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DOI: 10.1017/wet.2025.10050

Short title: Soybean herbicide program

Full-season herbicide programs to control a seven-way-resistant Palmer amaranth accession under soybean technologies

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Abstract

A seven-way herbicide-resistant Palmer amaranth accession (MSR2) was identified in AR. Herbicide programs providing season-long control of this problematic accession need to be investigated, especially within the current soybean portfolio. Therefore, this study aimed to evaluate the efficacy of different soybean herbicide programs for controlling seven-way-resistant Palmer amaranth accession, MSR2, emphasizing the contribution of residual herbicides to full-season suppression. Field experiments were conducted in 2022 and 2023 in Fayetteville, AR, in an area infested by MSR2. A total of 14 herbicide programs were tested, targeting available soybean technologies that enable glyphosate, glufosinate, dicamba, and 2,4-D. All herbicide programs had one or two postemergence herbicides applied at early postemergence (EPOST) and late postemergence (LPOST). Additionally, eight herbicide programs included residual herbicides at preemergence (PRE; *S*-metolachlor plus metribuzin) and EPOST (*S*-metolachlor). A nontreated control was included for comparison. Visible Palmer amaranth control (%) was assessed at LPOST and 2 weeks after LPOST (2 WA LPOST). Palmer amaranth plants were counted from two 0.25 m^2 quadrats randomly marked at each evaluation, and the density reduction (%) was calculated compared to the nontreated control. Preplanned orthogonal contrasts were conducted to compare herbicide programs with or without residual herbicides. Overall, in both years, the highest MSR2 control at both evaluations was observed in the herbicide programs that included residuals at PRE and EPOST with postemergence treatments of 2,4-D or dicamba (single or mixed). For Palmer amaranth density, herbicide programs that relied on residuals at PRE and EPOST with sequential postemergence applications of 2,4-D plus glufosinate or dicamba plus glyphosate obtained higher reduction levels. Findings reveal that the addition of residual herbicides is crucial in controlling multiple-herbicide-resistant Palmer amaranth biotypes, like MSR2. Herbicide programs based solely on postemergence applications were ineffective in controlling accession MSR2.

Nomenclature: 2,4-D; dicamba; glufosinate; glyphosate; Palmer amaranth, *Amaranthus palmeri* S. Watson; soybean, *Glycine max* (L.) Merr.

Keywords: multiple herbicide resistance; overlapping herbicides; residual herbicides; season-long weed control; synthetic auxins

Introduction

Arkansas is one of the top soybean-producing states in the United States, currently ranking 10th and 1st in soybean production in the national and southern rankings, respectively (USDA-NASS 2025). In recent decades, one major threat to soybean production in AR is the long-standing struggle to control Palmer amaranth effectively. Early records of this weed reported its potential to adapt and compete, as described by the botanist Dr. Sauer: “Of all the dioecious amaranths, *A. palmeri* has been by far the most successful as a weedy invader of artificial habitats” (Sauer 1957). Palmer amaranth is a highly competitive dioecious weed species that exhibits a rapid growth rate and prolific seed production (around 600,000 seeds plant^{-1}) (Horak and Loughin 2000; Keeley et al. 1987). Palmer amaranth interference with soybean can substantially impact crop canopy formation and grain yield (Klingaman and Oliver 1994). Therefore, it is essential to remove Palmer amaranth early in the crop season.

Glyphosate [Weed Science Society of America (WSSA)/Herbicide Resistance Action Committee (HRAC) group 9] and fomesafen (WSSA/HRAC group 14) were among the primary postemergence herbicides used to control Palmer amaranth in genetically modified and conventional soybean fields in AR, respectively. However, with the confirmation of Palmer amaranth accessions resistant to glyphosate and/or fomesafen, fewer options remained available (Norsworthy et al. 2008; Salas et al. 2016). Recently, resistance to postemergence herbicides from WSSA/HRAC groups 4, 5, 10, and 27 has been detected among Palmer amaranth populations from AR (Carvalho-Moore et al. 2025; Hwang et al. 2023; Priess et al. 2022; Singh et al. 2018). Glufosinate-resistant (WSSA/HRAC group 10) Palmer amaranth accessions were confirmed in AR in 2022 (Priess et al. 2022). Glufosinate is a crucial postemergence herbicide for controlling many resistant Palmer amaranth accessions, and the presence of resistant accessions will likely be an issue to farmers in infested areas.

Following the initial report of glufosinate resistance, further studies were conducted with glufosinate-resistant Palmer amaranth accessions, revealing the co-occurrence of resistance to postemergence herbicides from a total of seven sites of action (Carvalho-Moore et al. 2025). The accession MSR2, which showed high levels of glufosinate resistance, was selected for additional field experiments testing the efficacy of different preemergence (PRE) and postemergence herbicides. Under field conditions, a higher number of PRE herbicides achieved satisfactory control ($\geq$ 90%) of MSR2 for longer periods compared to postemergence chemistries tested.

https://doi.org/10.1017/wet.2025.10050 Published online by Cambridge University Press

Paraquat was the only postemergence herbicide to obtain MSR2 control above 90% (Carvalho-Moore et al. 2025). Previous research with other herbicide-resistant Palmer amaranth or waterhemp [*Amaranthus tuberculatus* (Moq.) J.D. Sauer] accessions showed that control was achievable for longer periods with full-season herbicide programs that included a robust PRE application followed by postemergence plus residual herbicides (Arneson et al. 2023; Chahal et al. 2018; Kumar et al. 2019; Meyer et al. 2015). Limited studies are available that precisely assess whole-season control programs for multiple herbicide-resistant Palmer amaranth accessions. Overall, previous investigations with different multiple herbicide-resistant Palmer amaranth accessions have demonstrated that control can be achieved through timely PRE and postemergence herbicide programs that incorporate effective residual herbicides (Chahal et al. 2018; Liu et al. 2021; Meyer et al. 2015).

Given the increasing number of herbicide-resistant Palmer amaranth accessions with multiple resistance (Heap 2025) and the limited number of effective postemergence soybean herbicides, it is necessary to develop herbicide programs that will successfully provide full-season control of troublesome accessions carrying resistance to multiple herbicides within the current soybean portfolio. Therefore, this study aimed to evaluate the efficacy of different soybean herbicide programs for controlling a seven-way herbicide-resistant Palmer amaranth accession, MSR2, with emphasis on the contribution of residual herbicides to season-long weed control.

Materials and Methods

Field experiments were conducted to evaluate the potential of different soybean herbicide programs in controlling Palmer amaranth accession harboring herbicide resistance to multiple herbicides, like MSR2. To have a field infested with MSR2, seeds of this accession were spread over a 2 hectares (ha) secluded area at the Milo J. Shult Agricultural Research and Extension Center in Fayetteville, AR (36°5’31” N, 94°11’05” W), and incorporated with a rototiller in the summer of 2021 (Carvalho-Moore et al. 2025). After Palmer amaranth plants germinated, glufosinate at 656 g ai ha^{-1} (labeled rate) was applied to the entire field, and MSR2 survivors were allowed to produce seeds. The selected field had no previous presence of Palmer amaranth and was previously cultivated with pasture before the experiment began. The field consisted of Captina silt loam soil with an organic matter of 2.6% and a pH of 6.6. In consecutive years, the whole field was mowed and sprayed with glufosinate at termination, and survivors were allowed

https://doi.org/10.1017/wet.2025.10050 Published online by Cambridge University Press

to produce seeds for the following year.

A randomized complete block design with four replications was used, and the experiment was repeated in 2022 and 2023. In both years, plots measured 1.8-m wide by 6-m long. Although the experiment targeted soybean technologies, it was conducted soybean-free due to the variety of herbicides used. The targeted traits were Roundup Ready® or Liberty Link® (programs 2, 3, 4, and 5), Enlist® (programs 6, 7, 8, 9, 10, 11, and 12), and XtendFlex® (programs 13, 14, and 15) as shown in Table 1. A nontreated control was included for comparison.

Due to the varying rainfall conditions, the days between preemergence (PRE), early postemergence (EPOST), and late postemergence (LPOST) treatments varied over the years. In 2022, the PRE treatments were applied on June 29th (initiation date) and did not receive more than 1 cm of rainfall up to 30 days after the treatment (Figure 1). As a result, Palmer amaranth germination was delayed, and EPOST applications occurred 40 days after PRE treatments on August 8th when Palmer amaranth plants were 5 to 10 cm in height. The LPOST applications occurred 13 days after EPOST. In 2023, the PRE treatments were applied on June 6th, and within 5 days, the field received above 4 cm of rainfall, which enabled germination and herbicide activation. The EPOST applications occurred 21 days after PRE on June 27th when Palmer amaranth plants were 8 to 12 cm in height. The LPOST applications occurred 22 days after EPOST. The weather station from which the rainfall data (Figure 1) was obtained and the field used for the experiment were located approximately 1 km apart.

A CO_2-pressurized backpack sprayer equipped with a four-nozzle handheld boom and calibrated to deliver 140 L ha^{-1} at 4.8 km h^{-1} was used for herbicide applications. The treatments that included the herbicide dicamba used 110015 TTI nozzles (Turbo Teejet Induction; TeeJet® Technologies, Glendale Heights, IL, USA), while 110015 AIXR nozzles (Air Induction Extended Range; TeeJet® Technologies, Glendale Heights, IL, USA) were used for the other herbicides.

Visible Palmer amaranth control was assessed at LPOST and 2 weeks after LPOST (2 WA LPOST). Control was evaluated on a 0 to 100% scale using the Frans et al. (1986) scale, where 0% represented no control and 100% represented complete weed mortality. Besides control, Palmer amaranth plants were counted at each evaluation from two 0.25 m^2 quadrats randomly marked in each plot at the PRE application. Density reduction was calculated as a percentage of the nontreated control for each replication, using Equation 1:

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$$\text{Density reduction (\%)} = \left[\frac{\text{nontreated} - \text{individual plot}}{\text{nontreated}}\right] \times 100 \ [1]$$

Additionally, preplanned orthogonal contrasts were conducted to compare herbicide programs with (programs 4, 5, 7, 9, 10, 12, 14, and 15) and without (programs 2, 3, 6, 8, 11, and 13) residual herbicides.

Data Analysis

Data collected were subjected to analysis of variance (ANOVA) in JMP Pro 18.0.2 (SAS Institute, Cary, NC). Due to a significant year-by-treatment interaction, data were analyzed by year. Following Shapiro-Wilk normality and goodness of fit tests, Palmer amaranth control and density reduction data were analyzed using the generalized linear mixed model with a beta and normal distribution, respectively (Gbur et al. 2012). Means were separated using Fisher's protected least significant difference (LSD; $\alpha = 0.05$), if significant. Graphs depicting rainfall data were produced in SigmaPlot 15.0 (Systat Software Inc., San Jose, CA, USA).

Results and Discussion

Significant differences were observed across the multiple soybean herbicide programs evaluated for controlling the troublesome accession MSR2 (Table 2 and Table 3). Overall, in both years, the highest MSR2 control levels were observed in the herbicide programs that included residuals at PRE and EPOST plus 2,4-D or dicamba, alone or mixed with other postemergence herbicides, at EPOST and LPOST (Table 2). In these herbicide programs, MSR2 control ranged from 88% to 97% at LPOST and increased at 2 WA LPOST, with average control ranging from 90% to 99%. Previous investigations with robust PRE applications, followed by synthetic auxin applications (2,4-D or dicamba) at postemergence, revealed that crops obtained similar improved control in various Palmer amaranth or waterhemp populations (Duenk et al. 2023; Houston et al. 2020; Kaur et al. 2024; Kumar et al. 2019; Meyer et al. 2015).

In this study, the application of 2,4-D EPOST, plus effective residual herbicides PRE and EPOST, resulted in cleaner plots at termination, with control levels > 90% at the 2 WA LPOST evaluation (Table 2). The accession MSR2 was previously confirmed to carry resistance to 2,4-D, glufosinate, and glyphosate, all of which were used in this study (Carvalho-Moore et al. 2025; Priess et al. 2022). High resistance levels were observed in MSR2 to glufosinate and glyphosate, ranging from 21- up to 110-fold compared to the susceptible accessions. Conversely, low-level resistance was observed for 2,4-D, ranging from 2.8- to 4.2-fold (Carvalho-Moore et al. 2025; Priess et al. 2022). The Palmer amaranth density at EPOST differed between years, with

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nontreated plots averaging 66 and 470 plants m^{-2} in 2022 and 2023, respectively. Additionally, the programs that received PRE applications showed an average MSR2 control at EPOST of 92% and 97% in 2022 and 2023, respectively, which illustrated the effectiveness of these herbicide programs, regardless of 2,4-D resistance. Nonetheless, additional practices should be introduced to minimize further increases in resistance levels, and the continuous use of 2,4-D, with or without residuals, is unlikely to be a long-term option in fields infested with a problematic Palmer amaranth accession, such as MSR2. Moreover, other Palmer amaranth accessions resistant to 2,4-D have been identified, further broadening the area where 2,4-D-based herbicide systems should be used with caution (Carvalho-Moore et al. 2025; Hwang et al. 2023; Kumar et al. 2019).

Of the herbicide programs evaluated, program 15 (Table 1), which included residuals at PRE and EPOST with a mixture of dicamba plus glyphosate at EPOST and LPOST, achieved outstanding Palmer amaranth control (≥ 96%) in both years and evaluations (Table 2). Likewise, studies conducted in Georgia and North Carolina with glyphosate-resistant Palmer amaranth populations achieved increased control in systems that included PRE herbicides with dicamba plus glyphosate at EPOST and mid-postemergence (Cahoon et al. 2015). However, postemergence applications of dicamba in soybean are currently not permitted in the United States (Hightower 2024), limiting options that farmers have available to control Palmer amaranth. Additionally, Palmer amaranth accessions resistant to dicamba have been reported in AR and TN (Carvalho-Moore et al. 2025; Foster and Steckel 2022).

The program that consisted of sequential applications of 2,4-D plus glufosinate at EPOST and LPOST with no residuals was less effective in controlling MSR2 in 2023. Low control was also observed in the following year when glufosinate was added to 2,4-D in a different study evaluating the effect of mixtures and rates of 2,4-D alone or mixed with different herbicides on MSR2 control (Baxley et al. 2025). Glufosinate and 2,4-D are often applied in combination, and an additive effect has been observed in Palmer amaranth and other species (Chitband et al. 2025; Ganie and Jhala 2017; Kouame et al. 2024). Thus far, no reports of antagonism between glufosinate and 2,4-D in Palmer amaranth have been reported. Several factors can influence herbicide interactions (Green 1989), and additional research is needed with the MSR2 accession to determine the causal effect.

The programs with no residuals, which relied solely on postemergence applications of

https://doi.org/10.1017/wet.2025.10050 Published online by Cambridge University Press

glyphosate or glufosinate (herbicide programs 2 and 3; Table 1), had the lowest control in both evaluations and years, ranging from 20% to 49% (Table 2). In comparison, the combination of residual herbicides at PRE or EPOST with glufosinate or glufosinate plus glyphosate at EPOST and LPOST (herbicide programs 4 and 5) had a higher level of MSR2 control. However, the average control at 2 WA LPOST was not suitable, ranging from 70% to 84%. Therefore, additional herbicides or weed management practices would still be necessary if a farmer opts to use these programs. Previous investigations with MSR2 have detected high levels of resistance to glufosinate and glyphosate (Carvalho-Moore et al. 2025; Priess et al. 2022), and a lack of control was anticipated in programs based on these herbicides.

Palmer amaranth density reduction (%) was different among the herbicide programs tested at both evaluations and years (Table 3). Similar to what was observed in the MSR2 control in 2022, herbicide programs that included residuals with postemergence applications of 2,4-D or dicamba had greater density reduction (≥ 89% reduction) at all evaluation timings. In 2023, a higher plant density was observed in this field, and a more pronounced density reduction was observed in treatments that included residual herbicides at PRE and EPOST. Consequently, a satisfactory reduction in plant density occurred even in treatments where control was deemed low or unacceptable, such as glufosinate- or glyphosate-based programs. Sequential applications of glufosinate or glyphosate did not control the Palmer amaranth seedlings that escaped residual control in these specific programs due to high resistance to these herbicides. The escapees were able to grow taller and healthier compared to plots where no residual was applied, with hundreds of plants competing for resources (data not shown). Additionally, the herbicide programs that included residuals at PRE and EPOST, partnered with postemergence dicamba plus glyphosate or 2,4-D plus glufosinate mixtures, achieved significant reductions in Palmer amaranth density, with density reductions of ≥ 98% in both years and evaluations.

At the termination evaluation (2 WA LPOST), contrasts revealed that residual herbicides PRE and EPOST increased Palmer amaranth control and density reduction in both years (Tables 2 and 3). In 2022, average control was 91% and 71% in programs with and without residuals at PRE and EPOST, respectively. Density reduction was 91% and 36% in programs with and without residuals, respectively. In 2023, the average control was 88% and 43% in programs with and without residuals at PRE and EPOST, respectively. Density reduction this year was 94% and 41% in programs with and without residuals, respectively. Similar results were observed when soybean herbicide programs with PRE followed by EPOST treatments had higher Palmer amaranth control and soybean yield compared to treatments with EPOST and LPOST that included no residual herbicides (McDonald et al. 2021). However, results will likely differ with other PRE herbicides and combinations, as different levels of control were observed for MSR2 (Carvalho-Moore et al. 2025; Priess et al. 2022). Previous research with different Palmer amaranth accessions or herbicide-resistant waterhemp accessions had varied efficacy among herbicides, even within the same site of action (Houston et al. 2019; Schwartz-Lazaro et al. 2017; Symington et al. 2023).

Practical Implications

In the present study, the addition of herbicides with residual activity is crucial in controlling troublesome Palmer amaranth accession, MSR2. Herbicide programs based solely on postemergence applications were ineffective in providing extended control of the seven-way-resistant Palmer amaranth accession, MSR2. In general, the highest MSR2 control and density reduction levels were observed in herbicide programs that included PRE herbicides combined with residuals added to 2,4-D or dicamba, either as single or mixed applications with other postemergence herbicides. For density reduction, programs including residuals with postemergence applications of 2,4-D plus glufosinate or dicamba plus glyphosate achieved excellent performance, with reductions of ≥98%. However, postemergence applications of dicamba in soybean and cotton fields are currently banned, and low-level resistance to 2,4-D has been identified in MSR2. The use of 2,4-D on seven-way-resistant accessions similar to the one tested here should be avoided or used in conjunction with effective residual herbicides. Stacking herbicides from multiple sites of action, via both residual and postemergence applications, remains a sound approach for controlling herbicide-resistant Palmer amaranth accessions (Norsworthy et al. 2012). Therefore, additional postemergence herbicides are needed, but options are currently limited. Novel traits and herbicide technologies may enter the soybean portfolio in the upcoming years, providing additional herbicide options over the ones tested here (Anonymous 2025a; Anonymous 2025b; Effertz 2021; Findley et al. 2020; Witschel et al. 2021; Woolard et al. 2025). Furthermore, the inclusion of management practices to reduce weed seed production and deposition in the soil seedbank, such as harvest weed seed control, crop rotation, and diversification in herbicide sites of action, is recommended to further support the chosen chemical system (Bagavathiannan and Norsworthy 2012; Norsworthy et al. 2016; Soltani et al.

2023; Winans et al. 2023). A zero-tolerance approach should be used to avoid seedbank replenishment (Norsworthy et al. 2012). Regardless of the level of control, Palmer amaranth plants surviving herbicide applications can produce viable seeds (Jones et al. 2024), and a single plant can produce thousands of seeds (Keeley et al. 1987). Although this study only included the population MSR2, these findings are likely applicable to northeast AR due to the facility on how resistance can spread within Palmer amaranth populations (Bagavathiannan and Norsworthy 2016; Norsworthy et al. 2014; Sosnoskie et al. 2012).

Acknowledgments

The authors thank the University of Arkansas Division of Agriculture for the research support. The colleagues from the Weed Science group are acknowledged, especially Leonard Piveta, for assistance with field experiments.

Funding

BASF Corporation funded this project.

Competing Interests

The authors Ingo Meiners and Aimone Porri are affiliated with BASF Corporation and BASF SE. The other authors declare no conflict of interest.

https://doi.org/10.1017/wet.2025.10050 Published online by Cambridge University Press

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Table 1. Herbicides used for multiple-resistant Palmer amaranth accession (MSR2) control in soybean program experiment conducted at the Milo J. Shult Agricultural Research and Extension Center, Fayetteville, AR, in 2022 and 2023. [abc]

Program number	Herbicide (s)	WSSA/HRAC group number	Trade name	Rate	Application timing
				g ai or ae ha^{-1}	
1	Nontreated				
2	glyphosate	9	Roundup PowerMAX® 3	1,260	EPOST
	glyphosate	9	Roundup PowerMAX® 3	1,260	LPOST
3	glufosinate	10	Liberty®	656	EPOST
	glufosinate	10	Liberty®	656	LPOST
4	*S*-metolachlor plus metribuzin	15 and 5	Boundary®	1,400 plus 350	PRE
	glufosinate	10	Liberty®	656	EPOST
	S-metolachlor	15	Dual II Magnum®	1,400	EPOST
	glufosinate	10	Liberty®	656	LPOST
5	*S*-metolachlor plus metribuzin	15 and 5	Boundary®	1,400 plus 350	PRE
	glufosinate	10	Liberty®	656	EPOST
	glyphosate	9	Roundup PowerMAX® 3	1,260	EPOST
	S-metolachlor	15	Dual II Magnum®	1,400	EPOST
	glufosinate	10	Liberty®	656	LPOST

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	glyphosate	9	Roundup PowerMAX® 3	1,260	LPOST
6	2,4-D	4	Enlist One®	1,064	EPOST
	2,4-D	4	Enlist One®	1,064	LPOST

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Table 1 continued. Herbicides used in the soybean program experiment conducted at the Milo J. Shult Agricultural Research and Extension Center, Fayetteville, AR, in 2022 and 2023. [abc]

Program number	Herbicide (s)	WSSA/HRAC group number	Trade name	Rate	Application timing
				g ai or ae ha^{-1}	
7	*S*-metolachlor plus metribuzin	15 and 5	Boundary®	1,400 plus 350	PRE
	2,4-D	4	Enlist One®	1,064	EPOST
	S-metolachlor	15	Dual II Magnum®	1,400	EPOST
	2,4-D	4	Enlist One®	1,064	LPOST
8	2,4-D plus glyphosate	4 and 9	Enlist Duo®	1,064 plus 1120	EPOST
	2,4-D plus glyphosate	4 and 9	Enlist Duo®	1,064 plus 1120	LPOST
9	*S*-metolachlor plus metribuzin	15 and 5	Boundary®	1,400 plus 350	PRE
	2,4-D plus glyphosate	4 and 9	Enlist Duo®	1,064 plus 1120	EPOST
	S-metolachlor	15	Dual II Magnum®	1,400	EPOST
	2,4-D plus glyphosate	4 and 9	Enlist Duo®	1,064 plus 1120	LPOST
10	*S*-metolachlor plus metribuzin	15 and 5	Boundary®	1,400 plus 350	PRE
	2,4-D plus glyphosate	4 and 9	Enlist Duo®	1,064 plus 1120	EPOST

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	S-metolachlor	15	Dual II Magnum®	1,400	EPOST
	glufosinate	10	Liberty®	656	LPOST
11	2,4-D	4	Enlist One®	1,064	EPOST
	glufosinate	10	Liberty®	656	EPOST
	2,4-D	4	Enlist One®	1,064	LPOST
	glufosinate	10	Liberty®	656	LPOST

Table 1 continued. Herbicides used in the soybean program experiment conducted at the Milo J. Shult Agricultural Research and Extension Center, Fayetteville, AR, in 2022 and 2023. [ab]

Program number	Herbicide (s)	WSSA/HRAC group number	Trade name	Rate	Application timing
				g ai or ae ha^{-1}	
12	*S*-metolachlor plus metribuzin	15 and 5	Boundary®	1,400 plus 350	PRE
	2,4-D	4	Enlist One®	1,064	EPOST
	glufosinate	10	Liberty®	656	EPOST
	S-metolachlor	15	Dual II Magnum®	1,400	EPOST
	2,4-D	4	Enlist One®	1,064	LPOST
	glufosinate	10	Liberty®	656	LPOST
13	dicamba	4	XtendiMax®	560	EPOST
	dicamba	4	XtendiMax®	560	LPOST
14	*S*-metolachlor plus metribuzin	15 and 5	Boundary®	1,400 plus 350	PRE
	dicamba	4	XtendiMax®	560	EPOST
	S-metolachlor	15	Dual II Magnum®	1,400	EPOST
	dicamba	4	XtendiMax®	560	LPOST
15	*S*-metolachlor plus metribuzin	15 and 5	Boundary®	1,400 plus 350	PRE
	dicamba	4	XtendiMax®	560	EPOST
	glyphosate	9	Roundup PowerMAX® 3	1,260	EPOST
	S-metolachlor	15	Dual II Magnum®	1,400	EPOST

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dicamba	4	XtendiMax®	560	LPOST
glyphosate	9	Roundup PowerMAX® 3	1,260	LPOST

[a] Abbreviations: WSSA, Weed Science Society of America; HRAC, Herbicide Resistance Action Committee; PRE, preemergence; EPOST, early postemergence; LPOST, late postemergence.

[b] Volatility reduction agent at 1.46 L ha^{-1} and drift reduction agent at 0.5% v/v were added to applications with dicamba.

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Table 2. Herbicide-resistant Palmer amaranth (MSR2) control (%) at late postemergence (LPOST) and 2 weeks after (WA) LPOST application in 2022 and 2023.[abc]

	Herbicide program			Palmer amaranth control			
				At LPOST		2 WA LPOST	
Crop system	Preemergence	Early postemergence (EPOST)	Late postemergence (LPOST)	2022	2023	2022	2023
				-------------------------------%-------------------------------			
Roundup Ready or LibertyLink	none	glyphosate	glyphosate	20 G	22 D	25 C	25 D
	none	glufosinate	glufosinate	28 G	49 C	27 C	41 D
	S-metolachlor plus metribuzin	glufosinate plus *S*-metolachlor	glufosinate	74 DEF	87 B	70 B	77 C
	S-metolachlor plus metribuzin	glufosinate plus glyphosate plus *S*-metolachlor	glufosinate plus glyphosate	77 CDEF	91 AB	72 B	84 BC
Enlist	none	2,4-D	2,4-D	71 EF	60 C	86 AB	80 C
	S-metolachlor plus	2,4-D plus *S*-metolachlor	2,4-D	90 AB	95 AB	93 A	98 A

https://doi.org/10.1017/wet.2025.10050 Published online by Cambridge University Press

	metribuzin						
	none	2,4-D plus glyphosate	2,4-D plus glyphosate	85 BCDE	60 C	95 A	76 C
	S-metolachlor plus metribuzin	2,4-D plus glyphosate plus *S*-metolachlor	2,4-D plus glyphosate	88 ABC	95 AB	96 A	97 A
	S-metolachlor plus metribuzin	2,4-D plus glyphosate plus *S*-metolachlor	glufosinate	95 AB	89 AB	95 A	90 ABC
	none	2,4-D plus glufosinate	2,4-D plus glufosinate	86 ABCD	56 C	93 A	33 D

Table 2 continued. Herbicide-resistant Palmer amaranth (MSR2) control (%) at late postemergence (LAPOST) and 2 weeks after (WA) LPOST application in 2022 and 2023. [abc]

	Herbicide program			Palmer amaranth control			
				At LAPOST		2 WA LPOST	
Crop system	Preemergence	Early postemergence (EPOST)	Late postemergence (LPOST)	2022	2023	2022	2023
				------------------------------%------------------------------			

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Enlist	*S*-metolachlor plus metribuzin	2,4-D plus glufosinate plus *S*-metolachlor	2,4-D plus glufosinate	97 A	96 AB	99 A	98 A
XtendFlex	none	dicamba	dicamba	66 F	55 C	84 AB	82 BC
	S-metolachlor plus metribuzin	dicamba plus *S*-metolachlor	dicamba	93 AB	94 AB	98 A	98 A
	S-metolachlor plus metribuzin	dicamba plus glyphosate plus *S*-metolachlor	dicamba plus glyphosate	96 A	97 A	98 A	99 A
			p-value	<0.0001	<0.0001	<0.0001	<0.0001
Contrast							
With vs. without residual herbicides						91 vs. 71**	88 vs. 43***

[a] Herbicide rates are described in Table 1.

[b] Means within the same column followed by the same letter are not different according to Fisher's protected least significant difference (α=0.05).

[c] Indicates significant difference at the *P = 0.05 to 0.01, **P = 0.01 to 0.001, ***P ≤ 0.001 levels for contrasts.

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Table 3. Herbicide-resistant Palmer amaranth (MSR2) density reduction (%) at late postemergence (LAPOST) and 2 weeks after (WA) LPOST application in 2022 and 2023.[abc]

	Herbicide program			Palmer amaranth density reduction							
				At LPOST				2 WA LPOST			
Crop system	Preemergence	Early postemergence (EPOST)	Late postemergence (LAPOST)	2022		2023		2022		2023	
				----------------------------%-----------------------------							
Roundup Ready or LibertyLink	none	glyphosate	glyphosate	-45	C	44	BC	-24	CD	28	CD
	none	glufosinate	glufosinate	-27	C	54	BC	-38	D	19	D
	S-metolachlor plus metribuzin	glufosinate plus *S*-metolachlor	glufosinate	71	AB	98	A	79	AB	98	A
	S-metolachlor plus metribuzin	glufosinate plus glyphosate plus *S*-metolachlor	glufosinate plus glyphosate	61	AB	99	A	67	AB	98	A
Enlist	none	2,4-D	2,4-D	22	BC	61	B	29	BC	61	BC
	S-metolachlor plus metribuzin	2,4-D plus *S*-metolachlor	2,4-D	88	AB	99	A	95	A	99	A
	none	2,4-D plus glyphosate	2,4-D plus	75	AB	71	AB	94	A	68	B

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			glyphosate								
	S-metolachlor plus metribuzin	2,4-D plus glyphosate plus *S*-metolachlor	2,4-D plus glyphosate	89	AB	99	A	98	A	99	A
	S-metolachlor plus metribuzin	2,4-D plus glyphosate plus *S*-metolachlor	glufosinate	83	AB	71	AB	91	A	81	AB
	none	2,4-D plus glufosinate	2,4-D plus glufosinate	69	AB	21	C	82	AB	10	D

Table 3 continued. Herbicide-resistant Palmer amaranth (MSR2) density reduction (%) at late postemergence (LAPOST) and 2 weeks after (WA) LPOST application in 2022 and 2023. [abc]

	Herbicide program			Palmer amaranth density reduction							
			Late	At LAPOST				1-2 WAT LAPOST			
Crop system	Preemergence	Early postemergence (EPOST)	postemergence (LAPOST)	2022		2023		2022		2023	
				----------------------------%----------------------------							
Enlist	*S*-metolachlor plus metribuzin	2,4-D plus glufosinate plus *S*-metolachlor	2,4-D plus glufosinate	99	A	100	A	100	A	99	A

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XtendFlex	none	dicamba	dicamba	46	AB	43	BC	78	AB	73	AB
	S-metolachlor plus metribuzin	dicamba plus *S*-metolachlor	dicamba	89	AB	99	A	98	A	100	A
	S-metolachlor plus metribuzin	dicamba plus glyphosate plus *S*-metolachlor	dicamba plus glyphosate	98	A	100	A	99	A	99	A
			p-value	0.0018		<0.0001		<0.0001		<0.0001	
Contrast											
With vs. without residual herbicides								91 vs. 36***		94 vs. 41***	

[a] Herbicide rates are described in Table 1.

[b] Means within the same column followed by the same letter are not different according to Fisher's protected least significant difference (α=0.05).

[c] Indicates significant difference at the *P = 0.05 to 0.01, **P = 0.01 to 0.001, or ***P ≤ 0.001 levels for contrasts.

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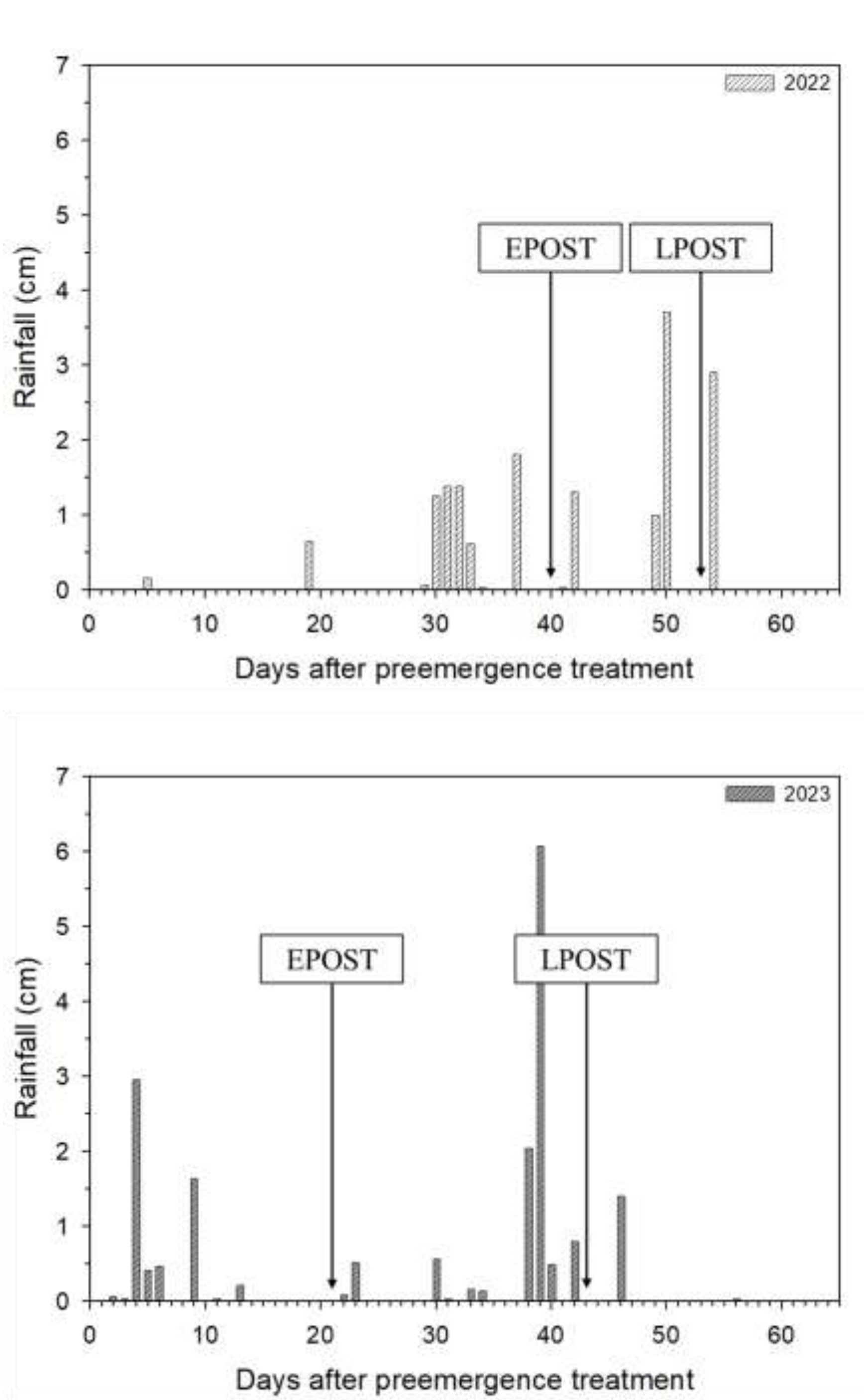

Figure 1. Rainfall (cm) events at the Milo J. Shult Agricultural Research and Extension Center, Fayetteville, AR, in 2022 and 2023, from the beginning (at preemergence) to the termination of the experiment. Box with "EPOST" represents time of early postemergence applications at days after preemergence treatment. Box with "LPOST" represents time of late postemergence applications at days after preemergence treatment.

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