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Control of glyphosate- and mesotrione-resistant Palmer amaranth in glyphosate- and glufosinate-resistant corn

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Abstract

Increasing reports of herbicide-resistant Palmer amaranth (*Amaranthus palmeri* S. Watson) pose a serious management concern for Kansas corn (*Zea mays* L.) producers. The objectives of this study were to evaluate various herbicide programs, including preemergence (PRE) alone, PRE followed by (fb) early postemergence (EPOST), and PRE fb late POST (LPOST) for control of glyphosate- and mesotrione-resistant (GMR) Palmer amaranth in glyphosate- and glufosinate-resistant corn, and their effect on crop injury, yield, and net economic return. Field experiments were conducted in 2018 and 2019 in grower fields with natural infestations of GMR Palmer amaranth near Seward in Stafford County, KS. Preemergence programs, including dicamba + thiencarbazone-methyl + atrazine and dicamba + [atrazine, bicyclopyrone, mesotrione, S-metolachlor (ABMS)] or dicamba + ABMS in mixtures with atrazine, mesotrione, S-metolachlor, and metribuzin provided 89–93% control of GMR Palmer amaranth 3 wk after PRE. Preemergence fb EPOST programs provided 87–96% control of GMR Palmer amaranth at 2 wk after EPOST through 7 wk after LPOST. In comparison, PRE-only programs provided 62–82% and PRE fb LPOST programs provided 75–86% control. The various herbicide programs resulted in greater corn grain yield ranging from 9,207 to 10,508 kg ha^{-1} compared with 6,056 kg ha^{-1} in the nontreated control. The highest net return (\$1,300 ha^{-1}) was achieved from dicamba + ABMS + atrazine applied PRE fb EPOST application of ABMS + atrazine. These results suggest that effective PRE fb EPOST herbicide programs consisting of multiple sites of actions are available and provide effective control of GMR Palmer amaranth in glyphosate- and glufosinate-resistant corn.

1 | INTRODUCTION

Palmer amaranth (*Amaranthus palmeri* S. Watson) is the most troublesome broadleaf weed species in agronomic crops in the United States (Van Wychen, 2017), including Kansas (Kumar et al., 2020). It is a dioecious (male and female flower are on separate plants) summer annual weed that belongs to the pigweed (Amaranthaceae) family and is a native to the southwestern United States (Sauer, 1957; Ward et al., 2013). Due to its dioecious obligate outcrossing nature, Palmer amaranth manifests high genetic diversity within and among populations (Adhikary & Pratt, 2015) and can outcross with other species in the pigweed family (Jhala et al., 2021). Several unique biological traits such as extended emergence period

Abbreviations: ABMS, atrazine, bicyclopyrone, mesotrione, S-metolachlor; EPOST, early POST; Fb, followed by; GMR, glyphosate- and mesotrione-resistant; HPPD, 4-hydroxyphenylpyruvate dioxygenase; LPOST, late POST; POST, postemergence; PRE, preemergence; PS, photosystem; SOA, site of action.

(early May–late September), high photosynthetic rate (80 μ mol CO_2 m^{-2} s^{-1}), rapid plant growth rate (0.10–0.21 cm growing degree d^{-1}), and prodigious amount of seed production make Palmer amaranth the most difficult-to-control weed species (Horak & Loughin, 2000; Keeley, 1987; Steckel et al., 2004). This species can also tolerate shade and water stress conditions, allowing it to withstand moisture and light-limited environments (Chahal, Irmak, et al., 2018; Ehleringer, 1983; Jha et al., 2008; Wright et al., 1999). Season-long interference at densities of 0.5–8 plants m^{-1} row reduced corn (*Zea mays* L.) yield from 11 to 91% and produced 140,000–514,000 Palmer amaranth seeds m^{-2}, respectively (Massinga et al., 2001).

Glyphosate and 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitors are important herbicides for weed control in glyphosate-resistant corn production due to their compatibility with other herbicide sites of action (SOAs), broad-spectrum weed control, and crop safety (Bollman et al., 2008; Swanton et al., 2007). However, continuous and repeated use of these herbicides has led to the evolution of resistance to both SOAs in Palmer amaranth populations in Kansas and some neighboring states (Chahal et al., 2015; Jhala et al., 2014; Kumar et al., 2020). An HPPD-resistant Palmer amaranth population was first reported in Kansas in 2009 (Nakka, Godar, Thompson, et al., 2017; Nakka, Godar, Wani, et al., 2017; Nakka, Thompson, et al., 2017). This population also exhibited resistance to HPPD inhibitors (mesotrione, pyrasulfotole, tembotrione, and topramezone), photosystem (PS) II inhibitors (atrazine), and acetolactate synthase inhibitors (thifensulfuron-methyl) (Heap, 2021; Nakka, Godar, Thompson, et al., 2017; Nakka, Godar, Wani, et al., 2017; Nakka, Thompson, et al., 2017). Resistance to glyphosate in Palmer amaranth was first reported in Kansas in 2011 and is now common among field populations (Heap, 2021; Kumar et al., 2020). More recently, several Palmer amaranth populations from south-central Kansas have shown reduced sensitivity (putative resistance) to glyphosate, mesotrione, atrazine, and chlorsulfuron (Kumar et al., 2020). In addition, multiple resistance to herbicides from five different SOA groups, including 2,4-D, glyphosate, chlorsulfuron, atrazine, mesotrione, as well as reduced sensitivity to fomesafen has been reported in a single Palmer amaranth population in Kansas (Kumar, Liu, Boyer, et al., 2019).

Previous studies have documented the effectiveness of various PRE-only or PRE followed by (fb) POST herbicides for controlling HPPD- and photosystem (PS) II inhibitor-resistant Palmer amaranth in corn (Chahal & Jhala, 2018; Chahal et al., 2015; Chahal, Ganie, et al., 2018; Chahal, Irmak, et al., 2018). For instance, pyroxasulfone + fluthiacet-ethyl + atrazine, saflufenacil + dimethenamid-P, and mesotrione + S-metolachlor + atrazine applied PRE fb POST application of glufosinate alone or in tank-mixture with dicamba provided 92–98% control of HPPD- and PS II inhibitor-resistant Palmer amaranth at 28 d after POST in glyphosate- and glufosinate-resistant corn (Chahal & Jhala, 2018). Similarly, PRE applied pyroxasulfone + fluthiacet-ethyl + atrazine, acetochlor, saflufenacil + dimethenamid-P, and mesotrione + S-metolachlor + atrazine fb POST application of dicamba or dicamba + diflufenzopyr provided 89–98% end-season control of HPPD- and PS II inhibitor-resistant Palmer amaranth in conventional corn (Chahal, Irmak, et al., 2018). In a separate study, PRE-applied saflufenacil + dimethenamid-P or pyroxasulfone + saflufenacil provided 80–82% control of HPPD- and PS II inhibitor-resistant Palmer amaranth compared with 65 and 39% control with saflufenacil and pyroxasulfone applied alone at 3 wk after PRE, respectively (Chahal, Ganie, et al., 2018). In that same study, pyroxasulfone + saflufenacil or saflufenacil + dimethenamid-P applied PRE fb glyphosate + topramezone + dimethenamid-P + atrazine, glyphosate + diflufenzopyr + dicamba + pyroxasulfone, glyphosate + diflufenzopyr + pendimethalin, or glyphosate + diflufenzopyr + dicamba + atrazine applied POST provided up to 98% control of HPPD- and PS II inhibitor-resistant Palmer amaranth 3 wk after POST. All these aforementioned studies were conducted in north-central Nebraska in grower fields with high silt content (57%) and high organic matter (3.5%) (Chahal, Ganie, et al., 2018; Chahal, Irmak, et al., 2018; Chahal & Jhala, 2018).

Increasing cases of multiple herbicide-resistant Palmer amaranth in Kansas necessitates the implementation of alternative herbicide strategies for management (Kumar et al., 2020). Limited information exists on using overlapping soil-residual (PRE) herbicides (with multiple SOAs) for Palmer amaranth control in south-central Kansas where soils are sandy and low in organic matter content (usually <2%). More specifically, little is known on the effectiveness of a premix of atrazine, bicyclopyrone, mesotrione, and S-metolachlor (ABMS) applied PRE alone vs. split applications (PRE fb POST) for controlling glyphosate- and mesotrione-resistant (GMR) Palmer amaranth in irrigated corn in sandy soils. The objectives of this research were to determine the effectiveness of PRE-only, PRE fb early POST (EPOST), and PRE fb late POST (LPOST) herbicide programs for control of GMR Palmer amaranth, corn yield, and net economic return in glyphosate- and glufosinate-resistant corn.

Core Ideas

- Herbicide programs were evaluated for controlling multiple herbicide-resistant Palmer amaranth.
- PRE followed by early POST programs provided 87–96% control of Palmer amaranth.
- The majority of programs protected against corn yield losses of 34–41% and improved net return.

2 | MATERIALS AND METHODS

2.1 | Field experiments and treatments

Field experiments were conducted in 2018 (38.0832° N, 98.5029° W; elevation at 582 m) and 2019 (38.1129° N, 98.4823° W; elevation at 582 m) in grower fields near Seward in Stafford County, KS. Field sites were under no-tillage and central pivot sprinkler irrigation with a corn–soybean [*Glycine max* (L.) Merr.] rotation the previous 5 yr. Each year, a different grower field site was selected that had natural infestation of Palmer amaranth population with resistance to glyphosate and mesotrione. Palmer amaranth population at the 2018 field site was 7-fold resistant to glyphosate and fourfold resistant to mesotrione compared with a susceptible population (Kumar, Liu, & Lambert, 2019); whereas the resistance levels were not determined in the Palmer amaranth population from the 2019 field site (survived glyphosate at 1,260 g acid equivalent ha^{-1} and mesotrione at 105 g a.i. ha^{-1} in greenhouse conditions). Soil type at the 2018 field site was sandy clay (86% sand, 6% silt, and 8% clay) with an organic matter of 1.8% and a pH of 7.4. Similarly, soil type at the 2019 field site was sandy silt (74% sand, 14% silt, and 12% clay) with an organic matter of 1.6% and a pH of 7.6. Glyphosate- and glufosinate-resistant corn hybrid (DKC 64-34RIB) was planted on 24 Apr. 2018 at a seeding rate of 74,257 seeds ha^{-1}, and on 6 June 2019 at a seeding rate of 86,419 seeds ha^{-1}. Because of frequent rainfall events, corn planting in the 2019 growing season was delayed until June. Agronomic practices, including fertilizers and disease and insect management, were adopted as recommended by Kansas State University for corn production in central Kansas (Ciampitti et al., 2021). Ten herbicide programs, including PRE, PRE fb EPOST, and PRE fb LPOST, were investigated (Table 1). Treatments were arranged in a randomized complete block design with four replications. Each plot was 3 m wide by 9 m long that accommodated four corn rows at a row spacing of 0.76 m. A nontreated control was included for comparison. The PRE and POST herbicides were applied with glyphosate at 1,060 g acid equivalent ha^{-1} plus ammonium sulfate at 2% w/v. In addition, all PRE herbicide programs included dicamba in tank-mixture with glyphosate (a standard practice for weed control at the time of crop planting under no-till production). The PRE herbicides were applied after corn planting on 24 Apr. 2018 and 5 June 2019, whereas EPOST and LPOST herbicides were applied on 17 May (8-to-10-cm tall Palmer amaranth) and 1 June (15-to-18-cm tall Palmer amaranth) 2018 and on 18 June (7-to-10-cm tall Palmer amaranth) and 17 July (16-to-20-cm tall Palmer amaranth) 2019, respectively. Herbicides were applied using a CO_2-pressurized backpack sprayer equipped with TeeJet AIXR 110015 flat spray nozzle tips (Spraying Systems Co.) calibrated to deliver 141 L ha^{-1} of the spray solution. All four rows of corn in each plot were treated during each herbicide application.

2.2 | Data collection

Visible estimates of Palmer amaranth control (%) were recorded on a scale of 0 to 100% (0 = no control and 100 = complete control) 3 wk after PRE, 2 wk after EPOST, and 2 and 7 wk after LPOST herbicide application. Corn injury (%) was also visually assessed on a scale of 0 to 100% (0 = no injury and 100 = plant death) at 3 wk after PRE, 2 wk after EPOST, and 7 wk after LPOST. In addition, Palmer amaranth density was recorded at 3 wk after PRE, 2 wk after EPOST, and 7 wk after LPOST using two 0.25 m^2 quadrats placed between the middle two corn rows in each plot. At maturity, corn grain yields were determined by harvesting the middle two rows with a plot combine. Corn grain yield was adjusted to 15% moisture.

2.3 | Economic analysis

Net return was estimated using the following equation (Bradley et al., 2000; Edwards et al., 2014):

$$\text{Net return} = \text{Gross revenue} - \text{herbicide program cost} \quad (1)$$

Gross revenue was calculated by multiplying the corn yield from each plot with an average grain price (\$0.15 kg^{-1}) in Kansas at corn harvest during the experimental years (USDA NASS, 2019). Cost of herbicide programs included the average herbicide cost per hectare (Peterson et al., 2019) and an herbicide application cost of \$14.15 ha^{-1} application^{-1} (KDA & LUSP, 2018).

2.4 | Statistical analyses

Data were tested for normality of residuals and homogeneity of variance using PROC UNIVARIATE in SAS (Version 9.3) (SAS Inc.). Palmer amaranth density data were square-root transformed before analysis to improve the normality of residuals and homogeneity of variance; however, back-transformed means were presented based on the interpretation from transformed data. Visual estimates of Palmer amaranth control (%) from nontreated plots were excluded from the analysis. Data were subjected to PROC MIXED in SAS 9.3 to test the significance of variance. The ANOVA model included herbicide treatments, year, and herbicide treatments × year interaction as fixed effects. Replication and interactions involving replication were considered as random effects in the model. The herbicide treatment × year interaction was nonsignificant ($P \geq .05$) for all variables; therefore, data were

TABLE 1 List of herbicide programs tested for controlling glyphosate- and mesotrione-resistant Palmer amaranth in glyphosate- and glufosinate-resistant corn near Seward, KS, in 2018 and 2019

Herbicide[a]	Rate	Timing	Manufacturer	Trade name
	g ae or a.i. ha^{-1}			
Thiencarbazone-methyl + atrazine	129 + 840	PRE	Bayer Crop Science + Syngenta Crop Protection, Inc.	Corvus + Aatrex
ABMS	1,090	PRE	Syngenta Crop Protection	Acuron
ABMS + atrazine fb ABMS + atrazine	550 + 280 fb 550 + 280	PRE fb EPOST	Syngenta Crop Protection + Syngenta Crop Protection fb Syngenta Crop Protection	Acuron + Aatrex fb Acuron + Aatrex
ABMS + atrazine + S-metolachlor + mesotrione fb ABMS + atrazine + S-metolachlor + mesotrione	550 + 280 + 535 + 35 fb 550 + 280 + 535 + 35	PRE fb EPOST	Syngenta Crop Protection	Acuron + Aatrex + Dual II Magnum + Callisto fb Acuron + Aatrex + Dual II Magnum + Callisto
ABMS + mesotrione fb ABMS + mesotrione	721 + 35 fb 361 + 35	PRE fb EPOST	Syngenta Crop Protection + Syngenta Crop Protection fb Syngenta Crop Protection	Acuron + Callisto fb Acuron + Callisto
ABMS + S-metolachlor fb ABMS + S-metolachlor	721 + 534 fb 361 + 534	PRE fb EPOST	Syngenta Crop Protection + Syngenta Crop Protection fb Syngenta Crop Protection	Acuron + Dual II Magnum fb Acuron + Dual Magnum
ABMS + atrazine fb ABMS + atrazine	721 + 280 fb 361 + 280	PRE fb EPOST	Syngenta Crop Protection + Syngenta Crop Protection fb Syngenta Crop Protection	Acuron + Aatrex fb Acuron + Aatrex
ABMS + metribuzin fb ABMS	550 + 158 fb 550	PRE fb EPOST	Syngenta Crop Protection + Bayer Crop Science fb Syngenta Crop Protection	Acuron + Sencor fb Acuron
ABMS fb ABMS + (dicamba + diflufenzopyr)	550 fb 550+ 98	PRE fb LPOST	Syngenta Crop Protection fb Syngenta Crop Protection + BASF Corporation	Acuron fb Acuron + Status
ABMS fb ABMS + glufosinate	550 fb 550 + 450	PRE fb LPOST	Syngenta Crop Protection fb Syngenta Crop Protection + BASF Corporation	Acuron fb Acuron + Liberty
Nontreated control	—	—	—	—

Note. a.e., acid equivalent; ABMS, atrazine + bicyclopyrone + mesotrione + S-metolachlor; PRE, preemergence; EPOST, early postemergence; LPOST, late postemergence; fb, followed by.

[a]All PRE treatments were applied with dicamba at 280 g ha^{-1}. All PRE and POST treatments were applied with glyphosate at 1,060 g ha^{-1}. The POST treatments included nonionic surfactant at 0.25% v/v and ammonium sulfate at 2% w/v.

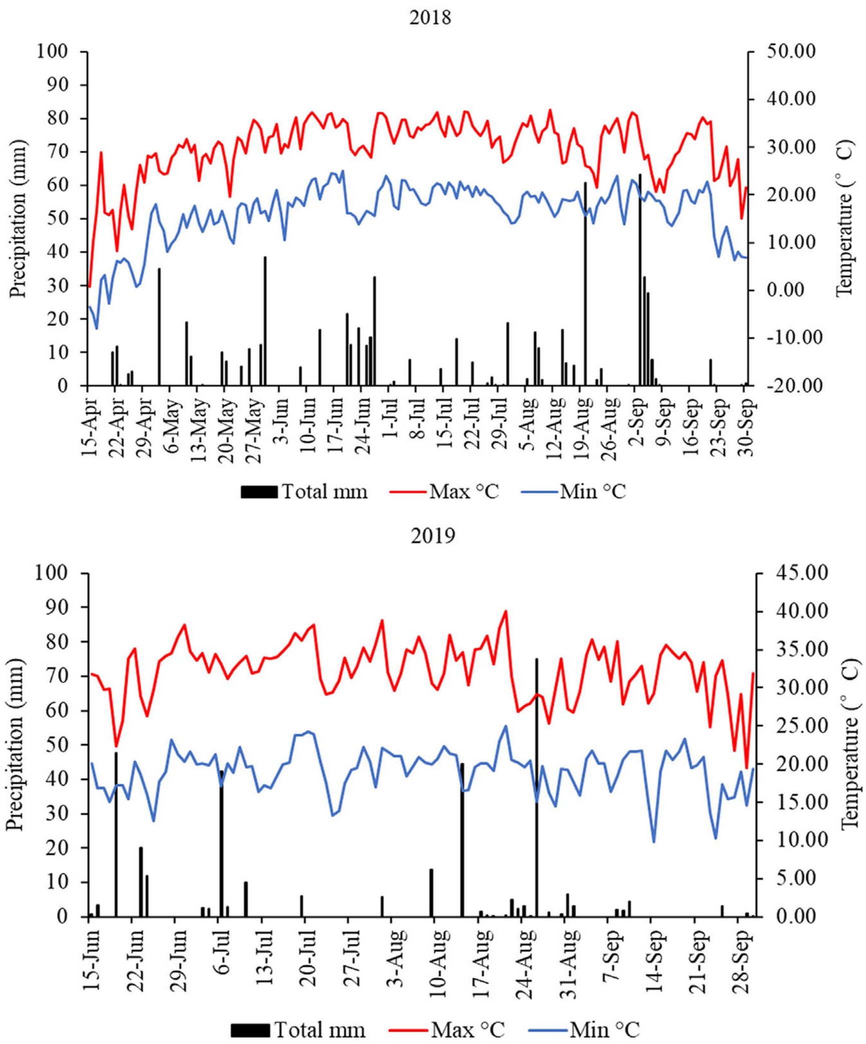

FIGURE 1 Air temperature and precipitation in 2018 and 2019 growing seasons near Seward, KS

averaged across years. Treatment means were separated using Fisher's protected LSD test (α = .05).

3 | RESULTS AND DISCUSSION

The average monthly air temperature at Seward, KS, ranged from 10 to 27 ˚C in the 2018 growing season (15 Apr.–30 Sept.) and 25 to 27 ˚C in the 2019 growing season (15 June–30 Sept.) (Figure 1). The seasonal accumulated precipitation was 368 mm in 2018 and 326 mm in 2019 (Figure 1). An irrigation amount of 153 and 203 mm supplemented seasonal precipitation using a central pivot sprinkler system in the 2018 and 2019 growing seasons, respectively. Little-to-no visible corn injury was observed with any of the PRE, EPOST, or LPOST herbicides evaluated in this study (data not shown).

3.1 | Palmer amaranth control

Palmer amaranth control with the various herbicides did not differ between the 2 yr (p = .231). Averaged across 2 yr, PRE herbicide programs, including dicamba + thiencarbazone-methyl + atrazine, dicamba + ABMS alone or in various combinations with atrazine, mesotrione, S-metolachlor, and metribuzin provided excellent control (89–93%) of GMR Palmer amaranth at 3 wk after APRE (Table 2). However, control with dicamba + thiencarbazone-methyl + atrazine and dicamba + ABMS PRE-only programs declined over the growing season and ranged from 62 to 72% at the final evaluation (Table 2). In contrast, Kohrt and Sprague (2017) previously reported 83–98% control of Palmer amaranth resistant to glyphosate, atrazine, and acetolactate synthase inhibitors at 10 wk after PRE alone with treatments of mesotrione + atrazine, S-metolachlor + atrazine, mesotrione + S-metolachlor, and ABMS in field corn. These differences in residual activity of PRE programs for Palmer amaranth control in the current study vs. previous reports by Kohrt and Sprague (2017) may be due to differences in soil texture, organic matter, soil moisture, herbicide rates, and herbicide resistance status of target Palmer amaranth populations. Compared with PRE-only programs, all PRE fb EPOST (i.e., two pass) programs of ABMS alone or in

TABLE 2 Control of glyphosate- and mesotrione-resistant Palmer amaranth in glyphosate- and glufosinate-resistant corn with various herbicide programs averaged across the 2018 and 2019 growing seasons near Seward, KS

Herbicide program[a]	Rate	Application timing	Palmer amaranth control[b] 3 wk after PRE	2 wk after EPOST	2 wk after LPOST	7 wk after LPOST
	g a.i. or a.e. ha^{-1}		%			
Thiencarbazone-methyl + atrazine	129 + 840	PRE	90 a	82 b	72 c	62 d
ABMS	1,090	PRE	92 a	81 b	77 c	72 c
ABMS + atrazine fb ABMS + atrazine	550 + 280 fb 550 + 280	PRE fb EPOST	92 a	95 a	92 a	92 a
ABMS + atrazine + S-metolachlor + mesotrione fb ABMS + atrazine + S-metolachlor + mesotrione	550 + 280 + 535 + 35 fb 550 + 280 + 535 + 35	PRE fb EPOST	93 a	95 a	91 ab	89 a
ABMS + mesotrione fb ABMS + mesotrione	721 + 35 fb 361 + 35	PRE fb EPOST	91 a	96 a	91 ab	89 a
ABMS + S-metolachlor fb ABMS + S-metolachlor	721 + 534 fb 361 + 534	PRE fb EPOST	90 a	92 a	87 ab	85 ab
ABMS + atrazine fb ABMS + atrazine	721 + 280 fb 361 + 280	PRE fb EPOST	91 a	96 a	87 ab	87 a
ABMS + metribuzin fb ABMS	550 + 158 fb 550	PRE fb EPOST	92 a	93 a	90 ab	88 a
ABMS fb ABMS + (dicamba + diflufenzopyr)	550 fb 550+ 98	PRE fb LPOST	89 a	75 c	86 c	86 ab
ABMS fb ABMS + glufosinate	550 fb 550 + 450	PRE fb LPOST	90 a	75 bc	86 c	79 bc
Nontreated control	—	—	—	—	—	—
Preplanned contrast comparison						
PRE vs. PRE fb EPOST				82 vs. 95**	75 vs. 90**	67 vs. 88**
PRE vs. PRE fb LPOST				82 vs. 75**	75 vs. 86**	67 vs. 83**
PRE fb EPOST vs. PRE fb LPOST				95 vs. 75**	90 vs. 86**	88 vs. 83**

Note. a.e., acid equivalent; ABMS, atrazine + bicyclopyrone + mesotrione + S-metolachlor; PRE, preemergence; EPOST, early postemergence; LPOST, late postemergence; fb, followed by.

[a]All PRE treatments were applied with dicamba at 280 g ha^{-1}. All PRE and POST treatments were applied with glyphosate at 1,060 g ha^{-1}. All POST treatments included nonionic surfactant at 0.25% v/v and ammonium sulfate at 2% w/v.

[b]Means within a column with similar letters are not significantly different based on Fisher's protected LSD test ($\alpha = .05$).

** Significant at $p \leq .05$.

TABLE 3 Density of glyphosate- and mesotrione-resistant Palmer amaranth and grain yield of glyphosate- and glufosinate-resistant corn treated with various herbicide programs averaged across the 2018 and 2019 growing seasons near Seward, KS

Herbicide program[a]	Rate	Timing	Palmer amaranth density		Grain yield
			3 wk after PRE	12 wk after LPOST	
	g a.e. or ai ha^{-1}		plants m^{-2}		kg ha^{-1}
Thiencarbazone-methyl + atrazine	129 + 840	PRE	7 cd	23 ab	9,207 a
ABMS	1,090	PRE	11 cd	26 ab	9,583 a
ABMS + atrazine fb ABMS + atrazine	550 + 280 fb 550 + 280	PRE fb EPOST	11 cd	19 ab	10,508 a
ABMS + atrazine + S-metolachlor + mesotrione fb ABMS + atrazine + S-metolachlor + mesotrione	550 + 280 + 535 + 35 fb 550 + 280 + 535 + 35	PRE fb EPOST	8 cd	7 b	9,301 a
ABMS + mesotrione fb ABMS + mesotrione	721 + 35 fb 361 + 35	PRE fb EPOST	7 cd	27 ab	10,215 a
ABMS + S-metolachlor fb ABMS + S-metolachlor	721 + 534 fb 361 + 534	PRE fb EPOST	8 cd	36 ab	10,002 a
ABMS + atrazine fb ABMS + atrazine	721 + 280 fb 361 + 280	PRE fb EPOST	18 bc	3 b	9,647 a
ABMS + metribuzin fb ABMS	550 + 158 fb 550	PRE fb EPOST	3 d	8 b	9,492 a
ABMS fb ABMS + (dicamba + diflufenzopyr)	550 fb 550 + 98	PRE fb LPOST	18 bc	3 b	9746 a
ABMS fb ABMS + glufosinate	550 fb 550 + 450	PRE fb LPOST	16 bcd	22 ab	9,862 a
Nontreated control	—	—	37 a	54 a	6,056 b

Note. a.e., acid equivalent; ABMS, atrazine + bicyclopyrone + mesotrione + S-metolachlor; PRE, preemergence; EPOST, early postemergence; LPOST, late postemergence; fb, followed by. Means within a column with similar letters are not significantly different based on Fisher's protected LSD test ($\alpha = .05$).

[a]All PRE treatments were applied with dicamba at 280 g ha^{-1}. All PRE and POST herbicide treatments were applied with glyphosate at 1,060 g ha^{-1}. All POST treatments included nonionic surfactant at 0.25% v/v and ammonium sulfate at 2% w/v.

combination with atrazine, S-metolachlor, or mesotrione provided 85–96% control of GMR Palmer amaranth at 2 wk after EPOST and 2 and 7 wk after LPOST in the current study (Table 2). These results indicated that PRE herbicides combined with EPOST programs helped to extend the duration of Palmer amaranth control. Chahal, Irmak, et al. (2018) previously concluded that season-long control of Palmer amaranth resistant to HPPD- and PS II-inhibitors can be achieved by using PRE fb POST programs that include herbicides with overlapping residual activity, consistent with the results from this study. Control with PRE fb LPOST programs of ABMS + (dicamba + diflufenzopyr) and ABMS + glufosinate ranged from 79 to 86% at final evaluation (7 wk after LPOST). Reduction in Palmer amaranth control observed with LPOST programs was primarily due to large-sized Palmer amaranth plants at the time of LPOST applications and additional emergence of Palmer amaranth cohorts in late season. Contrast analysis also revealed that PRE fb EPOST programs provided greater control of GMR Palmer amaranth at 2 wk after EPOST through 7 wk after LPOST compared with PRE-only and PRE fb LPOST programs (Table 2).

3.2 | Palmer amaranth density

All tested herbicide programs reduced Palmer amaranth density 51–92% compared with nontreated control (37 plants m^{-2}) at 3 wk after PRE (Table 3). Dicamba + ABMS + metribuzin applied PRE had only 3 Palmer amaranth plants m^{-2} at 3 wk after PRE (Table 3) compared with 7–18 plants m^{-2} for remaining herbicide programs. Palmer amaranth density 12 wk after POST (end-season) did not differ among the herbicide programs evaluated (19–36 plants m^{-2}). Except for four herbicide programs tested, there was no decrease in Palmer amaranth density compared with nontreated control (54 plants m^{-2}), indicating a late-season Palmer amaranth cohort emerged in those plots. Late-emerging Palmer amaranth cohorts have minimal effect on corn grain yields, but they can add seed to the soil seedbank and lead to future infestations if left uncontrolled. The seed rain potential of late-season Palmer amaranth escapes from Texas cotton (*Gossypium hirsutum* L.) fields has been estimated to be 13.9 million seeds ha^{-1} (Werner et al., 2020). Therefore, it is highly important to control the late-emerging cohorts of GMR

TABLE 4 Gross income and net return from grain yield of glyphosate- and glufosinate-resistant corn treated with various herbicide programs near Seward, KS

Herbicide program[a]	Rate	Timing	Program cost[b]	Gross income[c]	Net return[d]
	g a.e. or a.i. ha^{-1}		$ ha^{-1}		
Thiencarbazone-methyl + atrazine	129 + 840	PRE	145	1,340 a	1,180 ab
ABMS[¶]	1,090	PRE	178	1,394 a	1,202 ab
ABMS + atrazine fb ABMS + atrazine	550 + 280 fb 550 + 280	PRE fb EPOST	200	1,529 a	1,300 a
ABMS + atrazine + S-metolachlor + mesotrione fb ABMS + atrazine + S-metolachlor + mesotrione	550 + 280 + 535 + 35 fb 550 + 280 + 535 + 35	PRE fb EPOST	251	1,353 a	1,074 bc
ABMS + mesotrione fb ABMS + mesotrione	721 + 35 fb 361 + 35	PRE fb EPOST	208	1,486 a	1,250 ab
ABMS + S-metolachlor fb ABMS + S-metolachlor	721 + 534 fb 361 + 534	PRE fb EPOST	234	1,455 a	1,193 ab
ABMS + atrazine fb ABMS + atrazine	721 + 280 fb 361 + 280	PRE fb EPOST	200	1,404 a	1,175 ab
ABMS + metribuzin fb ABMS	550 + 158 fb 550	PRE fb EPOST	206	1,381 a	1,147 ab
ABMS fb ABMS + (dicamba + diflufenzopyr)	550 fb 550 + 98	PRE fb LPOST	223	1,418 a	1,167 ab
ABMS fb ABMS + glufosinate	550 fb 550 + 450	PRE fb LPOST	218	1,435 a	1,189 ab
Nontreated control	—	—	0	881 b	881 c

Note. a.e., acid equivalent; ABMS, atrazine + bicyclopyrone + mesotrione + S-metolachlor; PRE, preemergence; EPOST, early postemergence; LPOST, late postemergence; fb, followed by. Means within a column with similar letters are not significantly different based on Fisher's protected LSD test (α = .05).

[a]All PRE treatments were applied with dicamba at 280 g ha^{-1}. All PRE and POST treatments were applied with glyphosate at 1060 g ha^{-1}. All POST treatments included nonionic surfactant at 0.25% v/v and ammonium sulfate at 2% w/v.

[b]Program cost included an average cost of herbicide, ammonium sulfate, and nonionic surfactant, as well as the cost of application ($19.93 ha^{-1} application^{-1}).

[c]Gross income was calculated by multiplying the average corn yield from each treatment by the average grain price ($0.15 kg^{-1}) received in Kansas at harvest time during 2019.

[d]Net return was calculated by subtracting herbicide program cost from gross income.

Palmer amaranth for managing soil seedbank to prevent future infestations.

3.3 | Corn grain yield

Reduced Palmer amaranth interference with the herbicide programs (PRE-only, PRE fb EPOST, or PRE fb LPOST) evaluated in this study resulted in higher corn grain yield compared with the nontreated control (Table 3). Averaged across 2 yr, season-long GMR Palmer amaranth interference in the nontreated control reduced corn grain yield by 42% compared with the top yielding treatment. There was no significant difference in corn grain yield among the herbicide programs tested in this study, and the grain yield ranged from 9,207 to 10,215 kg ha^{-1} (Table 3).

3.4 | Economic analysis

Herbicide programs improved gross income compared with the nontreated control ($881 ha^{-1}). However, there were no differences in gross income among the herbicide programs tested and ranged from $1,340 to $1,529 ha^{-1} (Table 4). Similarly, herbicide programs had higher net return ($1,074–1,300 ha^{-1}) compared with the nontreated control ($881 ha^{-1}). Dicamba + ABMS + atrazine applied PRE fb EPOST application of ABMS + atrazine had the highest net return ($1,300 ha^{-1}) that did not differ from the rest of the treatments except for dicamba + ABMS + atrazine + S-metolachlor + mesotrione PRE fb EPOST application of ABMS + atrazine + S-metolachlor + mesotrione ($1,074 ha^{-1}) (Table 4).

4 | CONCLUSIONS AND PRACTICAL IMPLICATIONS

This study demonstrated that PRE-only programs, including dicamba + thiencarbazone-methyl + atrazine and dicamba + ABMS provided excellent, early-season control (90–92%) of GMR Palmer amaranth. The addition of atrazine, mesotrione, S-metolachlor alone or in a mixture with dicamba + ABMS did not improve the early-season control of GMR Palmer amaranth. However, PRE-only programs failed to provide season-long control (62–72% at final evaluation) of GMR Palmer amaranth, and a follow-up EPOST program of ABMS alone or in combination with atrazine, mesotrione, S-metolachlor alone or in a mixture improved Palmer amaranth control 85–92%. These results also highlight that ABMS as an overlapping residual herbicide applied (alone or in mixtures) in split applications (PRE fb EPOST) had prolonged activity on the GMR Palmer amaranth compared with ABMS + dicamba applied PRE alone in sandy soils with low organic matter content. All PRE fb EPOST programs improved end-season control of GMR Palmer amaranth compared with PRE-only programs. No differences were observed in corn yield from PRE-only, PRE fb EPOST, or PRE fb LPOST programs. Late-emerging cohorts or survivors of Palmer amaranth (even at low densities observed in this study) should be controlled to prevent potential replenishment of GMR Palmer amaranth soil seedbank (Crow et al., 2015, 2016). Controlling late-season cohorts or weed escapes is an important component of an integrated weed management program for managing herbicide resistance (Taylor & Hartzler, 2000; Neve et al., 2011).

The use of a single herbicide SOA is no longer effective for managing Palmer amaranth because resistance to multiple herbicide SOAs is evident in Kansas and neighboring states (Chahal & Jhala, 2018; Kumar, Liu, Boyer, et al., 2019; Kumar et al., 2020). Effective PRE fb EPOST herbicide strategies (layered soil residual with multiple SOAs) investigated in this study should be used for controlling GMR Palmer amaranth and improve net returns in glyphosate- and glufosinate-resistant corn. Future research should also investigate use of other integrated weed management tactics, including cover crops, improved crop rotations, targeted tillage, and harvest weed seed control methods, such as chaff lining and weed seed destructor, for effectively managing GMR Palmer amaranth seedbanks.

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AUTHOR CONTRIBUTIONS

Rui Liu: Data curation, Formal analysis, Investigation, Writing-original draft. Vipan Kumar: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing-review & editing. Amit Jhala: Data curation, Methodology, Validation, Writing-review & editing. Prashant Jha: Conceptualization, Methodology, Validation, Writing-review & editing. Phil Stahlman: Conceptualization, Validation, Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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