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Control of Photosystem II– and 4-Hydroxyphenylpyruvate Dioxygenase Inhibitor–Resistant Palmer Amaranth (*Amaranthus palmeri*) in Conventional Corn

Weed Management-Major Crops

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Nomenclature:
Acetochlor; atrazine; dicamba; diflufenzopyr; dimethenamid-P; fluthiacet-ethyl; halosulfuron; mesotrione; pyroxasulfone; saflufenacil; *S*-metolachlor; Palmer amaranth, *Amaranthus palmeri* S. Wats; corn, *Zea mays* L.

Key words:
Multiple sites of action; net return; PRE followed by POST; resistance management; weed control

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Abstract

Palmer amaranth, a dioecious summer annual weed species, is the most troublesome weed in agronomic crop production systems in the United States. Palmer amaranth resistant to photosystem (PS) II- and 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitors is of particular concern in south central Nebraska. The objectives of this study were to determine the effect of PRE followed by POST herbicide programs on PS II- and HPPD-inhibitor-resistant Palmer amaranth control, crop yield, and net economic return in conventional corn. A field study was conducted in 2014, 2015, and 2016 in a grower's field infested with PS II- and HPPD-inhibitor-resistant Palmer amaranth near Shickley in Fillmore County, Nebraska. A contrast analysis suggested that mesotrione + *S*-metolachlor + atrazine applied PRE provided 83% Palmer amaranth control at 21 d after application compared to 78 and 72% control with pyroxasulfone + fluthiacet-ethyl + atrazine and saflufenacil + dimethenamid-P, respectively. Most of the PRE followed by POST herbicide programs provided ≥85% Palmer amaranth control. Based on contrast analysis, POST application of dicamba + diflufenzopyr provided 93% Palmer amaranth control compared to 87, 79, and 42% control with dicamba, dicamba + halosulfuron, and acetochlor, respectively, at 28 d after POST. All PRE followed by POST herbicide programs, aside from mesotrione + *S*-metolachlor + atrazine followed by acetochlor (2,530 to 7,809 kg ha^{-1}), provided 9,550 to 10,500 kg ha^{-1} corn yield compared with 2,713 to 6,110 kg ha^{-1} from nontreated control. Similarly, PRE followed by POST herbicide programs, except for mesotrione + *S*-metolachlor + atrazine followed by acetochlor ($191 and $897 ha^{-1}), provided similar net return of $427 to $707 ha^{-1} and $1,127 to $1,727 ha^{-1} in 2014 and 2015-16, respectively. It is concluded that herbicide programs based on multiple sites of action are available for control of PS II- and HPPD-inhibitor-resistant Palmer amaranth in conventional corn.

Palmer amaranth, a native plant of the southwestern United States, is a C_4 dioecious species belonging to the family Amaranthaceae (Sauer 1957). Palmer amaranth biotypes resistant to microtubule- (Group 3), acetolactate synthase- (Group 2), photosystem (PS) II- (Group 5), 5-enol-pyruvylshikimate-3-phosphate synthase- (Group 9), hydroxyphenylpyruvate dioxygenase- (HPPD; Group 27), and protoporphyrinogen oxidase- (Group 14) inhibitors have been reported in different states in the United States (Heap 2017). Palmer amaranth biotypes resistant to two or more herbicide sites of action have also been confirmed (Heap 2017; Jhala et al. 2014), thus reducing the number of available herbicide control options.

Nebraska is the third largest producer of corn in the United States, with 3.8 million hectares planted in 2017 (USDA-NASS 2017). A Palmer amaranth biotype resistant to PS II- (atrazine) and HPPD-inhibitors (mesotrione, tembotrione, and topramezone) was reported in a continuous seed corn production field in south-central Nebraska (Jhala et al. 2014). PS II- and HPPD-inhibitors are the most commonly used herbicides for weed control in corn because of their PRE and POST activity, broad weed control spectrum, and crop safety, particularly in sweet corn, seed corn, and popcorn (Bollman et al. 2008; Fleming et al. 1988; Swanton et al. 2007). The evolution of PS II- and HPPD-inhibitor–resistant Palmer amaranth in Nebraska is a management challenge for growers because it reduces the number of

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herbicide options for effective Palmer amaranth control in corn. Additionally, a Palmer amaranth biotype resistant to glyphosate has recently been confirmed in a production field under glyphosate-resistant (GR) corn–soybean rotation in south-central Nebraska (Chahal et al. 2017).

Several growers avoid PRE herbicide application to reduce production costs and depend only on POST herbicides such as glyphosate for weed control. Schuster and Smeda (2007) reported reduced common waterhemp density (<5 plants m^{-2}) at 25 d after PRE (DAPRE) herbicide applications in corn compared to no weed suppression without PRE. Avoiding PRE herbicides allows early-season crop–weed competition. Corn has a critical period of weed control up to six to seven weeks after emergence or the 3- to 14-leaf stage, and weed competition during this stage could result in a yield penalty (Hall et al. 1992). In addition, avoiding PRE herbicides can cause high weed densities at the POST application timing, resulting in a potential increase in weed selection pressure for resistance against POST herbicides. Growers need alternative herbicide programs for effective management of herbicide-resistant (HR) Palmer amaranth in their production fields. This includes a combination of PRE followed by POST herbicides with multiple sites of action, herbicide rotation, rotation of HR crop traits, and rotation with conventional cultivars (Norsworthy et al. 2012; Oliveira et al. 2017).

The development of HR crops involves the selection of resistance traits using traditional genetic methods or the integration of transgenic traits using genetic engineering, an expensive and time-consuming process until seed commercialization (Reddy and Nandula 2012). Growers purchasing HR crop seeds are required to sign the seed company's technology/stewardship agreement, which does not allow them to use the harvested seed for planting in the future (Anonymous 2017b; Anonymous 2017d). Therefore, growers need to purchase the HR crop seeds every season. Additionally, growers are required to pay technology fees along with the seed cost for HR crops, which increases production costs (Edwards et al. 2014; Johnson et al. 2000; Rice et al. 2001). The south-central area of Nebraska has a significant number of fields under hybrid seed corn production and GR corn–soybean rotation (Chahal et al. 2017; Jhala et al. 2014). Additionally, the area under conventional corn production has been increasing in Nebraska for the last few years to reduce the cost of production due to low commodity prices and the rotation of herbicides with different sites of action, specifically to reduce the overreliance on glyphosate, as six weed species have evolved resistance to glyphosate in Nebraska (Chahal et al. 2017; Ganie and Jhala 2017; Heap 2017; Sarangi et al. 2015).

Information is not available regarding the control of PS II- and HPPD-inhibitor–resistant Palmer amaranth in conventional corn. The objectives of this study were to determine the effect of PRE followed by POST herbicide programs on PS II- and HPPD-inhibitor–resistant Palmer amaranth control, crop yield, and net economic return in conventional corn. We hypothesized that multiple sites of action PRE followed by POST herbicide programs will provide effective control of PS II- and HPPD-inhibitor–resistant Palmer amaranth and prevent yield reductions in conventional corn.

Materials and Methods

A field study was conducted in 2014, 2015, and 2016 in a grower's field in which the presence of PS II- and HPPD-inhibitor–resistant Palmer amaranth had been confirmed near Shickley in Fillmore County, Nebraska (40.46°N, 97.80°E). The field had been under seed corn production for the previous eight years, with continual use of PS II- and HPPD-inhibiting herbicides. Soil at the experimental site was a Crete silt loam (fine, smectitic, mesic Pachic Udertic Argiustolls) with a pH of 6.5, 26% sand, 57% silt, 17% clay, and 3.5% organic matter. Conventional corn hybrid Stine 9631E was seeded at 87,500 seeds ha^{-1} in rows spaced 76 cm apart on June 3, 2014; May 30, 2015; and June 1, 2016. Herbicide programs were arranged in a randomized complete block design with four blocks using field slope as the blocking factor. The experimental site was under a center-pivot irrigation system and plots were 3 m wide and 9 m long, consisting of four rows of corn. Monthly mean air temperatures, along with total precipitation during the 2014, 2015, and 2016 growing seasons and the 30-year average for the research site, are provided in Table 1. During 2014 and 2015, 13 to 28 cm of rainfall was received within 2 DAPRE, while 7 cm of rainfall was received at 14 DAPRE at the experimental site in 2016.

Table 1. Monthly mean air temperature and total precipitation during the 2014, 2015, and 2016 growing seasons and 30-year averages at Shickley, Nebraska.[a]

	Mean temperature				Total precipitation			
Month	2014	2015	2016	30-yr average	2014	2015	2016	30-yr average
	——————C———————				——————mm——————			
March	5	7	9	5	2	12	14	48
April	11	12	12	11	94	42	99	68
May	18	17	16	17	57	108	200	124
June	23	23	25	22	154	264	7	117
July	23	24	25	25	56	124	55	86
August	23	22	23	24	154	69	147	88
September	19	22	20	19	76	104	52	86
October	14	14	15	12	47	22	64	59
Annual	11	12	13	11	664	908	726	763

[a]Mean air temperature and total precipitation data were obtained from NWS-COOP (2017).

Herbicide programs included PRE followed by POST herbicides with a total of 16 program combinations, including a nontreated control (Table 2). The herbicide rates and application timings, depending on Palmer amaranth growth stage, were based on herbicide label recommendations in corn in Nebraska. Herbicides were applied with a CO_2-pressurized backpack sprayer consisting of a four-nozzle boom fitted with AIXR 110015 flat-fan nozzles (TeeJet Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60189) calibrated to deliver 140 L ha^{-1} at 276 kPa. PRE herbicides were applied within 3 d after planting corn, and POST herbicides were applied when Palmer amaranth was 12 to 15 cm tall.

Palmer amaranth control was visually estimated at 21 DAPRE; 14, 28, and 56 d after POST (DAPOST); and at harvest based on a 0% to 100% scale, with 0% corresponding to no control and 100% corresponding to plant death. A similar scale was used to assess corn injury at 7, 14, and 21 d after PRE and POST herbicide applications, with 0% corresponding to no injury and 100% corresponding to plant death. Palmer amaranth density was assessed from two randomly selected 0.25 m^2 quadrats per plot at

Table 2. Herbicide products, rates, and application timing for control of photosystem II- and 4-hydroxyphenylpyruvate dioxygenase-inhibitor–resistant Palmer amaranth in conventional corn in field experiments conducted at Shickley, Nebraska in 2014, 2015, and 2016.[a]

Herbicide program[b]	Trade name	Rate	Application timing	Manufacturer
		g ai or ae ha^{-1}		
Pyroxasulfone + fluthiacet-ethyl + atrazine fb dicamba	Anthem ATZ fb	1,580	PRE fb	FMC Corporation, Philadelphia, PA 19103
	Clarity	280	POST	BASF Corporation, Research Triangle Park, NC 27709
Pyroxasulfone + fluthiacet-ethyl + atrazine fb dicamba + diflufenzopyr	Anthem ATZ fb	1,580	PRE fb	FMC Corporation
	Status	196	POST	BASF Corporation
Pyroxasulfone + fluthiacet-ethyl + atrazine fb dicamba + halosulfuron	Anthem ATZ fb	1,580	PRE fb	FMC Corporation
	Yukon	284	POST	Gowan Company, Yuma, AZ 85364
Pyroxasulfone + fluthiacet-ethyl + atrazine fb acetochlor	Anthem ATZ fb	1,580	PRE fb	FMC Corporation
	Warrant	2,320	POST	Monsanto Company, St. Louis, MO 63167
Acetochlor fb dicamba	Degree fb	2,130	PRE fb	Monsanto Company
	Clarity	280	POST	BASF Corporation
Acetochlor fb dicamba + diflufenzopyr	Degree fb	2,130	PRE fb	Monsanto Company
	Status	196	POST	BASF Corporation
Acetochlor fb dicamba + halosulfuron	Degree fb	2,130	PRE fb	Monsanto Company
	Yukon	284	POST	Gowan Company
Saflufenacil + dimethenamid-P fb dicamba	Verdict fb	390	PRE fb	BASF Corporation
	Clarity	280	POST	
Saflufenacil + dimethenamid-P fb dicamba + diflufenzopyr	Verdict fb	390	PRE fb	BASF Corporation
	Status	196	POST	
Saflufenacil + dimethenamid-P fb dicamba + halosulfuron	Verdict fb	390	PRE fb	BASF Corporation
	Yukon	284	POST	Gowan Company
Saflufenacil + dimethenamid-P fb acetochlor	Verdict fb	390	PRE fb	BASF Corporation
	Warrant	2,320	POST	Monsanto Company
Mesotrione + *S*-metolachlor + atrazine fb dicamba	Lumax EZ fb	2,780	PRE fb	Syngenta Crop Protection, Inc., Greensboro, NC 27419
	Clarity	280	POST	BASF Corporation
Mesotrione + *S*-metolachlor + atrazine fb dicamba + diflufenzopyr	Lumax EZ fb	2,780	PRE fb	Syngenta Crop Protection
	Status	196	POST	BASF Corporation
Mesotrione + *S*-metolachlor + atrazine fb dicamba + halosulfuron	Lumax EZ fb	2,780	PRE fb	Syngenta Crop Protection
	Yukon	284	POST	Gowan Company
Mesotrione + *S*-metolachlor + atrazine fb acetochlor	Lumax EZ fb	2,780	PRE fb	Syngenta Crop Protection
	Warrant	2,320	POST	Monsanto Company

[a]Abbreviations: AMS, ammonium sulfate (DSM Chemicals North America Inc., Augusta, GA); fb, followed by; NIS, nonionic surfactant (Induce, Helena Chemical Co., Collierville, TN); POST, postemergence; PRE, preemergence.
[b]All POST herbicide programs except acetochlor were mixed with AMS at 2.5% (wt/v) and NIS at 0.25% (v/v). PRE applications were made within 3 d after planting corn, and POST herbicides were applied when Palmer amaranth was 12 to 15 cm tall.

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21 DAPRE and 28 DAPOST herbicide applications. Aboveground biomass of Palmer amaranth was harvested from the same quadrat areas as used for density data collection at 28 DAPOST, oven-dried at 65 C for 3 days, and weighed. Palmer amaranth density and biomass data were converted into percent density or biomass reduction compared with the nontreated control plots using the following formula (Ganie et al. 2017; Sarangi et al. 2017):

$$\text{Biomass or Density reduction}\,(\%) = \frac{(C - B)}{C} \times 100, \qquad [1]$$

where C is the biomass or density of the nontreated control plot, and B is the biomass or density collected from the experimental (herbicide treated) plot. At maturity, corn was harvested from the middle two rows of each plot with a small-plot combine, and weight and moisture content were measured. Corn yields were adjusted to 15.5% moisture content (Ganie et al. 2017).

Economic analysis was performed to evaluate the profit and risk associated with each PRE followed by POST herbicide program. Net return from herbicide programs was calculated using the conventional corn yield from each replication and herbicide program cost (Bradley et al. 2000; Edwards et al. 2014; Johnson et al. 2000):

$$\text{Net return} = \text{Gross revenue} - \text{Herbicide program cost}. \qquad [2]$$

Gross revenue was calculated by multiplying the conventional corn yield from each replication for each program by the average grain price (\$0.14 kg^{-1}) received in Nebraska at harvest time during the experimental years (USDA-NASS 2016). Each herbicide program cost included the average herbicide cost per hectare obtained from three agricultural chemical dealers in Nebraska and a custom application cost of \$18.11 ha^{-1} application^{-1}.

Statistical Analysis

Palmer amaranth control estimates, net return, density reduction, aboveground biomass reduction, and corn injury and yield data were subjected to ANOVA using the PROC GLIMMIX procedure in SAS version 9.3 (SAS Institute Inc., Cary, NC 27513). Herbicide programs and experimental years were considered fixed effects, whereas replications were considered a random effect in the model. Data were combined over years when there was no year by herbicide program interaction. Year by herbicide program interactions for Palmer amaranth control, density, and biomass reduction were not significant; therefore, data were combined over three years. However, year by herbicide program interaction was significant for corn yield and net return, with no difference between 2015 and 2016; therefore, yield and net return data were combined for 2015 and 2016 and presented separately for 2014. The nontreated control was not included in the data analysis for control estimates and percent density and biomass reduction. Before analysis, data were tested for normality and homogeneity of variance using the Shapiro-Wilk goodness-of-fit and Levene's tests in SAS. To meet the normality and homogeneity of variance assumption for ANOVA, all data, aside from corn yield, were arcsine square-root transformed before analysis; however, back-transformed data are presented with mean separation based on the transformed data. Where the ANOVA indicated herbicide program effects were significant, means were separated at $P \le 0.05$ with Tukey-Kramer's pairwise comparison test to reduce type I error for the series of comparisons. Preplanned single degree-of-freedom contrast statements were used to determine relative efficacy of PRE and POST herbicides for Palmer amaranth control, density, and biomass reduction.

Results and Discussion

Palmer Amaranth Control

PS II- and HPPD-inhibitor–resistant Palmer amaranth was controlled 68% to 86% with pyroxasulfone plus fluthiacet-ethyl plus atrazine (1,580 g ha^{-1}), saflufenacil plus dimethenamid-P (390 g ha^{-1}), or mesotrione plus *S*-metolachlor plus atrazine (2,780 g ha^{-1}) at 21 DAPRE application (Table 3). The contrast analysis suggested that mesotrione plus *S*-metolachlor plus atrazine applied PRE provided 83% Palmer amaranth control compared to 78%, 72%, and 68% control with pyroxasulfone plus fluthiacet-ethyl plus atrazine, saflufenacil plus dimethenamid-P, and acetochlor, respectively, at 21 DAPRE (Table 4). Similarly, Kohrt and Sprague (2017) reported 80% to 97% Palmer amaranth control with mesotrione plus *S*-metolachlor plus atrazine or saflufenacil plus dimethenamid-P at 45 DAPRE. However, Oliveira et al. (2017) reported ≥95% control of HPPD inhibitor–resistant tall waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer], a species closely related to Palmer amaranth, with mesotrione plus *S*-metolachlor plus atrazine or pyroxasulfone plus fluthiacet-ethyl plus atrazine at 30 DAPRE in Nebraska. Janak and Grichar (2016) reported >95% Palmer amaranth control with PRE applications of saflufenacil plus dimethenamid-P or mesotrione plus *S*-metolachlor plus atrazine. Aulakh and Jhala (2015) reported 96% common waterhemp control with PRE application of saflufenacil plus dimethenamid-P at 15 DAPRE. At the research site, poor Palmer amaranth control was observed by the grower with the POST application of PS II- and HPPD-inhibitors in previous years, resulting in high seed additions to the soil seedbank. During the experimental years, a very high density of Palmer amaranth, ranging from 300 to 400 plants m^{-2}, could explain the <85% Palmer amaranth control with PRE herbicides in this study.

Palmer amaranth control was improved when PRE herbicides were followed by POST herbicides. PRE herbicides followed by POST application of dicamba, dicamba plus diflufenzopyr, or dicamba plus halosulfuron controlled Palmer amaranth 74% to 98% throughout the season (Table 3). Similarly, Oliveira et al. (2017) reported 91% control of HPPD inhibitor–resistant tall waterhemp with mesotrione plus *S*-metolachlor plus atrazine followed by dicamba plus diflufenzopyr at 32 DAPOST. PRE herbicides followed by acetochlor applied POST provided 26% to 70% Palmer amaranth control throughout the season because acetochlor is a soil residual herbicide and cannot control emerged weeds. Furthermore, most of the Palmer amaranth plants were 12 to 15 cm tall when POST herbicides were applied, resulting in poor control with acetochlor applied POST. Based on contrast analysis, dicamba or dicamba plus diflufenzopyr applied POST provided 88% to 97% Palmer amaranth control compared to 80% to 86% and 44% to 66% control with dicamba plus halosulfuron and acetochlor, respectively, at 14 and 56 DAPOST (Table 5). Similar Palmer amaranth control has been reported in previous studies; for example, Jhala et al. (2014) reported 90% control of PS II- and HPPD-inhibitor–resistant Palmer amaranth with dicamba at 21 DAPOST. A recent study in Tennessee reported 89% control of glyphosate-resistant Palmer amaranth with dicamba plus diflufenzopyr at 28 DAPOST (Crow et al. 2016). Kohrt and Sprague (2017) reported 91% to 94% Palmer amaranth control with dicamba or dicamba plus diflufenzopyr at 14 DAPOST. In addition, Schuster and Smeda (2007) reported >95% common waterhemp control with a 35 DAPOST application of dicamba plus diflufenzopyr. Previous studies have reported

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Table 3. Effect of herbicide programs on photosystem II- and 4-hydroxyphenylpyruvate dioxygenase-inhibitor–resistant Palmer amaranth control in conventional corn in field experiments conducted at Shickley, Nebraska in 2014, 2015, and 2016.[a]

Herbicide program[b]	Rate	Application timing	Control[c,d] 21 DAPRE	14 DAPOST	28 DAPOST	56 DAPOST	At harvest
	g ai or ae ha^{-1}		%				
Nontreated control	-	-	-	-	-	-	-
Pyroxasulfone + fluthiacet-ethyl + atrazine fb dicamba	1,580	PRE fb	77 abc	84 abc	90 ab	92 a	95 a
	280	POST					
Pyroxasulfone + fluthiacet-ethyl + atrazine fb dicamba + diflufenzopyr	1,580	PRE fb	79 abc	90 a	95 a	97 a	96 a
	196	POST					
Pyroxasulfone + fluthiacet-ethyl + atrazine fb dicamba + halosulfuron	1,580	PRE fb	74 abc	82 abc	78 abc	86 ab	85 ab
	284	POST					
Pyroxasulfone + fluthiacet-ethyl + atrazine fb acetochlor	1,580	PRE fb	83 ab	70 cd	61 cd	68 b	69 c
	2,320	POST					
Acetochlor fb dicamba	2,130	PRE fb	77 abc	78 bcd	83 ab	88 a	91 ab
	280	POST					
Acetochlor fb dicamba + diflufenzopyr	2,130	PRE fb	65 cd	80 abc	90 ab	93 a	95 a
	196	POST					
Acetochlor fb dicamba + halosulfuron	2,130	PRE fb	62 d	80 abc	76 abc	85 ab	85 ab
	284	POST					
Saflufenacil + dimethenamid-P fb dicamba	390	PRE fb	73 abc	74 cd	85 abc	80 ab	89 ab
	280	POST					
Saflufenacil + dimethenamid-P fb dicamba + diflufenzopyr	390	PRE fb	74 abc	80 abc	90 ab	94 a	97 a
	196	POST					
Saflufenacil + dimethenamid-P fb dicamba + halosulfuron	390	PRE fb	68 bcd	75 cd	80 bc	85 ab	87 ab
	284	POST					
Saflufenacil + dimethenamid-P fb acetochlor	390	PRE fb	74 a-c	51 e	28 e	26 c	60 c
	2,320	POST					
Mesotrione + *S*-metolachlor + atrazine fb dicamba	2,780	PRE fb	86 a	85 abc	90 ab	92 a	94 a
	280	POST					
Mesotrione + *S*-metolachlor + atrazine fb dicamba + diflufenzopyr	2,780	PRE fb	81 abc	87 ab	95 ab	97 a	98 a
	196	POST					
Mesotrione + *S*-metolachlor + atrazine fb dicamba + halosulfuron	2,780	PRE fb	82 abc	81 abc	83 ab	86 a	87 ab
	284	POST					
Mesotrione + *S*-metolachlor + atrazine fb acetochlor	2,780	PRE fb	85 a	66 de	38 de	37 c	70 c
	2,320	POST					

[a]Abbreviations: AMS, ammonium sulfate (DSM Chemicals North America Inc., Augusta, GA); fb, followed by; NIS, nonionic surfactant (Induce, Helena Chemical Co., Collierville, TN); POST, postemergence; PRE, preemergence.
[b]All POST herbicide programs, except acetochlor, were mixed with AMS at 2.5% (wt/v) and NIS at 0.25% (v/v). PRE applications were made within 3 d after planting corn, and POST herbicides were applied when Palmer amaranth was 12 to 15 cm tall.
[c]Means within columns with no common letter(s) are significantly different according to Tukey-Kramer's pairwise comparison test ($P \leq 0.05$).
[d]Data from the nontreated control were not included in analysis.

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Table 4. Contrast means for control and density reduction of photosystem II- and 4-hydroxyphenylpyruvate dioxygenase-inhibitor–resistant Palmer amaranth at 21 d after a preemergence application in conventional corn in field experiments conducted at Shickley, Nebraska in 2014, 2015, and 2016.[a]

Herbicide program	Control	Density reduction[b]
	————————%————————	
Pyroxasulfone + fluthiacet-ethyl + atrazine vs. saflufenacil + dimethenamid-P	78 vs. 72*	75 vs. 71
Pyroxasulfone + fluthiacet-ethyl + atrazine vs. acetochlor	78 vs. 68*	75 vs. 52*
Pyroxasulfone + fluthiacet-ethyl + atrazine vs. mesotrione + *S*-metolachlor + atrazine	78 vs. 83*	75 vs. 81*
Saflufenacil + dimethenamid-P vs. acetochlor	72 vs. 68*	71 vs. 52*

[a]Single degree-of-freedom contrast analysis; *indicates significance at $P < 0.05$.
[b]Palmer amaranth density data were converted into percent density reduction compared with the nontreated control using the following formula: $\text{Density reduction}\,(\%) = \frac{(C-B)}{C} \times 100$, where *C* is the density of the nontreated control plot and *B* is the density collected from the experimental plot.

increased weed control by tank-mixing diflufenzopyr with dicamba; however, the synergistic effect was species-specific (Grossmann et al. 2002; Lym and Deibert 2005; Wehtje 2008). There is no published evidence of the synergistic effects of dicamba and diflufenzopyr for Palmer amaranth control.

Palmer Amaranth Density and Shoot Biomass Reduction

Palmer amaranth control results were reflected in Palmer amaranth density and aboveground biomass. PRE herbicides aside from acetochlor (52%) reduced Palmer amaranth density 67% to 86% compared with the nontreated control at 21 DAPRE (Table 6). The contrast analysis suggested that mesotrione plus *S*-metolachlor plus atrazine provided 81% density reduction compared to 71% to 75% with pyroxasulfone plus fluthiacet-ethyl plus atrazine and saflufenacil plus dimethenamid-P at 21 DAPRE (Table 4). Palmer amaranth density reduction was improved when PRE herbicides were followed by POST herbicides. At 28 DAPOST, 83% to 95% Palmer amaranth density reduction was observed with pyroxasulfone plus fluthiacet-ethyl plus atrazine or mesotrione plus *S*-metolachlor plus atrazine applied PRE followed by dicamba or dicamba plus diflufenzopyr POST, saflufenacil plus dimethenamid-P followed by dicamba plus diflufenzopyr, or pyroxasulfone plus fluthiacet-ethyl plus atrazine followed by dicamba plus halosulfuron. The remainder of the herbicide programs resulted in 49% to 76% density reduction. Similarly, Oliveira et al. (2017) reported >95% density reduction of HPPD inhibitor–resistant tall waterhemp with mesotrione plus *S*-metolachlor plus atrazine applied PRE followed by dicamba plus diflufenzopyr applied POST at 32 DAPOST. Based on contrast analysis, POST application of dicamba plus diflufenzopyr provided 85% density reduction compared to 73% to 75% density reduction with dicamba or dicamba plus halosulfuron at 28 DAPOST (Table 5).

Palmer amaranth aboveground biomass was reduced 73% to 94% with most PRE followed by POST herbicide programs at 28 DAPOST (Table 6). However, PRE herbicides followed by acetochlor applied POST provided 44% to 64% biomass reduction because acetochlor was not able to control emerged weeds. Palmer amaranth biomass reduction observed with the herbicide programs coincides with control and density reduction at 28 DAPOST (Tables 3 and 6). The contrast analysis suggested 79% to 87% Palmer amaranth biomass reduction with POST applications of dicamba, dicamba plus diflufenzopyr, or dicamba plus halosulfuron at 28 DAPOST (Table 5). Similarly, Jhala et al. (2014) reported 73% to 85% biomass reduction of PS II and HPPD inhibitor–resistant Palmer amaranth with POST application of dicamba in Nebraska.

Corn Injury and Yield

No corn injury was observed at 7, 14, and 21 d after PRE or POST herbicide applications in the three year study (data not shown). Previous studies have also reported no corn injury with PRE applications of mesotrione plus *S*-metolachlor plus atrazine at 1,880 and 2,960 g ha^{-1} and twice the labeled rate of acetochlor

Table 5. Contrast means for photosystem II- and 4-hydroxyphenylpyruvate dioxygenase-inhibitor–resistant Palmer amaranth control at 14, 28, and 56 d after POST (DAPOST) and at harvest and for density and biomass reduction at 28 DAPOST in conventional corn in field experiments conducted at Shickley, Nebraska in 2014, 2015, and 2016.[a]

Herbicide program	Control				Density reduction[b]	Biomass reduction[b]
	14 DAPOST	28 DAPOST	56 DAPOST	At harvest		
	————————————%————————————					
Dicamba vs. dicamba + diflufenzopyr	80 vs. 84	87 vs. 93*	88 vs. 95	92 vs. 97	73 vs. 85*	84 vs. 87
Dicamba vs. dicamba + halosulfuron	80 vs. 80	87 vs. 79*	88 vs. 86	92 vs. 86	73 vs. 75	84 vs. 79
Dicamba vs. acetochlor	80 vs. 62*	87 vs. 42*	88 vs. 44*	92 vs. 66*	73 vs. 70	84 vs. 55*
Dicamba + diflufenzopyr vs. dicamba + halosulfuron	84 vs. 80*	93 vs. 79*	95 vs. 86*	97 vs. 86*	85 vs. 86	87 vs. 79

[a]Single degree-of-freedom contrast analysis; asterisk indicates significance at $P < 0.05$.
[b]Palmer amaranth density and biomass data were converted into percent density or biomass reduction compared with the nontreated control using the following formula: $\text{Biomass or Density reduction}\,(\%) = \frac{(C-B)}{C} \times 100$, where *C* is the biomass or density of the nontreated control plot and *B* is the biomass or density collected from the experimental plot.

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Table 6. Effect of herbicide programs on photosystem II- and 4-hydroxyphenylpyruvate dioxygenase-inhibitor–resistant Palmer amaranth density reduction at 21 d after PRE (DAPRE) and 28 d after POST (DAPOST), biomass reduction at 28 DAPOST, and corn yield in conventional corn in field experiments conducted at Shickley, Nebraska in 2014, 2015, and 2016.[a]

Herbicide program[b]	Rate	Application timing	Density reduction[c,d] 21 DAPRE	28 DAPOST	Biomass reduction[c,d]	Yield[c] 2014	2015-16
	g ai or ae ha^{-1}		——————%——————			——kg ha^{-1}——	
Nontreated control	-	-	-	-	-	2,713 b	4,583 d
Pyroxasulfone + fluthiacet-ethyl + atrazine fb dicamba	1,580	PRE fb	73 ab	83 ab	90 a	5,684 a	12,870 ab
	280	POST					
Pyroxasulfone + fluthiacet-ethyl + atrazine fb dicamba + diflufenzopyr	1,580	PRE fb	75 ab	95 a	92 a	5,468 a	12,851 ab
	196	POST					
Pyroxasulfone + fluthiacet-ethyl + atrazine fb dicamba + halosulfuron	1,580	PRE fb	68 ab	80 ab	73 ab	5,692 a	11,973 ab
	284	POST					
Pyroxasulfone + fluthiacet-ethyl + atrazine fb acetochlor	1,580	PRE fb	82 a	76 b	58 bc	4,795 a	10,529 bc
	2,320	POST					
Acetochlor fb dicamba	2,130	PRE fb	52 b	61 bc	79 ab	5,229 a	13,064 ab
	280	POST					
Acetochlor fb dicamba + diflufenzopyr	2,130	PRE fb	53 b	73 b	78 ab	5,999 a	12,809 ab
	196	POST					
Acetochlor fb dicamba + halosulfuron	2,130	PRE fb	51 b	76 b	77 ab	5,580 a	11,667 ab
	284	POST					
Saflufenacil + dimethenamid-P fb dicamba	390	PRE fb	71 ab	63 bc	82 ab	4,407 a	12,311 ab
	280	POST					
Saflufenacil + dimethenamid-P fb dicamba + diflufenzopyr	390	PRE fb	76 ab	86 ab	82 ab	5,102 a	12,943 ab
	196	POST					
Saflufenacil + dimethenamid-P fb dicamba + halosulfuron	390	PRE fb	67 ab	75 b	83 ab	4,989 a	13,391 ab
	284	POST					
Saflufenacil + dimethenamid-P fb acetochlor	390	PRE fb	69 ab	49 c	64 bc	5,280 a	9,476 cd
	2,320	POST					
Mesotrione + *S*-metolachlor + atrazine fb dicamba	2,780	PRE fb	84 a	83 ab	85 ab	4,183 ab	13,863 ab
	280	POST					
Mesotrione + *S*-metolachlor + atrazine fb dicamba + diflufenzopyr	2,780	PRE fb	86 a	84 ab	94 a	5,442 a	14,317 a
	196	POST					
Mesotrione + *S*-metolachlor + atrazine fb dicamba + halosulfuron	2,780	PRE fb	73 ab	70 b	83 ab	4,915 a	12,786 ab
	284	POST					
Mesotrione + *S*-metolachlor + atrazine fb acetochlor	2,780	PRE fb	82 a	66 bc	44 c	2,530 b	7,809 cd
	2,320	POST					

[a]Abbreviations: AMS, ammonium sulfate (DSM Chemicals North America Inc., Augusta, GA); fb, followed by; NIS, nonionic surfactant (Induce, Helena Chemical Co., Collierville, TN); POST, postemergence; PRE, preemergence.
[b]All POST herbicide programs, except acetochlor, were mixed with AMS at 2.5% (wt/v) and NIS at 0.25% (v/v). PRE applications were made within 3 d after planting corn and POST herbicides were applied when Palmer amaranth was 12 to 15 cm tall.
[c]Means within columns with no common letter(s) are significantly different according to Tukey-Kramer's pairwise comparison test ($P \leq 0.05$).
[d]Percent density and biomass reduction data of the nontreated control were not included in analysis. Palmer amaranth density and biomass data were converted into percent density or biomass reduction compared with the nontreated control plots using the following formula: $\text{Biomass / Density reduction}(\%) = \frac{(C-B)}{C} \times 100$., where C is the biomass or density of the nontreated control plot and B is the biomass or density collected from the experimental plot.

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Table 7. Cost of herbicide programs for controlling photosystem II- and 4-hydroxyphenylpyruvate dioxygenase-inhibitor–resistant Palmer amaranth in conventional corn and net return from corn yield in field experiments conducted at Shickley, Nebraska in 2014, 2015, and 2016.[a]

				Gross income from corn yield[d,e]		Net return[d,e]	
Herbicide program[b]	Rate	Application timing	Program cost[c]	2014	2015/16	2014	2015/16
	g ai or ae ha^{-1}		———$ ha^{-1}———				
Nontreated control	-	-	0	302 b	638 c	302 b	638 c
Pyroxasulfone + fluthiacet-ethyl + atrazine fb dicamba	1,580	PRE fb	123.93	792 a	1,723 ab	668 a	1,599 ab
	280	POST					
Pyroxasulfone + fluthiacet-ethyl + atrazine fb dicamba + diflufenzopyr	1,580	PRE fb	164.71	762 a	1,721 ab	597 a	1,556 ab
	196	POST					
Pyroxasulfone + fluthiacet-ethyl + atrazine fb dicamba + halosulfuron	1,580	PRE fb	158.81	793 a	1,598 ab	634 a	1,439 ab
	284	POST					
Pyroxasulfone + fluthiacet-ethyl + atrazine fb acetochlor	1,580	PRE fb	158.99	668 a	1,397 abc	509 a	1,238 abc
	2,320	POST					
Acetochlor fb dicamba	2,130	PRE fb	87.91	728 a	1,745 ab	640 a	1,662 ab
	280	POST					
Acetochlor fb dicamba + diflufenzopyr	2,130	PRE fb	128.69	836 a	1,715 ab	707 a	1,586 ab
	196	POST					
Acetochlor fb dicamba + halosulfuron	2,130	PRE fb	157.37	777 a	1,555 ab	620 a	1,398 abc
	284	POST					
Saflufenacil + dimethenamid-P fb dicamba	390	PRE fb	88.36	614 a	1,645 ab	526 a	1,557 ab
	280	POST					
Saflufenacil + dimethenamid-P fb dicamba + diflufenzopyr	390	PRE fb	129.14	711 a	1,733 ab	582 a	1,604 ab
	196	POST					
Saflufenacil + dimethenamid-P fb dicamba + halosulfuron	390	PRE fb	123.24	695 a	1,795 ab	572 a	1,672 ab
	284	POST					
Saflufenacil + dimethenamid-P fb acetochlor	390	PRE fb	123.43	735 a	1,250 abc	612 a	1,127 abc
	2,320	POST					
Mesotrione + *S*-metolachlor + atrazine fb dicamba	2,780	PRE fb	155.67	583 ab	1,862 ab	427 ab	1,706 a
	280	POST					
Mesotrione + *S*-metolachlor + atrazine fb dicamba + diflufenzopyr	2,780	PRE fb	197.17	758 a	1,924 a	561 a	1,727 a
	196	POST					
Mesotrione + *S*-metolachlor + atrazine fb dicamba + halosulfuron	2,780	PRE fb	190.55	685 a	1,781 ab	494 a	1,590 ab
	284	POST					
Mesotrione + *S*-metolachlor + atrazine fb acetochlor	2,780	PRE fb	190.74	382 a	1,088 bc	191 b	897 bc
	2,320	POST					

[a]Abbreviations: fb, followed by; POST, postemergence; PRE, preemergence.
[b]All POST herbicide programs except acetochlor were mixed with ammonium sulfate at 2.5% (wt/v) and nonionic surfactant at 0.25% (v/v).
[c]Program cost includes an average cost of herbicide, ammonium sulfate, and nonionic surfactant, as well as the cost of application ($18.11 ha^{-1} application^{-1}) from two independent sources in Nebraska.
[d]Gross revenue was calculated by multiplying the conventional corn yield from each replication for each program by the average grain price ($0.14 kg^{-1}) received in Nebraska at harvest time during the experimental years. Net return was calculated as gross income from conventional corn yield for each replication minus herbicide program cost.
[e]Means within columns with no common letter(s) are significantly different according to Tukey-Kramer's pairwise comparison test ($P \leq 0.05$).

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(Chikoye et al. 2009; Janak and Grichar 2016). Ganie et al. (2017) observed 2% to 4% corn injury at 7 DAPRE with saflufenacil plus dimethenamid-P at a rate higher (780 g ha^{-1}) than that applied in this study (390 g ha^{-1}). Some studies also reported minimal to no corn injury with dicamba (600 g ha^{-1}), dicamba plus diflufenzopyr (200 g ha^{-1}), or dicamba plus halosulfuron (380 g ha^{-1}) at 14 DAPOST (Ganie et al. 2017; Kohrt and Sprague 2017; Soltani et al. 2008). VanGessel et al. (2016) reported hybrid corn stunting and leaf chlorosis up to 10% at 7 DAPOST application of dicamba plus diflufenzopyr at twice (588 g ha^{-1}) the labeled rate. Dicamba plus diflufenzopyr is a new safened formulation of dicamba that can be applied to corn plants from 10 cm to 90 cm tall or the 2- to 10-leaf stage (whichever comes first), assuring reduced corn injury (Anonymous 2017c). In contrast, dicamba can be applied to up to 5-leaf or 20-cm-tall corn or at reduced rates later in the season using drop nozzles, also known as a directed spray (Anonymous 2017a). Grossmann et al. (2002) reported reduced absorption of dicamba into corn leaves with the addition of diflufenzopyr, and hence, lower corn injury compared to dicamba applied alone.

Corn yield was comparatively lower in 2014 due to damage from strong winds during rainfall in August. In 2014, corn yield of 4,100 to 6,000 kg ha^{-1} was achieved from all PRE followed by POST herbicide programs except for mesotrione plus *S*-metolachlor plus atrazine followed by acetochlor (2,530 kg ha^{-1}). In 2015/2016, all herbicide programs provided similar corn yield of 10,500 to 14,000 kg ha^{-1}, aside from saflufenacil plus dimethenamid-P or mesotrione plus *S*-metolachlor plus atrazine applied PRE followed by acetochlor applied POST (7,800 to 9,500 kg ha^{-1}) (Table 6). The reduced corn yield with most PRE herbicides followed by POST application of acetochlor could be explained by reduced Palmer amaranth control and density and biomass reduction throughout the season since acetochlor applied POST was not able to control emerged Palmer amaranth plants.

Economic Analysis

The cost of PRE followed by POST herbicide programs ranged from $87.91 to $197.17 ha^{-1} and provided $1,088 to $1,924 ha^{-1} gross income from corn yield in 2015/2016 compared to $382 to $836 ha^{-1} in 2014 (Table 7) because of lower corn yield in 2014 (Table 6) due to damage from strong winds and rain. In 2014 and 2015/2016, PRE followed by POST programs aside from mesotrione plus *S*-metolachlor plus atrazine followed by acetochlor ($191 and $897) provided net returns of $427 to $707 and $1,127 to $1,727, respectively. Though statistically similar to other programs, PRE herbicides followed by dicamba, dicamba plus diflufenzopyr, or dicamba plus halosulfuron applied POST provided $427 to $707 and $1,398 to $1,727 net returns in 2014 and 2015/2016, respectively.

Practical Implications

Several fields in Nebraska are under GR corn production using glyphosate as a POST herbicide option for weed control (Chahal et al. 2017; Jhala et al. 2014). Studies conducted at the research site indicate that PS II- and HPPD-inhibitor–resistant Palmer amaranth was sensitive to glyphosate since this herbicide was not applied over the past eight years as the field was kept under conventional seed corn production (data not shown). However, because of the evolution and occurrence of GR Palmer amaranth and other GR weeds in Nebraska (Chahal et al. 2017; Heap 2017), glyphosate should not be considered as a single management option. Results of this study indicate that Palmer amaranth can be effectively controlled without glyphosate using PRE followed by POST herbicides with different sites of action. In addition, economic analysis suggests that the use of distinct sites of action PRE herbicides followed by POST application of dicamba-based herbicides tested in this study provided higher gross income and net returns. However, there is an urgent need to adopt an integrated weed management approach that includes the use of a different sites of action PRE followed by POST herbicide program, crop rotation, the rotation of different HR cultivars with conventional crop cultivars, tillage, and harvest weed seed control methods to mitigate the evolution and spread of multiple HR Palmer amaranth.

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