecithin, vitamins, mineral salts, and antioxidants (Zeller, 1999; Rogalska-Niedźwiedź, 2000). The spread of soybean cultivation in Europe is much slower than in countries such as the United States, Brazil, or Argentina, and is determined by climatic factors characteristic of the region (Gawęda et al., 2020; Nendel et al., 2023). According to Donau Soja Market Report (2024) soybean area in Europe increased to 5.6 mln ha. In contrast, the area under soybean cultivation on Poland reached 79.815 thousand hectars (according to ARiMR Report). As a plant originating in the Far East, it has high heat and water requirements (Vollmann et al., 2000), especially in critical periods, i.e. germination and flowering (Eyherabide, Cendoya, 2002). A water deficit during these periods slows plant development and limits productivity. Unfortunately, the rainfall deficit observed in the last decade is due to persistent climate change and is a global phenomenon described not only in Argentina, Brazil, and the United States, but also increasingly in Central and Southern Europe (Nendel et al., 2023). Another cause of soybean crop failure is cold stress. Cold stress is a phenomenon occurring mainly in regions of Central and Northern Europe and affects the initial growth of soybean. It often slows plant development and thereby increases pressure from weeds, which make better use of habitat conditions in the initial period of soybean growth. The greatest losses in soybean yields are believed to be generated by dicotyledonous weeds, which compete with soybean plants for nutrients, water, and light (Stefanic et al., 2022). A lack of effective management of weed infestation can reduce soybean yields by as much as 90%, which directly affects the profitability of cultivation of this legume plant (Gawęda et al., 2020). An appropriate choice of herbicides protects the plantation throughout the growing period and guarantees yield stability and quality. The available assortment of products for protecting soybean against weeds is limited by EC regulations (Matyjaszczyk, Skrzecz, 2020), which arise from EU policy on the European Green Deal and restrictions on the use of plant protection products in crop cultivation. Therefore particular attention should be paid to the choice of active ingredients enabling sufficient protection of the plantation against agricultural pests.

An important challenge for agriculture in the 21st century is the continual effort to achieve sustainable food production by taking into account the needs of consumers, producers, and the environment. Integrated plant protection is a key element of this system. Important agricultural practices supporting integrated plant protection include the choice of cultivars, proper soil cultivation, the use of cover crops, and a long crop rotation. All of these practices contribute to regulation of weed infestation, and thus to the promotion of sustainable soybean production. According to some researchers, weed infestation can be regulated by using broad-spectrum herbicides (Landau et al., 2022). Guaratini et al. (2006) analysed numerous cases of biotypes of weeds resistant to herbicides and demonstrated that the use of herbicides with different mechanisms of action is a viable alternative to standard herbicide application. This has also been confirmed by Silva et al. (2023), who showed that rational management of herbicides with different mechanisms of action is a very important practice in weed control. In addition, the use of herbicides with little residual activity in the soil and optimization of doses and the number of applications reduces selection pressure, lowering the risk of selection of plants resistant to the herbicides. It is worth noting that while a mixture of herbicides with different active ingredients increases their efficacy, it can be harmful to legume plants.

The aim of the study was to compare the plant morphology, seed yield and weed infestation of soybean crop, cultivar 'Merlin', depending on the weed management and weather conditions. The research hypothesis assumed that i) weather conditions in early vegetative stages modify herbicide effects on plant traits and soybean yield, ii) herbicide selection significantly influences the shaping of plant quantitative traits, which is reflected in the level of yield obtained

MATERIALS AND METHODS

Location of the experiment, soil and weather conditions

A two-years field experiment were conducted at the Bayer Technical Advisory Center in the village of Chechło (50°24′37″N 18°24′17″E) in 2019 and 2020. Experiment was conducted on Luvic Phaeozem, according to WRB soil classification (Anjos et al., 2015). The plots were set up on the second class, and good wheat complex (silt loam), with moderate humus content (1.3%). The content of nutrients in the soil, which was analysed before experiment setting, was as follows: P_2O_5 – 181 mg/kg of soil, K_2O – 168 mg/kg of soil, Mg – 104 mg/kg of soil, and N – 696 mg/kg of soil. The soil pH was 6.72.

The mean/sum, maximum and minimum values in the soybean growing season (April–September) for temperature were: 15.9 °C, 19.7 °C, 9.6 °C and for the precipitation: 487 mm, 107 mm, 57 mm (weather station in Bayer Technical Advisory Center in Chechło; observation period: 1991–2021). In 2019 temperature was higher compared to the long-term mean in April, June and August, whereas in 2000 only in August (Table 1). In both seasons, the amount of precipitation was usually lower in nearly all months, with the exception of May when in 2019 the precipitation was higher compared to the long-term data.

Table 1. Temperature and rainfall conditions in vegetation period (2019–2020).

Year	APR	MAY	JUN	JUL	AUG	SEP	Mean/Sum
Mean of temperature [°C]							
2019	10.6	12.1	22.4	19.6	20.9	14.5	16.7
2020	9.44	11.4	17.7	18.9	20.3	14.9	15.4
Multi-year (1991–2021)	9.6	14.4	17.8	19.7	19.5	14.9	15.9
Sum of precipitation [mm]							
2019	38.2	94.0	10.6	23.0	5.00	1.80	172.6
2020	4.20	56.0	1.40	4.00	15.0	12.8	93.40
Multi-year (1991–2021)	57	82	87	107	77	77	487

Table 2. Selyaninov's coefficient (K) during the vegetation of soybean in 2019–2020.

Year	APR	MAY	JUN	JUL	AUG	SEP
2019	1.20 (md)#	2.58 (vw)	0.16 (ed)	0.39 (ed)	0.08 (ed)	0.04 (ed)
2020	0.15 (ed)	1.64 (mw)	0.03 (ed)	0.07 (ed)	0.25 (ed)	0.29 (ed)

ed – extremely dry, md – moderately dry, mw – moderately wet, vw – very wet

Rainfall and temperature conditions during the study period were characterized by Selyaninov's hydrothermal coefficient (K) (Table 2). Selyaninov's coefficient was calculated using the following equation: $K = P/0.1\ \Sigma t$, where P is the monthly rainfall total in mm, and Σt is the monthly sum of daily average air temperature >0°C (Skowera, 2014).

A division into 10 classes of values for the K coefficient was used to distinguish both extremely dry and extremely wet conditions. The ranges of values were as follows: extremely dry (ed) $K \leq 0.4$; very dry (vd) $0.4 < K \leq 0.7$; dry (d) $0.7 < K \leq 1.0$; moderately dry (md) $1.0 < K \leq 1.3$; optimal (o) $1.3 < K \leq 1.6$; moderately wet (mw) $1.6 < K \leq 2.0$; wet (w) $2.0 < K \leq 2.5$; very wet (vw) $2.5 < K \leq 3.0$; extremely wet (ew) $K > 3.0$.

Based on the K values, it was determined that the year 2019 was more favourable in terms of relations among rainfall and air temperature than the year 2020, in which extremely dry periods predominated during the growing period.

Agricultural practices

The forecrop to soybean was common oat (*Avena sativa*). In the second 10 days of November, winter ploughing was carried out to a depth of 25 cm. Field work was resumed after the snow had receded and it was possible to enter the field. Harrowing was carried out to stop evaporation. Pre-sowing cultivation was carried out using a tilling to a depth of 8 cm. Mineral fertilizers were applied to the soil the day before it was prepared for sowing, in the third 10-day of April. Taking into account the content of elements in the soil and the requirements of soybean, Polifoska 6 NPK(S) 6–20–30–(7) was applied in the amount of 250 kg/ha, and ammonium nitrate 32%N was applied as a starter fertilizer in the amount of 20 kg/ha. Soybean was sown at the end of the third 10-day of April in each year of the study, when the soil temperature had reached 9°C. The Zurn D82 plot seeder was used. The area of the single plot was 13 m^2. Due to the favourable conditions for soybean growth and development, a density of 70 plants/m^2 was adopted. For a 95% germination rate and 1000 seed weight of 145 g, the sowing rate was 107 kg/ha. The sowing depth was established at 3 cm. The seeds before sowing were treated with conventional seed dressing (Fix Fertig), containing bacteria *Bradyrhizobium japonicum*.

Experimental design

This study focused on chemical reduction of the occurrence of weeds in the experimental plots. The field experiment was set up in a randomized block design in 3 replications. The first experimental factor was the timing of herbicide application: post-sowing (PS) and pre-emergence (PE). The second factor was application of the herbicide combination: 'Artist WG' (A); 'Metron 700 SC' + 'Mero' (MM); 'Sencor Liquid 600 SC' (S); 'Bandur 600 SC' + 'Sencor Liquid 600 SC' (BS); 'Bandur 600 SC' + 'Metron 700 SC' (BM); Control (C). In order to have orthogonal field experiment two control (with water application) treatments were used. Herbicides were used in the following doses: Sencor Liquid 600 SC at 0.55 l/ha; Bandur 600 SC at 1.5 l/ha and Sencor Liquid 600 S.C. at 0.3 l/ha; Bandur

Table 3. The characteristic of selected herbicides (MRiRW, 2025) assess in field experiment.

Herbicide	Active substance	Chemical group	Mechanism of action
Sencor Liquid 600 SC	metribuzin 600 g/l	triazine group	Blocking the photosynthetic light response complex, leading to inhibition of weed growth and sweeping
Bandur 600 SC	aclonifen 600 g/l	diphenylether group	Blocks enzymes involved in two important processes – chlorophyll synthesis and karotenoid synthesis
Metron 700 SC	metamitron 700 g/l	triazine group	Blocking the photosynthetic light response complex, leading to inhibition of weed growth and sweeping
Artist WG (= Plateen 41,5 WG)	flufenacet 240 g/l	oxyacetamide group	It acts by inhibiting amino acid biosynthesis, which leads to the disruption of metabolic processes in weed cells and their inhibition.
	metribuzin 175 g/l	triazine group	Blocking the photosynthetic light response complex, leading to inhibition of weed growth and sweeping

600 SC at 1.5 l/ha and Metron 700 SC at 2 l/ha; Artist WG at 2 kg/ha; Metron 700 SC at 3 l/ha + Mero (oil adjuvant) at 2 l/ha.

The selection of herbicides for study was based on farmers' willingness to use them in order to control weeds infestation in soybean. The characteristic of selected herbicides are described in Table 3.

Spraying to reduce weed infestation was carried out at two different times: five days after sowing (BBCH 03–07, PS) and before full emergence (BBCH 08–10, PE).

The herbicides were applied using the Agrotop 2.0 bicycle sprayer. The same amount of working solution was applied to all experimental plots, amounting to 300 litres per hectare. It was not necessary to add more water, because the soil at that time was sufficiently moist in both years. Solution in the amount of 300 l/ha ensures uniform cover of the field surface, which directly translates into the efficacy of the plant protection product. Moisture and wind conditions did not interfere with the procedures.

To determine the degree of weed infestation and thus the efficacy of the herbicides at both application times, a control plot was left without herbicide application. The effectiveness of the applied herbicides was determined by taking the weed infestation in the control plot as 100%. In all plots, weeds were determined according to the agricultural weed atlas (Pawłowska, Hołubowicz-Kliza, 1995) and counted in three randomly selected 50 cm × 50 cm plots. Weed control effectiveness of 85–100% was defined as high efficacy, 70–85% as medium, below 70% as poor (Podolska, 2014).

The most prevalent weeds in the control plots were *Echinochloa crus-galli* (L.) P.Beauv., *Chenopodium album* L., *Thlaspi arvense* L. As the dominant weeds in the soybean crop, they served as model species for assessment of the efficacy of each herbicide. The efficacy of the herbicides was evaluated four weeks after sowing, at the end of May according to EPPO principles. Table 4 presents the percentage efficacy of weed control depending on the time of herbicides application.

During the field observations, weeds monitoring showed diverse reaction to the herbicides application. Characteristic discolouration was observed mainly on the weeds leaves.

Phytotoxicity in the soybean plants was assessed in the third 10-day in May. The phytotoxicity of the applied herbicides was assessed according to a 9-point scale (where: 1 – no damage, 2 – very mild symptoms, 3 – slight symptoms – discoloration, 4 – strong symptoms – do not always affect the yield, 5 – slight damage, 6 – obvious damage – necrosis, 7 – severe damage – necrosis, 8 – very strong damage, 9 – complete destruction of plants) (Barbaś et al., 2024). The results are presented in Table 5.

Plants were harvested each year in the third 10-day period of September. A few days before harvest (BBCH 99), 20 plants were randomly collected from each plot for biometric measurements: plant height, height of the first pod setting, number of fruiting nodes per plant, dry weight of plants, pod number per plant, seed number per plant, and seed weight per plant.

The plants were harvested using the Wintersteiger Delta plot combine. The seeds were fully ripe but with a moisture level above 25%, so they required drying. Immediately after harvest, the samples were labelled and prepared for drying. Parameters such as TSW, and yield were determined when the moisture level of the seeds had reached about 14%.

Statistical analysis

Statistical analysis of the results was performed in Statistica 13.1 by two-way analysis of variance (ANOVA). Tukey's test was used to compare means at a significance level of 0.05.

RESULTS

Effect of the choice of herbicides and timing of application on soybean weed control

The data of weed control efficiency presented in Table 4. Data analysis showed that time of herbicides application affected the weed control efficiency. Regardless of the herbicide application (PS vs PE), the use of Sencor Liquid 600 (S), Bandur 600 SC + Sencor Liquid 600 (BS) or Bandur 600 SC+ Metron 700 SC (BM) was very effective (100%) in soybean protection against selected weeds, the lowest efficiency (40–83%) was achieved after the post-sowing application of Metron 700 SC + Mero (MM).

Phytotoxicity symptoms (Table 5) were observed at an early stage of crop development in soybean after Sencor Liquid 600 (S) or Bandur 600 SC + Sencor Liquid 600 (BS) application. Only very slight damages of plant tissues were observed. A maximum phytotoxicity of 15% is considered acceptable by herbicide users. Regardless of the time of herbicide application, Artist WG or Metron 700 SC + Mero showed very low phytotoxicity. No visible symptoms on soybean plants were detected.

Effect of the choice of herbicides and times of application on soybean plant habit

The statistical analysis showed a significant effect of herbicide protection on morphological traits, and seed yield (Tables 6, 7).

Application of 'Artist' resulted in an increase in the total dry weight of the plants, and in the number of fruiting nodes per plant. It showed no phytotoxic effects, irrespective of the times of application (after sowing and before emergence) (Table 5). The lack of phytotoxic effect positively influenced the productivity of the soybean plants.

Table 4. Percentage efficacy of herbicides (2019–2020).

Commercial product	Time of herbicide application	*Echinochloa crus-galli*	*Chenopodium album*	*Thlaspi arvense*
Artist WG (A)	post-sowing (PS)	95	100	100
Metron 700 SC + Mero (MM)		40	83	83
Sencor Liquid 600 SC (S)		100	100	100
Bandur 600 SC + Sencor Liquid 600 SC (BS)		100	100	100
Bandur 600 SC + Metron 700 SC (BM)		100	100	100
Artist WG (A)	pre-emergence (PE)	100	100	100
Metron 700 SC + Mero (MM)		45	80	90
Sencor Liquid 600 SC (S)		100	100	100
Bandur 600 SC + Sencor Liquid 600 SC (BS)		100	100	100
Bandur 600 SC + Metron 700 SC (BM)		100	100	100

Table 5. Herbicide phytotoxic effects in seedling phase of soybean (2019–2020).

Commercial product	Time of herbicide application	Phytotoxicity on a scale from 1 to 9[#]	Plant tissues damage of soybean [%]
Artist WG (A)	post-sowing (PS)	1	0
Metron 700 SC + Mero (MM)		1	0
Sencor Liquid 600 SC (S)		2	10
Bandur 600 SC + Sencor Liquid 600 SC (BS)		2	7
Bandur 600 SC + Metron 700 SC (BM)		1	0
Artist WG (A)	pre-emergence (PE)	1	0
Metron 700 SC + Mero (MM)		1	0
Sencor Liquid 600 SC (S)		2	15
Bandur 600 SC + Sencor Liquid 600 SC (BS)		2	10
Bandur 600 SC + Metron 700 SC (BM)		2	3

1 – no symptoms, 2 – very mild symptoms

Table 6. Selected morphological characteristics of soybean depending on herbicide control.

Treatment		Plant height [cm]	Height of 1st pod setting [cm]	No. of fruiting nodes per plant	Dry weight of plant [g]
Year (Y)	2019	67.2 b	5.34 b	4.54 b	33.8
	2020	109.7 a	11.7 a	17.3 a	34.3
	P value $_{<0.05}$	<0.0001	<0.0001	<0.0001	ns
Herbicides (H)	Artist (A)	90.6 ab	7.64 b	13.2 a	37.8 a
	Sencor (S)	90.8 a	9.16 a	10.1 c	34.1 abc
	Bandur + Metron (BM)	84.0 d	8.21 ab	10.8 bc	34.4 ab
	Bandur + Sencor (BS)	87.9 bc	8.17 ab	12.6 ab	36.7 ab
	Metron + Mero (MM)	90.1 abc	9.11 a	9.50 c	32.1 bc
	Control (C)	87.5 c	8.75 ab	9.15 c	29.3 c
	P value $_{<0.05}$	<0.0001	<0.0001	<0.0001	<0.0001
Time of herbicide application (M)	Post-sowing (PS)	90.1 a	7.94 b	11.5 a	36.1 a
	Pre-emergence (PE)	86.8 b	9.08 a	10.2 b	32.0 b
	P value $_{<0.05}$	<0.0001	<0.0001	<0.002	<0.0001
	Y × H	<0.0001	<0.0001	<0.0001	<0.0001
	Y × M	<0.0001	<0.0001	<0.003	<0.0001
	H × M	<0.0001	<0.0001	<0.0001	<0.0001
	Y × H × M	<0.0001	<0.0001	<0.0001	<0.0001

ns – not significant at p≤0.05

Different letters denote significant differences (p ≤ 0.05).

Table 7. Yield and yield components of soybean depending on the choice of herbicides and timing of application.

	Treatment	No. of pods per plant	No. of seeds per pod	No. of seeds per plant	Weight of seeds per plant [g]	TSW [g]	Seed yield [t/ha]
Year (Y)	2019	50.5 a	2.08 a	103.7 a	12.2	122.9 b	3.31 a
	2020	35.7 b	1.89 b	68.9 b	12.5	187.8 a	2.45 b
	P value $_{<0.05}$	<0.0001	<0.0001	<0.0001	ns	<0.0001	<0.0001
Herbicides (H)	Artist (A)	50.9 a	2.03	102.8 a	14.9 a	148.3	3.45 a
	Sencor (S)	39.6 c	1.99	79.3 cd	11.5 cd	157.7	2.93 c
	Bandur + Metron (BM)	44.7 b	1.95	88.0 bc	12.8 bc	148.2	3.11 bc
	Bandur + Sencor (BS)	47.3 ab	2.04	95.1 ab	13.8 ab	158.3	3.22 ab
	Metron + Mero (MM)	37.0 c	1.99	75.7 d	10.7 d	163.9	2.53 d
	Control (C)	39.2 c	1.93	76.7 d	10.3 d	155.7	2.05 e
	P value $_{<0.05}$	<0.0001	ns	<0.0001	<0.0001	ns	<0.001
Time of herbicide application (M)	Post-sowing (PS)	44.9 a	1.95 b	88.3	12.9 a	155.1	3.09 a
	Pre-emergence (PE)	41.3 b	2.02 a	84.2	11.8 b	155.6	2.67 b
	P value $_{<0.05}$	<0.0001	<0.011	ns	<0.004	ns	<0.0001
	Y × H	<0.0001	<0.002	<0.0001	<0.0001	<0.008	<0.0001
	Y × M	<0.001	ns	<0.009	<0.003	ns	<0.001
	H × M	<0.0001	ns	<0.0001	<0.0001	ns	<0.018
	Y × H × M	<0.0001	ns	<0.0001	<0.0001	<0.002	<0.0001

ns – not significant at p≤0.05

Different letters denote significant differences (p ≤ 0.05).

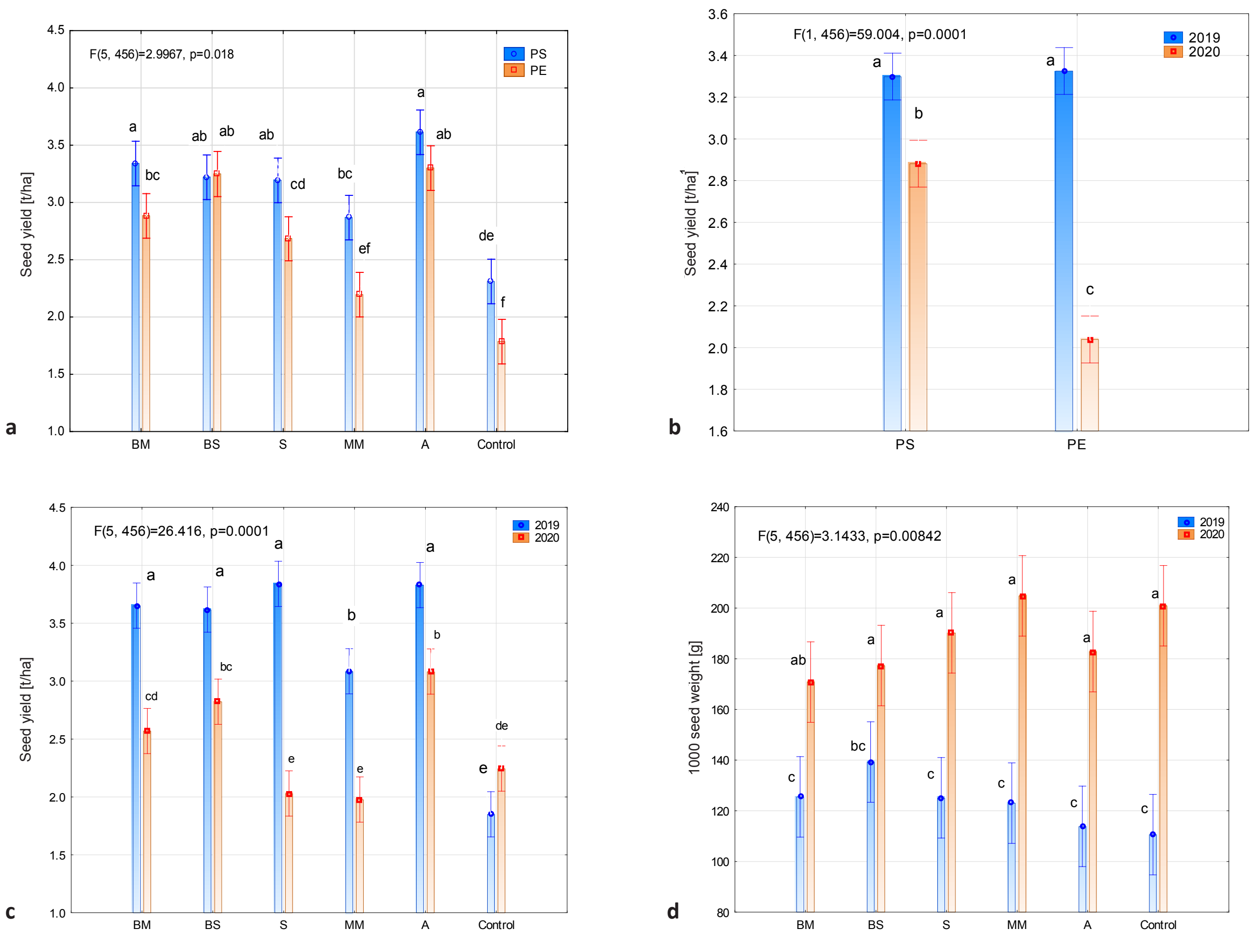

Figure 1. a) Interaction of the choice of herbicides and times of application on seed yield; b) interaction of the times of application and year on yield; interaction of the choice of herbicides and year on c) yield and d) 1000 seed weight. Capital letter symbols: see Table 4. Different lower case letters on each chart denote significant differences.

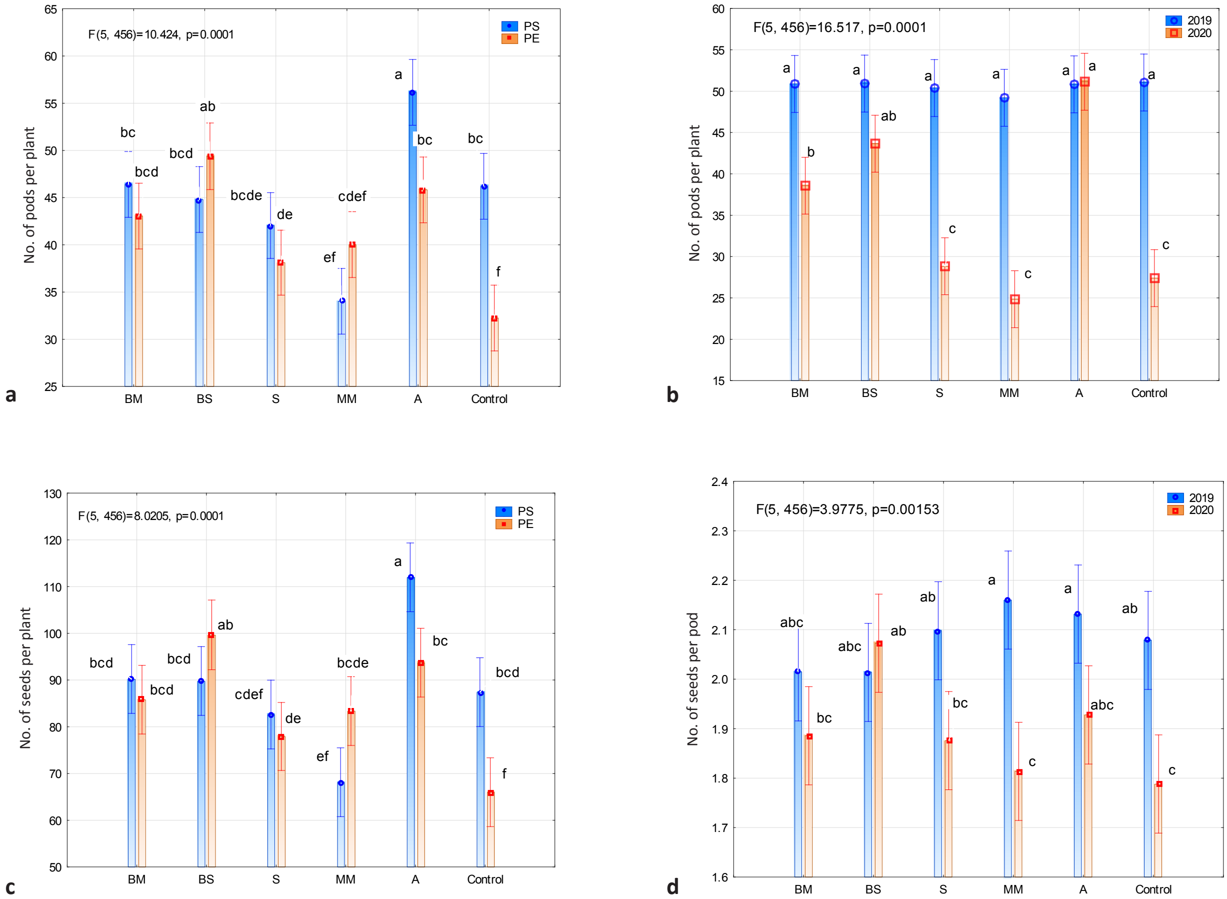

Figure 2. Effect of the interaction of the choice of herbicides and timing of application on a) number of pods per plant and c) number of seeds per plant and the choice of herbicides and year on b) number of pods per plant and d) number of seeds per pod. Capital letter symbols: see Table 4. Different lower case letters on each chart denote significant differences.

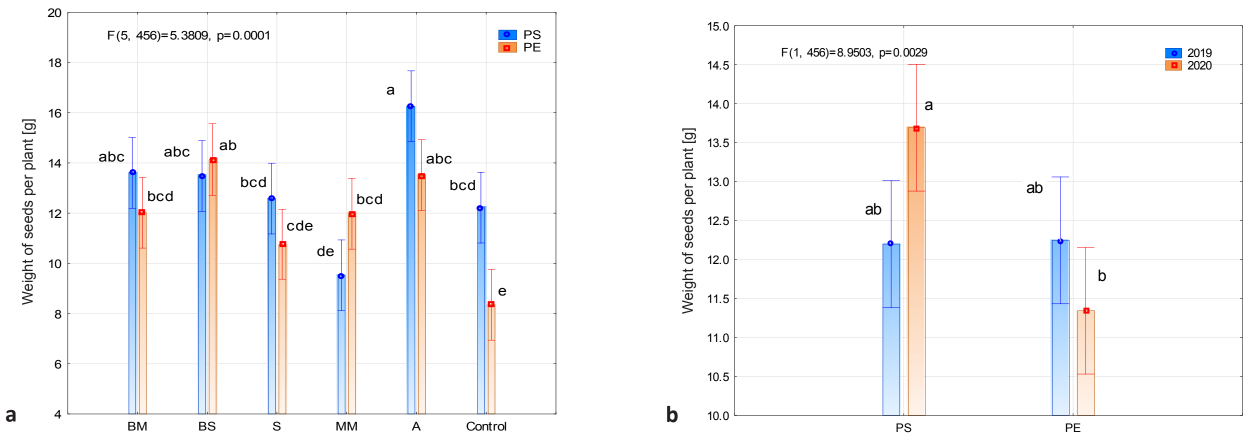

Figure 3. Effect of a) the interaction of the choice of herbicides and timing of application and b) the interaction of the timing of application and year on seed weight per plant. Capital letter symbols: see Table 4. Different lower case letters on each chart denote significant differences.

Following application of 'Artist', the number of pods was significantly higher than in the control treatment. These traits also resulted in a significantly greater seed yield than in the object without the treatment (Table 7).

A contrasting effect was observed following application of 'Sencor'. The use of this herbicide showed a greater of phytotoxicity for the young seedlings, irrespective of the times of application (after sowing and before emergence), and had a negative impact on the productivity of individual plants, compared to Artist WG. Significant reductions in pod number compared to Artist WG were also observed. The use of the herbicide Sencor had a significantly positive effect mainly on plant height and the height of the first pod setting. Following the application of this herbicide, the plants were slightly taller, with the first pods set higher, than in the control treatment (Table 6). The combination of two herbicides (BM and BS) slightly affected soybean plants, but phytotoxicity of BS was a bit higher (Table 5). Despite the phytotoxic effect observed on the soybean leaves following the application of the BS herbicide combination, it was not shown to adversely affect the yield. In the treatments protected with the BS herbicide combination, the seed number and seed weight per plant as well as the seed yield were significantly higher than for the MM combinations.

The interaction between years and experimental factors was shown to have a significant effect on main morphological characteristics and seed yield (Fig. 1–3). Applying herbicides immediately after sowing (PS) was more effective in the year with less total rainfall (2020), than in the wet year (2019). Application of Artist WG herbicide at post sowing contributed to the highest seed yield compared to control (Fig. 1 a-b). Among the herbicides compared in the study, the best effects on seed yield were obtained following application of the herbicide Artist (Fig. 1c). In the case of 1000 seed weight, however, significantly better effects were obtained by applying a combination of the Metron and Mero (MM) (Fig. 1d).

The best results of soybean plant productivity characterised by number of seed and pods were obtained after Artist WG application (Fig. 2). The interaction between the times of application and the choice of herbicides was shown to significantly affect the pod number per plant and seed number per plant (Fig. 2a, Fig. 2c). Application of the herbicide Artist after sowing of soybean (PS) resulted in a significant increase in the morphological parameters analysed in the study. Weather conditions in 2019 had no significant impact on the pod number or seed number per plant (Fig. 2b-c). In the following year, however, the use of Artist effectively increased the pod number and seed number per plant, compared to control.

The interaction of the choice of herbicides and times of application was shown to have a significant effect on seed weight per plant (Fig. 3). Significantly higher seed weight per plant compared to control was observed following application of the herbicide Artist after sowing (PS) (Fig. 3a). In the year 2019 with higher total rainfall (especially during soybean sowing), the time of herbicide application was significantly less effective, compare to dry year 2020 in determining seed weight per plant. In contrast, in the year with low total rainfall during sowing of soybean (April – Table 1), significantly higher seed weight per plant was shown in the treatments protected with herbicides immediately after sowing; the difference amounted to about 2 grams per plant (Fig. 3b).

DISCUSSION

The efficacy of herbicide protection depended on the herbicide combination used and the time of application. Previous studies have suggested that different herbicides should be used in sequence in soybean cultivation in order to ensure that the soybean plants prevail over the weeds (Watts et al., 1997; Soltani et al., 2009). Sequential application of herbicides before and after sowing is effective at controlling the main noxious species of weeds, monocotyledonous and dicotyledonous (Song et al., 2020). Our findings demonstrated that a one well-selected herbicide can be equal effective as a combination of herbicides at controlling weeds in a soybean crop. However, the time when the herbicides are applied and the weather at the time of sowing are important factors. In the year with low rainfall at sowing time, plant productivity was significantly higher in the treatments protected with herbicides immediately after sowing, whereas no significant difference in the times of plant protection was shown in the wet year.

The application of herbicides immediately after sowing was a highly effective plant protection solution. Among the herbicide combinations compared in the study, the best effects in terms of protection against weeds, the degree of phytotoxicity, and soybean yield were obtained following application of the herbicide Artist (flufenacet 240 g/l + metribuzin 175 g/l). The application of this herbicide immediately after sowing effectively reduced weed infestation, showed no phytotoxic effect, and enabled a high seed yield. According to Kolmanič and Leskovšek (2017), Artist exhibits strong phytotoxicity for soybean plants, manifested as chlorosis and necrosis. Those findings were not confirmed in the present study; the soybean plants treated with this herbicide showed no signs of phytotoxicity.

A different effect was obtained following application of the herbicide Metron, which poorly protected the soybean plantation against *Echinochloa crus-galli*. Unfortunately, the presence of *Echinochloa crus-galli* dominated the soybean crop, reducing its seed yield. Gugała and Zarzecka (2012) describe a positive effect of Metron 700 SL + Fusilade Forte 150 EC in the form of increased seed yield of narrow-leaved lupin. The present study did not confirm those findings, as among the herbicides compared, the Metron + Mero combination resulted in poor soybean yield which was only slightly higher than in the control treatment.

It is worth drawing attention to the effects of the herbicide Sencor Liquid, whose application resulted in symptoms of phytotoxicity on the soybean plants. Ciesielska and Wysmułek (2012) reported that Sencor Liquid was highly effective during experiments lasting several years, but in extreme cases it can negatively affect crop quality and yield. The authors observed a negative effect of the metribuzin contained in Sencor Liquid in certain potato cultivars, i.e. poorer crop quality and lower yield (Ciesielska, Wysmułek, 2012). These observations are supported by the present study, in which symptoms of phytotoxicity were noted following the use of this agent.

The experiment demonstrated very favourable effects in the treatments in which combinations of two herbicides, and thus several active ingredients, were analysed. The herbicide combinations Bandur + Metron and Bandur + Sencor Liquid effectively protected the plantation against weed infestation. Following the application of these herbicide combinations, the presence of weeds was not observed in the canopy during the entire soybean growing period. Grzanka et al. (2022) reported very high efficacy of herbicide protection following the application of various herbicide combinations. The authors recommend combining several active ingredients with complementary effects. The present study demonstrates the need to effectively reduce weed infestation in soybean plantations, which indirectly and directly translates into the quality and yield of the crop. Gawęda et al. (2020) and Gawęda and Kopcewicz (2023) reported negative effects of weed infestation on soybean crop. The authors indicated the importance of managing weed infestation before sowing and immediately after sowing in order to keep the plantation free of weeds throughout the growing period. The time of application of a given herbicide significantly influences its efficacy and phytotoxicity for soybean. According to Ceretta et al. (2023), post-sowing application is most effective and least harmful to crop plants, which is supported by the present study.

CONCLUSIONS

1. A water deficit during sowing of soybean necessitates herbicide application immediately after sowing, whereas in conditions of adequate rainfall, the slight delaying of application does not matter.
2. Post-sowing application of flufenacet 240 g/l + metribuzin 175 g/l (herbicide Artist) resulted the highest seed yield, and gave an effective broad spectrum of weed control.
3. The timing of herbicides application significantly affects phytotoxicity for soybean plants and some biometric parameters such as number of pods per plant, weight and number of seeds per plant. Among the herbicides compared in the present study, Artist can be recommended as highly effective, especially in the conditions of a rainfall deficit at the time of sowing of soybean.
4. Among the herbicide combinations compared in the study, Bandur 600 SC (aclonifen) + Sencor Liquid 600 SC (metribuzin) can be recommended, as this combination is highly effective at regulating weed infestation in the soybean crop. Despite the observation of some degree of phytotoxicity (7–10%), this combination contributes to high soybean yield.

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