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Late postemergence glufosinate-based programs for glyphosate-resistant Palmer amaranth control in dicamba/glufosinate/glyphosate-resistant soybean

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Abstract

Glyphosate-resistant (GR) Palmer amaranth (*Amaranthus palmeri* S. Watson) is widespread in the Central Great Plains. Introduction of newly developed dicamba/glufosinate/glyphosate (DGG)-resistant soybean varieties allows postemergence (POST) applications of dicamba and glufosinate for in-season control of GR Palmer amaranth. Limited information exists on the effectiveness of glufosinate applied late-POST for tall (70–90 cm) GR Palmer amaranth control in DGG-resistant soybean. The objectives of this study were to (1) determine the effectiveness of late-POST glufosinate-based programs for GR Palmer amaranth control, and (2) determine the impact of those programs on soybeans grain yields. Ten glufosinate-based programs were tested in a field study at Kansas State University Agricultural Research Center near Hays, Kansas. Results indicated that single (655 or 737 g ha^{-1}) and all sequential (594 followed by [*fb*] 594, 655 *fb* 594, and 737 *fb* 594 g ha^{-1}) applications (7-days apart) of glufosinate provided 87%–93% control of GR Palmer amaranth 28 days after last POST (DALPOST). Palmer amaranth control with single late-POST application of glufosinate (594 g ha^{-1}) or glufosinate plus *S*-metolachlor did not exceed 84% at 28 DALPOST. Majority of the evaluated programs reduced shoot dry weights of GR Palmer amaranth by 83%–91%. The least control (11%) and shoot dry weight reduction (33%) of GR Palmer amaranth were observed with glyphosate *fb* glyphosate. Glufosinate-based programs resulted in soybean grain yield of 626–701 kg ha^{-1}. These results conclude that glufosinate applied late-POST may provide effective control of tall GR Palmer amaranth in DGG-resistant soybeans.

1 | INTRODUCTION

Palmer amaranth (*Amaranthus palmeri* L. Watts.) is among the most troublesome summer annual broadleaf weeds in agronomic crops in the United States (Van Wychen, 2017), including Kansas (Kumar et al., 2020). Palmer amaranth is a member of the pigweed (Amaranthaceae) family and is native

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Abbreviations: DALPOST, days after last POST; DGG, dicamba/glufosinate/glyphosate; EPOST, early POST; fb, followed by; GR, glyphosate-resistant; POST, postemergence; PRE, preemergence.

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to the southwest United States and northwest Mexico (Sauer, 1957; Ward et al., 2013). Palmer amaranth possesses several unique characteristics, including an extended emergence period (early May to late September), rapid plant growth rate, dioecy (male and female flowers are on separate plants), high outcrossing potential (can outcross within and between species in the pigweed family) and high genetic diversity within and among populations, and prolific seed production (up to 0.6 million seeds per female plant) (Adhikary & Pratt, 2015; Horak & Loughin, 2000; Keeley et al., 1987; Steckel et al., 2004; Ward et al., 2013). Season-long competition from Palmer amaranth at a density of 10 plants m^{-2} reduced soybean grain yield by 68% in Arkansas, USA (Klingaman & Oliver, 1994).

Due to greater genetic diversity and prolific seed production, Palmer amaranth exhibits a high propensity to evolve herbicide resistance (Heap, 2023; Ward et al., 2013). For instance, Palmer amaranth populations resistant to herbicides that inhibit acetolactate synthase (ALS), 5-enolpyruvyl shikimate-3-phosphate synthase (EPSPS), microtubule assembly (MTA), photosystem II (PS II), 4-hydroxyphenyl pyruvate dioxygenase (HPPD), and protoporphyrinogen oxidase (PPO) have been widely reported (Heap, 2023). Glyphosate-resistant (GR) Palmer amaranth was first confirmed in Kansas in 2011 (Heap, 2023); as of 2023, it is widely spread in several counties in Kansas (Kumar et al., 2020). More recently, Palmer amaranth with resistance to 2,4-D in Kansas, to dicamba in Tennessee, and to *S*-metolachlor and glufosinate in Arkansas have also been reported (Brabham et al., 2019; Foster & Steckel, 2022; Kumar et al., 2019; Priess et al., 2022). In addition, multiple resistance to five to six herbicide sites of action has also been reported in Palmer amaranth populations in Kansas and Arkansas (Heap, 2023; Kumar et al., 2019, 2020).

Effective control of GR Palmer amaranth in no-till dryland soybean primarily relies on two-pass herbicide programs (residual herbicides applied at planting followed by an early POST [EPOST] herbicide) (Kumar et al., 2020). However, escapes from EPOST and the late-season emergence pattern of Palmer amaranth are generally observed in the Central Great Plains region (Liu et al., 2022). Few escaped or late-emerged female Palmer amaranth plants can produce a significant amount (>50,000 seeds per plant) of seeds (Kumar, Liu, Jhala, et al., 2021) and can substantially contribute to the soil seed bank (Jha & Norsworthy, 2009). Therefore, management of those late-emerged Palmer amaranth cohorts with mid- to late-season herbicide applications is crucial in soybean fields where no preemergence (PRE) herbicide was applied, and postemergence (POST) herbicide is the only option in a no-till dryland production system (de Sanctis et al., 2021).

Dicamba/glufosinate/glyphosate (DGG)-resistant soybean (XtendFlex, Bayer CropScience) was commercially launched in 2021 in the United States and Canada. The adoption of DGG-resistant soybean allows growers to use single or sequential applications of low-volatile dicamba formulations and glufosinate for in-season control of GR weeds such as waterhemp (*Amaranthus tuberculatus* L.) and Palmer amaranth (Jones et al., 2022; Meyer et al., 2015). However, the cut-off dates for POST dicamba applications on DGG-resistant soybean vary from state to state according to recent changes approved by the EPA. For the 2023 growing season, no POST dicamba applications are allowed on DGG-resistant soybean after June 12 or V4 growth stage (whichever comes first) in Iowa, Illinois, Indiana, and south of Interstate 94 in Minnesota (Jenkins, 2023). Furthermore, the cut-off date for POST dicamba applications on DGG-resistant soybeans is June 20 for South Dakota and June 30 for all other states (Jenkins, 2023). These restrictions leave glufosinate as a sole POST herbicide option for late-season control of GR weeds in DGG-resistant soybean.

Core Ideas

- Late-POST glufosinate-based herbicide programs were evaluated in dicamba/glufosinate/glyphosate (DGG)-resistant soybeans.
- Single (655 or 737 g ha^{-1}) and all sequential late-POST glufosinate programs provided 87%–93% control of GR Palmer amaranth.
- The majority of glufosinate-based programs reduced shoot dry weights of GR Palmer amaranth by 83%–91%.
- Late-POST glufosinate programs had 56%–61% higher soybean yield compared to glyphosate followed by glyphosate.

Glufosinate is a contact, broad-spectrum POST herbicide that inhibits the glutamine synthetase enzyme in plants, which eventually lead to cell membrane disruption and necrosis (Haas & Muller, 1987; Hinchee et al., 1993). Glufosinate can be applied in single or sequential applications from emergence up to R1 growth stage of DGG-resistant soybean and its efficacy depends on the growth stage of the weed (Anonymous, 2019; Aulakh & Jhala, 2015). However, soybean growers often apply POST herbicides when Palmer amaranth is in variable heights (de Sanctis et al., 2021). Furthermore, temperature and relative humidity are known to influence the efficacy of glufosinate (Anderson et al., 1993). The objectives of this research were to (1) determine the efficacy of glufosinate-based herbicide programs applied late-POST on GR Palmer amaranth (70–90 cm tall) control, and (2) the impact of those programs on GR Palmer amaranth biomass

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and DGG-resistant soybean grain yields in no-till dryland Central Grain Plains region.

2 | MATERIALS AND METHODS

2.1 | Field study

A field study was conducted at Kansas State University Agricultural Research Center (KSU-ARC) near Hays, Kansas (38.86177˚N, 99.33396˚W) in 2022 growing season. Soil type at the study site was Roxbury silt loam with pH of 7.8 and organic matter of 2.0%. The study site was under no-till dryland system with a typical 3-year crop rotation wheat (*Triticum aestivum* L.) followed by (*fb*) summer crop *fb* fallow for >10 years. Paraquat at 560 g ha^{-1} was applied at the study site for control of existing weeds such as kochia (*Bassia scoparia* L.), blue mustard (*Chorispora tenella* L.), and horseweed (*Conyza canadensis* L.) before soybean planting. The experimental site had a natural seed bank of GR Palmer amaranth.

Study was conducted in a randomized complete block design (RCBD) with four replications. A DGG-resistant soybean (XtendFlex$^{\hat{a}}$ soybean) variety ‘AG37XF1’ was planted at 387,543 seeds ha^{-1} in 76-cm spaced rows (4 rows $plot^{-1}$) in 3.0 × 9.1 m plots on May 25, 2022. A blanket treatment of glyphosate (1260 g ae ha^{-1}) along with ammonium sulfate (AMS) at 2% wt/v was applied at V2–V3 growth stage of soybean to control green foxtail. All emerged Palmer amaranth plants had shown little to no injury to glyphosate, further indicating the presence of GR Palmer amaranth population at the study site (data not shown). All late-POST programs (Table 1) of glufosinate were applied with a CO_2-operated backpack sprayer equipped with flat-fan nozzles (Turbo Teejet XR 110015; Spraying Systems Co.), calibrated to deliver 140 L ha^{-1} of spray solution at 276 kPa. First, late-POST treatments were applied at V7 growth stage (Palmer amaranth plants were 70–90 cm tall and majority of them were at inflorescence initiation stage) of soybean on July 25, 2022; whereas, sequential late-POST treatments were applied 7 days later on August 2, 2022, when soybean was at R1 growth stage and Palmer amaranth was 90–120 cm in nontreated control plots. GR Palmer amaranth control was assessed visually at 7, 14, and 28 days after last POST (DALPOST) on a scale of 0%–100% (where 0% = no control and 100% = complete control/plant death). Control ratings were based on chlorosis, stunting, and/or necrosis of treated GR Palmer amaranth plants compared to nontreated plants. At 28 DALPOST, Palmer amaranth plants were manually harvested at the soil level using a 1 m^2 quadrat from the center of each plot. The harvested samples from each plot were oven-dried at 65˚C for 5 days to determine aboveground shoot dry weights. Palmer amaranth shoot dry weights from herbicide-treated plots were

TABLE 1 List of herbicide treatments, rates, application timing, trade names, manufacturers, and adjuvants used in field study to evaluate the effect of late-season application of glufosinate-based programs on glyphosate-resistant Palmer amaranth control in 2022 growing season at Kansas State University Agricultural Research Center near Hays, Kansas.

Herbicide	Rate (g ha^{-1})	Timing (SGS)	Trade name	Manufacturer	Adjuvant (% vol/vol)
Glufosinate	594	V7	Liberty 280 SL	BASF Corp.	AMS 3%
Glufosinate	655	V7	Liberty 280 SL	BASF Corp.	AMS 3%
Glufosinate	737	V7	Liberty 280 SL	BASF Corp.	AMS 3%
Glufosinate *fb* glufosinate	594 *fb* 594	V7 *fb* R1	Liberty 280 SL	BASF Corp.	AMS 3%
Glufosinate *fb* glufosinate	655 *fb* 594	V7 *fb* R1	Liberty 280 SL	BASF Corp.	AMS 3%
Glufosinate *fb* glufosinate	737 *fb* 594	V7 *fb* R1	Liberty 280 SL	BASF Corp.	AMS 3%
Glufosinate + acifluorfen	655 + 280	V7	Liberty 280 SL + Ultra Blazer	BASF Corp., UPL NA Inc.	AMS 3% + NIS 0.5%
Glufosinate + *S-metolachlor*	655 + 1,337	V7	Liberty 280 SL + Dual II Magnum	BASF Corp., Syngenta Crop Protection	AMS 3% + NIS 0.5%
Glufosinate + pyroxasulfone + fluthiacet-methyl	655 + 128 + 132	V7	Liberty 280 SL + Anthem Max	BASF Corp., FMC Corp.	AMS 3% + NIS 0.5%
Glyphosate *fb* glyphosate	1,260 *fb* 1,260	V7 *fb* R1	Roundup PowerMax	Bayer CropScience	AMS 3% + NIS 0.5%

Abbreviations: AMS, ammonium sulfate; *fb*, followed by; NIS, nonionic surfactant; SGS, soybean growth stage.

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expressed as a percent shoot dry weight reduction relative to the nontreated plots using Equation 1:

$$Y = \left[(A - B)/A\right] \times 100 \qquad (1)$$

where Y represents GR Palmer amaranth shoot dry weight reduction (%), A is the averaged shoot dry weights from nontreated plots, and B is the shoot dry weight from herbicide-treated plot. Soybean grain yields (kg ha^{-1}) were estimated by harvesting the middle two rows from each plot using a plot combined at maturity. Soybean grain yields were adjusted to 13% moisture content.

2.2 | Statistical analysis

Data were subjected to analysis of variance (ANOVA) using the PROC MIXED procedure in SAS 9.3. Data were checked for ANOVA assumptions (normality of residuals and homogeneity of variance) using PROC UNIVARIATE in SAS (SAS Institute), and all data met those assumptions. The ANOVA model included all late-POST glufosinate treatments as fixed effects and replications as random effects. Data on GR Palmer amaranth control (%) from nontreated plots were excluded from the analyses. Treatment means were separated using a Fisher's protected LSD test ($p < 0.05$).

3 | RESULTS AND DISCUSSION

The 2022 growing season at the study site had relatively warmer and drier weather conditions than a typical growing season. Mean monthly air temperatures of 24, 27, 26, 22, and 14°C were observed in June, July, August, September, and October, respectively (Figure 1). The average daily relative humidity on July 25 (first late-POST application) and August 2 (sequential late-POST application) was 76% and 45%, respectively (Figure 1). Below-average precipitation occurred in 2022, with total monthly precipitation of 36, 45, 35, 54, and 4 mm in June, July, August, September, and October, respectively (Figure 1). The soil moisture was below normal, particularly during the reproductive growth stages of soybean.

3.1 | Palmer amaranth control and shoot dry weights reduction

GR Palmer amaranth control was significantly influenced by late-POST programs at 7, 14, and 28 DALPOST ($p \leq 0.05$ for each). At 7 DALPOST, all glufosinate-based programs provided 84%–95% control (Table 2). With a single late-POST application at V7 soybean growth stage, control improved from 84% to 92% as glufosinate rate increased from 594 g ha^{-1} to 737 g ha^{-1}. A sequential late-POST glufosinate application at 594 g ha^{-1} during R1 soybean growth stage improved GR Palmer amaranth control by 11% and 6% following a previous glufosinate treatment at 594 g ha^{-1} or 655 g ha^{-1} applied at V7 soybean growth stage, respectively. Besides, tank-mix application of residual herbicides with 655 g ha^{-1} of glufosinate at V7 soybean growth stage provided similar control of GR-Palmer amaranth as two sequential late-POST glufosinate applications. Vann et al. (2017) also observed no glufosinate rate differences for Palmer amaranth control with two sequential glufosinate applications. Similar treatment differences were observed at 14 DALPOST with Palmer amaranth control varied from 83% to 95% with all glufosinate-based treatments. By 28 DALPOST, Palmer amaranth control was still >90% with two late-POST glufosinate treatments made at V7 followed by R1 soybean stages. This level of control was higher than a single late-POST glufosinate treatment at 594 g ha^{-1} or where a glufosinate + S-metolachlor tank mixture was used at the V7 soybean stage (Table 2). With a single V7 stage application, GR Palmer amaranth control was similar regardless of glufosinate rates. Similarly, Vann et al. (2017) reported disappearance of glufosinate rate effect with time for the control of 5- to 35-cm tall Palmer amaranth. As expected, glyphosate had little effect on GR Palmer amaranth with ≤12% control after two sequential treatments at 1260 g ha^{-1} at V7 *fb* R1 soybean growth stage.

Glufosinate applied late-POST in this study was highly effective, and provided ≥82% control of tall (70–90 cm) GR Palmer amaranth. Norsworthy et al. (2008) reported ≥99% control of GR-Palmer amaranth with glufosinate applied when Palmer amaranth plants were at six leaves growth stage. In Connecticut, glufosinate applied at 590 g ha^{-1} provided complete control of a multiple herbicide-resistant Palmer amaranth (Aulakh et al., 2021). Other researchers found sequential applications of glufosinate were more effective than a single application for controlling broadleaf and grass weeds (Aulakh & Jhala, 2015; Hoffner et al., 2012; Jhala et al., 2017; Wiesbrook et al., 2001). Moreover, glufosinate efficacy on weeds also varies with the application time of the day. Palmer amaranth was controlled 97% when glufosinate was applied mid-day compared with 63% control when glufosinate was applied at sunrise (Copeland et al., 2019). Coetzer et al. (2001) observed relative humidity and air temperature-dependent variation in Palmer amaranth control by glufosinate. They noted that Palmer amaranth control was improved by 17%–35% 1 day after glufosinate application as the relative humidity increased from 35% to 90%.

Shoot dry weight reduction of GR Palmer amaranth was consistent with the control results at 28 DALPOST (Table 1). Late-POST glufosinate-based programs, except for a single application of glufosinate at 594 g ha^{-1} at V7 soybean growth

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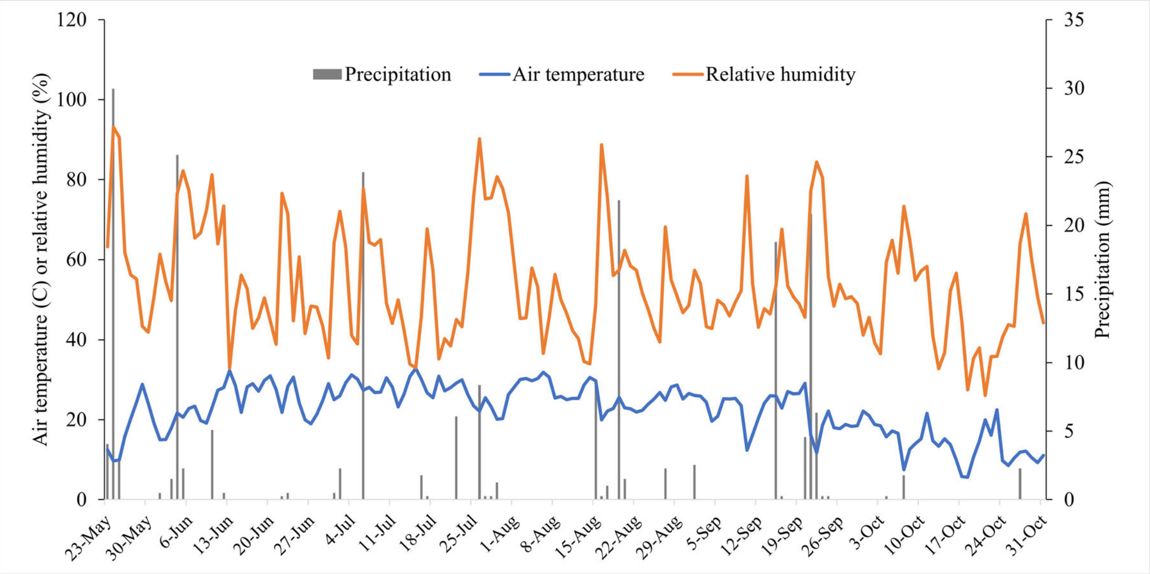

FIGURE 1 Daily air temperature (C), relative humidity (%), and precipitation (mm) during the 2022 soybean growing season at Kansas State University Agricultural Research Center near Hays, Kansas.

stage, were similar with 83%–91% reduction in GR Palmer amaranth shoot dry weights compared to the nontreated control. Similar reductions in weed biomass with glufosinate have previously been reported (Aulakh & Jhala, 2015; Vann et al., 2017).

3.2 | Soybean grain yield

Late-POST glufosinate-based programs resulted in higher soybean grain yields than the nontreated control or a glyphosate *fb* glyphosate. The highest soybean yield (701 kg ha^{-1}) was observed with 737 g ha^{-1} of glufosinate at V7 soybean growth stage *fb* 594 g ha^{-1} of glufosinate at R1 soybean growth stage. This level of soybean grain yield was higher than observed with glufosinate + aciflourfen, glufosinate + S-metolachlor, glyphosate *fb* glyphosate, and the nontreated control with 470, 444, 270, and 218 kg ha^{-1} respectively. Although the GR Palmer amaranth control was similar to other glufosinate-based programs, the glufosinate + acifluorfen or S-metolachlor tank-mix had an adverse impact on soybean yield. This was perhaps due to higher soybean injury (approximately 15%–18%) from these programs compared to <6% injury with all other glufosinate-based programs (data not shown). Soybean injury from aciflourfen was characterized as necrosis, chlorosis, and height reduction. Aciflourfen was found to be highly injurious (>20%) to soybean (Aulakh et al., 2016). In another study, Aulakh and Jhala (2015) observed approximately 20% injury to soybean with an EPOST application of glufosinate + acetochlor or glufosinate + S-metolachlor tank mixture. However, observed EPOST injury in their research was transitory and therefore, had no impact on soybean grain yield.

Lower than normal soybean grain yields were produced in this study. Typical grain yield for this soybean maturity group at the KSU-ARC is 1512 kg ha^{-1} (Kumar, Liu, Peterson, et al., 2021). Below average soybean grain yields in current study could be attributed to the exceptionally hot and dry weather conditions at reproductive growth stage during 2022. The cumulative precipitation for the 2022 soybean-growing season was 261 mm as compared to the historic average of 406 mm.

4 | CONCLUSIONS AND PRACTICAL IMPLICATIONS

GR Palmer amaranth presents a serious challenge to soybean production because effective herbicides in soybean are dwindling. Glufosinate-resistant soybean was first released for large-scale commercial cultivation in 2009, although limited cultivation had already begun in 1999 (Wiesbrook et al., 2001). Glufosinate is a POST, contact herbicide for control of emerged broadleaf, and grass weeds in glufosinate-resistant soybean (Aulakh & Jhala, 2015; Haas & Muller, 1987; Jhala et al., 2017). In this study, several late-POST glufosinate-based herbicide programs effectively controlled (≥82%) 70–90 cm tall GR Palmer amaranth. Single late-POST glufosinate application at ≥655 g ha^{-1} during the V7 soybean growth stage was similar to two late-POST applications at V7 and R1 soybean growth stages. Consequentially, glufosinate-based programs produced similar soybean yields,

TABLE 2 Effect of late-season applied glufosinate-based programs on glyphosate-resistant Palmer amaranth control, shoot dry weight reduction and grain yields of glyphosate/dicamba/glufosinate-resistant soybean in no-till dryland.

Herbicide	Rate (g ha^{-1})	7 DALPOST	14 DALPOST	28 DALPOST	Shoot dry weight reduction	Grain yield (kg ha^{-1})
		% control			% of nontreated	
Nontreated	–	–	–	–	–	218 d
Glufosinate	594	84 e	83 d	82 c	75 b	562 ab
Glufosinate	655	88 cd	88 c	87 abc	83 a	539 ab
Glufosinate	737	92 ab	91 abc	88 abc	85 a	558 ab
Glufosinate *fb* glufosinate	594 *fb* 594	95 a	95 a	91 ab	91 a	626 a
Glufosinate *fb* glufosinate	655 *fb* 594	94 a	93 abc	92 ab	89 a	650 a
Glufosinate *fb* glufosinate	737 *fb* 594	95 a	94 ab	93 a	89 a	701 a
Glufosinate + acifluorfen	655 + 280	90 bc	89 bc	89 abc	86 a	470 bc
Glufosinate + *S-metolachlor*	655 + 1,337	92 ab	88 c	84 bc	84 a	444 bc
Glufosinate + pyroxasulfone + fluthiacet	655 + 128 + 132	93 ab	92 abc	89 abc	86 a	524 ab
Glyphosate *fb* glyphosate	1,260 *fb* 1,260	10 e	12 e	11 d	33 c	270 d

Note: Means within each column followed by similar alphabets are not different according to Fisher's Protected LSD ($p < 0.05$) test.

Abbreviations: DALPOST, days after last POST; *fb*, followed by, POST, postemergence.

which were higher, compared to the nontreated control or glyphosate *fb* glyphosate. Mixing glufosinate with pyroxasulfone + fluthiacet at V7 soybean growth stage provided similar soybean grain yield compared with single or sequential late-POST glufosinate applications. Contrary to previous findings, a late-POST aciflourfen or *S*-metolachlor mixed with glufosinate caused severe injury to soybean that resulted in reduced soybean yields than a glufosinate + pyroxasulfone + fluthiacet.

Recently, Palmer amaranth populations resistant to ALS-inhibitors, glufosinate, glyphosate, HPPD-inhibitor, PPO-inhibitor, and synthetic auxins herbicides have been documented in multiple states in the United States (Aulakh et al., 2021; Chahal et al., 2015, 2018; Foster & Steckel, 2022; Heap, 2023; Kumar et al., 2019; Priess et al., 2022; Salas et al., 2016; Varanasi et al., 2018). Evolution of multiple herbicide resistance in Palmer amaranth would defy chemical control even in crops with stacked gene herbicide resistant trait technologies. Therefore, future research efforts should investigate combination of chemical control with ecological weed management tactics such as competitive crop rotation, cover crop, planting densities, tillage, and harvest weed seed control (HWSC) techniques (weed seed destructor and chaff lining) for managing GR Palmer amaranth. In this context, a multi-state (Iowa, Kansas, and Arkansas) field research is underway to investigate the long-term impact of multitactic approaches (cover crops, herbicides, and HWSC techniques) on GR pigweeds seedbanks. Future research should also investigate the weed control efficacy and soybean safety of late-POST glufosinate + PPO-inhibitor herbicides tank-mixes under different relative humidity and temperature regimes. Tank mixing residual herbicides with a viable late-season POST treatment is often recommended for safeguarding herbicide-resistant crop technologies and managing herbicide-resistant weeds (Norsworthy et al., 2012). Addition of a late-POST residual herbicide offer added advantages, for example, diversity of herbicide sites of action which will alleviate the selection pressure of a single herbicide (Diggle et al., 2003; Johnson et al., 2012) and reduce the weed seed bank in the soil (Legleiter et al., 2009).

AUTHOR CONTRIBUTIONS

Vipan Kumar: Conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing–original draft. **Jatinder Aulakh**: Data curation, validation, writing–original draft, writing–review and editing. **Rui Liu**: Investigation, methodology, validation, writing–review and editing. **Amit Jhala**: Conceptualization, validation, visualization, writing–review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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