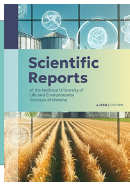
Received 30.01.2026 Revised 27.04.2026 Accepted 24.06.2026 Published: 14.08.2026

Vol. 22, No. 4
2026



Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en e-ISSN 2223-1609

UDC 632.51:632.954 DOI: 10.31548/dopovidi/4.2026.156

Integrated strategies for controlling segetal flora, taking into account multiple herbicide resistance in cereal agrocenoses

Olena Koberniuk*
PhD in Agricultural Sciences, Associate Professor
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
https://orcid.org/0000-0002-1380-7976

Olesia Horodyska
PhD in Agricultural Sciences, Associate Professor
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
https://orcid.org/0000-0001-8747-6957

Valeriy Tarasyuk
PhD in Agricultural Sciences, Associate Professor
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
https://orcid.org/0000-0002-4207-1013

Abstract. The study's goal was to ascertain the impact of a combination of herbicidal and agronomic practices on the structure of the segetal flora, the distribution of resistant biotypes and the productivity of the cereal agrocenosis. The study employed field, weighing, morphometric, soil analysis and computational methods, with statistical analysis of the results. It was found that a comparison of the five treatments revealed varying degrees of restructuring of the weed community – ranging from the untreated control to the standard treatment, the active ingredient rotation, the herbicide + agronomic practices treatment as well as the entire solution. The overall population of species dropped from 15 in the control to 11 in the standard treatment, 9 in the active ingredient rotation treatment, 8 in the herbicide + agronomic techniques treatment, and 6 in the integrated system. The number of dominant species fell from 5 to 2, whilst weed density during the tillering stage decreased from 126.4 to 42.6 plants/m^2. The Shannon index decreased from 2.31 to 1.36, reflecting a change in the diversity of the floristic structure. In the multiple herbicide resistance block, the standard treatment only partially suppressed resistant biotypes; active ingredient rotation enhanced this effect, whilst

Suggested Citation:
Koberniuk, O., Horodyska, O., & Tarasyuk, V. (2026). Integrated strategies for controlling segetal flora, taking into account multiple herbicide resistance in cereal agrocenoses. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 22(4), 156-177. doi: 10.31548/dopovidi/4.2026.156.

**Corresponding author (olena.koberniuk@outlook.com)*

the herbicide + agronomic practices treatment and the integrated system reduced their contribution to the weed biomass structure. The proportion of biotypes resistant to acetolactate synthase inhibitors decreased from 60.8% to 36.1%, whilst the post-treatment survival rate of resistant plants fell from 100% to 11.9%. The reproductive component was characterised by a reduction in seed productivity from 15.8 to 1.9 thousand seeds/m^2 and a decrease in the potential number of seedlings emerging from the soil seed bank from 84.6 to 24.1 per m^2. Against this backdrop, the crop's yield response improved from the standard treatment to the active ingredient rotation treatment, the herbicide + agronomic practices treatment and the integrated system: biological grain yield increased from 4.08 to 6.14 t/ha, whilst yield potential realisation rose from 58.3% to 87.7%. The practical significance of the research resides in the application of its results by agronomists, farms and grain producers in cereal cultivation techniques and weed control schemes

Keywords: post-treatment survival; weed community; proportion of biotypes; coenotic pressure; biological grain yield

Introduction

The relevance of this study stems from the spread of segetal flora in cereal agrocenoses and the increasing proportion of biotypes resistant to herbicides with different modes of action. This research is prompted by the declining effectiveness of standard chemical control programmes, increasing soil moisture deficits, uneven rainfall patterns, and the need to maintain crop productivity without excessive herbicide application. An assessment of integrated strategies makes it possible to determine how the weed component, multiple herbicide resistance and cereal crop productivity are changing under the current technological and climatic pressures on crops in Ukraine as a whole. The focus of this study stems from the fact that cereal cropping systems are characterised by the repeated use of the same or similar herbicides, which maintains selection pressure and contributes to the accumulation of multiple herbicide-resistant biotypes. Under such conditions, weeds with varying sensitivity to active ingredients persist in crops, the floristic structure of the weed community changes, seed regeneration of the segetal flora is maintained, and the effectiveness of individual control measures is reduced. This complicates weed management and the stable establishment of grain crop yields under field conditions across various plant protection systems in agricultural production.

In their evaluation of herbicide combinations, V. Zadorozhnyi *et al.* (2025) focused on the efficacy of combined herbicide application in maize for grain crops. The combination of active ingredients with different modes of action provided marked suppression of both dicotyledonous and grassy weeds. Using a resistant biotype as test material, V.V. Schwartau *et al.* (2023) investigated the characteristics of *Echinochloa crus-galli* resistance to acetolactate synthase (ALS) inhibitors under Ukrainian conditions. The resistance that had developed complicated herbicide control and necessitated the use of alternative modes of action. Within the framework of winter wheat protection technology, N. Hrytsiuk *et al.* (2023) characterised the impact of a harmful biota control system on the state of the agrocenosis in the Northern Forest-Steppe of Ukraine. The scheme applied was accompanied by a reduction in weed abundance and a shift in their species composition within the crop. In studies on the integrated management of resistant weeds, B.D. Tidemann *et al.* (2023) examined a combination of crop rotation diversity, increased sowing rates and techniques to limit seed regeneration. Such approaches reduced the density of individual resistant species, although the response of the weed community remained species-specific.

In summarising approaches for cereal crops, A. Chaudhary *et al.* (2022) analysed integrated weed management in wheat and barley. Herbicide treatments were considered in combination with agronomic practices, competitive varieties and crop rotation. In the context of herbicide resistance scenarios, V. Kumar *et al.* (2023) systematised the main mechanisms of weed resistance and the challenges involved in controlling them. The spread of resistant populations was widespread and required systematic management within the framework of integrated strategies. Combining mechanical and chemical methods, M. Saile *et al.* (2022) examined the use of pre-emergence and post-emergence herbicides in conjunction with sensor-guided harrowing and inter-row cultivation in cereal crops. This approach was considered as a component of integrated weed management in the context of the rise of resistant populations and associated yield losses. In a long-term crop rotation system, E.C. Rudell *et al.* (2023) assessed the effects of cover crops, crop rotation and herbicide control on the weed component of the agrocenosis. The combination of these practices was associated with increased crop biomass and yield, and reduced weed density.

In the context of the development of herbicide-tolerant crops, X. Hou *et al.* (2025) summarised approaches to weed management in the face of spreading resistance. A promising direction was identified as the combination of chemical, cultural and mechanical measures with precision control technologies. As part of their monitoring of grass weeds, V.B. Vijayarajan *et al.* (2022) analysed the distribution of problematic species, the status of herbicide resistance and control practices in Ireland. Under non-inversion tillage, weed pressure remained higher, and the main risks were associated with resistant populations of Lolium multi-florum and Alopecurus myosuroides.

In a regional survey of resistant weeds, C.M. Geddes *et al.* (2024) investigated their distribution, prevalence and impact in Saskatchewan. The economic losses to production were found to be significant, and amongst grass weeds, the most significant impact was associated with *Avena fatua* and a high prevalence of resistance to ACCase and ALS inhibitors. In the field of digital control technologies, S. Ghatrehsamani *et al.* (2023) summarised the potential of artificial intelligence for the detection, mapping and management of herbicide-resistant weeds. The combination of remote sensing, recognition algorithms and precision management was considered a promising tool to complement integrated pest management systems.

At the same time, the specific features of the restructuring of the segetal flora under the influence of various control systems, the relationship between resistance, coenotic activity and seed regeneration of weeds, as well as the link between these changes and the development of cereal crop yield, remain insufficiently understood. The aim of the study was to assess the effectiveness of integrated strategies for controlling the segetal flora and their impact on weed multiple herbicide resistance and cereal crop yield. The research objectives were to determine changes in the floristic, coenotic and reproductive structure of the segetal flora under different control systems, to establish indicators of weed multiple herbicide resistance, and to analyse the response of cereal crop yield to the measures applied. The research hypothesis was that integrated systems are more effective at reducing weed infestation, multiple herbicide resistance and increasing crop yield. The null hypothesis was that different control systems do not cause significant changes in these indicators.

Materials and Methods

The field experiment was carried out in 2025 on a commercial winter wheat field located in the village of Sozonivka, Kirovohrad Oblast, Ukraine. The trial was established within an agrocenosis of the "Podolyanka" winter wheat variety. The trial included a winter wheat variety regionalised for the conditions of central Ukraine, characterised by uniform growth (No. 00007009 in the Register of Plant Varieties), stable field germination and widespread cultivation in the region's commercial crops, whilst excluding varieties with unstable winter survival, uneven spring regrowth, susceptibility to lodging and pronounced morphological heterogeneity. Growing conditions for the 2025 harvest were characterised by a moisture deficit, elevated temperatures during the spring and summer, and uneven rainfall, which intensified competition between the crop and the segetal flora and created a context for the persistence of biotypes with lower sensitivity to herbicides. On regular medium-loamy chernozem, the experimental plot was set up. For the persistence of genotypes under severe humidity, the experimental plot was established. The humus concentration was 3.48%, the pH of the salt extract was 6.4, the nitrate nitrogen level reached 17.9 mg/kg, the available phosphorus concentration amounted to 58.6 mg/kg, and the exchangeable potassium level was 94.3 mg/kg in the 0-30 cm arable soil layer. Sunflower served as the preceding crop. Pre-sowing soil preparation included cultivation at a depth of 5-6 cm and surface levelling, whereas the primary tillage consisted of stubble cultivation to 8-10 cm, followed by ploughing to 22-24 cm. Throughout the research, the stipulations of the Convention on Biological Diversity (1992) concerning the preservation of biological variety and the safeguarding of the natural elements of the agroecosystem were followed.

The mineral nutrient regime was kept the same across all treatments and was formulated according to the $N_{60}P_{60}K_{60}$ scheme. Phosphate and potash fertilisers were applied during primary tillage, ammonium nitrate was applied before sowing, and urea was applied in the spring during the spring tillering stage. Sowing was performed during the second ten-day period of September 2024 using a grain drill set at 15 cm between rows. In the control, standard and active ingredient rotation treatments, as well as in the "herbicide + agronomic practices" scheme, the sowing rate was set at 5 million viable seeds per hectare, whilst in the integrated system it was increased to 5.5 million viable seeds per hectare. Apart from the approaches to weed control under investigation, the other elements of the cultivation technology were identical across all treatments.

The experimental design was based on a randomised block design with four replicates. Each treatment was assigned to plots of 50 m^2, whereas evaluations were performed on a central 32 m^2 sampling area. The study included five variants: control (no herbicides); standard treatment (tribenuron-methyl + florasulam); active ingredient rotation (pendimethalin; pyroxulam + fluroxypyr); herbicide + agronomic practices (pinoxaden + fluroxypyr); integrated system (pendimethalin + diflufenican; pyroxulam + fluroxypyr). In the standard treatment, post-emergence spraying was carried out during the tillering stage of winter wheat. In the active ingredient rotation treatment, pendimethalin was applied in the autumn after sowing but before emergence, whilst the mixture of pyroxulam and fluroxypyr was applied in the spring during the tillering stage. In the "herbicide + agronomic practices" treatment, post-emergence application of pinoxaden + fluroxypyr was combined with early spring harrowing using light tine harrows. In the integrated system, soil application of pendimethalin + diflufenican was combined with spring post-emergence spraying with a mixture of pyroxulam + fluroxypyr, an increased sowing rate and mechanical weed control. All herbicide treatments were applied with an Amazone UF 1201 field sprayer (Amazone, Germany) during the cooler morning or evening hours. Spraying was performed only when the ambient temperature remained below 25°C and air movement was under 3-4 m/s. The application rate of the working solution in all treatments involving herbicide control was 200 l/ha.

Weed species were recorded within 1 m^2 sampling quadrats formed using a metal frame. Plant specimens requiring more detailed examination were identified with an Eschenbach Mobilux portable magnifier equipped with

6×magnification and LED illumination (Eschenbach Optik GmbH, Germany). The final list contained every weed species that had been morphologically identified within the survey area. After counting the number of weeds per species using the field recording program on a Getac ZX70 tablet (Getac Technology Corporation, Taiwan) to record each individual, the number of dominating species was ascertained. Species were judged dominant if their share of the overall count surpassed 10%, according to formula (1):

$$D = \sum d_i, \quad (1)$$

where D is the number of dominant species; d_i is the dominance indicator for the i-th species: 1 if the species' proportion exceeds 10%, and 0 in other cases.

The proportion of annual dicotyledonous species, %, was determined based on the biological classification of the flora, including seedling traits, leaf venation, and life cycle type, utilizing a field guide and a Bresser Erudit DLX 20×-40× magnifier (Bresser GmbH, Germany). The calculation was carried out using formula (2):

$$P_{ad} = \frac{n_{ad}}{N_{\Sigma}} \times 100, \quad (2)$$

where P_{ad} – proportion of annual dicotyledonous species, %; n_{ad} – number of annual dicotyledonous plants, plants; N_{Σ} – total number of segetal flora plants, units.

The proportion of annual grass species, %, was determined after identifying members of the Poaceae family based on leaf blade shape, the presence of a tillering node and sheath structure, using a Carson MicroBrite Plus 60×-120× pocket microscope (Carson Optical Inc., USA). Calculations were performed using formula (3):

$$P_{az} = \frac{q_{az}}{Q_{tot}} \times 100, \quad (3)$$

where P_{az} – proportion of annual grass species, %; q_{az} – number of annual grass species, plants; Q_{tot} – total number of all weeds, plants.

The proportion of perennial root-sprouting species, %, was determined following an assessment of the underground parts on core samples collected using the Eijkelkamp Root Auger Set (Royal Eijkelkamp, Netherlands). This group included species with a pronounced root-sprout mode of vegetative regeneration; the calculation was carried out using formula (4):

$$P_{bk} = \frac{m_{bk}}{M_f} \times 100, \quad (4)$$

where P_{bk} – proportion of perennial root-sprout species, %; m_{bk} – number of plants of perennial root-sprout species, units; M_f – total number of weed plants, units

The Shannon species diversity index (H) is determined by the relative proportion of each species (p) in relation to the total number of weeds, as processed digitally from the floristic matrix in PAST 4.13 (Norway). The calculation was performed using formula (5):

$$H' = -\sum_{i=1}^{s} p_i \ln p_i, \quad (5)$$

where H' is the Shannon species diversity index, units; p_i is the proportion of the i-th species in the total number of species in the segetal flora; is the total number of species.

Weed density during the tillering stage of the crop, plants/m^2, was counted within a 1.0 m^2 Herbiseed Quadrat aluminium frame (Herbiseed, UK). Counts were carried out specifically throughout the cultivation phase of the cereal plant to compare weed infestation levels at the same stage of crop development.

The proportion of biotypes resistant to ALS inhibitors, %, was assessed in a growth evaluation subsequent to the treatment of the plants with a diagnostic dose of tribenuron-methyl in a Binder KBWF 240 climate chamber (Binder GmbH, Germany). Biotypes in which growth and green foliage were maintained were classified as resistant. The proportion of biotypes resistant to ACCase inhibitors, %, was assessed following testing with pinoxaden, with the working solution applied using a backpack micro-sprayer (Generation III Research Sprayer, DeVries Manufacturing, USA). The proportion of biotypes resistant to synthetic auxins, %, was determined by their response to fluroxypyr following cultivation of the plants in Modiform Standard Tray 104 growing containers (Modiform B.V., Netherlands). Biotypes without irreversible shoot deformation were classified as resistant. The proportion of biotypes resistant to two modes of action, %, was determined following sequential testing of the same samples against the combinations ALS + ACCase, ALS + synthetic auxins, or ACCase + synthetic auxins, with the response recorded using a Canon EOS R50 digital visual monitoring system (Canon Inc., Japan). The post-treatment survival rate of resistant plants, %, was determined under field conditions by counting the number of living individuals remaining on permanently marked microplots following herbicide application, using FieldScout Plot Markers (Spectrum Technologies Inc., USA). Plants with an active growth point and undamaged foliage were classified as alive; the computation was executed utilising a formula (6):

$$V_r = \frac{n_{surv}}{n_{pre}} \times 100, \quad (6)$$

where V_r is the post-treatment survival rate of resistant plants, %; n_{surv} is the number of plants surviving after treatment, units; n_{pre} is the number of plants before treatment, units

The proportion of resistant biotypes in the total weed biomass, %, was determined after separate collection of resistant and non-resistant plants, drying in a Memmert UF55 drying oven (Memmert GmbH, Germany) and weighing on RADWAG AS 220.R2 analytical balances (RADWAG, Poland). The calculation was performed using formula (7):

$$M_{res} = \frac{m_{res}}{m_{weed}} \times 100, \quad (7)$$

where M_{res} is the proportion of resistant biotypes in the total weed biomass, %; m_{res} is the dry weight of resistant plants, g; m_{weed} is the total dry weight of weeds, g.

The proportion of biotypes resistant to three modes of action, %, was determined following a full cycle of tests for ALS inhibitors, ACCase inhibitors and synthetic auxins, with viability recorded in the Panasonic Toughbook FZ-G2 electronic logbook (Panasonic Connect Co., Japan).

Weed dry biomass, g/m^2, was quantified after the plants had been harvested, oven-dried to a stable mass in an SNOL 58/350 drying chamber (AB Umega Group, Lithuania), and subsequently weighed using KERN EMS 12K0.1 laboratory scales (KERN & Sohn GmbH, Germany). The survey characterised the accumulation of structural phytomass in the weed layer. Weed fresh biomass, g/m^2, was registered directly after collection using CAS SW-20 portable field scales (CAS Corporation, Republic of Korea). Weighing was carried out before drying to record the actual mass of the plants at the time of the survey. The percentage of ground area occupied by weeds was estimated with a 100-cell Braun-Blanquet grid frame (Eijkelkamp, Netherlands). Projective cover was calculated as the share of the surveyed soil surface overlain by the vertical projection of weed stems and foliage.; the calculation was carried out using formula (8):

$$C_{pr} = \frac{g_{cov}}{g_{all}} \times 100, \quad (8)$$

where C_{pr} is the weed projective cover, %; g_{cov} is the number of cells occupied by the weed projection; g_{all} is the total number of cells in the survey grid.

Mean weed-canopy height, cm, was determined with a 2 m Nedo mEssfix telescopic measuring rod (Nedo GmbH & Co. KG, Germany). The resulting measurements served to evaluate differences in the vertical growth of the weed stand among the experimental treatments.The proportion of PAR intercepted by weeds, %, was determined using an AccuPAR LP-80 ceptometer (METER Group, USA) based on the difference in photosynthetically active radiation flux above and below the weed layer. The coefficient of coenotic stress was calculated as the ratio of the dry mass of weeds to the dry mass of cultivated plants after separate weighing on an OHAUS Adventurer AX4202 balance (OHAUS Corporation, USA). This index was utilised to evaluate intensity of weed pressure on the crop component using formula (9):

$$K_{cen} = \frac{B_w}{B_c}, \quad (9)$$

where K_{cen} is the coenotic stress coefficient, units; B_w is the dry mass of weeds, g; B_c is the dry mass of cultivated plants, g. Losses of available soil moisture in the 0-20 cm layer due to weed competition, in mm, were determined after soil samples were collected using an AMS Regular Soil Probe 7/8 (AMS Inc., USA) and subsequently dried.

The number of generative weed plants, plants/m^2, was recorded in a 1 m^2 sampling area delineated with a Hummert Quadrat frame (Hummert International, USA). Only plants with developed inflorescences, fruits or seed heads were recorded. The average number of seeds per plant was determined following individual examination of representative plants using a Pfeuffer Contador electronic counter (Pfeuffer GmbH, Germany). This indicator characterised the individual seed productivity of a weed plant. The seed productivity of the segetal flora, in thousands of seeds per m^2, was calculated as the product of the density of generative plants and the average number of seeds per plant, converted to thousands. The calculation was performed using formula (10):

$$S_p = \frac{G_p \times \overline{N_s}}{1000}, \quad (10)$$

where S_p is the seed productivity of the segetal flora, thousand seeds/m^2; G_p is the number of generative weed plants, plants/m^2; $\overline{N}_s$ is the average number of seeds per plant, seeds.

The mass of 1,000 seeds of leading weeds, expressed in grams, was assessed subsequent to the standard sample, was prepared and weighed using a Sartorius Secura 225D-1S microbalance (Sartorius AG, Germany). For the analysis, purified seeds of dominant species, free from impurities, were used. The proportion of viable seeds in the soil seed bank, %, was determined after washing the seeds to remove soil, germination in a Panasonic MLR-352H-PE chamber (Panasonic Healthcare Co., Japan) and testing non-germinated seeds using the tetrazolium test. Soil seed-bank density in the 0-10 cm horizon, expressed as thousands of seeds per square metre, was quantified after soil-core collection and fractionation of the samples with a Retsch Test Sieve set (Retsch GmbH, Germany). This indicator characterised the level of weed seed accumulation in the arable soil layer. The potential number of seedlings emerging from the soil seed bank in the following season, in plants/m^2, was ascertained using the vegetative sprouting of soil specimens in Stuewe Deepot D40 trays (Stuewe & Sons, USA) under controlled moisture conditions. Seedling counts were carried out throughout the entire wave germination cycle.

The density of productive stems, in stems per square metre, was determined using the Burgon & Ball Quadrat Frame (Burgon & Ball, UK) based on the quantity of fruitful stems within the survey area. The number of grains per ear was determined following individual threshing of the ears using an Elmor C1 seed counter (Elmor Angewandte Elektronik AG, Switzerland). Typical ears without mechanical damage were selected for analysis. The grain weight per ear, g, was determined after individual threshing and weighing on an A&D HR-202i balance (A&D Company, Japan). The weight of 1,000 grains, in grams, was obtained by counting weighing a standard sample on a a Precisa 360EP balance (Precisa Gravimetrics AG, Switzerland). This method was used to compare the degree of grain filling between the treatments. Biological grain yield, t/ha, was determined by the method of continuous plot-by-plot harvesting, followed by weighing on Mettler Toledo PFA579 platform scales (Mettler-Toledo AG, Switzerland) and conversion to standard moisture content. The calculation was carried out using formula (11):

$$Y_b = \frac{m_h \times 10}{S_h}, \quad (11)$$

where Y_b is the biological grain yield, t/ha; m_h is the grain mass from the reference plot, kg; S_h is the area of the reference plot, m^2.

The yield increase compared to the control, in t/ha, was determined by subtracting the control yield from the yield of the experimental treatment. This indicator was defined as the absolute quantity of grain additionally obtained compared with the untreated control; the calculation was carried out using formula (12):

$$\Delta Y = Y_t - Y_c, \qquad (12)$$

where ΔY – yield gain relative to the control, t/ha; Y_t – yield in the experimental treatment, t/ha; Y_c – yield in the control, t/ha.

Yield potential realisation, %, was defined as the ratio of the actual yield to the maximum yield level achievable for the variety and was used to assess the extent to which the crop's productive potential was realised under the experimental conditions; it was calculated using formula (13):

$$R_p = \frac{Y_f}{Y_{pot}} \times 100, \qquad (13)$$

where R_p – realisation of yield potential, %; Y_f – actual yield, t/ha; Y_{pot} – potential yield of the variety, t/ha.

For all indicators, the arithmetic mean ($\bar{x}$) and the coefficient of variation (V, %) were determined. The normality of the distribution was tested using the S. Shapiro & M. Wilk (1965) criterion, and the homogeneity of variances was tested using the H. Levene (1960) criterion. Calculations were carried out using Statistica 10.0 (StatSoft Inc., USA) and IBM SPSS Statistics 26 (IBM Corp., USA).

Results

In treatments with varying levels of control intensity, the floristic structure of the segetal flora changed progressively from the control treatment, through the standard and active ingredient rotation treatments, to the herbicide + agronomic practices treatment and the integrated system. The total number of species decreased from 15 in the control to 6 in the integrated system, with the standard treatment, active ingredient rotation treatment and herbicide + agronomic practices treatment forming a gradual transition between these extremes. A similar pattern was observed in the number of dominant species, which decreased from 5 to 2. This indicated that each subsequent control treatment narrowed the floristic composition and gradually simplified the internal organisation of the weed community, with the most pronounced restructuring occurring under the integrated system. A consistent trend in changes was also observed in the distribution of biological groups across all five treatments. The proportion of annual dicotyledonous species decreased progressively from the control to the integrated system – from 47.6% to 36.4%, whilst the standard treatment, active ingredient rotation treatment and the herbicide + agronomic practices treatment occupied intermediate positions in this sequence. The proportion of annual grass species showed a similar trend, decreasing from 30.8% to 24.8%. Against this backdrop, the proportion of perennial root-sprouting species, by contrast, increased from 21.6% in the control to 38.8% in the integrated system. These trends indicated that, as control measures were intensified, the annual component of the flora declined, whilst the relative proportion of perennial forms increased, and the floristic structure shifted towards a different biological composition.

Weed density during the crop's tillering stage also varied in stages across all five treatments. In the control treatment, it reached 126.4 plants/m^2, whilst in the integrated system it fell to 42.6 plants/m^2; the standard treatment, active ingredient rotation treatment and herbicide + agronomic practices treatment showed a gradual intermediate reduction in weed infestation. This meant that each subsequent treatment reduced not solely the aggregate quantity of weeds but furthermore the spatial connectivity of the weed canopy. With this transition from control to an integrated system, the ability of the segetal flora to form localised clusters, maintain a more continuous cover and sustain the previous intensity of competitive pressure on crop plants was weakened. The Shannon index confirmed that the changes concerned not only the number of species but also the evenness of their distribution within the community. Its value decreased progressively from 2.31 in the control to 1.36 in the integrated system, whilst the standard treatment, active ingredient rotation treatment and the herbicide + agronomic practices treatment occupied intermediate positions in the overall series. This indicated that, as the intensity of control increased, the floristic structure became not only poorer in species composition but also less even in terms of the internal proportions of its components. Thus, all five treatments exhibited a sequential dynamic in which the control treatment retained the most diverse and structurally complex weed community, the standard and active ingredient rotation treatments resulted in an intermediate restructuring, the herbicide + agronomic practices treatment further restricted the weed component, whilst the integrated system resulted in the most pronounced reduction in species composition, the dominant core, density and diversity of the segetal flora (Table 1).

Table 1. *Floristic composition of the segetal flora in a cereal agrocenosis*

Indicator	Control (without herbicides)	Standard Treatment (tribenuron-methyl + + florasulam)	Active Ingredient Rotation (pendimethalin; pyroxulam + + fluroxypyr)	Herbicide + + Agronomic Practices (pinoxaden + + fluroxypyr)	Integrated System (pendimethalin + + diflufenican; pyroxulam + + fluroxypyr)
Total number of segetal flora species, species	15	11	9	8	6
Number of dominant species, species	5	4	3	3	2
Proportion of annual dicotyledonous species, %	47.6	44.2	41.8	39.5	36.4
Proportion of annual grass species, %	30.8	29.6	27.9	26.3	24.8
Proportion of perennial root-sprout species, %	21.6	26.2	30.3	34.2	38.8
Weed density during the crop's tillering stage, plants/m^2	126.4	78.9	63.5	54.7	42.6
Shannon species diversity index, units	2.31	1.94	1.73	1.58	1.36

Source: developed by the authors based on equations (1-5)

Thus, the floristic structure of the segetal flora in the cereal agrocenosis changed simultaneously across four analytical parameters: total species richness, composition of dominant species, abundance, and the relationship between diversity and evenness. The cumulative nature of these changes gave rise to a different type of weed community, characterised by a narrower floristic base, a simplified internal organisation and weaker structural cohesion between individual components. Under these conditions, the conditions for the multi-component recovery of the segetal flora, the long-term maintenance of coenotic tension and the sustained presence of weeds within the crop throughout the growing season were weakened.

Changes in multiple herbicide resistance indicators reflected varying levels of effectiveness among the control systems: ranging from a less restricted development of resistant biotypes in the control and standard treatment to their more noticeable suppression under the active ingredient rotation treatment, the herbicide + agronomic practices treatment and the integrated system. The most prevalent type of resistance remained insensitivity to ALS inhibitors, the proportion of which decreased from 60.8% in the control to 36.1% in the integrated system, whilst the standard treatment, active ingredient rotation treatment and herbicide + agronomic practices treatment showed a gradual transition along this spectrum. A similar trend was observed in the proportion of biotypes resistant to acetyl-CoA carboxylase inhibitors: from 29.4% in the control to 16.8% in the integrated system. These trends indicated that the standard treatment only partially reduced the resistant component, whilst the active ingredient rotation treatment and the "herbicide + agronomic practices" treatment amplified this effect, and the most pronounced reduction occurred under the integrated system. Resistance to synthetic auxins also decreased progressively across all five treatments: from 38.2% in the control to 21.9% in the integrated system. This indicator reflected the proportion of biotypes that remained viable after exposure to herbicides with an auxin-like mechanism of action, i.e. it characterised yet another avenue of adaptation of the segetal flora to chemical pressure. The standard treatment, active ingredient rotation treatment and the herbicide + agronomic practices treatment successively reduced the prevalence of this group, but not as sharply as the integrated system. Thus, a common pattern was observed across the three main types of resistance: their proportion was highest in the control treatment and lowest in the integrated system, whilst the other treatments showed a gradual narrowing of the resistance spectrum without a sharp break between the individual components of the control system.

A separate section on multiple herbicide resistance focused on biotypes capable of combining several resistance mechanisms. The proportion of strains resistant to two modes of action decreased from 25.7% in the control to 9.7% in the integrated system, whilst the standard treatment, active ingredient rotation treatment and herbicide + agronomic practices treatment formed a continuous range of changes between them. The proportion of biotypes resistant to three modes of action also decreased – from 10.2% to 2.8%. This figure should be interpreted as the highest level of multiple herbicide resistance, where the same biotype remained insensitive simultaneously to ALS inhibitors, acetyl-CoA carboxylase inhibitors and synthetic auxins. In this sequence of comparisons, it is evident that each subsequent control treatment weakened the combined resistance; however, the most significant reduction in the reserve for multiple-pathway adaptation was observed only under the integrated system. Post-treatment survival of resistant plants was 100% in the control and decreased to 11.9% in the integrated system, whilst the standard treatment, active ingredient rotation treatment and the herbicide + agronomic practices treatment consistently occupied intermediate positions. In the control treatment, the post-treatment survival of resistant plants corresponded to the background level of weed component persistence in the absence of herbicidal intervention, whilst in the other control systems this indicator decreased progressively. The proportion of resistant biotypes in the total weed biomass also varied progressively – from 52.4% in the control to 18.5% in the integrated system. This indicator characterised not only the numerical presence of resistant forms, but also their actual contribution to the composition of the weed community. Thus, a consistent pattern was observed across all five treatments: the control retained the highest proportion of multiple herbicide-resistant biotypes, whilst the standard treatment and active ingredient rotation only partially reduced this; the "herbicide + agronomic practices" treatment further exacerbated this limitation, whilst the integrated system was associated with the lowest values for the prevalence, survival and biomass contribution of resistant biotypes (Table 2).

Table 2. *Level of multiple herbicide resistance in the weed component of the agrocenosis*

Indicator	Control (without herbicides)	Standard treatment (tribenuron-methyl + + florasulam)	Active ingredient rotation (pendimethalin; pyroxulam + + fluroxypyr)	Herbicide + + agronomic practices (pinoxaden + + fluroxypyr)	Integrated system (pendimethalin + + diflufenican; pyroxulam + + fluroxypyr)
Proportion of biotypes resistant to ALS inhibitors, %	60.8	58.3	49.7	44.6	36.1
Proportion of biotypes resistant to ACCase inhibitors, %	29.4	28.7	24.9	21.6	16.8
Proportion of biotypes resistant to synthetic auxins, %	38.2	36.5	31.8	27.3	21.9
Proportion of biotypes resistant to two modes of action, %	25.7	24.8	19.6	15.4	9.7
Proportion of biotypes resistant to three modes of action, %	10.2	9.8	7.1	5.4	2.8
Post-treatment survival of resistant plants, %	100.0	42.6	28.3	21.7	11.9
Proportion of resistant biotypes in the total weed biomass, %	52.4	47.9	38.6	29.8	18.5

Source: developed by the authors based on equations (6-7)

Consequently, the indicators of multiple herbicide resistance in the segetal flora changed simultaneously across four analytical parameters: the prevalence of ALS-resistant biotypes, the prevalence of forms with combined resistance, the proportion of ACCase-resistant components, and the level of post-treatment survival of resistant plants. The cumulative nature of these changes gave rise to a different type of resistance structure within the weed community, within which the range of adaptive combinations narrowed, the internal stability of the resistant portion of the population weakened, and its ability to sustain continuous self-renewal in the crop declined. Under these conditions, opportunities for the accumulation of multiple-pathway adaptation, stable survival of post-treatment selection, and the long-term maintenance of a stable presence of resistant biotypes within the cereal agrocenosis were reduced.

The coenotic indicators of the segetal flora revealed consistent changes across the range from the control to the integrated system, including the standard treatment, active ingredient rotation treatment and the herbicide + agronomic practices treatment. An initial reduction in the dry weight of weeds occurred as early as the transition from the control to the standard treatment – from 188.6 to 109.4 g/m^2 – after which the reduction continued in the active ingredient rotation treatment and herbicide + agronomic practices treatment, whilst in the integrated system the figure reached its lowest level. A similar trend was observed for fresh weight, which decreased from 308.7 in the standard treatment to 142.3 g/m^2 in the integrated system, whilst the active ingredient rotation treatment and the herbicide + agronomic practices treatment formed a gradual transition between these values. Consequently, the changes affected not only the structural dry matter but also the total volume of weed biomass in the crop. The spatial characteristics of the weed layer also changed in stages. Weed projective cover in the control and standard treatments decreased from 43.7% to 26.8%, and continued to decline in the active ingredient rotation treatment and the herbicide + agronomic practices treatment, reaching a minimum in the integrated system. The average height of the weed canopy decreased from 24.1 to 20.3 cm during the transition from the active ingredient rotation treatment to the herbicide + agronomic practices treatment, after which the weed canopy lost even more of its vertical height in the integrated system. This indicated that the standard treatment primarily limited the area of weed spread, whilst the subsequent treatments increasingly weakened both the horizontal and vertical development of the weed canopy.

The light and water aspects of competition also revealed a stepwise dynamic across all treatments. The proportion of PAR intercepted decreased from 21.9% in the control to 8.7% in the integrated system, whilst the active ingredient rotation treatment and the herbicide + agronomic practices treatment occupied intermediate positions between them. Losses of available soil moisture in the 0-20 cm layer decreased from 24.6 to 12.9 mm when moving from the control to the active ingredient rotation treatment, whilst in the herbicide + agronomic practices and integrated systems, they decreased even more sharply. This sequence indicated that the reduction in weed pressure was manifested not only in less shading of the crop but also in a gradual reduction in the drying out of the root zone. These changes were comprehensively reflected in the coenotic stress coefficient, which decreased from 0.76 to 0.34 in the control and the 'herbicide + agronomic practices' treatment, whilst reaching an even lower value in the integrated system. Thus, the standard treatment, active ingredient rotation treatment, the herbicide + agronomic practices treatment, and the integrated system did not result in separate, isolated states, but rather a sequential series of reductions in the coenotic activity of the segetal flora. Within this sequence, the control treatment maintained the highest values for dry and fresh weight, weed projective cover, canopy height, interception of photosynthetically active radiation, losses of available soil moisture and the coenotic stress coefficient; the standard treatment provided the first significant reduction; active ingredient rotation further intensified this reduction; the "herbicide + agronomic practices" treatment further reduced the weed component, whilst the integrated system resulted in the lowest level of coenotic load in the crop (Table 3).

Table 3. *Coenotic indicators of the segetal flora in cereal crops*

Indicator	Control (without herbicides)	Standard Treatment (tribenuron-methyl + + florasulam)	Active Ingredient Rotation (pendimethalin; pyroxulam + + fluroxypyr)	Herbicide + + Agronomic Practices (pinoxaden + + fluroxypyr)	Integrated System (pendimethalin + + diflufenican; pyroxulam + + fluroxypyr)
Dry weight of weeds, g/m^2	188.6	109.4	86.2	67.8	49.5
Fresh weight of weeds, g/m^2	514.2	308.7	249.6	196.4	142.3
Weed projective cover, %	43.7	26.8	21.4	16.2	10.8
Average height of the weed layer, cm	39.4	28.6	24.1	20.3	16.8
Proportion of PAR intercepted by weeds, %	35.2	21.9	17.6	13.4	8.7
Losses of available soil moisture in the 0-20 cm layer due to competition from weeds, mm	24.6	15.8	12.9	9.7	6.4
Coefficient of coenotic stress, units	0.76	0.51	0.43	0.34	0.23

Source: developed by the authors based on equations (8-9)

Consequently, the coenotic organisation of the segetal flora in cereal crops underwent simultaneous changes across four analytical parameters: dry matter accumulation, spatial cover, contribution to the interception of photosynthetically active radiation, and integral coenotic stress. The combined effect of these shifts resulted in a different type of weed component presence within the agrocenosis, characterised by lower spatial connectivity, weaker involvement in the redistribution of light and trophic resources, and a reduced ability to maintain sustained competitive pressure on cultivated plants. Under these conditions, the segetal flora lost some of the mechanisms that ensured its stable retention within the crop area, the consistent accumulation of phytomass, and the preservation of a functionally intact weed layer throughout the growing season.

The reproductive indicators of the segetal flora reflected differences in the quantity of weeds capable of seed production, as well as in the characteristics of the seed produced and the soil seed bank. The number of generative plants differed most significantly between the control and the standard treatment: in the herbicide-free treatment, it amounted to 37.8 plants/m^2, whereas after the application of tribenuron-methyl with florasulam, it decreased to 22.4 plants/m^2. In the active ingredient rotation treatment, the herbicide + agronomic practices treatment and the integrated system, the proportion of plants completing their development with a generative phase subsequently decreased. Individual seed productivity also varied depending on the control system. Under the standard treatment, a single generative plant produced an average of 296 seeds, whereas in the active ingredient rotation treatment, the figure was 231 seeds. This indicated that the active ingredient rotation limited not only the number of generative plants but also the productivity of plants that completed their full life cycle. In the herbicide + agronomic practices treatment and the integrated system, individual seed productivity remained lower than under less intensive control schemes. The seed productivity of the segetal flora was determined by a combination of the number of generative plants and the average seed production per individual. In the control treatment, it amounted to 15.8 thousand seeds/m^2, whereas under the herbicide + agronomic practices treatment it fell to 3.8 thousand seeds/m^2. Consequently, even the preservation of a portion of the generative plants did not maintain the previous level of seed replenishment, as their individual productivity simultaneously decreased. The weight of 1,000 seeds of dominant weeds characterised the physical parameters of the diaspores. Under the active ingredient rotation treatment, it was 1.58 g, and under the integrated system, 1.27 g. This ratio indicated that, under a more comprehensive control regime, not only did the volume of the seed flow change, but so did the size and mass characteristics of the seeds produce.

The proportion of viable seeds in the soil seed bank also depended on the treatment. Under the standard treatment, it stood at 56.7%, whereas in the herbicide + agronomic practices treatment it fell to 41.3%. This meant that it was not only the number of seeds entering the soil that changed, but also the proportion of material capable of participating in the next regeneration cycle. The density of the soil seed bank in the 0-10 cm layer reflected the accumulated reproductive reserve. Under the standard treatment, it amounted to 17.8 thousand seeds/m^2, whilst under the integrated system it was 8.6 thousand seeds/m^2. The potential number of seedlings in the following season varied in line with this reserve: under the active ingredient rotation treatment, it was 46.5 plants/m^2, whilst under the integrated system it was 24.1 plants/m^2. Overall, the results showed that the control systems influenced the reproductive potential of the segetal flora through the number of generative plants, seed yield, seed weight, seed viability, soil seed bank and expected weed regrowth (Table 4).

Table 4. *Reproductive parameters of the segetal flora under different control systems*

Indicator	Control (without herbicides)	Standard Treatment (tribenuron-methyl + + florasulam)	Active Ingredient Rotation (pendimethalin; pyroxulam + + fluroxypyr)	Herbicide + + Agronomic practices (pinoxaden + + fluroxypyr)	Integrated System (pendimethalin + + diflufenican; pyroxulam + + fluroxypyr)
Number of generative weed plants, plants/m^2	37.8	22.4	17.3	12.6	8.1
Average number of seeds per plant, seeds	418	296	231	176	119
Seed productivity of the segetal flora, thousand seeds/m^2	15.8	8.7	5.9	3.8	1.9
Mass of 1,000 seeds of dominant weeds, g	1.86	1.71	1.58	1.43	1.27
Proportion of viable seeds in the soil seed bank, %	69.4	56.7	48.9	41.3	33.6
Seed density in the soil profile in the 0-10 cm layer, thousand seeds/m^2	23.4	17.8	14.1	11.2	8.6
Potential number of seedlings from the soil seed bank in the next season, plants/m^2	84.6	58.3	46.5	35.7	24.1

Source: derived by the authors based on formula (10)

Consequently, the reproductive system of the segetal flora underwent restructuring simultaneously at several levels: in terms of the number of generative plants, individual seed productivity, the quality of the seeds produced, and their potential for subsequent dispersal. Taken together, these changes gave rise to a different type of reproduction within the weed component, characterised by lower seed production intensity, reduced consistency in the transition from the generative phase to a new germination cycle, and more limited opportunities for the long-term self-sustainment of the segetal flora within the cereal agrocenosis. At the same time, the changes affected not only individual reproductive indicators but also the sequence of relationships between them, as the reduction in generative activity, the decrease in seed productivity and the limitation on the utilisation of the soil seed bank weakened the continuity of weed layer regeneration. Under these conditions, the reproductive cycle of the segetal flora lost some of its internal integrity, and the reproduction of the weed component became less stable in terms of both time and population.

The development of grain crop yield was influenced by simultaneous changes in plant density, ear parameters, grain filling and the extent to which yield potential was realised. The density of the productive stem stand responded to the switch from the control treatment to the standard treatment: in the herbicide-free treatment, it stood at 426 stems/m^2, whilst under the standard treatment with tribenuron-methyl and florasulam, it increased to 468 stems/m^2. The active ingredient rotation, the herbicide + agronomic practices treatment, and the integrated system further enhanced the contribution of surviving shoots to the formation of the productive tier. The number of grains per ear varied not only as a result of higher stem density but also due to the more complete progression through the generative phases. In the active ingredient rotation treatment, the number of grains per ear was 29.4, whilst in the herbicide + agronomic practices treatment it was 30.7. Compared with the standard treatment, these treatments had a higher number of formed grains, whilst the integrated system was characterised by the fullest utilisation of the reproductive elements of the ear. The grain weight per ear reflected a combination of grain number and filling intensity. Under standard treatment, this figure stood at 1.06 g, whilst under the integrated system it rose to 1.27 g. The active ingredient rotation and the herbicide + agronomic practices treatment demonstrated a higher grain weight per year compared with the standard, indicating a more complete production process at the level of the individual ear.

The weight of 1,000 grains was used to characterise the quality of the crop and the degree of grain filling. In the control treatment, this was 39.6 g, whilst in the treatment involving the active ingredient rotation, it increased to 43.1 g. Following the introduction of the agronomic component, this indicator approached the level of the integrated system, indicating a gradual increase in grain filling as competition from segetal flora decreased. Biological grain yield summarised the changes in all structural elements of productivity. Under the standard treatment, it stood at 5.02 t/ha, whilst in the herbicide + agronomic practices treatment, it was 5.78 t/ha. Active ingredient rotation yielded a higher yield compared with the baseline herbicide-only treatment, whilst the integrated system combined the highest density of productive stems, grain set and grain weight. The yield gain relative to the control demonstrated the proportion of the crop that was preserved through weed management. With the active ingredient rotation, the yield gain was 1.35 t/ha, whilst with the integrated system it was 2.06 t/ha. The standard treatment and the herbicide + agronomic practices treatment differed in terms of yield gain, as the latter combined chemical control with a further reduction in competitive pressure. The realisation of yield potential varied in line with the accumulation of advantages in the productivity structure. In the standard treatment, this reached 71.7%, whilst under the herbicide + agronomic practices treatment it reached 82.6%. Active ingredient rotation brought the crop closer to fully utilising its yield potential, whilst the integrated system completed this process through the simultaneous increase in productive stem number, grain number per ear, grain weight per ear and biological grain yield (Table 5).

Table 5. *Grain crop yield under different control systems*

Indicator	Control (without herbicides)	Standard Treatment (tribenuron-methyl + + florasulam)	Active Ingredient Rotation (pendimethalin; pyroxulam + + fluroxypyr)	Herbicide + + Agronomic practices (pinoxaden + + fluroxypyr)	Integrated System (pendimethalin + + diflufenican; pyroxulam + + fluroxypyr)
Density of productive stems, plants/m^2	426	468	482	497	514
Number of grains per ear, grains	24.8	27.9	29.4	30.7	32.1
Grain weight per ear, g	0.92	1.06	1.14	1.19	1.27
Weight of 1,000 grains, g	39.6	41.8	43.1	44.0	45.2
Biological grain yield, t/ha	4.08	5.02	5.43	5.78	6.14
Yield gain relative to the control, t/ha	0.00	0.94	1.35	1.70	2.06
Yield potential realisation, %	58.3	71.7	77.6	82.6	87.7

Source: developed by the authors based on equations (11-13)

Consequently, the productivity of the cereal crop was restructured simultaneously across four analytical parameters: productive stem density, grain number per ear, thousand-grain weight and biological grain yield. The combined effect of these changes gave rise to a different pattern of yield potential realisation, characterised by fuller utilisation of the sown area, closer coordination between the individual structural elements of the yield, and greater completeness of the production process from stem formation to grain filling. At the same time, the dependence of the final result on the compensatory role of individual plants decreased, as the main burden of yield formation shifted to a more uniformly functioning crop community. Under this arrangement, the productive process relied not on the local strengthening of individual components, but on a more balanced interaction between plant density, the generative development of the ear and the accumulation of grain mass, which ensured a more stable yield formation across the sown area.

Discussion

The findings demonstrated that the integrated system had an impact on both the internal structure of the segetal flora and the overall degree of weed infestation. A decline in the quantity of species, a reduction in the quantity of dominant species, lower weed density and a change in the Shannon index indicated a restructuring of the community from a multi-component model to a simpler structure with a narrower range of ecological niches. This transformation was accompanied by a weakening of the spatial connectivity of the weed layer and a reduction in the ability of the segetal flora to sustain long-term self-regeneration within the crop. Results on multiple herbicide resistance also showed that different control systems led to varying selection pressures within weed populations. The high proportion of ALS-resistant biotypes in the control treatment and the noticeable presence of forms resistant to two modes of action indicated an already established adaptive pool capable of sustaining the recovery of the weed component following herbicide application. The reduction in the proportion of ACCase-resistant biotypes and in the post-treatment survival of resistant plants under the integrated system indicated a limitation not only on the current presence of resistant forms but also on their subsequent establishment within the agrocenosis.

Within the framework of agronomic combinations of control methods, the studies by R.P. Dubey *et al.* (2023) and M.N. Khasraw *et al.* (2023) focused on integrated weed management through a combination of herbicidal and non-chemical approaches. In the study by R.P. Dubey *et al.*, weed control in millet crops was examined in terms of critical periods of competition, mechanical cultivation and the combination of management strategies, which made it possible to link the effectiveness of control to the spatial and temporal limitation of the weed component. In the study by M.N. Khasraw *et al.*, sowing dates, seed rates and herbicide control for wheat were interpreted as elements of a unified system aimed at reducing weed biomass and maintaining yield. The present study expanded on this logic, as the assessment covered not only the overall reduction in weed infestation but also changes in floristic structure, coenotic pressure, multiple herbicide resistance, reproductive reserve and the crop's productive response. This was confirmed by a reduction in weed density from 126.4 to 42.6 plants/m^2 and an increase in biological grain yield from 4.08 to 6.14 t/ha. It was precisely this approach that made it possible to trace how the integrated system influenced not only the current weed population but also the mechanisms of their subsequent self-sustainment within the agrocenosis.

In the context of herbicide use and the search for alternative solutions, the work of T.K. Das *et al.* (2024) and B.A. Khan *et al.* (2024) focused primarily on assessing the efficacy of herbicides, their environmental risks and their technological prospects. In the study by T.K. Das *et al.* herbicide protection was examined in terms of the balance between agronomic benefits, economic outcomes and potential impacts on non-target components of the agroecosystem. In the publication by B.A. Khan *et al.* nanoherbicides were treated as one of the approaches to improving the precision of pesticide application and reducing the use of active ingredient in wheat crops. Against this background, the present study had a clearer field-based focus, as the resistant component was assessed not as a general technical problem, but as part of the actual structure of the segetal flora. This was confirmed by a reduction in the proportion of biotypes resistant to ALS inhibitors from 60.8% to 36.1% and a decrease in the post-treatment survival rate of resistant plants from 100% to 11.9%. This approach made it possible to link herbicide load not only to control efficacy but also to changes in the coenotic role of resistant biotypes, their contribution to weed biomass and subsequent reproductive recovery within the agrocenosis.

In the field of sustainable and resistance-oriented weed management, the work of T.D. Xuan *et al.* (2025) and J.K. Soni *et al.* (2023) addressed either general strategies for sustainable weed management or the history of resistance development in a specific problematic species. The paper by T.D. Xuan *et al.* summarised conventional and "smart" approaches to weed control within a sustainable production system, with an emphasis on the integration of mechanical, cultural and digital tools. The paper by J.K. Soni *et al.* examined the evolution, current status and methods of controlling herbicide-resistant Phalaris minor. This study proved to be broader in scope, as resistance was not confined to a single species or a narrow conceptual framework, but was considered as part of the overall restructuring of the cereal agrocenosis. Alongside multiple herbicide resistance, the study analysed the floristic structure, coenotic indicators, reproductive traits and crop productivity parameters. This approach demonstrated how integrated control altered not only the presence of resistant forms, but also the conditions for their long-term persistence, spatial distribution and involvement in the subsequent weed cycle.

In the context of herbicide-free and model-based approaches, the work of D.J. Bloomer *et al.* (2024) and M. Renton *et al.* (2024) focused on finding ways to reduce selection pressure on weed populations, but approached the problem from different angles. D.J. Bloomer *et al.* examined robotic systems and pulsed micro-electrical treatments as tools for the direct physical removal of weeds in vegetable and field crops in New Zealand. M. Renton *et al.* focused on herbicide mixtures which, under simulated conditions, slowed the development of monogenic and polygenic resistance more effectively than crop rotation or the application of individual active ingredients. Consequently, in the work by D.J. Bloomer *et al.*, the emphasis was on the technological replacement of part of chemical control, whereas in the work by M. Renton *et al.*, it was on predicting the evolutionary response of weeds to various herbicide treatment regimens. In the present study, these approaches were combined at the level of the field agrocenosis: the integrated system was evaluated not only in terms of suppressing the resistant component, but also in terms of changes in coenotic activity, reproductive reserve and crop productivity. This was confirmed by a reduction in weed dry matter from 188.6 to 49.5 g/m^2 and a decrease in soil seed bank density from 23.4 to 8.6 thousand seeds/m^2. This approach made it possible to demonstrate not an isolated technological or model-based advantage, but the field results of integrated weed control, in which weed suppression was combined with a reduction in their future regrowth.

Within the framework of the cultural and mechanical components of integrated weed management, the papers by K.R. Grint *et al.* (2022) and P.J. Kanatas & I. Gazoulis (2022) examined methods of reducing weed pressure through cover crops, increased sowing rates, inter-row cultivation and the combination of these techniques with herbicides. K.R. Grint *et al.* found that rye, used as a cover crop and destroyed at the time of sowing the main crop, reduced early-season weed density and biomass in a no-till system. P.J. Kanatas & I. Gazoulis demonstrated that increased sowing rates, mechanical control and herbicide application in chickpeas altered the weed composition and were accompanied by higher yields. Compared with these approaches, in this study, cultural and herbicidal measures were associated not only with a reduction in weed infestation but also with a more profound restructuring of the weed system: this included a reduction in the species core, a narrowing of spatial coverage, a restriction on seed renewal, and a lower contribution of resistant biotypes to the maintenance of the agrocenosis.

In the context of pesticide-free systems and production constraints, the studies by M. Saile *et al.* (2023) and S.T. McDonald *et al.* (2023) focused on the practical difficulties of weed control in modern agriculture. M. Saile *et al.* investigated Weed management in an organic agricultural system with mineral fertilizers, linking this issue to the environmental consequences of pesticide use, the risk of residues in produce, and the spread of resistant biotypes. S.T. McDonald *et al.*, based on a survey in Nebraska, summarised the farmers' perspective on weed problems, available control methods and constraints that determined the choice of practical solutions on farms. What these studies had in common was that weeds were viewed not as a separate phytosanitary factor, but as a problem linked to technological, environmental and production constraints. At the same time, the difference lay in the fact that M. Saile *et al.* analysed control options under pesticide-free conditions, whilst S.T. McDonald *et al.* documented practical barriers and solutions shaped by farmers' production experience. Against this background, the present study focused on the problem within the context of a cereal agrocenosis, where not only general weed suppression was observed, but also changes in floristic structure, coenotic tension, reproductive renewal and multiple herbicide resistance. This was confirmed by a reduction in the number of dominant species from 5 to 2 and a decrease in weed cover from 43.7% to 10.8%. This approach made it possible to link the phytosanitary status of the crop to its productive response, rather than limiting the discussion solely to technical difficulties or production-based assessments of control systems.

As part of the analysis of species-specific weed infestation and timing of intervention, the studies by A. Raza *et al.* (2023) examined the ecological characteristics of specific problematic weeds and methods for controlling them in field crops. A. Raza *et al.* focused on the bioecology of *Chenopodium murale* and approaches to its control in Asian agroecosystems, that is, at the level of the individual species, its adaptive traits and its ability to persist in crop fields. In terms of herbicidal efficacy and the global spread of resistance, the work of P.E. Hulme (2022) and M.S. Kalyani *et al.* (2024) have been associated with different scales of analysis – ranging from individual active ingredients to global patterns of herbicide-resistant weed development in cereal crops. M.S. Kalyani *et al.* assessed the biological efficacy of new herbicidal molecules in leguminous crops, where the primary focus was on weed suppression as the agronomic outcome of product application. P.E. Hulme summarised the factors determining the species richness of herbicide-resistant weeds in the world's major cereal crops, that is, at the level of large-scale spatial and production patterns. In this study, both approaches were combined in a field experiment through the analysis not only of weed control but also of the multiple herbicide-resistant fraction of the population. The study covered the prevalence of resistance to ALS inhibitors, the presence of biotypes with combined resistance to several modes of action, changes in the proportion of the ACCase-resistant component, and limitations on the post-treatment persistence of resistant plants. Through this approach, herbicidal efficacy was considered in conjunction with the population structure of the weeds, rather than in isolation from it.

In terms of production decisions and cultural control measures, the studies by M. Espig *et al.* (2022) and A. Kumari *et al.* (2023) focused on farmers' behaviour regarding herbicide use and on the role of cover crops in reducing weed pressure. M. Espig *et al.* analysed the factors determining the intensity of herbicide application on arable land in New Zealand and linked this to a shift towards a more integrated approach to weed management. A. Kumari *et al.* investigated how a rye cover crop altered the critical period for weed control in soya, i.e., how the cover crop component influenced the temporal pattern of competition. In this study, a similar concept of reducing reliance on herbicides was implemented through a combination of increased sowing rates, mechanical suppression and various herbicide strategies in winter wheat crops. The assessment covered not only the temporal limits of weed pressure, but also the dry and fresh weight of weeds, projective cover, interception of photosynthetically active radiation, reproductive renewal of the segetal flora, and yield formation parameters. This approach made it possible to demonstrate how a change in the management regime simultaneously affected both the coenotic activity of weeds and crop productivity. The results obtained showed that integrated control of the segetal flora altered both the degree of weed proliferation and the floristic composition, the coenotic activity, reproductive renewal and the multiple herbicide-resistant component of the weed community, accompanied by better realisation of the cereal crop's productive potential.

Conclusions

The study compared five systems for controlling segetal flora in a cereal agrocenosis. The level of multiple herbicide resistance also depended on the control system: under the standard treatment, the number of species decreased to 11; under the active ingredient rotation treatment, to 9; under the herbicide + agronomic practices treatment, to 8; and under the integrated system, to 6. In the control treatment, the proportion of biotypes resistant to ALS inhibitors was 60.8%; under the standard treatment, it was 58.3%; under the active ingredient rotation treatment, 49.7%; in the herbicide + agronomic practices treatment – 44.6%, and under the integrated system – 36.1%. The post-treatment survival rate of resistant plants varied most significantly following the transition from the control to the herbicide treatments: from 100% in the control to 42.6% under the standard treatment, 28.3% under the active ingredient rotation treatment, 21.7% under the herbicide + agronomic practices treatment, and 11.9% under the integrated system. The coenotic indicators confirmed a weakening of the competitive role of the weed layer. The dry weight of weeds was 188.6 g/m^2 in the control, 109.4 g under the standard treatment, 86.2 g under active ingredient rotation, 67.8 g in the herbicide + agronomic practices treatment and 49.5 g under the integrated system. Weed cover decreased from 43.7% to 10.8%, whilst the coenotic stress coefficient fell from 0.76 to 0.23. At the same time, the height of the weed canopy, the interception of photosynthetically active radiation and losses of available soil moisture were reduced. The reproductive potential of the segetal flora was also reduced. Seed yield stood at 15.8 thousand seeds per square metre in the control plot, 8.7 thousand under the standard treatment, 5.9 thousand under the active ingredient rotation treatment, 3.8 thousand in the herbicide + agronomic practices treatment and 1.9 thousand under the integrated system. The potential number of seedlings emerging from the soil seed bank decreased from 84.6 to 24.1 plants/m^2. The yield of the cereal crop showed the opposite trend. biological grain yield increased from 4.08 tonnes per hectare in the control to 5.02 t under the standard treatment, 5.43 t under the active ingredient rotation treatment, 5.78 t under the herbicide + agronomic practices treatment and 6.14 t under the integrated system. Yield potential realisation increased from 58.3% to 87.7%. Consequently, the integrated system proved to be the most effective, as it simultaneously limited the floristic, resistant, coenotic and reproductive recovery of the segetal flora and ensured the best yield response from the cereal crop. The constraints of the research were rooted in the circumstance that the field experiment was conducted within a single region, a single growing season and a single cereal crop, which restricted the possibility of broader extrapolation of the results.

Further research should focus on long-term testing of integrated systems under various soil and climatic conditions, for different crops, and with an in-depth analysis of the mechanisms underlying the development of multiple herbicide resistance in weeds.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Bloomer, D.J., Harrington, K.C., Ghanizadeh, H., & James, T.K. (2024). Robots and shocks: Emerging non-herbicide weed control options for vegetable and arable cropping. *New Zealand Journal of Agricultural Research*, 67(1), 81-103. doi: 10.1080/00288233.2023.2252769.

[2] Chaudhary, A., Chhokar, R.S., & Singh, S. (2022). Integrated weed management in wheat and barley: Global perspective. In P. Lal Kashyap, V. Gupta, O. Prakash Gupta, R. Sendhil, K. Gopalareddy, P. Jasrotia & G. Pratap Singh (Eds.), *New horizons in wheat and barley research: Crop protection and resource management* (pp. 545-615). Singapore: Springer. doi: 10.1007/978-981-16-4134-3_20.

[3] Convention on Biological Diversity. (1992, June). Retrieved from https://www.cbd.int/convention/text.

[4] Das, T.K., Behera, B., Nath, C.P., Ghosh, S., Sen, S., Raj, R., & Paramanik, B. (2024). Herbicides use in crop production: An analysis of cost-benefit, non-target toxicities and environmental risks. *Crop Protection*, 181, article number 106691. doi: 10.1016/j.cropro.2024.106691.

[5] Dubey, R.P., Chethan, C.R., Choudhary, V.K., & Mishra, J.S. (2023). A review on weed management in millets. *Indian Journal of Weed Science*, 55(2), 141-148. doi: 10.5958/0974-8164.2023.00025.4.

[6] Espig, M., Dynes, R.A., Henwood, R.J., & James, T.K. (2022). The drivers of herbicide use among arable farmers in Canterbury, New Zealand: Toward an integrated approach. *Society & Natural Resources*, 35(3), 281-300. doi: 10.1080/08941920.2022.2032516.

[7] Geddes, C.M., Pittman, M.M., Sharpe, S.M., & Leeson, J.Y. (2024). Distribution, frequency, and impact of herbicide-resistant weeds in Saskatchewan. *Canadian Journal of Plant Science*, 104(5), 495-513. doi: 10.1139/cjps-2024-0017.

[8] Ghatrehsamani, S., Jha, G., Dutta, W., Molaei, F., Nazrul, F., Fortin, M., Bansal, S., Debangshi, U., & Neupane, J. (2023). Artificial intelligence tools and techniques to combat herbicide resistant weeds – a review. *Sustainability*, 15(3), article number 1843. doi: 10.3390/su15031843.

[9] Grint, K.R., Arneson, N.J., Oliveira, M.C., Smith, D.H., & Werle, R. (2022). Cereal rye cover crop terminated at crop planting reduces early-season weed density and biomass in Wisconsin corn-soybean production. *Agrosystems, Geosciences & Environment*, 5(1), article number e20245. doi: 10.1002/agg2.20245.

[10] Hou, X., Yang, Y., Liu, Q., & Zhang, B. (2025). Evolution and future directions in herbicide-resistant crop development and weed management. *Rice*, 18, article number 114. doi: 10.1186/s12284-025-00869-2.

[11] Hrytsiuk, N., Bakalova, A., Ivaschenko, I., & Kotkova, T. (2023). Technology of protection of winter wheat from harmful biota in the Northern Forest-Steppe of Ukraine. *Scientific Horizons*, 3(26), 48-57. doi: 10.48077/scihor3.2023.48.

[12] Hulme, P.E. (2022). Global drivers of herbicide-resistant weed richness in major cereal crops worldwide. *Pest Management Science*, 78(5), 1824-1832. doi: 10.1002/ps.6800.

[13] Kalyani, M.S., Ameena, M., Srinivas, Y., Shanavas, S., Susha, V.S., & Sethulakshmi, V.S. (2024). Bio-efficacy of new herbicide molecules for weed management in grain legumes. *Journal of Advances in Biology and Biotechnology*, 27(1), 191-204. doi: 10.9734/JABB/2024/v27i1691.

[14] Kanatas, P.J., & Gazoulis, I. (2022). The integration of increased seeding rates, mechanical weed control and herbicide application for weed management in chickpea (*Cicer arietinum* L.). *Phytoparasitica*, 50(1), 255-267. doi: 10.1007/s12600-021-00955-3.

[15] Khan, B.A., Nadeem, M.A., Najeeb Alawadi, H.F., Ayub, M.A., Mahmood, A., Abbas, T., Nijabat, A., Ameen, M., Abdullah, F., Oraby, H., & Elnaggar, N. (2024). An overview of the role of nanoherbicides in tackling challenges of weed management in wheat: A novel approach. *Green Processing and Synthesis*, 13(1), article number 20240021. doi: 10.1515/gps-2024-0021.

[16] Khasraw, M.N., Kareem, S.H., Mustafa, K.M., Aziz, O.K., Arif, M., Anwar, A., & Hussain, M. (2023). Integrated weed management in wheat by using sowing time, seed rate and herbicides. *Advances in Weed Science*, 41, article number e020230037. doi: 10.51694/AdvWeedSci/2023;41:00022.

[17] Kumar, V., Singh, M., Kaur, R., & Jhala, A.J. (2023). The scenario of herbicide-resistant weeds: Management challenges and perspectives. *Indian Journal of Weed Science*, 55(2), 123-132. doi: 10.5958/0974-8164.2023.00023.0.

[18] Kumari, A., Price, A.J., Korres, N., Gamble, A., & Li, S. (2023). Influence of a cereal rye cover crop on the critical period for weed control in soybean. *Weed Technology*, 37(1), 25-33. doi: 10.1017/wet.2022.100.

[19] Levene, H. (1960). Robust tests for equality of variances. In I. Olkin (Ed.), *Contributions to probability and statistics: essays in honor of harold hotelling* (pp. 278-292). Redwood City: Stanford University Press.

[20] McDonald, S.T., Sarangi, D., Rees, J.M., & Jhala, A.J. (2023). A follow-up survey to assess stakeholders' perspectives on weed management challenges and current practices in Nebraska, USA. *Agrosystems, Geosciences & Environment*, 6(3), article number e20425. doi: 10.1002/agg2.20425.

[21] Raza, A., Ali, H.H., Zaheer, M.S., Iqbal, J., Seleiman, M.F., Sattar, J., Ali, B., Khan, S., Arjumend, T., & Chauhan, B.S. (2023). Bio-ecology and the management of *Chenopodium murale* L.: A problematic weed in Asia. *Crop Protection*, 172, article number 106332. doi: 10.1016/j.cropro.2023.106332.

[22] Renton, M., Willse, A., Aradhya, C., Tyre, A., & Head, G. (2024). Simulated herbicide mixtures delay both specialist monogenic and generalist polygenic resistance evolution in weeds. *Pest Management Science*, 80(11), 5983-5994. doi: 10.1002/ps.8331.

[23] Rudell, E.C., Zanrosso, B.A., Frandaloso, D., Giacomini, A.J., Spadotto, D.V., Vargas, L., Nunes, A., & Santos, F. (2023). Integrated weed management strategies in a long-term crop rotation system. *Advances in Weed Science*, 41, article number e020220053. doi: 10.51694/AdvWeedSci/2023;41:00026.

[24] Saile, M., Spaeth, M., & Gerhards, R. (2022). Evaluating sensor-based mechanical weeding combined with pre-and post-emergence herbicides for integrated weed management in cereals. *Agronomy*, 12(6), article number 1465. doi: 10.3390/agronomy12061465.

[25] Saile, M., Spaeth, M., Schwarz, J., Bahrs, E., Claß-Mahler, I., & Gerhards, R. (2023). Weed control in a pesticide-free farming system with mineral fertilisers. *Weed Research*, 63(3), 196-206. doi: 10.1111/wre.12581.

[26] Schwartau, V.V., Mykhalska, L.M., Makoveychuk, T.I., & Tretiakov, V.O. (2023). Identification of a herbicide-resistant biotype of Echinochloa crus-galli in Ukraine. *Biosystems Diversity*, 31(3), 297-304. doi: 10.15421/012334.

[27] Shapiro, S.S., & Wilk, M.B. (1965). An analysis of variance test for normality (complete samples). *Biometrika*, 52(3-4), 591-611. doi: 10.1093/biomet/52.3-4.591.

[28] Soni, J.K., Nibhoria, A., Punia, S.S., Yadav, D.B., Choudhary, V.K., Lalramhlimi, B., & Navik, O. (2023). Herbicide resistant Phalaris minor in India – history of evolution, present status and its management. *Phytoparasitica*, 51(2), 353-378. doi: 10.1007/s12600-022-01039-6.

[29] Tidemann, B.D., Harker, K.N., Shirtliffe, S., Willenborg, C., Johnson, E., Gulden, R., Lupwayi, N., Turkington, T., & Zuidhof, J. (2023). Using integrated weed management systems to manage herbicide-resistant weeds in the Canadian Prairies. *Frontiers in Agronomy*, 5, article number 1304741. doi: 10.3389/fagro.2023.1304741.

[30] Vijayarajan, V.B., Fealy, R.M., Cook, S.K., Onkokesung, N., Barth, S., Hennessy, M., & Forristal, P.D. (2022). Grass-weed challenges, herbicide resistance status and weed control practices across crop establishment systems in Ireland's mild Atlantic climate. *Frontiers in Agronomy*, 4, 1063773. doi: 10.3389/fagro.2022.1063773.

[31] Xuan, T.D., Khanh, T.D., & Minh, T.T. (2025). Implementation of conventional and smart weed management strategies in sustainable agricultural production. *Weed Biology and Management*, 25(1), article number e70000. doi: 10.1111/wbm.70000.

[32] Zadorozhnyi, V., Korniichuk, O., Chernelivska, O., & Suslyk, L. (2025). Efficiency of using herbicide combinations in grain corn crops. *Feeds and Feed Production*, 100, 127-135. doi: 10.31073/kormovyrobnytstvo2025100-10.

Інтегровані стратегії контролю сегетальної флори з урахуванням мультирезистентності до гербіцидів у зернових агроценозах

Олена Кобернюк
Кандидат сільськогосподарських наук, доцент
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
https://orcid.org/0000-0002-1380-7976
Олеся Городиська
Кандидат сільськогосподарських наук, доцент
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
https://orcid.org/0000-0001-8747-6957
Валерій Тарасюк
Кандидат сільськогосподарських наук, доцент
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
https://orcid.org/0000-0002-4207-1013

Анотація. Метою дослідження було встановити вплив поєднання гербіцидних і агротехнічних прийомів на структуру сегетальної флори, поширення стійких біотипів і продуктивність зернового агроценозу. У роботі застосували польові, вагові, морфометричні, ґрунтово-аналітичні та розрахункові методи зі статистичною обробкою результатів. Встановлено, що порівняння п'яти варіантів контролю показало різний ступінь перебудови бур'янового угруповання – від необробленого контролю до стандартної схеми, ротації діючих речовин, гербіцидно-агротехнічного варіанта та інтегрованої системи. Загальна кількість видів зменшувалася з 15 у контролі до 11 за стандартної схеми, 9 за ротації, 8 за поєднання гербіциду з агротехнікою та 6 за інтегрованого контролю. Кількість домінантних видів скоротилася з 5 до 2, а щільність бур'янів у фазу кущення – зі 126,4 до 42,6 шт./м^2. Індекс Шеннона знижувався від 2,31 до 1,36, що відображало зміну різнорідності флористичної структури. У блоці мультирезистентності стандартна схема лише частково обмежувала стійкі біотипи, ротація посилювала цей ефект, а гербіцидно-агротехнічний та інтегрований варіанти зменшували їхню участь у структурі бур'янової біомаси. Частка біотипів, стійких до інгібіторів ацетолактатсинтази, зменшилася з 60,8 % до 36,1 %, а післяобробна виживаність резистентних рослин – зі 100 % до 11,9 %. Репродуктивний блок характеризувався скороченням насіннєвої продуктивності з 15,8 до 1,9 тис. насінин/м^2 і зменшенням потенційної кількості сходів із ґрунтового банку з 84,6 до 24,1 шт./м^2. На цьому тлі врожайна реакція культури посилювалася від стандартної схеми до ротації, гербіцидно-агротехнічного варіанта та інтегрованої системи: біологічна врожайність зерна підвищилася з 4,08 до 6,14 т/га, а реалізація потенціалу врожайності – з 58,3 % до 87,7 %. Практична цінність дослідження полягає у використанні його результатів агрономами, фермерськими господарствами та виробниками зерна в технологіях вирощування зернових культур і схемах контролю бур'янів

Ключові слова: післяобробна виживаність; бур'янове угруповання; частка біотипів; ценотична напруга; біологічна врожайність