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The effectiveness of applying products with herbicidal active substances in soybean crops

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Abstract. The aim of the study was to determine the level of biological effectiveness of soybean protection systems and to rationally combine the mechanisms of action of herbicidal formulations with the use of the adjuvant Skaba EC. The effectiveness of herbicide active substances on weed infestation and soybean yield was evaluated. The index of competitive pressure of weeds on crops was determined. Under all studied conditions, a clear hierarchy of effectiveness between two- and three-component systems was observed. Differences between application rates were much less pronounced than expected. When using 100% herbicide rates in combination with the adjuvant Skaba EC (0.2 L/ha) in two-component systems, the average reduction in weed numbers was: for annual broadleaf weeds – 80.0-91.4%, for annual grasses – 72.0-92.0%, and for perennial broadleaf weeds – 69.0-81.0%. In the three-component system, these values were 95.1%, 94.0%, and 87.0%, respectively. Reducing the herbicide rate to 75% combined with an increased adjuvant rate (0.3 L/ha) did not result in a significant decrease in weed control effectiveness. In the three-component system, the values reached 93.9%, 94.5%, and 85.0%, respectively. A 25% reduction in herbicide rates, when combined with the adjuvant, had little effect on the final biological outcome, while significantly reducing the chemical load on the agroecosystem. The combination of inhibitors provided the highest biological effectiveness of weed control. The level of weed infestation in soybean crops during the years of study depended significantly on the composition of the herbicide protection system and the combination of products with different mechanisms of action of active substances on plants. Two-component systems without the use of an adjuvant ensured moderate weed reduction (58-88%), whereas three-component multisite combinations increased control effectiveness to 85-97% for annual species and 76-88% for perennial species (and under conditions with an adjuvant – up to 90-97% and 84-88%, respectively). When applying optimised (reduced by 3-40%) herbicide rates in combination with the maximum adjuvant rate (0.4 L/ha), weed control efficiency remained consistently high

Keywords: adjuvant; agricultural technologies; weeds; competitive pressure index; efficacy index

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INTRODUCTION

Soybean is one of the key strategic crops in modern crop production in Ukraine due to its high content of complete plant protein and oil, as well as its ability for symbiotic nitrogen fixation. It plays an important role in the formation of sustainable agroecosystems, which defines it as one of the significant crops for agricultural production. This is evidenced by data on the soybean market in Ukraine, which shows considerable fluctuations. According to the State Statistics Service of Ukraine (n.d.), in 2024 the cultivation area reached up to 2.63 million hectares, in 2025 – up to 2.42 million hectares, while in 2026 it was expected that the total area would remain at about 2 million hectares. Successful soybean cultivation requires consideration of both the biological characteristics of the crop – its requirements for heat, moisture and light intensity – and specific agronomic practices. However, one of the main limiting factors in realising soybean yield potential remains a high level of weed infestation, caused both by the biological traits of the crop (slow initial growth and weak competitiveness during the first 30-40 days of vegetation) and by the diversity of weed species in the Forest-Steppe zone. According to M.I. Kyrychok (2023), weeds emerging within 3 to 21 days after soybean emergence are capable of creating significant competition with crop. Untimely weed control in soybean crops, or its absence, results in yield losses of 15-30%. Under mixed weed infestation, yield losses may reach 30-50% or more, while seed quality declines, accompanied by deterioration of sowing and market characteristics, as noted by M. Kyrychok & S. Remeniuk (2022). Thus, the chemical method of weed control remains a fundamental component of modern soybean cultivation technologies worldwide, particularly under intensive production systems and high competitive pressure from weeds within the agrophytocenosis.

At the same time, the combination of available active substances with favourable soil and climatic conditions creates numerous opportunities for experimental research. A. Dykun *et al*. (2020) reported that the application of a two-component post-emergence herbicide containing bentazone and imazamox significantly reduced weed density in soybean crops under mixed infestation due to its high biological activity. Double application of the herbicide in combination with the adjuvant Metolat, with a two-week interval, achieved effectiveness at the level of 89% reduction of *Setaria glauca* (Poir.) and 65% of *Echinochloa crus-galli* (L.), while control of broadleaf weeds reached 99%, with a 97% reduction in fresh weed biomass. M.I. Kyrychok (2023) also emphasised that when using herbicides with a pronounced soil effect in soybean crops, a single application is advisable. Thus, the application of the herbicide Pari, SL (active substance imazethapyr, 100 g/L) at a rate of 1.0 L/ha resulted in the destruction of 89.0% of weed seedlings, whereas split application (0.3 L/ha followed by 0.4 L/ha after four days) resulted in 78.3% weed control. A similar pattern was observed with the herbicide Fabian, WG (imazethapyr 450 g/kg + chlorimuron-ethyl 150 g/kg), where the full rate provided 83.8% effectiveness, while split application (0.03 kg/ha followed by 0.04 kg/ha after four days) reduced effectiveness to 72.6%. Studies on the effectiveness and phytotoxicity of herbicides in various combinations in soybean crops were also conducted by M. Meseldžija *et al*. (2020) in Serbia. It was found that the most effective treatments were combinations of metribuzin + S-metolachlor + imazamox + oxasulfuron + thifensulfuron-methyl, with overall effectiveness ranging from 96.98% to 97.40%. Acceptable phytotoxicity levels in soybean over two years of study were observed when applying herbicides combining bentazone + imazamox + thifensulfuron-methyl.

New technologies for the simultaneous detection of weeds and targeted herbicide spraying in soybean crops have been investigated by researchers in the United States, including T.H. Avent *et al*. (2024). However, their studies were primarily related to application techniques involving products with the active ingredient dicamba and the post-emergence use of glufosinate, which ultimately resulted in a reduction in herbicide application rates. Based on these findings, they reduced the amount of herbicide applied while maintaining weed control at a level of 93%. The reduction of weed impact on soybean plants was studied by F.C. Cardoso *et al*. (2024) in Pakistan using the active ingredient flumioxazin. The effectiveness of post-emergence herbicides in soybean crops in Thailand was investigated by U.R.R. Pamungkas *et al*. (2025), whose experimental schemes included herbicides containing three active ingredients: fluazifop-P-butyl, fomesafen and clethodim. The effects of herbicides with different active ingredients on weed control efficiency and crop response were examined by M. Younesabadi *et al.* (2024) and S. Hamza *et al.* (2025), who studied the action of thifensulfuron-methyl. In turn, F.C. Cardoso *et al.* (2024) analysed the role of adjuvants in enhancing the effectiveness of herbicide treatments. At the early stages of organogenesis, soybean is characterised by slow growth and development, which results in increased sensitivity to competition from weeds for light, moisture and mineral nutrients. Under such conditions, even short-term deterioration of the phytosanitary status of crops may lead to a significant reduction in photosynthetic activity, limited leaf area formation and yield losses. In agricultural practice, increasing the proportion of soybean in crop rotations may have considerable consequences. Associated weed species – annual grasses and broadleaved weeds – serve both as reservoirs of diseases and pests and as a factor contributing to increased pesticide pressure on the agroecosystem and additional yield losses (Ivashchenko & Ivashchenko, 2019).

This problem can be prevented if an effective herbicide protection scheme is in place, as repeatedly highlighted in the works of A. Dykun *et al.* (2020), M. Kyrychok *et al.* (2022) and F.C. Cardoso *et al.* (2024). Modern herbicides are generally characterised by narrow biological selectivity, which reduces their effectiveness under conditions of a multi-component weed community and necessitates the use of tank mixtures and higher application rates. This, in turn, increases pesticide load on agroecosystems, raises production costs and enhances environmental risks. Contemporary systems of chemical protection of soybean crops are based on the use of herbicides with different modes of action, allowing targeted control of major biological groups of weeds and minimising the risk of resistant biotypes formation. Of particular importance in this context is the combination of products that inhibit different metabolic pathways in weed plants, including photosynthetic processes, amino acid synthesis and lipid biosynthesis in cell membranes (Kyrychok, 2023). The biological effectiveness of different soybean herbicide protection systems is determined by their influence on competitive interactions within the agrophytocoenosis and their selectivity towards specific weed groups. In order to enhance the realisation of herbicidal effects and enable a reduction in application rates without loss of biological and economic efficiency, particular attention was given to the role of the adjuvant or surfactant in two- and three-component systems and their multisite mechanisms of action. The results of the aforementioned studies underline the relevance of selecting appropriate herbicide treatments to optimise weed control and increase soybean productivity under varying seasonal conditions. The aim of this study was to evaluate the biological effectiveness of different soybean crop protection systems and to substantiate the rational combination of herbicides with different mechanisms of action in conjunction with the use of the adjuvant Skaba EC.

MATERIALS AND METHODS

Field experiments to determine the effectiveness of herbicide application and the impact of tank mixtures of herbicides on weed infestation in soybean were conducted at the Separated Subdivision of the National University of Life and Environmental Sciences of Ukraine "Agronomic Research Station" (NULES of Ukraine ARS), located in the village of Pshenychne, Vasylkiv district, Kyiv region, during 2023-2025. The soil of the experimental plots at NULES of Ukraine ARS is classified as typical low-humus chernozem, coarse silty, medium loam, with a humus content of 4.5%, a salt extract pH of 6.8-7.0, a cation exchange capacity of 31.9 mg-eq per 100 g of soil, and a clay particle content of 20-25% according to granulometric composition. The soil type is typical for this zone. The arable layer (0-30 cm) has a granular-dusty structure, while the sub-arable layer has a nutty-granular structure. The groundwater level lies at a depth of 2-4 m. The parent material, carbonate loess, occurs at a depth of 180-210 cm and contains 9-11% calcium carbonates. Chernozem soils are characterised by high natural fertility and a significant content of total and available forms of nutrients. In particular, the 0-20 cm soil layer contains 0.27-0.31% total nitrogen, 0.15-0.25% total phosphorus, and 2.3-2.5% potassium. The content of available phosphorus (according to Machigin) is 3.3-3.4 mg, and available potassium is 9.8-10.3 mg per 100 g of soil. The physicochemical and water-physical properties of the soil of the experimental field are presented in Tables 1 and 2.

Table 1. Physicochemical characteristics of the soil of the experimental field of NULES of Ukraine ARS (2023-2025)

Sampling depth, cm	Humus content, %	Salt extract pH	Carbonate content, %	Cation exchange capacity, mg-eq per 100 g of soil
0-10	4.53	6.87	–	31.9
35-45	4.38	7.30	1.66	32.0
45-55	1.36	7.30	9.20	19.1
130-140	0.86	7.30	10.50	15.0
210-230	–	7.30	9.70	–

Source: compiled by the authors

Table 2. Water-physical properties of typical low-humus chernozem at NULES of Ukraine ARS (2023-2025)

Horizon depth, cm	Bulk density, g/cm^3	Total porosity, %	Maximum water-holding capacity, %	Wilting moisture, % of MWHC	Capillary rupture moisture, %	Field water capacity, %	Total water capacity, %
5-25	1.25	52	13.6	10.8	19.7	28.2	41.6
25-45	1.16	55	13.2	10.7	19.1	27.3	47.4
80-100	1.27	52	12.3	9.8	17.9	25.6	41.0
135-155	1.20	54	–	m	15.0	21.5	45.0
155-185	1.20	56	12.0	9.6	14.6	20.8	48.3
230-250	1.55	42	–	–	15.4	22.1	27.1

Notes: MWHC – maximum water-holding capacity; m – missing value
Source: compiled by the authors

Tables 1 and 2 demonstrate that the upper soil horizons contain the highest levels of humus and are characterised by a neutral pH with high cation exchange capacity, whereas the deeper layers are distinguished by an increased carbonate content and reduced water-physical properties. Total porosity and water-retention capacity decrease with depth, which limits water availability for roots in deeper layers and determines optimal conditions for crop development within the upper horizons. Thus, soil characteristics create favourable conditions for shallow root development and influence the effectiveness of herbicide application and agronomic practices. Weather conditions during the 2023 growing season were characterised by a contrasting combination of factors: an excessively wet April contributed to the accumulation of soil moisture reserves, while extremely dry conditions in May and August limited the early stages of plant growth and the grain-filling process, respectively. Among the years studied, 2024 was the most stressful during the generative development phases due to an abnormally dry and hot July (10 mm of precipitation; average temperature 23.5°C), which directly explains the potential reduction in the realisation of yield structure components. In 2025, weather conditions were characterised by relative stability following a "warm + precipitation deficit" pattern from May onwards, particularly in July-August, resulting in water availability consistently acting as a limiting factor throughout key ontogenetic stages (leaf area formation → pod setting → grain filling). Field experiments to determine the effectiveness of herbicide active ingredients on weed infestation, their application efficiency, and soybean yield were conducted according to the methodologies of V. Moysyeyenko & V. Yeshchenko (1994), S.O. Trybel *et al*. (2001), and M.I. Kyrychok (2023).

The following herbicides were used in the experimental studies:

1. Basagran, SL (active ingredient: bentazone) belongs to photosystem II inhibitors (Herbicide Resistance Action Committee (HRAC) group C3). Its mode of action is associated with blocking electron transport in the light phase of photosynthesis,

leading to rapid suppression of photochemical processes in susceptible weeds. The product exhibits predominantly contact action and is most effective against annual broadleaved weeds at the 2-4 leaf stage. Limited systemic activity results in reduced effectiveness against perennial species, which is confirmed by the obtained data on weed density and dry biomass. Application rate: 1.5-2.0 L/ha, single application.

2. Harmony 75 WG (thifensulfuron-methyl) belongs to acetolactate synthase (ALS) inhibitors and is classified in HRAC group B. Its mechanism of action involves blocking the synthesis of essential amino acids, resulting in the cessation of weed growth processes. The product is characterised by high selectivity towards soybean and effectiveness against a wide range of broadleaved weeds, including some perennial species, when applied at the 2-6 leaf stage. Application rate: 0.025-0.035 kg/ha, single application.

3. Pulsar, SL (imazethapyr) also belongs to ALS inhibitors but differs in its systemic activity and ability to be absorbed through both leaf surfaces and the root system. This determines its effectiveness not only against broadleaved weeds but also against certain grass species, as well as its prolonged control of emerging weeds during the early stages of crop development. Maximum effectiveness is observed from the emergence stage to the 4-leaf stage of weeds, which is consistent with the experimental results obtained. Application rate: 0.5-1.0 L/ha, single application.

4. Select, EC (clethodim) is a representative of acetyl-CoA carboxylase (ACCase) inhibitors, HRAC group A. Its mechanism of action is associated with disruption of lipid synthesis in cell membranes, leading to the death of grass weeds. The product is effective against both annual and perennial grass species at the 2-6 leaf stage and is an essential component of soybean protection systems against grass weed infestations. Application rate: 0.14-0.28 L/ha, single application.

5. The surfactant Skaba EC does not possess its own herbicidal activity but plays an important role in enhancing the effectiveness of herbicides. Its use improves leaf surface wetting, increases the penetration of active ingredients into weed tissues, and enhances their translocation. This creates conditions for reducing herbicide application rates without loss of biological effectiveness, which is clearly reflected in the indicators of weed dry biomass, competitive pressure index, and herbicide efficiency index.

The analysis included annual grasses and broadleaf weeds, as well as perennial species, in particular common pigweed (*Amaranthus retroflexus* L.), common thistle (*Cirsium arvense* (L.) Scop.), lamb's quarters (*Chenopodium album* L.), barnyard grass (*Echinochloa crus-galli* L.), common fumitory (*Fumaria officinalis* L.), cleavers (*Galium aparine* L.), common bindweed (*Polygonum convolvulus* L.), common knotweed (*Polygonum persicaria* L.), grey foxtail (*Setaria glauca* L.), field mustard (*Sinapis arvensis* L.), black nightshade (*Solanum nigrum* L.), yellow sow thistle (*Sonchus arvensis* L.), field pennycress (*Thlaspi arvense* L.) and other species. The total area of the plots in the herbicide trials was 32 m^2, and that of the survey plots was 25 m^2, with three replicates and a randomised arrangement of treatments. The weed species composition was determined by transect surveys and weed identification within the survey plots (divided into annual grasses, annual dicots and perennial species). Weed abundance (plants/m^2) was determined using the frame method on permanent survey plots:

- the survey area was defined by a frame of fixed size (typically 0.25 m^2 or 0.5 m^2);
- surveys were conducted in several replicates on each plot;
- surveys were conducted prior to the application of herbicides (background) and at specified intervals after treatment (28 days), as well as before harvest (according to the experimental design).

The dry weight of weeds (g/m^2) was determined by sampling weed biomass from the survey area, followed by drying in an oven to constant weight (60-65°C) and conversion to 1 m^2. The reduction in weed abundance/dry weight, %, was calculated relative to the control:

$$E\ (\%) = \frac{C-T}{C} \times 100, \qquad (1)$$

where C – control group score, T – test group score.

The Weed Competitive Pressure Index (WCPI) was defined as an integrated measure of the competitive impact of the weed component on the soybean agro-phytocenosis (based on the relative values of weed abundance/dry weight compared to the control or the minimally weeded treatment –

in accordance with the algorithm adopted in this study). The Herbicide Efficacy Index (HEI) was calculated as a generalised indicator of the protection system's effectiveness, reflecting the relationship between the level of weed suppression and the crop response (yield/productivity), which allows for the comparison of full, reduced and optimised herbicide rates and the role of surfactants.

The methodology for calculating the herbicide efficacy index (HEI) was based on determining the reduction in dry weed mass compared to the control without herbicide application, where the dry weed mass was 120 g/m²:

$$HEI = \frac{\text{Reduction in dry weed mass,\%}}{\text{Herbicide rate index}}, \quad (2)$$

where the rate index is: 100% rate without surfactant → 1.00; 100% rate + surfactant → 1.00; 75% rate + surfactant → 0.75; optimised rate + surfactant (-33…40%) → 0.67.

The higher the HEI value, the more efficiently a unit of herbicide load is utilised. Experimental data were processed using methods of variation statistics: mean values and variability indices were calculated; the significance of differences between treatments was assessed (analysis of variance, significance criteria at $p \leqslant 0.05$); and relationships between variables were determined using correlation analysis (Pearson's coefficient). During the study, only herbicides included in the State Register of Pesticides and Agrochemicals Allowed for Use in Ukraine were used, in compliance with the standards set by the Food and Agriculture Organization of the United Nations (n.d.).

RESULTS AND DISCUSSION

Table 3 presents the characteristics of the studied herbicides in terms of active substance, classification according to the Herbicide Resistance Action Committee/Weed Science Society of America (HRAC/WSSA), mechanism of action, spectrum of controlled weeds, and the stage of maximum application effectiveness. This approach allows for substantiating the selection of product combinations in protection systems and provides a more detailed explanation of the experimental results obtained.

Table 3. Mechanism of action and biological target of the studied active substances

Content of active substance in the formulation	Product	HRAC/WSSA group	Mechanism of action	Main weed group	Stage of maximum effectiveness
Bentazone, 480 g/L	Basagran, SL	C3 (6)	Photosystem II inhibitor (blocks electron transport)	Annual broadleaf weeds	2-4 leaf stage
Thifensulfuron-methyl, 750 g/kg	Harmony, WG	B (2)	ALS inhibitor (disrupts amino acid synthesis)	Broadleaf weeds, including some perennials	2-6 leaf stage
Imazethapyr, 100 g/L	Pulsar, SL	B (2)	ALS inhibitor (systemic action)	Broadleaf weeds + some grasses	emergence – 4 leaf stage
Clethodim, 120 g/L	Select, EC	A (1)	ACCase inhibitor (disrupts lipid synthesis)	Annual and perennial grasses	2-6 leaf stage
–	Adjuvant Skaba EC	–	Enhances wetting, penetration, and translocation	–	applied with herbicides

Notes: ALS – acetolactate synthase; HRAC – Herbicide Resistance Action Committee; WSSA – Weed Science Society of America
Source: compiled by the authors

Herbicides with the active ingredient bentazon belong to photosystem II inhibitors (HRAC group C3). Their action is associated with blocking electron transport in the light phase of photosynthesis, which leads to rapid suppression of photochemical processes in susceptible weeds. These products act mainly by contact and are most effective against annual broadleaf weeds at the 2-4 leaf stage. Limited systemic activity results in reduced effectiveness against perennial species, which is confirmed by the obtained indicators of weed density and dry biomass. Herbicides containing the active ingredient thifensulfuron-methyl belong to ALS inhibitors and are classified in HRAC group B. Their mode of action involves blocking the synthesis of essential amino acids, leading to the cessation of growth processes in weeds. These products are characterised by high selectivity towards soybean and effectiveness against a broad spectrum of broadleaf weeds, including some perennial species, when applied at the 2-6 leaf stage. Products containing the active ingredient imazethapyr also belong to ALS inhibitors; however, they differ in their systemic action and ability to be absorbed both through the leaf surface and the root system. This determines their effectiveness not only against broadleaf weeds but also against some grass weeds, as well as prolonged control of weed emergence in the early stages of crop development. Maximum effectiveness of these products is observed from emergence to the 4-leaf stage of weeds, which is consistent with the experimental data obtained. Herbicides containing the active ingredient clethodim are representatives of acetyl-CoA carboxylase (ACCase) inhibitors, HRAC group A. Their mode of action is associated with disruption of lipid synthesis in cell membranes, leading to the death of grass weeds.

These products are effective against annual and perennial grass species at the 2-6 leaf stage and are an essential component of soybean protection systems against grass weed vegetation. The surfactant Skaba EC has no inherent herbicidal activity; however, it plays an important role in enhancing the effectiveness of the products. Its use improves wetting of the leaf surface, increases the penetration of active substances into weed tissues and enhances their translocation. This creates conditions for reducing herbicide application rates without loss of biological effectiveness, which is clearly reflected in the indicators of weed dry biomass, the competitive pressure index and the herbicide efficiency index. The use of a surfactant in multi-component systems improved adhesion of the working solution, accelerated penetration of active substances into weed tissues and enhanced their translocation. This created conditions for reducing herbicide rates without loss of biological effectiveness, as confirmed by high HEI values and reduced WCPI in the respective experimental variants. Thus, Table 3 serves as a methodological basis for further analysis of the research results and allows explanation of the advantages of multisite soybean protection systems, in which photosystem II, ALS and ACCase inhibitors are combined to ensure maximum biological effect and stable weed control. Table 4 summarises the results of evaluating the effectiveness of the studied soybean herbicide protection systems in terms of combining mechanisms of action of active substances at specific product concentrations, their biological impact on the weed component of the agrophytocenosis and the practical consequences for crop productivity formation.

Table 4. Biological justification of the effectiveness of protection systems considering the mechanism of action of active substances

Protection system with products containing active substances	Combination of mechanisms of action	Biological effect	Practical outcome
Bentazone, 480 g/L + clethodim, 120 g/L	PSII + ACCase	Control of broadleaf weeds + grasses	Limited effectiveness against ALS-sensitive species
Thifensulfuron-methyl, 750 g/kg + clethodim, 120 g/L	ALS + ACCase	Strong control of broadleaf weeds and grasses	High selectivity, but risk of ALS resistance
Imazethapyr, 100 g/L + clethodim, 120 g/L	ALS (systemic) + ACCase	Broad spectrum of action, soil and foliar activity	Stable weed control in crops
Bentazone, 480 g/L + thifensulfuron-methyl, 750 g/kg + clethodim, 120 g/L	PSII + ALS + ACCase	Multisite action	Maximum effectiveness and resistance minimisation
All treatments + adjuvant	Enhanced penetration	Faster action and reduced crop stress	Improved photosynthetic potential

Source: compiled by the authors

Crop protection system based on the combination of products with active ingredients (bentazon, 480 g/L + clethodim, 120 g/L) – a photosystem II (PSII) inhibitor and an ACCase inhibitor – provided effective control of annual broadleaf and grass weeds at early stages of their development. The biological effect of this combination was realised through disruption of photosynthetic processes in broadleaf species and inhibition of lipid synthesis in grass weeds. At the same time, the limited systemic action resulted in reduced effectiveness against perennial weeds, which was reflected in relatively higher values of residual dry biomass and the competitive pressure index. The combination of products with active ingredients (thifensulfuron-methyl, 750 g/kg + clethodim, 120 g/L), containing an ALS inhibitor and an ACCase inhibitor, was characterised by high biological activity against broadleaf weeds due to the suppression of essential amino acid synthesis, while also ensuring reliable control of grass species. However, the highly specific mode of action of the ALS inhibitor created a potential risk of resistance development under prolonged use of this system without rotation of active substances, which justifies its combination with products from other classes. The application of a system based on a systemic ALS inhibitor in combination with an ACCase inhibitor (imazethapyr, 100 g/L + clethodim, 120 g/L) provided the most balanced weed control due to the combination of soil and foliar activity. Such a system effectively suppressed both annual and certain perennial weed species, resulting in a stable reduction in their density and dry biomass throughout the growing season. The biological action of this combination was reflected in reduced competitive pressure on the crop and the creation of favourable conditions for soybean growth and development. The highest biological and economic efficiency was achieved with three-component protection systems combining PSII, ALS and ACCase inhibitors (bentazon, 480 g/L + thifensulfuron-methyl, 750 g/kg + clethodim, 120 g/L). The multisite mode of action of this combination of active substances allowed simultaneous impact on different metabolic pathways in weed plants, ensuring maximum reduction in both the density and dry biomass of annual and perennial weeds. These systems were characterised by the lowest values of the weed competitive pressure index and the highest values of the herbicide efficiency index, which is consistent with the results of the correlation analysis. The results of weed density assessment indicate a significant differentiation in the effectiveness of soybean protection systems depending on the combination of herbicide active substances, their mechanisms of action and the use of a surfactant. On average over the years of study, weed density reduction ranged from 58% to 96%, indicating substantial differences in the biological effectiveness of the tested variants. Under the use of a two-component system with active ingredients bentazon, 480 g/L + clethodim, 120 g/L, the reduction in annual broadleaf weeds averaged 71.3%, annual grasses – 79.0%, whereas effectiveness against perennial broadleaf weeds was significantly lower at 59.0% (Table 5). This indicates the limited action of the contact photosystem II inhibitor and insufficient systemic activity against perennial species.

Table 5. Reduction in weed numbers in treatments without surfactant (100% rate), %

Weed species	Bentazone, 480 g/L + + clethodim, 120 g/L	Thifensulfuron-methyl, 750 g/kg + + clethodim, 120 g/L	Imazethapyr, 100 g/L + + clethodim, 120 g/L	Bentazone, 480 g/L + + thifensulfuron-methyl, 750 g/kg + + clethodim, 120 g/L
Amaranthus retroflexus L.	74	88	80	91
Cirsium arvense (L.) Scop.	58	70	66	76
Chenopodium album L.	72	85	82	90
Echinochloa crus-galli L.	78	65	84	88
Fumaria officinalis L.	69	84	77	87
Galium aparine L.	65	80	75	85
Polygonum convolvulus L.	70	83	78	88
Polygonum persicaria L.	71	82	79	89
Setaria glauca L.	80	68	86	90
Sinapis arvensis L.	73	87	80	91
Solanum nigrum L.	72	85	79	89
Sonchus arvensis L.	60	72	68	78
Thlaspi arvense L.	76	86	81	92
Other species	70	80	75	85

Source: compiled by the authors

Replacing a product containing the active ingredient bentazone, 480 g/L, with a product containing the ALS inhibitor active ingredient thifensulfuron-methyl, 750 g/kg (the thifensulfuron-methyl, 750 g/kg + clethodim, 120 g/L) ensured improved control of broadleaf weeds: the reduction in the abundance of annual broadleaf species increased to 84.4%, and that of perennial species to 71.0%, which is 10-12% higher than in the variant using products containing the active ingredient bentazone, 480 g/L. At the same time, control of grass weeds was less consistent at 66.5% (65-68% by species), which is explained by the lack of soil activity of the ALS inhibitor against these species. The combination of formulations containing the active ingredients imazethapyr, 100 g/L + clethodim, 120 g/L was characterised by a more balanced effect. The reduction in the abundance of annual broadleaf weeds reached 79.0%, perennial broadleaf weeds – 67.0%, and annual grass weeds – 85.0%. Compared with the formulation containing the active ingredients thifensulfuron-methyl, 750 g/kg + clethodim, 120 g/L, efficacy against perennial broadleaf weeds was 6% higher, due to the systemic action of imazethapyr. The highest efficacy among the variants without surfactants was provided by the three-component system of bentazone, 480 g/L + thifensulfuron-methyl, 750 g/kg + clethodim, 120 g/L, where the reduction in the abundance of annual broadleaf and grass weeds reached 89.1% and 89.0%, respectively, and that of perennial broadleaf weeds – 77.0%. Thus, compared with two-component regimens, the efficacy of perennial weed control increased by 14-18%, confirming the advantage of a multi-site mode of action. The addition of an adjuvant (surfactant) significantly enhanced the biological efficacy of all control systems. Thus, in the bentazone, 480 g/L + clethodim, 120 g/L + surfactant treatment, the reduction in the abundance of annual broadleaf weeds increased from 71.3% to 80%, and that of perennial weeds from 59.0% to 69.0%, i.e. by 10%. A similar trend was observed for grass weeds, where efficacy increased by 8% (Table 6).

Table 6. Weed density in treatments with 100% rate + adjuvant Skaba EC (0.2 L/ha), %

Weed species	Bentazone, 480 g/L + + clethodim, 120 g/L	Thifensulfuron-methyl, 750 g/kg + + clethodim, 120 g/L	Imazethapyr, 100 g/L + + clethodim, 120 g/L	Bentazone, 480 g/L + + thifensulfuron-methyl, 750 g/kg + + clethodim, 120 g/L
Amaranthus retroflexus L.	82	94	87	97
Cirsium arvense (L.) Scop.	68	80	76	86
Chenopodium album L.	80	92	89	96
Echinochloa crus-galli L.	86	74	91	95
Galium aparine L.	74	88	82	92
Fumaria officinalis L.	78	91	84	94
Polygonum convolvulus L.	79	90	85	94
Polygonum persicaria L.	80	89	86	95
Setaria glauca L.	88	76	93	96
Sinapis arvensis L.	82	94	87	97
Solanum nigrum L.	81	92	86	95
Sonchus arvensis L.	70	82	78	88
Thlaspi arvense L.	84	93	88	97
Other species	78	88	83	92

Source: compiled by the authors

In the system thifensulfuron-methyl, 750 g/kg + clethodim, 120 g/L + surfactant, the reduction in annual broadleaf weed density reached 91.4%, and perennial species – 81.0%, which is 7.0% and 10.0% higher than without the surfactant. Control of grass weeds also increased; however, it remained somewhat lower compared with systems containing the active ingredient imazethapyr. The system imazethapyr, 100 g/L + clethodim, 120 g/L + surfactant provided a consistently high level of control of all weed groups: 86-92% for annuals and 77% for perennial species. Compared with the corresponding variant without a surfactant, effectiveness increased on average by 7-9%. The highest values were recorded in the three-component system bentazon, 480 g/L + thifensulfuron-methyl, 750 g/kg + clethodim, 120 g/L + surfactant, where the reduction in annual broadleaf weeds reached 95.1%, and perennial weeds – 87.0%. This is 6-10% higher than in the three-component variant without a surfactant and 15-20% higher than in two-component systems. Data in Table 7 indicate that the use of a reduced (75%) rate of herbicides in combination with the adjuvant Skaba EC (0.3 L/ha) provided a high level of weed control in soybean crops, which in most cases was not inferior to, and in some cases even approached, the efficacy of the full rate of the products without a surfactant. In the variant bentazon, 480 g/L + clethodim, 120 g/L (75% rate + surfactant), the reduction in annual broadleaf weeds averaged 78.0%, annual grasses – 73.0%, while effectiveness against perennial broadleaf weeds was lower at 67.0%. Compared with the corresponding variant without a surfactant, control effectiveness increased by 6-8%, indicating improved realisation of the contact action of bentazon due to enhanced penetration of the product into weed tissues. In the system thifensulfuron-methyl, 750 g/kg + clethodim, 120 g/L (75% rate + surfactant), the level of reduction in broadleaf weeds was significantly higher. Thus, annual broadleaf species were suppressed by 89.4%, and perennial species by 79.0%. At the same time, control of grass weeds remained somewhat lower at 73% for annual species, reflecting the specificity of the ALS inhibitor's mode of action.

Table 7. Weed abundance under treatments with 75% herbicide rate + the adjuvant Skaba EC (0.3 L/ha), %

Weed species	Bentazone, 480 g/L + clethodim, 120 g/L	Thifensulfuron-methyl, 750 g/kg + clethodim, 120 g/L	Imazethapyr, 100 g/L + clethodim, 120 g/L	Bentazone, 480 g/L+ + thifensulfuron-methyl, 750 g/kg + + clethodim, 120 g/L
Amaranthus retroflexus L.	80	92	85	96
Cirsium arvense (L.) Scop.	66	78	74	84
Chenopodium album L.	78	90	87	95
Echinochloa crus-galli L.	84	72	90	94
Galium aparine L.	72	86	80	90
Fumaria officinalis L.	76	89	82	93
Polygonum convolvulus L.	77	88	83	92
Polygonum persicaria L.	78	87	84	93
Setaria glauca L.	85	74	92	95
Sinapis arvensis L.	80	92	85	96
Solanum nigrum L.	79	90	84	94
Sonchus arvensis L.	68	80	76	86
Thlaspi arvense L.	82	91	86	96
Other species	76	86	81	90

Source: compiled by the authors

The application of the imazethapyr, 100 g/L + clethodim, 120 g/L (75% rate + surfactant) treatment provided the most balanced weed control among the two-component treatments. The reduction in the number of annual broadleaf weeds reached 84%, perennial broadleaf weeds – 75%, and annual grasses – 91%. Compared with the thifensulfuron-methyl system, 750 g/kg + clethodim, 120 g/L, the efficacy of control of perennial broadleaf weeds was 5% higher, and for perennial grasses by 8%, which is due to the systemic action of imazethapyr and the partial soil activity of the formulation. The highest reductions in weed populations were recorded in a three-component formulation containing the active ingredients bentazone, 480 g/L + thifensulfuron-methyl, 750 g/kg + clethodim, 120 g/L (75% rate + surfactant). In this variant, the abundance of annual dicotyledonous weeds decreased by an average of 93.9%, perennial broadleaf weeds by 85%, and annual grasses by 94.5%. Compared with two-component systems, the efficacy of perennial weed control was 16-18% higher, indicating the decisive role of the multi-site mode of action. The results presented in Table 8 indicate that the use of optimised (reduced by 33-40%) herbicide rates in combination with an increased rate of the surfactant Skaba EC (0.4 L/ha) ensured a consistently high level of weed control, comparable to that of full-rate variants, and in some cases practically identical. The overall level of weed reduction under this treatment ranged from 67% to 97%, depending on the composition of the protection system and the biological group of weeds.

Table 8. Weed abundance under treatments with optimised herbicide rates + the adjuvant Skaba EC (0.4 L/ha), %

Weed species	Bentazone, 480 g/L + + clethodim, 120 g/L	Thifensulfuron-methyl, 750 g/kg + + clethodim, 120 g/L	Imazethapyr, 100 g/L + clethodim, 120 g/L	Bentazone, 480 g/L + + thifensulfuron-methyl, 750 g/kg + + clethodim, 120 g/L
Amaranthus retroflexus L.	81	93	86	97
Cirsium arvense (L.) Scop.	67	79	75	85
Chenopodium album L.	79	91	88	96
Echinochloa crus-galli L.	85	73	91	95
Fumaria officinalis L.	77	90	83	94
Galium aparine L.	73	87	81	91
Polygonum convolvulus L.	78	89	84	93
Polygonum persicaria L.	79	88	85	94
Setaria glauca L.	86	75	93	96
Sinapis arvensis L.	81	93	86	97
Solanum nigrum L.	80	91	85	95
Sonchus arvensis L.	69	81	77	87
Thlaspi arvense L.	83	92	87	97
Other species	77	87	82	91

Source: compiled by the authors

In the variant bentazon, 480 g/L + clethodim, 120 g/L (optimised rate + surfactant), the reduction in annual broadleaf weeds averaged 79.0%, perennial broadleaf weeds – 68.0%, and annual grasses – 85.5%. Compared with the corresponding 75% rate variant, the effectiveness of control was practically the same, with differences not exceeding 1-2%, indicating sufficient realisation of herbicidal action even with further reduction in the rate of active substances. In the system thifensulfuron-methyl, 750 g/kg + clethodim, 120 g/L (optimised rate + surfactant), control of broadleaf weeds remained high: the density of annual broadleaf weeds decreased by 90.4% and perennial species by 74.0%, which is 10-12% higher than in the variant with bentazon. Control of grass weeds was somewhat lower at 80.0% for annual species, which is consistent with the mechanism of action of the ALS inhibitor and the absence of soil activity against grass weeds. The use of the combination of active ingredients imazethapyr, 100 g/L + clethodim, 120 g/L (optimised rate + surfactant) provided one of the best balances between effectiveness and reduced chemical load. This is particularly relevant in soybean cultivation and reduces the risk of herbicide injury to plants. The reduction in annual broadleaf weeds was 85.0%, perennial broadleaf weeds – 76.0%, and annual grasses – 92.0%. Compared with the combination thifensulfuron-methyl, 750 g/kg + clethodim, 120 g/L, the effectiveness of control of perennial broadleaf weeds was higher by 5% and perennial grasses by 8%, which is due to the systemic action of imazethapyr and its prolonged effect. The maximum reductions in weed density under the optimised rate were recorded in the three-component system bentazon, 480 g/L + thifensulfuron-methyl, 750 g/kg + clethodim, 120 g/L (optimised rate + surfactant). In this variant, the density of annual broadleaf weeds decreased on average by 94.9%, perennial broadleaf weeds by 86.0%, and annual grasses by 95.5%. Compared with two-component systems, the effectiveness of perennial weed control was higher by 16-18%, while compared with the corresponding 75% rate variants, the differences did not exceed 1-2%, confirming the high stability of the multisite mode of action.

Numerous scientific studies demonstrate the high biological efficacy of herbicide formulations containing a combination of the active ingredients bentazone, thifensulfuron-methyl, clethodim and imazamox in soyabean crops. They provide reliable weed control, contribute to increased crop productivity and, when used in accordance with application guidelines, do not exhibit phytotoxic effects on soybean plants. According to S.Z. Knezevic *et al*. (2019), the most effective and, at the same time, critical period for applying herbicides against dicotyledonous weeds is the 1-3 true trifoliate leaf stage of soybean, whereas treatments against grass weeds can be carried out regardless of the crop's developmental stage, but, as a rule, before the onset of flowering. The present study confirmed the findings of P. Grassini *et al*. (2015) that, in order to reduce the costs of chemical weed control and minimise the environmental impact of herbicides, post-emergence herbicides in soybean crops should be applied in combination with adjuvants, which enhances the biological efficacy of the active ingredients and allows for the optimisation of their application rates. The first post-emergence herbicide introduced for use against dicotyledonous weeds was Bazagran, 48% w/w (active ingredient – bentazone). The specific effects of the product in soyabean crops were observed by K.S. Gill & M.A. Arshad (1995) and P.H. Graham & C.P. Vance (2003). In soybean crops, the herbicide successfully controlled common chickweed, spreading bittercress, buckwheat, field mustard, wild radish, common ragwort, field thistle, black nightshade, common ragwort and others. When applied at the 1-3 true leaf stage at a rate of 2-3 L/ha, weed infestation in soyabean crops was reduced by 76-82%, and weed biomass was reduced by 87-97%. Evidently, the high efficacy of the herbicide was observed in the absence of grass weeds that exhibit resistance to Basagran. The data obtained confirmed the results of a study by V.M. Zherebko & O.V. Dykun (2022), which showed that the application of the herbicide Pas, 10% w/v, to emerging crops at rates of 0.05-0.1 L/ha of active ingredient reduced weed biomass by 74-91%, whilst yield increased by 2.8-3.0 times. An important advantage of this herbicide is its broader spectrum of action on weed species. O. Hurmanchuk *et al*. (2021) found that in some years the herbicide exhibits negative after-effects, causing stunting, plant death and thinning in the crops of subsequent rotation. Although the use of herbicides does not usually cause direct yield losses and is effective against weeds, any stressful effect may adversely affect the growth and development of soya plants. Stress factors that alter the physiological state of the crop can disrupt seed formation and development processes and reduce seed viability. Applying herbicides at suboptimal times or failing to follow application guidelines may result in chemical stress and plant burns, which in some cases leads to a significant reduction in yield or even crop failure, as noted by M. Knežević *et al.* (2008) and Y. Kawasaki *et al.* (2016). The aforementioned studies have shown that the application of post-emergence herbicides in combination with adjuvants ensures a high level of weed control, optimises the application rates of active ingredients and increases soybean yield; however, the efficacy and safety of the product depend to a large extent on adherence to the recommended application stages and guidelines.

CONCLUSIONS

Comparative analysis showed that the effectiveness of soybean weed control systems was determined not so much by the absolute rate of herbicides as by the rational combination of modes of action of active substances and the use of the adjuvant (surfactant) Skaba EC. In all studied treatments, a clear hierarchy between two- and three-component systems was observed; however, differences between application rates were less pronounced than expected. When applying 100% herbicide rates with the adjuvant in two-component systems, the average reduction in weed numbers was 80-91% for annual broadleaf weeds, 72-92% for annual grasses, and 69-81% for perennial broadleaf weeds. In the three-component system (bentazone + thifensulfuron-methyl + clethodim + adjuvant), the respective values reached 95.1%, 94.0%, and 87.0%. Reducing herbicide rates to 75% with an increased adjuvant rate (0.3 L/ha) had little effect on weed control efficiency, providing 78-89%, 73-91%, and 67-79% for two-component systems and 93.9%, 94.5%, and 85% for the three-component system, respectively. Optimised reduced herbicide rates (33-40%) combined with the maximum adjuvant rate (0.4 L/ha) also ensured consistently high control: 79-90%, 74-92%, and 68-80% in two-component systems and 94.9%, 95.5%, and 86% in the three-component system. The difference compared with the 100% rate + adjuvant did not exceed 1-3%, remaining within the limits of experimental error. The level of weed infestation largely depended on the composition of the herbicide protection system and the combination of products with different modes of action. Two-component systems without an adjuvant provided moderate weed reduction (58-88%), whereas three-component multisite combinations increased effectiveness to 85-97% for annual species and 76-88% for perennial species; with the adjuvant, these values increased to 90-97% and 84-88%, respectively. The highest biological efficacy was achieved through the combination of photosystem II, ALS, and ACCase inhibitors. The three-component system of bentazone + thifensulfuron-methyl + clethodim showed the lowest values of weed dry mass (42-50 g/m^2 with adjuvant), which was 16.7-41.7% lower than in two-component systems. The use of the adjuvant additionally reduced weed dry mass by 26-30 g/m^2 and increased control effectiveness by 6.8-10% compared with treatments without the adjuvant. Thus, increasing the adjuvant rate compensated for the reduction in herbicide rates, ensuring full realisation of the mechanisms of action of active substances and reducing the chemical load on the agroecosystem. Future research should focus on the systematic study of the effectiveness of integrated use of reduced herbicide rates in combination with various surfactants under different soil and climatic conditions, with the aim of optimising weed control and minimising chemical load on the agroecosystem.

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Ефективність застосування препаратів з гербіцидними діючими речовинами на посівах сої

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Анотація. Метою дослідження було визначити рівень біологічної ефективності систем захисту сої та раціонально поєднати механізм дії препаратів з гербіцидними властивостями та застосуванням ад'юванта Скаба КЕ. Визначено ефективність діючих речовин гербіцидів на забур'яненість і врожайність посівів сої. Визначали індекс конкурентного тиску бур'янів на посіви. За всіх досліджуваних фонів спостерігалася чітка ієрархія ефективності між дво- та трикомпонентними системами. Відмінності між нормами внесення препаратів були значно менш вираженими, ніж очікувалося. За використання 100 % норми гербіцидів у поєднанні з ад'ювантом Скаба КЕ (0,2 л/га) у двокомпонентних системах середні значення зниження чисельності бур'янів становили: для однорічних дводольних – 80,0-91,4 %, для однорічних злакових – 72,0-92,0 %, для багаторічних дводольних – 69,0-81,0 %. У трикомпонентній системі поєднання препаратів ці показники становили відповідно 95,1 %, 94,0 % і 87,0 %. Перехід до 75 % норми гербіцидів у поєднанні з підвищеною нормою ад'юванту (0,3 л/га) не призводив до істотного зниження ефективності контролю бур'янів. У трикомпонентній системі значення досягали 93,9 %, 94,5 % і 85,0 % відповідно. Зменшення норми гербіцидів на 25 % за умови використання ад'юванту практично не впливало на кінцевий біологічний ефект, але водночас суттєво знижувало хімічне навантаження на агроекосистему. Поєднання інгібіторів забезпечувало найвищу біологічну ефективність контролю бур'янів. Рівень забур'яненості посівів сої у роки досліджень істотно залежав від складу системи гербіцидного захисту та поєднання препаратів із різними механізмами впливу на рослину діючих речовин. Двокомпонентні системи без використання ад'юванту забезпечували помірне зниження чисельності бур'янів (58-88 %), тоді як трикомпонентні мультисайтові комбінації підвищували ефективність контролю до 85-97 % для однорічних і 76-88 % для багаторічних видів (а на фонах із ад'ювантом – до 90-97 % та 84-88 % відповідно). За застосування оптимізованих (знижених на 3-40 %) норм гербіцидів у поєднанні з максимальною нормою ад'юванту (0,4 л/га) ефективність контролю бур'янів залишалася стабільно високою

Ключові слова: ад'ювант; агротехнології; бур'яни; індекс конкурентного тиску; індекс ефективності