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Effect of plant height on control of multiple herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) in glufosinate/glyphosate-resistant corn

Ramandeep Kaur[1], Parminder S. Chahal[2], Yeyin Shi[3], Nevin C. Lawrence[4], Stevan Z. Knezevic[1] and Amit J. Jhala[1*]

[1]Department of Agronomy and Horticulture, University of Nebraska-Lincoln, Lincoln, NE, United States, [2]FMC Agricultural Solutions, Gretna, NE, United States, [3]Department of Biological Systems Engineering, University of Nebraska-Lincoln, Lincoln, NE, United States, [4]Panhandle Research Extension and Education Center, University of Nebraska-Lincoln, Scottsbluff, NE, United States

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EDITED BY
Simerjeet Kaur,
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University of Florida, United States
Wesley Everman,
North Carolina State University,
United States

*CORRESPONDENCE
Amit J. Jhala
Amit.Jhala@unl.edu

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Multiple herbicide-resistant (MHR) Palmer amaranth is a troublesome weed in several crops across the USA, including corn. Due to unavoidable weather conditions, it is sometimes not possible for growers to apply pre-emergence herbicide; therefore, post-emergence (POST) herbicide is needed for effective control of MHR Palmer amaranth. The objectives of this study were to evaluate the effect of POST herbicides applied at two heights (10-15 cm and 20-30 cm) for MHR Palmer amaranth control and their effect on Palmer amaranth biomass, density, and seed production as well as yield of glufosinate/glyphosate-resistant corn. Field experiments were conducted at a grower's field near Carleton, Nebraska, USA in 2020 and 2021. Control of MHR Palmer amaranth was affected by the plant height when herbicides were applied. Glufosinate, dicamba, dicamba/diflufenzopyr, and dicamba/tembotrione applied to 10-15 cm tall Palmer amaranth provided ≥ 94% control 30 d after EPOST (DAEPOST), whereas atrazine/bicyclopyone/mesotrione/*S*-metolachlor applied to 20-30 cm tall MHR Palmer amaranth provided 85% control in 2021. Glufosinate provided 85% to 90% control when applied to 20-30 cm tall Palmer amaranth in both years. At 90 DALPOST, dicamba, dicamba/diflufenzopyr, and dicamba/tembotrione applied to 10-15 cm tall Palmer amaranth provided ≥ 88% control. Dicamba/tembotrione, atrazine/bicyclopyone/mesotrione/*S*–metolachlor, and dicamba applied to 20-30 cm tall Palmer amaranth provided 85% to 92% control. Glufosinate, dicamba, and atrazine/bicyclopyone/mesotrione/*S*–metolachlor were the most effective for reducing Palmer amaranth density 2 to 19 plants m^{-2} when applied to 10-15 cm Palmer amaranth 30 DAEPOST compared with the nontreated control (137 plants m^{-2}) in 2021; however, when applied to 20-30 cm Palmer amaranth, glufosinate, and atrazine/bicyclopyone/mesotrione/*S*–metolachlor reduced density 5 to 19 plants m^{-2}. At 30 DAEPOST, glufosinate and atrazine/bicyclopyone/mesotrione/*S*–metolachlor had the lowest Palmer amaranth biomass (3-17 g m^{-2}). Corn yield in 2020 was higher than 2021 due to more rain in 2020. All herbicides resulted in a similar yield in 2020. Lower seed production of 6,269 and 1,953 seeds plant^{-1} for 10-15 cm and 20-30 cm MHR Palmer amaranth were recorded with dicamba and atrazine/bicyclopyone/mesotrione/*S*–metolachlor.

KEYWORDS

acetochlor, bicyclopyone, clopyralid, corn, *Zea mays* L., dicamba, diflufenzopyr, Palmer amaranth height

1 Introduction

Corn (*Zea mays* L.) is the most widely cultivated crop in the USA, and sixty-five herbicide-resistant weed species have evolved in corn-based cropping systems in the USA (Heap, 2023). Multiple herbicide-resistant Palmer amaranth (*Amaranthus palmeri* S.Watson) is one of these problematic weed species in this cropping system. The first case of herbicide-resistant Palmer amaranth was identified in South Carolina in 1989 with evolved resistance to trifluralin (Gossett et al., 1992). Thereafter, atrazine resistance was reported in Texas in 1993 (Ward et al., 2013). The first case of glyphosate-resistant Palmer amaranth was reported in Georgia in 2005 (Culpepper et al., 2006). Moreover, Palmer amaranth biotypes resistant to atrazine and HPPD-inhibiting herbicides have been documented in several states in the USA. Palmer amaranth resistant to 2,4-D, glyphosate, chlorsulfuron, atrazine, mesotrione, and fomesafen has been reported in Kansas (Kumar et al., 2019). By August 2023, Palmer amaranth had evolved resistance to herbicides belonging to 10 sites of action (Heap, 2023).

Palmer amaranth has an extended emergence period starting from March to October in the USA depending on the location (Chahal et al., 2021; Liu et al., 2022). A higher photosynthetic and growth rate, and greater seed production enhances its competitive ability and makes it the most difficult weed species to control in corn production system (Horak and Loughin, 2000; Ward et al., 2013; Korres et al., 2019). It can emerge in large densities as high as 1,000 plants m^{-2} year^{-1} (Jha and Norsworthy, 2009) and can exceed a height of 10 cm within nine days of emergence (Meyer and Norsworthy, 2020). A single female Palmer amaranth plant can produce 600,000 seeds plant^{-1} (Keeley et al., 1987; Burke et al., 2007). Massinga et al. (2001) showed that Palmer amaranth at 0.5–8 plants m^{-1} row reduced corn yield from 11% to 91% and produced 140,000–514,000 seeds m^{-2}, respectively. Similarly, in soybean [*Glycine max* (L.) Merr.], Palmer amaranth caused yield losses of 17% to 68% in Fayetteville, Arkansas (Klingaman and Oliver, 1994) and 79% in Topeka, Kansas (Bensch et al., 2003) when Palmer amaranth densities ranged from 0.3–10 plants m^{-1} row and 8 plants m^{-1} row, respectively.

Nomenclature: Acetochlor; bicyclopyone; clopyralid; corn, *Zea mays* L.; dicamba; diflufenzopyr; dimethenamid-*P*; flumetsulam; glufosinate; glyphosate; mesotrione; Palmer amaranth, Amaranthus palmeri S. Watson; *S*–metolachlor; tembotrione; topramezone.

Atrazine and HPPD-inhibiting herbicides are commonly used in corn due to their broad spectrum of weed control, flexible application timings, tank-mix compatibility, and crop safety (Sutton et al., 2002; Swanton et al., 2007; Bollman et al., 2008; Stephenson and Bond, 2012; Walsh et al., 2012); however, their continuous and repeated use has led to the evolution of resistance to both sites of action (SOA) in Palmer amaranth populations (Jhala et al., 2014; Chahal et al., 2015; Kumar et al., 2020). Glyphosate has been extensively used as a POST weed control option in glyphosate-resistant corn, and it is estimated that 125 million kg of glyphosate was applied in 2013, a 594% increase from 1996 (USGS, 2016). Glufosinate has been used as another option for controlling Palmer amaranth in glufosinate-resistant crops, but its timely applications are essential (Corbett et al., 2004; Barnett et al., 2013; Cahoon et al., 2015b). The efficacy of glufosinate is compromised when it is applied to Palmer amaranth taller than 12 cm (Steckel et al., 1997; Coetzer et al., 2002; Culpepper et al., 2010). It can be mixed with dicamba or glyphosate for POST control of Palmer amaranth (Norsworthy et al., 2012; Cahoon et al., 2015a), and glufosinate mixed with dicamba was effective for controlling ≥ 20 cm tall Palmer amaranth 12 d after application in XtendFlex (resistant to dicamba/glufosinate/glyphosate) cotton (*Gossypium hirsutum* L.) in North Carolina (Merchant et al., 2013; Vann et al., 2017). Similarly, Merchant et al. (2014) reported greater control of 20 cm tall Palmer amaranth with sequential applications of glufosinate plus 2,4-D compared with sequential applications of 2,4-D alone in cotton resistant to 2,4-D choline, glufosinate, and glyphosate.

Diversifying herbicide SOA and their timely applications is the foremost step for a successful weed management program. Palmer amaranth should be controlled when its height is below 12.5 cm (Gower et al., 2002). Sometimes, due to poor weather conditions, field conditions, and timing factors, herbicide applications become challenging for growers, and it is not possible to apply pre-emergence herbicide, causing growers to rely on POST herbicides. While relying on POST herbicide programs for MHR Palmer amaranth control, care should be taken not to apply herbicides too soon after both the crop and weeds emerge because this results in no control of later emerging Palmer amaranth populations (Gower et al., 2002). Thus, the objective of this study was to evaluate the effect of POST herbicides applied at two growth stages of MHR Palmer amaranth (10-15 cm and 20-30 cm) for control and their effect on Palmer amaranth biomass, density, and seed production as well as yield of glufosinate/glyphosate-resistant corn.

2 Materials and methods

2.1 Study site and experimental design

Field experiments were conducted near Carleton, Nebraska (40.30°N, 97.67°W) during 2020 and 2021. The soil at Carleton was silt loam (montmorillonitic, mesic, Pachic Argiustolls), with a pH of 6.0, 19.0% sand, 63.0% silt, 18.0% clay, and 2.5% organic matter. Glufosinate/glyphosate-resistant corn 'DKC 60-87 RIB' was planted on May 12, 2020, and May 18, 2021. Corn was planted under no-till conditions at a seeding rate of 64,220 seeds ha^{-1}. Individual plot dimensions were 3 m wide and 9 m long. The study was laid out in a randomized complete block design with four replicates. The experimental site was rainfed, and no supplemental irrigation was provided. Enlist ONE (2,4-D choline) was applied in early spring for control of glyphosate-resistant marestail (*Conyza canadensis* L. Cronq.). The site had a natural population of ALS-inhibitor/atrazine/glyphosate-resistant Palmer amaranth.

Treatments consisted of POST herbicides only depending on the height of Palmer amaranth (10 to 15 cm; and 20 to 30 cm tall), and no PRE herbicides were applied. Early-POST herbicide application was made to 10 to 15 cm tall Palmer amaranth on June 18, 2020, and June 16, 2021; late-POST herbicides were applied to 20 to 30 cm tall Palmer amaranth on June 23, 2020, and June 25, 2021. Herbicides were applied using a handheld CO_2-pressurized backpack sprayer equipped with AIXR 110015 flat-fan nozzles (TeeJet® Technologies, Wheaton, IL) calibrated to deliver 140 L ha^{-1} at 276 kPa at a constant speed of 4.8 km h^{-1}. Glufosinate was mixed with liquid ammonium sulfate at 3% vol vol^{-1} and was applied with XR 11005 flat-fan nozzles (TeeJet® Technologies). Nontreated and weed-free controls were included for comparison. Recommended adjuvants were added with each herbicide (Table 1).

2.2 Data collection

Palmer amaranth control was estimated visually using a 0% to 100% scale, with 0% equal to no control and 100% equal to complete plant death, at 30, 45, and 90 days after herbicide application in 2020 and 2021. Corn injury was assessed for every POST application and estimated on a scale of 0% to 100%, with 0% equivalent to no corn injury and 100% equivalent to plant death, at 15 and 30 d after treatment (DAT). MHR Palmer amaranth density was recorded by counting the number of Palmer amaranth plants in randomly placed 0.5 m^2 quadrats in each plot at 30 d after EPOST (DAEPOST) and 30 d after LPOST (DALPOST). Aboveground Palmer amaranth biomass was collected from 0.5 m^2 quadrats at 30 DAEPOST and 30 DALPOST in each plot. Biomass was clipped at the soil surface, dried at 65 C in an oven until a constant weight was achieved, and weighed. Corn grain was mechanically harvested both years of the study from the two center rows of each plot in mid-October. Grain weights were adjusted to 15% moisture content to calculate yields in kg ha^{-1}. Palmer amaranth seed production data were collected at the end of the season. Palmer amaranth seed heads were stripped from stems and separated by passing them through a series of standard laboratory sieves with mesh size scaling from 0.50 to 3.35 mm. Seeds collected from the 0.50 mm sieve was processed with a seed cleaner, thoroughly cleaned, and the number of seeds per female Palmer amaranth plant was recorded.

2.3 Statistical analysis

Data were performed in SAS 9.4 using Proc glimmix procedure. Year by-herbicide treatment and year-by-herbicide treatment by Palmer amaranth height interactions were evaluated. If by-herbicide

TABLE 1 Herbicides, rates, and products used for control of acetolactate synthase inhibitors/atrazine/glyphosate-resistant Palmer amaranth in glyphosate/glufosinate-resistant corn in afield experiment conducted near Carleton, Nebraska in 2020 and 2021.

Herbicide	Trade name	Rate [a]	Manufacturer	Adjuvants[a,b]
		g ae or ai ha^{-1}		
Glyphosate	Roundup Powermax	1260	Bayer CropScience	AMS
Glufosinate	Liberty	880	BASF	AMS
Dicamba	DiFlexx	560	Bayer CropScience	NIS, Class Act Ridion
Dicamba/tembotrione	DiFlexx Duo	900	Bayer CropScience	Class Act Ridion, COC
Dicamba/diflufenzopyr	Status	196	BASF	AMS, COC
Acetochlor/mesotrione	Harness Max	2160	Bayer CropScience	UAN, COC
Dimethenamid-*P*/topramezone	Armezon PRO	656	BASF	UAN, COC
Glyphosate/mesotrione/*S*–metolachlor	Halex GT	2210		NIS, AMS
Acetochlor/clopyralid/mesotrione	Resicore	2300	Corteva Agriscience	NIS, COC
Atrazine/bicyclopyone/mesotrione/*S*–metolachlor	Acuron	1930	Syngenta	COC
Clopyralid/flumetsulam	Hornet	165	AMVAC	COC, AMS

[a]ai, active ingredient; ae, acid equivalent; AMS, ammonium sulfate (N-Pak AMS Liquid, Winfield United, LLC., St. Paul, MN 55164); Crop Oil concentrate (COC); Non-ionic surfactant (NIS); Urea ammonium nitrate (UAN); WC, water conditioner (Class Act Ridion, Winfield United, Arden Hills, MN, 55126).
[b]AMS at 2.5-5% vol/vol, NIS at 0.25% vol/vol, COC 1.0% vol/vol, UAN 2.0 qt ac^{-1} and Class Act Ridion at 1% vol/vol were mixed with herbicide based on label recommendations.

treatment and year-by-herbicide treatment by Palmer amaranth height interactions were significant, data were analyzed separately by year. In the models separated by year, the interaction of herbicide treatment and Palmer amaranth height were considered fixed effects, whereas the replication, interaction of replication by herbicide treatment and Palmer amaranth height, interaction of replication by DAT by herbicide treatment and Palmer amaranth height were considered random effects. Assumptions of normality of residuals and homogeneity of variances were confirmed using PROC UNIVARIATE, with normal Q-Q plots and levene test, respectively, and analysis of variance (ANOVA) was conducted. Variables that failed variance assumptions were checked for outliers and heterogeneity of variances by plotting residual values.

Type III tests were used to assess fixed effects, and treatment comparisons were made based on Tukey Kramer's pairwise comparison test and Sidak adjustments. Palmer amaranth control ratings were log transformed and fit to generalized linear mixed-effect models using GLIMMIX procedure with beta distribution (link = "complementary log-log") based on the residual pseudo-likelihood (PL) technique, whereas Palmer amaranth seed production and aboveground Palmer amaranth biomass were log transformed and fit to generalized linear mixed-effect models using GLIMMIX procedure with gaussian (link = "identity") error distributions. Following treatment means separation, back-transformed values are presented in tables. Palmer amaranth density and corn yield data were analyzed with GLIMMIX using gaussian (link = "identity") error distributions selected for response variables based on the restricted maximum likelihood technique. The nontreated control was excluded from the Palmer amaranth control ratings analysis, however the weed-free check was excluded from the Palmer amaranth density, biomass, and seed production analysis because of no variance.

3 Results and discussion

Year-by-herbicide-by Palmer amaranth height interactions were significant for MHR Palmer amaranth control and density; therefore, data were separated and presented by year. However, year-by-herbicide-by Palmer amaranth height interaction were non-significant for MHR Palmer amaranth biomass and seed production, respectively; thus, pooled data were presented for these parameters. No herbicide and MHR Palmer amaranth height interactive effect was observed for corn yield; thus, simple means were presented for both years separately. Most of the programs displayed safety to glyphosate/glufosinate-resistant corn. Corn injury (bleaching and browning of leaves) were recorded with acetochlor/mesotrione, dimethenamid-*P*/topramezone, and acetochlor/clopyralid/mesotrione, and it ranges from 10% to 15% at 30 DAEPOST (data not shown).

3.1 Palmer amaranth control

The interaction of year-by-herbicide-by Palmer amaranth height on Palmer amaranth control was significant; therefore, data are presented by year. The herbicides tested in this study controlled 10-15 cm MHR Palmer amaranth 5% to 96% in both years 30 DAEPOST (Table 2). Herbicide treatments controlled MHR Palmer amaranth 5% to 55% in 2020, whereas in 2021, glufosinate, dicamba/diflufenzopyr, dicamba/tembotrione, and dicamba provided 94% and 96% control at 30 DAEPOST. However, Crow et al. (2015) determined that paraquat/*S*–metolachlor applied POST provided glyphosate-resistant Palmer amaranth control 97% at 14 d after application. Herbicides applied EPOST effectively controlled 10-15 cm tall Palmer amaranth in 2021 compared with 2020 at 30 DAEPOST. Glufosinate effectively controlled 20-30 cm MHR Palmer amaranth, and it accounts for ≥ 85% at 30 DAEPOST in both years. These results are in concordance with Shyam et al. (2021), who reported that glufosinate applied POST provided 88% Palmer amaranth control. In 2021, atrazine/bicyclopyone/mesotrione/*S*–metolachlor controlled 20-30 cm Palmer amaranth by 85%. The efficacy of this program might be due to multiple effective sites of action on MHR Palmer amaranth control. At 30 DALPOST, similar control of 20-30 cm MHR Palmer amaranth was observed with glufosinate and atrazine/bicyclopyone/mesotrione/*S*–metolachlor; however, dicamba, dicamba/tembotrione, and dicamba/diflufenzopyr provided > 90% control in both years. However, Bond et al. (2006) reported glyphosate and fomesafen controlled all accessions of Palmer amaranth of 15 cm to 60 cm tall Palmer amaranth at least 96% at 21 d after treatment at Arkansas.

At 45 DALPOST, dicamba, dicamba/diflufenzopyr, and dicamba/tembotrione provided 10-15 cm and 20-30 cm Palmer amaranth control by 85% to 86%, 82% to 91%, 80% to 88%, and 90 to 92%, 90% to 93%, 84 to 95%, respectively. These results are similar to those reported by McDonald et al. (2021), where dicamba applied POST provided 85% to 95% control of Palmer amaranth. Interestingly, the larger sized Palmer amaranth was controlled 81% to 88% by atrazine/bicyclopyone/mesotrione/*S*–metolachlor program in both years.

At 90 DALPOST, dicamba, dicamba/diflufenzopyr, and dicamba/tembotrione provided ≥ 80% control of 10-15 cm and 20-30 cm Palmer amaranth; however, atrazine/bicyclopyone/mesotrione/*S*–metolachlor effectively controlled 20-30 cm Palmer amaranth by 88%. Poor control by the remaining herbicides indicates that a single POST application is not sufficient to control MHR Palmer amaranth. Secondly, it is necessary to incorporate PRE with POST application for effective control of Palmer amaranth seedbank. Liu et al. (2021) noted that reduction in Palmer amaranth control observed with POST programs was primarily due to large-sized Palmer amaranth plants at the time of application, and additionally that there was synchronous emergence of Palmer amaranth in the late season.

3.2 Palmer amaranth density

The interaction of herbicide by Palmer amaranth height on Palmer amaranth density was significant. The MHR Palmer amaranth plants ranged from 93 to 166 m^{-2} in the nontreated control (Table 3). At 30 DAEPOST, for 10-15 cm Palmer amaranth, clopyralid/flumetsulam and glufosinate recorded 36 and 50 Palmer amaranth plants m^{-2} and the remaining herbicides were ineffective

TABLE 2 Interaction of POST herbicide and Palmer amaranth height (10-15 cm or 20-30 cm) for control of multiple herbicide-resistant Palmer amaranth in glyphosate/glufosinate-resistant corn in a field experiment conducted at Carleton, Nebraska, during the 2020 and 2021 growing seasons.

Herbicide	Palmer amaranth control [a,b,c]											
	30 DAEPOST [d]				30 DALPOST [d]		45 DALPOST [d]				90 DALPOST [d]	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2021	
	10-15 cm		20-30 cm		20-30 cm		10-15 cm		20-30 cm		10-15 cm	20-30 cm
	%											
Nontreated control	0	0	0	0	0	0	0	0	0	0	0	0
Weed free check	99 a	99 a	99 a	99 a	99 a	99 a	99 a	99 a	99 a	99 a	99 a	99 a
Glyphosate (1,260 g ai ha^{-1})	25 c	55 bc	23 cd	41 c	45 d	36 d	9 f	30 e	43 d	32 e	33 d	25 d
Glufosinate (880 g ai ha^{-1})	51 bc	94 a	85 a	90 a	85 bc	82 bcd	15 f	72 cde	76 cd	73 cd	44 d	66 cd
Dicamba (560 g ai ha^{-1})	33 c	96 a	55 bc	63 b	92 ab	91 ab	85 bc	86 bc	90 ab	92 ab	95 a	92 ab
Dicamba/tembotrione (900 g ai ha^{-1})	5 d	94 a	55 bc	0 e	93 ab	92 ab	80 cd	88 bc	95 a	84 bc	88 ab	85 b
Dicamba/diflufenzopyr (196 g ai ha^{-1})	27 c	94 a	48 c	0 e	93 ab	96 a	82 bcd	91 ab	93 a	90 ab	92 ab	80 bc
Acetochlor/mesotrione (2,160 g ai ha^{-1})	55 bc	74 bc	10 d	28 cd	73 cd	45 d	35 e	66 de	74 cd	57 d	38 d	33 d
Dimethenamid-*P*/topramezone (656 g ai ha^{-1})	33 c	70 bc	14 d	22 cd	73 cd	66 cd	15 f	40 e	58 d	60 d	23 d	53 cd
Glyphosate/mesotrione/*S*–metolachlor (2,210 g ai ha^{-1})	45 c	51 bc	49 c	5 e	29 d	5 e	38 e	32 e	20 e	25 e	8 de	0 e
Acetochlor/clopyralid/mesotrione (2,300 g ai ha^{-1})	52 bc	77 bc	17 d	41 c	77 cd	79 cd	40 e	39 e	66 d	81 bcd	31 d	48 d
Atrazine/bicyclopyone/mesotrione/*S*–metolachlor (1,930 g ai ha^{-1})	40 c	71 bc	42 b	85 a	86 bc	91 ab	5 f	70 cde	88 b	81 bcd	23 d	88 ab
Clopyralid/flumetsulam (165 g ai ha^{-1})	30 c	58 bc	19 d	26 cd	72 cd	15 e	20 f	37 e	52 d	50 d	29 d	38 d
P-value (Herbicide*Palmer amaranth height*Year)	< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001		< 0.0001	

[a]Year by herbicide by Palmer amaranth height for Palmer amaranth control was significant, therefore, data were presented separately for both years.
[b]Data for each year were log transformed before analysis; however, back-transformed values are presented based on interpretations of transformed data.
[c]Means presented within each column with no common letter(s) are significantly different according to estimated mean with Sidak adjustments and Tukey P value.
[d]DAEPOST, days after early-POST application; DALPOST, days after late-POST application.

in 2020, whereas in 2021, glufosinate and atrazine/bicyclopyone/mesotrione/*S*–metolachlor resulted in the lowest density, with 2 and 19 Palmer amaranth plants m^{-2}, respectively. For 20-30 cm Palmer amaranth, glufosinate was the only herbicide that reduced density as low as 5 Palmer amaranth plants m^{-2} in both years. Glufosinate was followed by atrazine/bicyclopyone/mesotrione/*S*-metolachlor, and acetochlor/clopyralid/mesotrione (19 and 23 plants m^{-2}) for effective control of 20-30 cm tall Palmer amaranth.

The efficacy of glufosinate applied to 10-15 cm Palmer amaranth varied at 30 DALPOST that resulted in 24 Palmer amaranth plants m-2 in both years. This was likely due to new emergence and lack of residual activity in glufosinate to provide control of Palmer amaranth 30 DALPOST. Dicamba/diflufenzopyr, dicamba and atrazine/bicyclopyone/mesotrione/*S*–metolachlor were effective in both years, with these treatments recording 8, 10, and 13 Palmer amaranth plants m^{-2}, respectively. Priess et al. (2022) concluded that dicamba followed by glufosinate provided 100% Palmer amaranth control when applied to less than 12 cm tall plants. For 20-30 cm Palmer amaranth, the least Palmer amaranth density was recorded with dicamba/tembotrione (24 plants/m^{-2}) in 2020, and atrazine/bicyclopyone/mesotrione/*S*–metolachlor, glufosinate, dicamba/tembotrione, and dicamba in 2021 (5 to 17 plants/m^{-2}).

3.3 Palmer amaranth biomass

The interaction of herbicide by Palmer amaranth height on Palmer amaranth biomass was significant (P < 0.0001), with most

TABLE 3 Multiple herbicide-resistant Palmer amaranth density as affected by POST herbicide and Palmer amaranth height (10-15 cm or 20-30 cm) in glyphosate/glufosinate-resistant corn in a field experiment conducted in Carleton, Nebraska, during the 2020 and 2021 growing seasons.

Herbicide	Palmer amaranth density[a,b]							
	number m^{-2}							
	30 DAEPOST [c]				30 DALPOST [c]			
	2020		2021		2020		2021	
	10-15 cm	20-30 cm	10-15 cm	20-30 cm	10-15 cm	20-30 cm	10-15 cm	20-30 cm
Nontreated control	98 abc	115 a	137 ab	113 abc	166 ab	137 ab	166 ab	93 bcde
Weed free check	0	0	0	0	0	0	0	0
Glyphosate (1,260 g ai ha^{-1})	106 abc	49 b	53 bc	49 bc	144 ab	58 bcde	144 ab	62 cdef
Glufosinate (880 g ai ha^{-1})	50 abc	5 c	2 d	5 d	24 cde	33 cde	24 def	12 f
Dicamba (560 g ai ha^{-1})	77 abc	28 b	16 cd	28 bc	10 e	73 bcde	10 f	17 ef
Dicamba/tembotrione (900 g ai ha^{-1})	146 ab	49 b	48 bc	49 bc	19 cde	24 cde	19 ef	15 ef
Dicamba/diflufenzopyr (196 g ai ha^{-1})	141 abc	67 ab	62 bc	67 bc	8 e	61 bcde	8 f	27 def
Acetochlor/mesotrione (2,160 g ai ha^{-1})	97 abc	55 ab	53 bc	55 bc	22 cde	101 ab	22 ef	55 cdef
Dimethenamid-*P*/topramezone (656 g ai ha^{-1})	83 abc	64 ab	32 bc	64 bc	33 cde	201 ab	33 def	53 cdef
Glyphosate/mesotrione/*S*–metolachlor (2,210 g ai ha^{-1})	154 a	77 ab	59 bc	77 bc	163 ab	109 abc	163 ab	118 bc
Acetochlor/clopyralid/mesotrione (2,300 g ai ha^{-1})	134 abc	23 b	54 bc	23 cd	104 abc	66 abcd	104 bcd	28 def
Atrazine/bicyclopyone/mesotrione/*S*–metolachlor (1,930 g ai ha^{-1})	97 abc	19 bc	19 cd	19 cd	13 de	57 bcde	13 ef	5 f
Clopyralid/flumetsulam (165 g ai ha^{-1})	36 bc	70 ab	146 a	70 bc	212 a	34 cde	212 a	118 bc
P-value (Herbicide* Palmer amaranth height*Year)	< 0.0001		< 0.0001		< 0.0001		< 0.0001	

[a]Year by herbicide by Palmer amaranth height for Palmer amaranth density was significant, therefore, data were presented separately for both years.
[b]Means presented within each column with no common letter(s) are significantly different according to estimated mean with sidak adjustments and Tukey P-value.
[c]DAEPOST, days after early-POST application; DALPOST, days after late-POST application.

herbicides providing higher biomass with the exception of glufosinate (3 g m^{-2}), atrazine/bicyclopyone/mesotrione/*S*–metolachlor (8 g m^{-2}), dicamba (20 g m^{-2}), and glyphosate (25 g m^{-2}) for 10-15 cm Palmer amaranth. However, for large sized Palmer amaranth, glufosinate (10 g m^{-2}), atrazine/bicyclopyone/mesotrione/*S*–metolachlor (17 g m^{-2}), acetochlor/clopyralid/mesotrione (20 g m^{-2}), and dicamba (27 g m^{-2}) provided lowest MHR Palmer amaranth biomass at 30 DAEPOST (Table 4). The effect of Palmer amaranth height on Palmer amaranth biomass in dicamba and atrazine/bicyclopyone/mesotrione/*S*–metolachlor applied EPOST can be attributed to the comparatively lower Palmer amaranth infestations observed in these respective treatments after application, thus causing the corn to achieve less weed competition. Early crop closure provided less space for late-emerging Palmer amaranth populations, and thus the lowest Palmer amaranth biomass was recorded in these treatments. These findings are in concordance with studies by Jha and Norsworthy (2009) in soybean.

At 30 DALPOST, dicamba/diflufenzopyr, atrazine/bicyclopyone/mesotrione/*S*–metolachlor, and dicamba reduced biomass ≥ 94% for 10-15 cm Palmer amaranth (7 to 10 g m^{-2}). This was followed by the acetochlor/mesotrione, dicamba/tembotrione, glufosinate, and dimethenamid-*P*/topramezone treatments, which provided 84% to 89% biomass reduction. For 20-30 cm Palmer amaranth, atrazine/bicyclopyone/mesotrione/*S*–metolachlor and glufosinate reduced biomass ≥ 90%, however, 15 to 16 g m^{-2} Palmer amaranth biomass was recorded for dicamba/tembotrione and dicamba (80% to 81% biomass reduction). The remaining programs recorded 104 to 161 and 27 to 113 g m^{-2} Palmer amaranth biomass for 10-15 cm and 20-30 cm heights, respectively. The higher biomass for 10-15 cm Palmer amaranth may be attributed to higher weed pressure in the beginning of the season and more infestations from late-emerging Palmer amaranth, whereas for large-sized Palmer amaranth, more intraspecific competition occurred within Palmer amaranth plants, and thus, a comparatively lower population and biomass were observed 30 DALPOST. Meyer and Norsworthy (2019) reported that a premix of 2,4-D plus glyphosate provided 92% reduction in 30 cm Palmer amaranth biomass, and that this mixture provides a benefit in delaying resistance. In contrast to our results, another study by Meyer and Norsworthy (2020) concluded that a single application of glufosinate (882 g ai ha^{-1}) provided 57% control of Palmer amaranth.

TABLE 4 Interaction of POST herbicide and Palmer amaranth height (10-15 cm or 20-30 cm) on Palmer amaranth aboveground biomass in glyphosate/glufosinate-resistant corn in a field experiment conducted at Carleton, Nebraska during the 2020 and 2021 growing seasons.

Herbicide	Palmer amaranth biomass [a,b,c]			
	g m^{-2}			
	30 DAEPOST [d]		30 DALPOST [d]	
	10-15 cm	20-30 cm	10-15 cm	20-30 cm
Nontreated control	117 a	112 a	156 ab	78 c-h
Weed free check	0	0	0	0
Glyphosate (1,260 g ai ha^{-1})	25 bcd	42 abc	137 abc	54 c-h
Glufosinate (880 g ai ha^{-1})	3 d	10 bcd	24 d-k	8 ijk
Dicamba (560 g ai ha^{-1})	20 bcd	27 bcd	10 h-k	16 g-k
Dicamba/tembotrione (900 g ai ha^{-1})	42 abc	43 abc	18 e-k	15g-k
Dicamba/diflufenzopyr (196 g ai ha^{-1})	55 ab	54 ab	7 jk	20 e-k
Acetochlor/mesotrione (2,160 g ai ha^{-1})	39 abc	39 abc	17 f-k	43 c-j
Dimethenamid-*P*/topramezone (656 g ai ha^{-1})	29 abc	49 ab	25 d-k	48 c-i
Glyphosate/mesotrione/*S*–metolachlor (2,210 g ai ha^{-1})	45 abc	73 ab	161 ab	113 bcd
Acetochlor/clopyralid/mesotrione (2,300 g ai ha^{-1})	51 ab	20 bcd	104 b-e	27 d-k
Atrazine/bicyclopyone/mesotrione/*S*–metolachlor (1,930 g ai ha^{-1})	8 cd	17 bcd	9 h-k	5 k
Clopyralid/flumetsulam (165 g ai ha^{-1})	112 a	39 abc	207 a	111 b-e
P-value (Herbicide* Palmer amaranth height)	< 0.0001		< 0.0001	

[a]Year by herbicide by Palmer amaranth height was non-significant; therefore, data were combined for both years.
[b]Data were log transformed before analysis; however, back-transformed values are presented based on interpretations of transformed data.
[c]Means presented within each column with no common letter(s) are significantly different according to estimated mean with Sidak adjustments and Tukey P-value.
[d]DAEPOST, days after early-POST application; DALPOST, days after late-POST application.

3.4 Corn yield

The interaction of herbicide by Palmer amaranth height by year was not significant, whereas interaction of herbicide by year was significant (P < 0.0001). This study was conducted under rainfed conditions, and no irrigation was applied; thus, lower yield was observed on an overall basis. Higher yields were recorded in 2020 compared to 2021, ranging from 7,558 to 11,558 kg ha^{-1} and 2,602 to 10,671 kg ha^{-1} (Table 5), which might be due to higher precipitation in 2020 during the growing season (data not shown). The maximum yield of 11,161 and 7,062 kg ha^{-1} was recorded when glufosinate was applied in 2020 and 2021, respectively. Among all of the herbicides, corn yield was similar in 2020 and higher than the nontreated control. In 2021, among the herbicide treatments, glufosinate recorded higher corn yield and was comparable with atrazine/bicyclopyone/mesotrione/*S*–metolachlor, glyphosate, and dimethenamid-*P*/topramezone. While corn grain yield reduction of up to 91% due to Palmer amaranth interference has previously been reported (Massinga et al., 2001), POST control of MHR Palmer amaranth provided by most herbicides in this study was substantial enough to prevent the yield losses observed in the nontreated control.

The main effect of Palmer amaranth height was significant for corn yield, with 7,815 and 7,029 kg ha^{-1} in 10-15 cm and 20-30 cm Palmer amaranth height, respectively (Table 5). Mahoney et al. (2021) indicated that cotton lint yield ranged from 1,070 to 1,240 kg lint ha^{-1} when there was no PRE herbicide applied and POST application was made at three weeks after cotton planting. Thus, the lowest yield indicates the importance of using PRE in a weed management program in most studies.

3.5 Palmer amaranth seed production

The interaction of herbicide by Palmer amaranth height on Palmer amaranth seed production was significant. In the nontreated control, a female Palmer amaranth plant produced 41,560 to 80,815 seeds $plant^{-1}$ (Table 6). Studies have reported that Palmer amaranth produced 514,000 seeds m^{-2}, 120,000 seeds m^{-2}, and 110,000 seeds m^{-2} at a density of 8 plants m^{-1} row, 5.2 plants m^{-1} row, and 1.8 plants m^{-2} in corn, peanut (*Arachis hypogaea* L.), and cotton, respectively (Massinga et al., 2001; Burke et al., 2007; MacRae et al., 2013). Herbicide applied L-POST when Palmer amaranth plants were 20-30 cm tall resulted in higher seed production, with the exception of atrazine/bicyclopyone/mesotrione/*S*–metolachlor (1,953 seeds $plant^{-1}$). The higher seed production of the large-sized Palmer amaranth may be attributed to Palmer amaranth populations emerging later in the season and the lower density of these large-sized Palmer amaranth observed in the treatments at harvest. Similarly, Miranda et al. (2022) and Caverzan et al. (2019)

TABLE 5 Effect of POST herbicide and Palmer amaranth height (10-15 cm or 20-30 cm) on corn yield in glyphosate/glufosinate-resistant corn in a field experiment conducted at Carleton, Nebraska during the 2020 and 2021 growing seasons.

Herbicide	Corn yield [a,b] kg ha^{-1}	
	2020	2021
Nontreated control	7,558 b	2,839 c
Weed-free	11,558 a	10,671 a
Glyphosate (1,260 g ai ha^{-1})	9,694 a	5,216 bc
Glufosinate (880 g ai ha^{-1})	11,161 a	7,062 b
Dicamba (560 g ai ha^{-1})	9,204 ab	4,006 c
Dicamba/tembotrione (900 g ai ha^{-1})	10,390 a	4,078 c
Dicamba/diflufenzopyr (196 g ai ha^{-1})	10,243 a	4,143 c
Acetochlor/mesotrione (2,160 g ai ha^{-1})	10,276 a	3,528 c
Dimethenamid-*P*/topramezone (656 g ai ha^{-1})	10,540 a	4,584 bc
Glyphosate/mesotrione/*S*–metolachlor (2,210 g ai ha^{-1})	10,389 a	3,354 c
Acetochlor/clopyralid/mesotrione (2,300 g ai ha^{-1})	10,610 a	4,037 c
Atrazine/bicyclopyone/mesotrione/*S*–metolachlor (1,930 g ai ha^{-1})	10,871 a	5225 bc
Clopyralid/flumetsulam (165 g ai ha^{-1})	9,129 ab	2,602 c
P-value (Herbicide*Year)	< 0.0001	
Palmer amaranth height		
10-15 cm	7,815 a	
20-30 cm	7,029 b	
P-value (Palmer amaranth height)	0.0003	
P-value (Palmer amaranth height*Year)	0.3902	
P-value (Herbicide*Palmer amaranth height)	0.2316	
P-value (Herbicide*Palmer amaranth height*Year)	0.8884	

[a]Year by Palmer amaranth height for corn yield was non-significant; therefore, data were combined across both years in Palmer amaranth height factor.
[b]Means presented within each column with no common letter(s) are significantly different according to estimated mean with Sidak adjustments and Tukey P-value.

concluded that Palmer amaranth seed production increased as its density decreased because of intraspecific competition within Palmer amaranth populations in dry bean (*Phaseolus vulgaris* L.).

Among the herbicides applied to Palmer amaranth when plants were 10-15 cm tall, dicamba, dicamba/diflufenzopyr, and dimethamid-*P*/topramezone recorded minimum seed production of 6,269, 7,876, and 8,542 seeds female plant^{-1}. When herbicides were

TABLE 6 Interaction of POST herbicide and Palmer amaranth height (10-15 cm and 20-30 cm) on Palmer amaranth seed production in glyphosate/glufosinate-resistant corn in a field experiment conducted at Carleton, Nebraska during the 2020 and 2021 growing seasons.

Herbicide	Palmer amaranth seed production [a,b] Number of seeds plant^{-1}	
	10-15 cm	20-30 cm
Nontreated control	80,815 a	41,560 ab
Weed-free	0	0
Glyphosate (1,260 g ae ha^{-1})	30,025 abcd	30,782 ab
Glufosinate (880 g ai ha^{-1})	15,206 bcde	11,029 b
Dicamba (560 g ae ha^{-1})	6,269 e	24,779 ab
Dicamba/tembotrione (900 g ai ha^{-1})	26,513 abcd	23,934 ab
Dicamba/diflufenzopyr (196 g ai ha^{-1})	7,876 de	10,692 b
Acetochlor/mesotrione (2,160 g ai ha^{-1})	14,446 bcde	21,477 ab
Dimethenamid-*P*/topramezone (656 g ai ha^{-1})	8,542 de	9,751 b
Glyphosate/mesotrione/*S*–metolachlor (2,210 g ai ha^{-1})	38,226 bc	32,737 ab
Acetochlor/clopyralid/mesotrione (2,300 g ai ha^{-1})	31,216 abcd	16,830 ab
Atrazine/bicyclopyone/mesotrione/*S*–metolachlor (1,930 g ai ha^{-1})	10,264 cde	1,953 c
Clopyralid/flumetsulam (165 g ai ha^{-1})	53,024 ab	58,787 a
P-value (Herbicide*Palmer amaranth height)	< 0.0001	

[a]Data were log transformed before analysis; however back-transformed values are presented based on interpretations of transformed data.
[b]Means presented within each column with no common letter(s) are significantly different according to estimated mean with Sidak adjustments and Tukey P-value.

applied to 20-30 cm tall Palmer amaranth, atrazine/bicyclopyone/mesotrione/*S*–metolachlor (1,953 seeds plant^{-1}), and dimethamid-*P*/topramezone (9,751 seeds plant^{-1}) reduced seed production.

4 Practical implications

Nebraska is one of the largest corn-producing states in the USA. Palmer amaranth resistant to ALS inhibitors, atrazine, and glyphosate is the number-one troublesome weed in corn-based cropping systems. The results of this study will provide growers with POST herbicide options under rescue conditions where PRE herbicide is not applied. We concluded that POST rescue programs are available for 10-15 cm and 20-30 cm MHR Palmer amaranth management. Among the herbicides applied to 10-15 cm tall Palmer amaranth, dicamba and dicamba/diflufenzopyr provided 92% to 95% control and reduced density as low as 8 to 10 plants m^{-2}, and biomass to 7 to

10 g m^{-2}. Atrazine/bicyclopyrone/mesotrione/*S*–metolachor was the best option for control of 20-30 cm tall MHR Palmer amaranth. Best management practices should be adopted; however, while applying POST herbicides such as the use of labeled nozzles and adjuvants, and application parameters such as wind speed and drift reducing agents should be taken into consideration to avoid corn injury and off-target herbicide injury (Anonymous, 2020). While not tested in this study, drop nozzles can be used for the targeted application of POST herbicide on Palmer amaranth for better control.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

RK: Data curation, Formal Analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. PC: Writing – review & editing. YS: Methodology, Writing – review & editing. NL: Writing – review & editing. SK: Writing – review & editing. AJ: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Visualization, Writing – review & editing.

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Conflict of interest

Author PC was employed by company FMC Agricultural Solutions.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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