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OPTIMIZING POST-EMERGENCE HERBICIDE PROGRAMS FOR RAGWEED *(Ambrosia artemisiifolia)* AND ASSOCIATED BROADLEAF WEEDS IN SUNFLOWER

Maria Alexandra FERENCZ-IEPAN, Saida FEIER DAVID, Sandra Florina LELE, Florica Emilia MORARIU, Igori BALTA, Ioan PEȚ

University of Life Sciences "King Mihai I" from Timisoara, 119 Calea Aradului, Timisoara, Romania

Corresponding author email: saida.feierdavid@usvt.ro

Abstract

Ambrosia artemisiifolia is one of the most problematic weeds in sunflower cultures, with major agronomic, environmental and public health implications. A post-emergence, double application experimental field trial was conducted in western Romania in a tribenuron-tolerant sunflower hybrid. The control of Halauxifen-methyl and Halauxifen-methyl+Tribenuron-methyl mixtures with or without the adjuvant isodecyl alcohol ethoxylate against A. artemisiifolia, Cirsium arvense, Persicaria maculosa and Hibiscus trionum was visually evaluated during five assessment dates. Crop phytotoxicity was evaluated as well, which remained low and transient throughout the trial. Treatment efficacies were species-dependent and against A. artemisiifolia, a single application of halauxifen-methyl at 1 L/ha achieved the highest efficacy, reaching complete control at 14 and 50 days after application. In contrast, halauxifen-methyl at 1 L/ha+tribenuron-methyl at 45 g/ha+90% isodecyl alcohol ethoxylate at 0,1% V/V consistently provided the strongest and most consistent suppression of C. arvense, P. maculosa, and H. trionum, while simultaneously remaining among the most efficient treatments against ragweed. These findings indicate that optimized post-emergence herbicide treatment can provide effective broadleaf weed management in Tribenuron-tolerant sunflower while maintaining acceptable crop safety.

Key words*: chemical weed control, halauxifen methyl, herbicide efficacy, sunflower, tribenuron methyl.*

INTRODUCTION

Sunflower, *Helianthus annuus* L., is one of the most important oilseed crops in Romania, a country that ranks among the leading sunflower producers in the European Union (Stoicea et al., 2022). High and stable yields in this crop depend largely on effective weed management, as sunflower is frequently infested by a broad spectrum of dicotyledonous weed species that compete directly with the crop for light, water, and nutrients (Jursík et al., 2020; Máčajová et al., 2022; Pinke et al., 2010). Among the most problematic species are *Ambrosia artemisiifolia* L., *Cirsium arvense* L., *Persicaria maculosa* Gray, and *Hibiscus trionum* L. (Anastasiu et al., 2024; European Commission. Joint Research Centre., 2021; Stoicea et al., 2022). Their presence in sunflower fields reduces yield, affects crop uniformity, contributes to the persistence of the soil seed bank, and increases the risk of herbicide resistance development (Knolmajer et al., 2025; Pinke et al., 2010; Vink et al., 2012). Under these conditions, the development of selective and efficient weed control programs becomes essential.

Synthetic auxin herbicides represent an important class of compounds used in the post-emergence control of broadleaf weeds. These herbicides induce severe physiological and morphological disturbances in susceptible plants, ultimately leading to their death (Grossmann, 2010; Morderer, 2018).

Halauxifen-methyl is a next-generation synthetic auxin herbicide with systemic activity, absorbed through the leaves and translocated to meristematic tissues, where it mimics the action of indole-3-acetic acid and disrupts normal plant growth processes (Ludwig-Müller et al., 2021; McCauley et al., 2020; Xu et al., 2022). This results in tissue curvature, growth abnormalities, chlorosis, necrosis, and finally the death of the target weed. Previous studies have shown that halauxifen-methyl is effective against a wide range of annual and perennial broadleaf weeds, including species with reduced sensitivity to older herbicides (Mehdizadeh et al., 2020;

Morderer, 2018; Xu et al., 2022; Zimmer et al., 2018).

Tribenuron-methyl, a sulfonylurea herbicide classified in HRAC Group B, has a different mode of action, inhibiting acetolactate synthase and thereby blocking the biosynthesis of branched-chain amino acids essential for cell division and plant survival (Bozic et al., 2012; Busi et al., 2018; Yu & Powles, 2014). In sunflower, its use is restricted to tribenuron-methyl-tolerant hybrids, but when combined with halauxifen-methyl it may broaden the weed control spectrum and reduce the risk of resistance development by targeting distinct biochemical pathways (Máčajová et al., 2022; Xu et al., 2022; Zimmer et al., 2018). In practice, the efficacy of such mixtures may be further influenced by the use of adjuvants, which improve retention, spreading, foliar penetration, and systemic uptake of active ingredients (HERA, 2009; Mehdizabeh et al., 2020; Talmage, n.d.). This is particularly relevant when target weed species have waxy or pubescent leaves, or when applications are carried out under less favorable environmental conditions.

Although several herbicides are currently registered for sunflower protection, comparative data regarding the efficacy of different rates, active ingredient combinations, sequential applications, and the role of adjuvants in optimizing weed control remain limited. Recent work also shows that the effect of adjuvants depends strongly on their influence on spray properties, droplet behavior, and retention, rather than on a universal increase in efficacy (Basílio et al., 2024). This gap is also especially important under current agricultural conditions, where increasing pressure from herbicide-tolerant or resistant weed species and European policies aimed at reducing chemical inputs require more precise and sustainable treatment strategies (European Commission. Joint Research Centre, 2021; Jursík et al., 2020; Stoicea et al., 2022). This topic also fits within the broader European regulatory framework for invasive alien species management (Branquart et al., 2016).

Therefore, the present study was undertaken to identify effective and reliable weed control strategies against major invasive broadleaf species, with particular emphasis on *A. artemisiifolia*, in sunflower. Beyond its agronomic relevance, common ragweed also has a well-documented public-health impact because of its highly allergenic pollen, which contributes substantially to seasonal allergy burden across Europe (Lake et al., 2017; Schaffner et al., 2020).

The present study extends previous research by comparatively evaluating halauxifen-methyl and tribenuron-methyl under several application strategies, including reduced doses, higher doses, sequential treatments, and the addition of a 90% isodecyl alcohol ethoxylate adjuvant. The objectives were to assess herbicide efficacy against the main invasive broadleaf weeds present in the experimental field, to evaluate crop selectivity in sunflower, and to determine the contribution of the adjuvant to treatment performance. Through this approach, the study aims to provide applied information relevant to the optimization of herbicide programs and to the integration of these strategies into sustainable weed management systems targeting *A. artemisiifolia*.

MATERIALS AND METHODS

1. *Site description and crop establishment*

The field experiment was conducted in 2024 near Hodoș village, Timiș County, Romania (45°40′29″N, 21°48′58″E), on a clay loam soil with 39% sand, 33% clay, and 26% silt. Soil pH was 7.09, organic matter content was 10.2%, humus exceeded 6%, and cation exchange capacity ranged from 22 to 26 meq 100 g^{-1}. The area is characterized by a temperate-continental climate, with mean annual precipitation of approximately 600 mm and mean temperatures of 20-24°C during the main crop-development period.

Seedbed preparation included disking, harrowing, and leveling. Before sowing, a compound NPK fertilizer (15:15:15) was incorporated at 300 kg ha^{-1}. No additional phytosanitary treatments were applied during the growing season. The tribenuron-methyl-tolerant sunflower hybrid SUVEX (KWS), selected for compatibility with the Express® herbicide system, was sown on 15 April 2024 at 70 cm row spacing, targeting a final density of 62,000 plants ha^{-1}. This compatibility is

associated with ALS-based tolerance to tribenuron-methyl, enabling selective post-emergence use of sulfonylurea herbicides in the crop.

2. ***Experimental design and treatments***

The experiment was established as a randomized complete block design (RCBD) with four replications. Eight treatment variants were evaluated, including an untreated control. The treatment structure was designed to compare reduced-rate mixture programs, a sequential reduced-rate mixture, a higher-rate single-application mixture, a halauxifen-methyl reference treatment, and a standard mixture-based program supported by adjuvant.

Two application timings were used: application A on 15 May 2024 and application B on 21 May 2024. Application B was used only for the sequential treatment (T5).

The experimental design compared reduced-rate, sequential, reference, and standard mixture-based herbicide treatments under field conditions. To improve foliar uptake and support treatment efficacy, a 90% isodecyl alcohol ethoxylate adjuvant was included in the relevant mixture-based treatments (Mehdizabeh et al., 2020). The treatment structure is summarized in Table 1.

Table 1. The applied treatments used during this trial

Trt.	Timing	Active Ingredient	Dosage	
T1	A	halauxifen-methyl +tribenuron-methyl	25	g/ha
	A	90% isodecyl alcohol ethoxylate	0.1	% V/V
T2	A	halauxifen-methyl + tribenuron-methyl	30	g/ha
	A	90% isodecyl alcohol ethoxylate	0.1	% V/V
T3	A	halauxifen-methyl +tribenuron-methyl	40	g/ha
	A	90% isodecyl alcohol ethoxylate	0.1	% V/V
T4	A	halauxifen-methyl +tribenuron-methyl	50	g/ha
	A	90% isodecyl alcohol ethoxylate	0.1	% V/V
T5	A	halauxifen-methyl + tribenuron-methyl	25	g/ha
	A	90% isodecyl alcohol ethoxylate	0.1	% V/V
	B	halauxifen-methyl + tribenuron-methyl	25	g/ha
	B	90% isodecyl alcohol ethoxylate	0.1	% V/V
T6	A	halauxifen-methyl	1	L/ha
T7	A	halauxifen-methyl	1	L/ha
	A	tribenuron-methyl	45	g/ha
	A	90% isodecyl alcohol ethoxylate	0.1	% V/V
T8	-	UNTREATED CONTROL	-	-

Reduced-rate mixture treatments T1-T3 consisted of halauxifen-methyl + tribenuron-methyl applied once at total rates of 25, 30, and 40 g ha^{-1}, respectively, each combined with 90% isodecyl alcohol ethoxylate at 0.1% V/V. T4 consisted of a single application of the same mixture at 50 g ha^{-1} plus adjuvant. T5 was a sequential reduced-rate program in which the 25 g ha^{-1} mixture plus adjuvant was applied twice at a six-day interval. T6 was the halauxifen-methyl reference treatment applied alone at 1 L ha^{-1}. T7 consisted of halauxifen-methyl at 1 L ha^{-1} combined with tribenuron-methyl at 45 g ha^{-1} and adjuvant at 0.1% V/V. T8 was the untreated control. These combinations, doses and rates were selected according to technical recommendations in order to optimize efficacy and limit phytotoxicity (EPPO, 2022).

Each plot measured 21 m^2 (3 × 7 m) and consisted of four sunflower rows. A 1m buffer was maintained between plots and around the experimental perimeter to reduce spray drift. Evaluations were made in the central plot area to minimize edge effects.

3. ***Herbicide application***

Herbicides were applied post-emergence when sunflower plants were at 4-6 true leaves (Stefanic et al., 2023). The initial weed density was assessed before herbicide application using quadrat counts and converted to plants/m^2. The added values were 58.86 plants/m^2 for *A. artemisiifolia*, 8.57 plants/m^2 for *C. arvense*, 6.29 plants/m^2 for *P. maculosa*, and 6.86 plants/m^2 for *H. trionum*. At the time of application, the target weed species were at 3-8 true leaves. Treatment applications were performed using a portable compressed-air boom sprayer equipped with six flat-fan nozzles, calibrated to deliver 250 L ha^{-1} at a constant pressure of 500 kPa. The adjuvant used in the study was a 90% isodecyl alcohol ethoxylate formulation applied at 0.1% V/V in the relevant treatments. Applications were performed under favorable agrotechnical and meteorological conditions, and the second sequential treatment was applied under comparable field conditions.

4. ***Crop safety and weed-control assessments***

Crop selectivity and weed-control efficacy were assessed visually after treatment application. Crop safety was evaluated through phytotoxicity scoring, crop vigor, and visible morphological injury. Phytotoxicity was rated on a 0-100% scale, where 0 indicated no visible crop injury and 100 indicated complete crop destruction. Crop vigor was rated on the same scale, where 100% indicated optimal plant development and uniformity. Leaf and stem deformation symptoms were recorded separately to characterize transient treatment-related responses.

Weed control efficacy was estimated visually as percentage reduction in weed presence relative to the untreated control. Visual control ratings were determined for the dominant broadleaf weeds present in the field: *Ambrosia artemisiifolia*, *Cirsium arvense*, *Persicaria maculosa*, and *Hibiscus trionum*. All assessments were based on four field replicates. Assessments were conducted at 3, 7, 14, 28, and 50 days after application (DAA), matching the evaluation schedule presented below.

5. ***Statistical Analysis***

Statistical analyses were performed to evaluate the effects of herbicide treatments, the influence of evaluation time, and the interaction between these two experimental factors on crop response and weed-control efficacy.

The experimental design was analyzed as a two-factor structure, with treatment as Factor A and evaluation time as Factor B. Two-way analysis of variance (ANOVA) was used to assess the main and interaction effects of treatment and evaluation time on phytotoxicity, crop vigor, incidence and severity of leaf and stem deformation, and weed-control efficacy for *A. artemisiifolia*, *C. arvense*, *P. maculosa*, and *H. trionum*. When significant differences were detected, means were compared using the Least Significant Difference (LSD) test and Duncan's multiple range test to identify statistically distinct groups among treatments and evaluation times. Significance thresholds were set at $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$. All datasets fulfilled the assumptions of normality and homogeneity of variance, and no data transformation was required. To complement variance analysis, cluster analysis based on Euclidean distance was used to group treatments and evaluation times according to biological similarity. In addition, factor contribution analysis was used to estimate the relative contribution of treatment, evaluation time, and their interaction to the total observed variability, thereby highlighting the relative importance of each experimental factor.
All statistical analyses were conducted using STATISTICA 13.3 software (StatSoft, USA), while descriptive statistics and graphical outputs were prepared in Microsoft Excel. Results are presented as mean values ± standard error.

RESULTS AND DISCUSSIONS

The present study shows that the agronomic value of post-emergence herbicide programs in tribenuron-tolerant sunflower should be assessed not only by peak efficacy against a single target weed, but by the combined balance of crop selectivity, persistence of visible crop response, and consistency of suppression across the full broadleaf spectrum present in the field. Under the conditions of this experiment, all tested programs avoided persistent crop injury, but they differed clearly in the breadth and stability of weed control. This is especially important in sunflower, where early weed interference has direct consequences for crop performance. Recent work has shown that even short delays in weed removal can reduce plant height, head diameter, and 1000-kernel weight, and that the beginning of the critical period of weed control may occur around the 4-6 leaf stage (Savić et al., 2025; Stefanic et al., 2023). This closely matches the application window used here and reinforces the agronomic importance of timely post-emergence intervention (Stefanic et al., 2023).

1. ***Phytotoxicity assessment***

A first important outcome of the study is the favorable crop tolerance of the tested hybrid. Table 2 presents the mean phytotoxicity values

visually assessed across four field replications for each treatment.

Two-way ANOVA showed that both treatment, Factor A, and evaluation time, Factor B, had a highly significant effect on phytotoxicity, with $F(7,148) = 11.03$, $p < 0.001$ and $F(4,148) = 27.34$, $p < 0.001$, respectively. The interaction between treatment and evaluation time was also significant, indicating that the crop response varied depending on the time of assessment. Student's test, compared with the untreated control T8, showed that T1, T2, and T3 did not induce statistically significant phytotoxicity, while T4 and T5 caused only slight and biologically acceptable visual effects. The highest phytotoxicity values were recorded in T6 and T7, at about 10%, indicating a more intense physiological response than in the other treatments.

In terms of evaluation time, phytotoxicity reached its maximum at the first assessment, 17 May, where it reached 3.75%, and then declined progressively to 0% at the final evaluation. This pattern indicates that the visual symptoms were concentrated in the earliest period after herbicide application and diminished as the crop recovered.

Table 2. Mean phytotoxicity values recorded after herbicide application

Treatment	Phytotoxicity (%)				
	3 DAA	7 DAA	14 DAA	28 DAA	50 DAA
T1	0	0	0	0	0
T2	0	0	0	0	0
T3	0	0	0	0	0
T4	5	0	0	0	0
T5	5	0	0	0	0
T6	10	5	0	0	0
T7	10	5	0	0	0
T8	0	0	0	0	0

Cluster analysis supported the same trend. T1, T2, T3, and T8 formed a group without visible symptoms, T4 and T5 formed an intermediate group with slight responses, and T6 and T7 formed a distinct group with more evident symptoms. Likewise, the first assessment date was clearly separated from the later evaluations, while the last three observation dates were grouped by the absence of symptoms. Although the differences among treatments and evaluation dates were statistically significant, phytotoxicity remained low and transient and disappeared completely by 50 days after application. These results indicate good crop selectivity and a strong recovery capacity of the tested sunflower hybrid. Similar temporary responses to synthetic auxin herbicides, including halauxifen-methyl, have also been reported in the literature, without long-term negative effects on crop development when treatments are applied at the appropriate growth stage and under suitable agronomic conditions (Grossmann, 2010; Morderer, 2018; Zimmer et al., 2018)

2. ***Crop vigor assessment***

Visual assessment of crop vigor showed that this parameter remained at a very high level throughout the entire observation period. The mean values of four replications per treatment are presented in Table 3.

Throughout the entire assessment period, all treated variants, T1-T7, maintained constant values of 100%, indicating very good tolerance of the sunflower crop to the applied treatments and the absence of any visible negative effect on plant development. The only reduction in crop vigor was recorded in the untreated control, T8, where values declined to 95% and then to 85% at the last two evaluations.

Table 3. Mean crop vigour values recorded after herbicide application

Treatment	Crop Vigor (%)				
	3 DAA	7 DAA	14 DAA	28 DAA	50 DAA
T1	100	100	100	100	100
T2	100	100	100	100	100
T3	100	100	100	100	100
T4	100	100	100	100	100
T5	100	100	100	100	100
T6	100	100	100	100	100
T7	100	100	100	100	100
T8	100	100	100	95	85

Analysis of variance showed that both treatment and evaluation time had a significant effect on crop vigor, and the interaction between the two factors was also significant. Student's test confirmed that the treated variants maintained a very high level of crop vigor, without visible reductions during the assessment period, whereas the untreated control showed a progressive decline in this parameter toward the end of the observation period. Cluster analysis supported the same

pattern, grouping the treated variants in an area characterized by high and stable vigor values, clearly distinct from the response of the untreated control.

These results show that the observed statistical differences were mainly driven by the decline in crop vigor in the untreated control, under conditions where weed competition was not controlled. From a biological point of view, the crop maintained an optimal level of vigor in all treated variants, confirming the very good selectivity of the tested herbicides and the good tolerance of the sunflower hybrid used in the experiment. Compared with the untreated control, the results also support the indirect role of herbicide intervention in maintaining crop physiological status and competitiveness through the reduction of weed pressure.

3. *Morphological symptoms induced by herbicide treatments*

To assess the morphological response of the crop to the applied treatments, leaf and stem deformation symptoms were recorded in terms of both severity and incidence. The values presented in Table 4 and Table 5 represent the mean of the four replications for each treatment and evaluation time, while the statistical interpretation was based on the full set of individual observations.

The highest leaf deformation values were recorded in T6 and T7 at 3 days after application, where they reached 10%, and declined to 5% at 7 days after application. In T4 and T5, symptoms were weakly expressed, with values of 5% at 3 days after application, and then disappeared completely. No leaf deformation was observed in T1, T2, T3, or T8 during the entire assessment period. In terms of incidence, symptoms were recorded only at 7 days after application, when T6 and T7 reached 100%, while all other treatments remained at 0%. At the later evaluations, incidence values were 0% for all treatments, showing that these symptoms were slight and transient under field conditions. Statistical analysis confirmed highly significant differences among treatments and evaluation times for both leaf deformation severity and incidence, $p < 0.001$. Stem deformation symptoms were observed only in some treatment variants at the first evaluation times. T4 and T5 reached values of 5% at 3 days after application, whereas higher values, 10%, were recorded in T6 and T7. At 7 days after application, deformation persisted only in T6 and T7, with values of 5%, and by 50 days after application all values had returned to 0%. The incidence data followed the same pattern. Thus, at 7 days after application, all plants in T6 and T7 showed slight stem deformation, whereas all other treatments recorded an incidence of 0%.

Table 4. Leaf deformation severity and incidence (%) at different evaluation times

Treatment	Leaf deformation			Leaf deformation incidence	
	3 DAA	7 DAA	50 DAA	7 DAA	50 DAA
T1	0	0	0	0	0
T2	0	0	0	0	0
T3	0	0	0	0	0
T4	5	0	0	0	0
T5	5	0	0	0	0
T6	10	5	0	100	0
T7	10	5	0	100	0
T8	0	0	0	0	0

At the final evaluation, stem deformation incidence was 0% in all experimental variants. Statistical analysis showed highly significant differences among treatments and evaluation times, $p < 0.001$, indicating that both treatment type and evaluation timing significantly influenced the occurrence of stem deformation. Comparison with the untreated control showed very significant differences in T6 and T7 and significant differences in T4 and T5, whereas T1, T2, and T3 did not differ significantly.

Table 5. Stem deformation severity and incidence (%) at different evaluation times

Treatment	Stem deformation			Stem deformation incidence	
	3 DAA	7 DAA	50 DAA	7 DAA	50 DAA
T1	0	0	0	0	0
T2	0	0	0	0	0
T3	0	0	0	0	0
T4	5	0	0	0	0
T5	5	0	0	0	0
T6	10	5	0	100	0
T7	10	5	0	100	0
T8	0	0	0	0	0

Cluster analysis confirmed this separation by distinguishing variants without symptoms from those in which stem deformation was more evident. Factor contribution analysis also

showed that treatment had a greater influence than evaluation time on stem deformation variability. Overall, the maximum values remained low, the symptoms declined over time, and their effects were reversible, confirming the good tolerance of the sunflower hybrid to the applied treatments.

Phytotoxicity and deformation symptoms were confined to the early post-application period and disappeared at later assessments, indicating that visible crop responses were transient rather than persistent. Even the strongest early responses, observed in T6 and T7, did not translate into lasting loss of crop performance. This pattern is consistent with previous studies describing short-lived auxinic symptomatology after post-emergence herbicide application, including temporary deformation, chlorosis, or growth disturbance, without evidence of sustained injury when treatments are applied at appropriate crop stages and under suitable agronomic conditions (Grossmann, 2010; Jursík et al., 2020; Morderer, 2018; Zimmer et al., 2018). From a practical standpoint, these results indicate that early visual stress should not automatically be interpreted as agronomically unacceptable when recovery is rapid and complete.

4. ***Herbicide efficacy on target weed species***

Herbicide efficacy was evaluated against the four main broadleaf weed species identified in the experimental field, namely *A. artemisiifolia*, *C. arvense*, *P. maculosa*, and *H. trionum*. Across all four species, efficacy generally increased from 7 to 14 days after application and then remained stable or changed only slightly by the final evaluation, indicating that treatment response became more pronounced after the first post-application interval.

The comparative analysis of the four weed species revealed clear differences among the tested variants in both control efficacy and the ability of the treatments to maintain this effect over time. This interpretation is consistent with current crop-weed competition frameworks, which emphasize that agronomic response depends not only on the presence of individual weeds, but also on the composition, persistence, and aggressiveness of the competing weed community (Savić et al., 2025).

Treatment ranking was species-dependent. Against *A. artemisiifolia*, the highest species-specific efficacy was recorded in T6, where control reached 95.0% at 7 DAA and 100.0% at both 14 and 50 DAA. T7 also performed strongly against this species, with values of 86.25%, 97.5%, and 97.5%, respectively. The comparative evolution of treatment efficacy across the four evaluated weed species is illustrated in Figure 1.

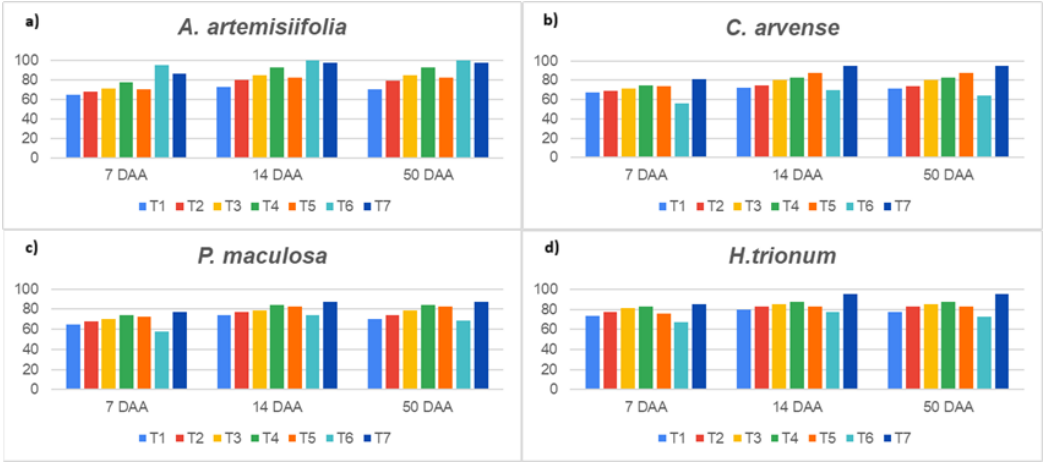


Figure 1. Comparative herbicide efficacy (%) against *A. artemisiifolia*, *C. arvense*, *P. maculosa*, and *H. trionum* at 7, 14, and 50 days after application. Values represent the mean of four field replications for each treatment

The values shown represent the mean efficacy recorded across the four field replications for each treatment at the selected evaluation timings. These dates were chosen because they reflect the main stages of post-emergence treatment performance, namely the fully expressed control phase, the persistence of efficacy over time, and the final level of weed suppression.

In contrast, T7 provided the strongest and most stable suppression of the other three species, reaching 95.0% against *C. arvense*, 87.5% against *P. maculosa*, and 95.0% against *H. trionum* at the later assessments. T4 and T5 also maintained high efficacy across several species, particularly against *C. arvense* and *P. maculosa*. T1 and T2 remained at intermediate levels, while T6, despite its excellent performance against *A. artemisiifolia*, showed weaker final control of *C. arvense*, *P. maculosa*, and *H. trionum*, with 63.75%, 68.75%, and 72.5%, respectively. The reduced-rate treatments T1, T2 and T3 should therefore be interpreted primarily as high selectivity but lower intensity control options. Their main strength was the absence of visible phytotoxicity and the preservation of maximal crop vigor throughout the experiment. However, their efficacy remained consistently below that of the stronger mixture-based treatments, particularly against the more difficult broadleaf species. From a management perspective, these treatments may be useful where crop safety is prioritized and weed pressure is moderate, but the present data do not support treating them as broadly equivalent alternatives to T4, T5, or T7 for robust spectrum-wide suppression.

Statistical analysis supported these differences. Treatment had a highly significant effect on efficacy in all four species, with $p < 0.001$ in each case. Evaluation time was also significant, reflecting the increase in efficacy after application and the stabilization of treatment response over time. The treatment × time interaction was significant as well, showing that treatment performance changed across evaluation dates. For *H. trionum*, the interaction was significant at $p < 0.01$, while for the other species it was highly significant, $p < 0.001$. Student's test confirmed that all herbicide treatments were significantly more effective than the untreated control. For *A. artemisiifolia*, efficacy means ranged from 63.3% to 90.4%, with T7, T5, and T4 grouped among the most effective treatments. For P. maculosa, T7 reached a mean efficacy of 84.2%, followed by T4, T5, and T3.

Cluster analysis supported the same general trend and showed a clear separation among treatments according to their efficacy level. For *A. artemisiifolia*, the clustering pattern indicated the clearest separation among treatments, distinguishing the untreated control from the most effective variants and from those with intermediate or lower efficacy. The upper part of the dendrogram, from Figure 2 was associated with treatments showing the highest and most persistent control, whereas the remaining active variants were grouped at lower efficacy levels.

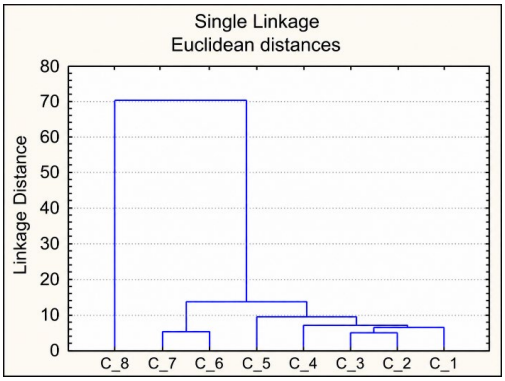


Figure 2. Dendrogram of herbicide treatments grouped according to the similarity of their efficacy in controlling *A. artemisiifolia* where C_1 = T1, C_2 = T2, C_3 = T3, C_4 = T4, C_5 = T5, C_6 = T6, C_7 = T7, and C_8 = T8, the untreated control

This trend was in agreement with the efficacy data, which placed T6 and T7 at the top of the response range and identified T4 as the strongest mixture-based treatment below them. For *C. arvense*, the untreated control formed a distinct cluster, T6 was separated as the least effective herbicide treatment, and the remaining variants were grouped within a higher-efficacy class. For *P. maculosa*, cluster analysis distinguished a high-efficacy group including T7, T4, T5, and T3, an intermediate group represented by T2 and T1, and a low-efficacy group represented by T6. For *H. trionum*, the untreated control and T7 were

clearly differentiated, while the remaining herbicide-treated variants were grouped at an intermediate efficacy level.

In *C. arvense*, *P. maculosa*, and *H. trionum*, factor contribution analysis showed that treatment explained most of the observed variability, with values of 96.9%, 98.4%, and 98.4%, respectively, whereas the contribution of evaluation time remained low, between 0.8% and 2.0%. These statistical results indicate that the herbicide program itself was the main determinant of control efficacy.

Overall, T4, T5, and especially T7 provided the most favorable results by combining high efficacy with good crop selectivity. T4, based on a single application of halauxifen-methyl + tribenuron-methyl at a total rate of 50 g/ha, provided a favorable balance between weed control and crop tolerance. Although it did not surpass T7, T4 clearly outperformed the lower-rate programs and, in several cases, approached the upper performance range of the strongest treatments. This makes T4 a practically relevant option because it achieved a favorable balance between crop safety and efficacy without requiring a sequential application strategy. In sunflower systems where strong broadleaf suppression is required, but a less intensive mixture-based treatment is preferred, T4 may represent a useful compromise.

T5 (halauxifen-methyl + tribenuron-methyl 25 g/ha + adjuvant), applied sequentially, maintained good efficacy and, in some of the evaluated species, provided better persistence of the control effect, suggesting that this strategy may be useful under conditions of high infestation pressure or staggered weed emergence. This may be particularly relevant where a single application does not adequately control weeds that emerge later, as emergence patterns can strongly influence the timing and persistence of post-emergence control (Marschner et al., 2024).

T6, corresponding to halauxifen-methyl applied at the registered dose, was highly effective against *A. artemisiifolia*, but its weaker performance against the other species indicates a narrower control spectrum than the variants based on active ingredient mixtures. This result is also important from a resistance-management perspective. Even when a single-active treatment performs very well against ragweed, more diversified post-emergence treatment strategies remain a safer agronomic option when resistance is developing in parallel. Recent work has shown that common ragweed is capable of evolving diverse ALS-resistance mechanisms within and among field populations, reinforcing the value of treatment structures that reduce dependence on a single mode of action (Busi et al., 2018; Knolmajer et al., 2025; Loubet et al., 2023). More recent field evidence has also documented broader multi-resistance patterns in common ragweed populations (D'Amico et al., 2024). In line with integrated weed-management strategies, these treatments should be combined with complementary agronomic and mechanical measures such as crop rotation, inter-row cultivation, field hygiene, and reduction of the soil seed bank, so that chemical control remains an effective but not isolated component of a durable control strategy (Kalogiannidis et al., 2022; Naeem et al., 2022).

The limitations of the present study should also be acknowledged. The experiment was designed to assess post-emergence weed-control efficacy and visible crop tolerance, but did not include yield, thousand-seed weight, or seed-quality measurements. However, the evaluation period up to 50 DAA covered the critical period of weed control in sunflower, during which weed interference can strongly affect yield components. Therefore, the clear differences in early and sustained weed suppression observed among treatments remain agronomically relevant, as effective weed control during this interval supports the protection of crop development and yield components.. Additional work is needed to determine whether the broad-spectrum efficacy advantage of T7 translates into improved productivity under field conditions and whether the strong ragweed control observed with T6 has any distinct effect on final crop output.

CONCLUSIONS

The control of problematic broadleaf weeds in sunflower remains a major agronomic challenge, especially where high infestation pressure and the need to reduce chemical inputs require more precise and flexible herbicide strategies.

This study showed that effective chemical control of the main broadleaf weeds in sunflower, namely *A. artemisiifolia*, *C. arvense*, *P. maculosa*, and *H. trionum*, can be achieved through optimized combinations of halauxifen-methyl and tribenuron-methyl. The results showed that high efficacy and good crop selectivity were not limited to standard rates only. Reduced-rate mixtures and sequential applications also gave satisfactory results when treatments were applied within the optimal window, namely when the sunflower crop had good tolerance and the weeds were still at early growth stages. This agrees with previous studies showing that optimized lower-dose herbicide strategies can still contribute meaningfully to ragweed suppression and more sustainable control approaches (Wang et al., 2022).

The trial also showed that some minor and transient physiological responses, such as slight leaf or stem deformation, may occur after application, but these did not affect overall crop performance. This confirms that treatment efficacy should be interpreted together with crop tolerance when new herbicide strategies are evaluated.

Another important result was the positive role of the isodecyl alcohol ethoxylate adjuvant, which improved uptake and helped maintain high control efficacy, especially in the strongest treatment variants. This suggests that adjuvant-supported treatments may offer greater flexibility for optimizing post-emergence weed control while maintaining a high level of performance.

Overall, the results support the integration of chemical control into broader weed-management systems. This is in line with recent ragweed reviews showing that long-term suppression of *A. artemisiifolia* requires diversified and integrated management strategies rather than reliance on a single control approach (Knolmajer et al., 2025). The most promising treatments, especially T4, T5, and T7, may be used successfully in sunflower fields heavily infested with problematic broadleaf weeds. Their effect can be strengthened further when combined with complementary agronomic practices such as crop rotation, inter-row cultivation, mulching, and early field hygiene.

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