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Comparison of residual activity of pre-emergence herbicides for control and seed production of multiple herbicide-resistant Palmer amaranth in food-grade white corn

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

[1]Department of Agronomy and Horticulture, University of Nebraska–Lincoln, Lincoln, Nebraska, USA

[2]FMC Agricultural Solutions, Gretna, Nebraska, USA

[3]Department of Biological Systems Engineering, University of Nebraska–Lincoln, Lincoln, Nebraska, USA

[4]Panhandle Research Extension and Education Center, University of Nebraska–Lincoln, Scottsbluff, Nebraska, USA

Correspondence
Amit J. Jhala, Department of Agronomy and Horticulture, University of Nebraska–Lincoln, 279 Plant Science Hall, Lincoln, NE 68583, USA.
Email: Amit.Jhala@unl.edu

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Abstract

Nebraska is the number-one producer of food-grade white corn (*Zea mays* L.) in the United States. Food-grade white corn has not been genetically engineered; therefore, non-selective herbicides such as glyphosate or glufosinate cannot be used. Multiple herbicide-resistant (MHR) Palmer amaranth (*Amaranthus palmeri* S. Watson) populations have been reported in multiple counties in Nebraska, and their management is a challenge, particularly for white corn producers. The objectives of this study were to evaluate the residual activity of pre-emergence (PRE) herbicides for acetolactate synthase inhibitor (halosulfuron-methyl)/atrazine/glyphosate-resistant Palmer amaranth control, density, biomass, seed production, and grain yield in food-grade white corn. Field experiments were conducted during summer 2020 and 2021 in a grower's field infested with MHR Palmer amaranth near Carleton, NE. All the PRE herbicides resulted in similar control (>90%) 30 days after PRE application (DAPRE) apart from atrazine (64%). At 45 DAPRE, acetochlor/mesotrione, atrazine/bicyclopyrone/mesotrione/*S*-metolachlor, and acetochlor/clopyralid/mesotrione controlled 90%–95% Palmer amaranth. Acetochlor/clopyralid/mesotrione and atrazine/bicyclopyrone/mesotrione/*S*-metolachlor provided 96%–99% MHR Palmer amaranth control and reduced Palmer amaranth density and biomass to 2–4 plants m^{-2} and 5–12 g m^{-2} 60 DAPRE. The highest corn yields of 12,139 kg ha^{-1} and 12,093 kg ha^{-1} in 2020 and 2021, respectively, were obtained with acetochlor/clopyralid/mesotrione. Palmer amaranth seed production was least with acetochlor/clopyralid/mesotrione (32,894 seeds m^{-2}). Tested residual PRE herbicides did not show corn injury and were safe to use in food-grade white corn. It is concluded that acetochlor/clopyralid/mesotrione and

Abbreviations: ALS, acetolactate synthase; GMO, genetically modified organism; HPPD, 4-hydroxyphenylpyruvate dioxygenase; MHR, multiple herbicide-resistant; POST, post-emergence; PRE, pre-emergence; PS II, photosystem II; 2,4-D, 2,4-dichlorophenoxyacetic acid.

atrazine/bicyclopyone/mesotrione/*S*-metolachlor are the best options for early season control of MHR Palmer amaranth in food-grade white corn.

1 | INTRODUCTION

Nebraska ranks first in non-genetically modified organism (non-GMO) food-grade white corn (*Zea mays* L.) production in the United States. It has been estimated that 5%–11% of corn area in the United States was planted with food-grade white corn in 2020 (USDA-NASS, 2020). The demand for non-GMO food products has increased in the United States from last several years (Bain & Selfa, 2017). Food-grade white corn has several nutritional benefits, such as its being a good source of fiber, vitamins B, C, and E, and potassium (Sheng et al., 2018). White corn can be roasted, grilled, steamed, or pureed in dips. Due to its strong aroma and flavor when baking or frying, it goes well in pastas and salads and is preferred for human consumption (Malvar et al., 2008). It pairs well with vegetables and meats such as basil, parsley, mint, cilantro, peas, squash, fennel, mushrooms, peppers, salty and nutty cheeses, pork, beef, poultry, and seafood (Sylvia, 2018).

Food-grade white corn has not been genetically engineered; therefore, glyphosate or glufosinate cannot be used for weed management. Multiple herbicide-resistant (MHR) Palmer amaranth (*Amaranthus palmeri* S. Watson) is a concern for white corn growers in a no-till production system. The characteristics of Palmer amaranth include faster growth habit, a high photosynthetic rate, continued emergence throughout the crop season, and prolific seed production, making it a troublesome weed species in corn production fields (Horak & Loughin, 2000; Sellers et al., 2003; Ward et al., 2013). In addition, Palmer amaranth is a dioecious species, meaning male and female plants are separate that increase the potential for gene flow and spread of herbicide resistance (Jhala et al., 2021). A single female Palmer amaranth plant per 9-m row of cotton (*Gossypium hirsutum* L.) in Texas, three plants per meter row of soybean [*Glycine max* (L.) Merr.] in Arkansas, and 0.5 plant per meter row of corn in Kansas reduced grain yield by 13%, 17%, and 11%, respectively (Klingaman & Oliver, 1994; Massinga et al., 2001; Morgan et al., 2001). Furthermore, Palmer amaranth emerged at the density of eight plants per meter corn row reduced yield by 91% (Massinga et al., 2001).

Glyphosate-resistant Palmer amaranth was first confirmed in Georgia in 2005 (Culpepper et al., 2006) and then in North Carolina (Culpepper et al., 2008). As of September 2023, glyphosate-resistant Palmer amaranth has been reported in 30 states in the United States (Heap, 2023). Palmer amaranth resistant to multiple herbicides, including acetolactate synthase (ALS), 4-hydroxyphenylpyruvate dioxygenase (HPPD), photosystem II (PS II) inhibitor, and glyphosate, has been reported in Nebraska (Chahal et al., 2017; Jhala et al., 2014). In other states, Palmer amaranth biotypes with multiple resistance to two or more herbicide sites of action have been confirmed (Garetson et al., 2019; Nandula et al., 2012; Sosnoskie et al., 2011). A Palmer amaranth biotype resistant to glufosinate has been confirmed in Arkansas (Barber et al., 2021) and dicamba-resistant Palmer amaranth in Tennessee (Foster & Steckel, 2022). In addition, Palmer amaranth resistant to atrazine, chlorsulfuron, 2,4-dichlorophenoxyacetic acid (2,4-D), glyphosate, and mesotrione has been reported in Kansas (Kumar et al., 2019, 2020). Kohrt et al. (2016) confirmed Palmer amaranth is resistant to ALS inhibitor, atrazine, and glyphosate in Michigan. In total, Palmer amaranth has been found resistant to 10 sites of action (Heap, 2023). Thus, effective management of Palmer amaranth is of the utmost importance, especially with integration of herbicides with different sites of action and residual activity (Mausbach et al., 2021).

Herbicide-resistant weeds have become widespread throughout the United States (Prince et al., 2012). The use of pre-emergence (PRE) herbicides with multiple sites of action is the cornerstone of a diversified herbicide program for management of herbicide-resistant weeds (Norsworthy et al., 2012). PRE herbicides benefit growers in several ways by reducing early season weed interference and often improving season-long Palmer amaranth control (Culpepper & York, 1998; Keeling et al., 2006; Reddy, 2001; Toler et al., 2002). Diuron, fluometuron, prometryn (PS II inhibitors), fomesafen (protoporphyrinogen oxidase inhibitors), pendimethalin (microtubule inhibitors), and pyrithiobac (ALS inhibitors) can be applied PRE in cotton for effective control of Palmer amaranth (York & Culpepper, 2009). Atrazine has been the most used herbicide for weed management in corn for many years in the United States. However, the effectiveness of ALS- and PS II-inhibiting herbicides has declined because of the presence of ALS- and PS II-inhibitor-resistant weeds (Foy & Witt, 1997; Parks et al., 1996; Sprague et al., 1997; Volenberg et al., 2000). Dicamba and 2,4-D are synthetic auxin herbicides used to control emerged broadleaf weeds prior to planting broadleaf crops or applied early post-emergence (POST) in grass crops such as corn, wheat, and sorghum (Peterson et al., 2016; Vink et al., 2012). Mesotrione and isoxaflutole have been shown to be effective for controlling *Amaranthus* spp. (Johnson et al., 2012; Sutton et al., 2002). The evolution of Palmer

amaranth resistant to PS-II and HPPD inhibitor has reduced the number of herbicide options for Palmer amaranth control in corn (Delye et al., 2013). A study in Nebraska reported that PS II- and HPPD-inhibiting herbicides combined with tank-mixture of glyphosate, dicamba plus dimethenamid-*P*, or pyroxasulfone were effective to control herbicide-resistant Palmer amaranth in corn (Chahal et al., 2018). However, the information for the residual activity of PRE herbicides in food-grade white corn for control of MHR Palmer amaranth was lacking in the literature. In addition, growers in Nebraska have been looking for PRE herbicide options for the effective control of MHR Palmer amaranth in food-grade white corn because POST herbicide options are limited. The objectives of this study were to compare the residual activity of PRE herbicides with different sites of action for early season control of MHR Palmer amaranth. Second, to evaluate the effect of residual PRE herbicide on Palmer amaranth density, biomass, seed production, and grain yield in food grade white corn.

Core Ideas

- Acetochlor/clopyralid/mesotrione and atrazine/bicyclopyone/mesotrione/*S*-metolachlor provided >90% control of Palmer amaranth at 45 and 60 days after application.
- Acetochlor/clopyralid/mesotrione and atrazine/bicyclopyone/mesotrione/*S*-metolachlor reduced Palmer amaranth density, biomass, and seed production and resulted in higher white corn yield.
- No corn injury was noticed in any of the pre-emergence (PRE) herbicides tested in this study.

2 | MATERIALS AND METHODS

2.1 | Study site

Field experiments were conducted during the summer in 2020 and 2021 in a grower's field located near Carleton, NE (40.30°N, 97.67°W). The soil was a silt loam (fine, montmorillonite, mesic Pachic Argiustoll) with 19% sand, 63% silt, 18% clay, 2.5% organic matter, and pH 6.0. The experimental site was infested primarily with MHR Palmer amaranth (Chahal et al., 2017). The 2,4-D ester (Weedone LV6; Nufarm Inc.) at 386 g ai ha^{-1} and paraquat (Gramoxone SL; Syngenta Crop Protection) at 840 g ai ha^{-1} with a nonionic surfactant (Induce; Helena Chemical) at 0.25% v/v were used for control of glyphosate-resistant horseweed/marestail (*Conyza canadensis* L. Cronq.) in early spring 2 weeks before planting corn in this study.

2.2 | Experimental design and herbicide treatments

The research site was under a continuous no-till glyphosate-resistant corn-soybean rotation for the last 8 years. Food-grade white corn P1306W was no-till planted on May 12 in 2020 and May 18 in 2021 at a seeding rate of 67,500 seeds ha^{-1}. The experimental site was under a rainfed irrigation system, and no supplemental irrigation was applied during both years. The treatments were arranged in a randomized complete block design with four replications. The plots were 3-m wide by 9-m long, where four corn rows per plot were spaced 76 cm apart. Fifteen PRE herbicides and a nontreated control were included for comparison (Table 1). PRE herbicides were applied within 2 days of corn planting on May 14 in 2020 and May 18 in 2021. Herbicides were applied using a handheld CO_2 pressurized backpack sprayer equipped with AIXR 110015 flat fan nozzles (TeeJet Technologies; Spraying Systems) calibrated to deliver 140 L ha^{-1} at 276 k Pa at a constant speed of 4.8 km h^{-1}.

2.3 | Data collection

Palmer amaranth control ratings were recorded visually at 15, 30, 45, 60, 75, and 90 days after PRE (DAPRE) herbicide was applied using a scale of 0%–100%, with 0% representing no Palmer amaranth control and 100% representing complete control (Mausbach et al., 2021). Palmer amaranth density was recorded at 15, 30, 45, 60, and 75 DAPRE by counting the Palmer amaranth plants in 0.5 m^2 quadrats placed randomly between the two center corn rows in each plot and converting into the number of plants per square meter. Above-ground biomass for Palmer amaranth plants surviving PRE herbicide treatments was collected at 30 and 60 DAPRE from randomly selected 0.5 m^2 quadrats, and the collected samples were put into paper bags, placed in an oven at 65°C for 7 days until a constant weight was obtained, then weighed.

Palmer amaranth seed production was recorded by placing a 1.0 m^2 quadrat in the center two rows of corn and collecting the seed heads of female plants from each quadrat. Palmer amaranth seed heads were stripped from the stems and separated by passing them through sieves with mesh sizes ranging from 0.50 to 3.35 mm. Material collected from the 0.50-mm sieve was processed with a seed cleaner that used air to remove the lighter floral chaff from the Palmer amaranth seeds. The seeds were thoroughly cleaned, and the

TABLE 1 Herbicides, rates, and products used for control of acetolactate synthase inhibitor/atrazine/glyphosate-resistant Palmer amaranth in food-grade white corn in field experiments conducted near Carleton, NE, in 2020 and 2021.

Herbicide program	Trade name	Rate (g ai ha^{-1})	Manufacturer
Atrazine/bicyclopyone/mesotrione/*S*-metolachlor	Acuron	2400	Syngenta
Atrazine	Atrazine	1200	Syngenta
Fluthiacet-methyl/pyroxasulfone	Anthem MAXX	150	FMC
Isoxaflutole	Balance Flaxx	52.5	Bayer CropScience
Atrazine/*S*-metolachlor	Bicep II Magnum	2770	Syngenta
Isoxaflutole/thiencarbazone-methyl	Corvus	129	Corteva Agriscience
Acetochlor/atrazine	Degree Xtra	3960	Bayer CropScience
Acetochlor/mesotrione	Harness Max	2700	Bayer CropScience
Flufenacet/isoxaflutole/thiencarbazone-methyl	TriVolt	610	Bayer CropScience
Acetochlor/clopyralid/ mesotrione	Resicore	2300	Corteva Agriscience
Acetochlor/flumetsulam/clopyralid	Surestart II	890	Corteva Agriscience
Dimethenamid-*P*	Outlook	736	BASF Corp.
Saflufenacil	Sharpen	62.4	BASF Corp.
Dimethenamid-*P*/saflufenacil	Verdict	780	BASF Corp.
Pyroxasulfone	Zidua	179	BASF Corp.

Abbreviation: ai, active ingredient.

seed weight and number of seeds per m^2 were determined. Corn was mechanically harvested from the center two corn rows in each plot using a plot combine (Gleaner K2; AGCO), weighted, and the yield was adjusted to 15.5% moisture content and converted into kg ha^{-1}.

2.4 | Statistical analysis

Palmer amaranth control, density, aboveground biomass, and corn yield data were subjected to analysis of variance using PROC GLIMMIX in SAS 9.4 (SAS Institute). Normality and homogeneity of error variances were confirmed by using PROC UNIVARIATE with normal Q-Q plots and the Levene test. Palmer amaranth control data were log-transformed using a beta (link = "complementary log-log") distribution. Palmer amaranth density and aboveground biomass were square-root transformed and fit to generalized linear mixed models using glmm functions gaussian (link = "identity") error distributions. Palmer amaranth seed production 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. Treatments and years were considered fixed effects, whereas replication was considered random effect in the model. 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.

3 | RESULTS AND DISCUSSION

Year-by-treatment interactions for Palmer amaranth control, density, biomass, and seed production were non-significant ($p > 0.05$); therefore, the data are combined for both years. Below average temperature and precipitation during the PRE herbicides application were recorded, and these were 15.0°C, 15.8°C and 80.3 mm, 81.5 mm for 2020 and 2021, respectively, as compared to 16.4°C and 135.4 mm in 30-year average (Table 2). There was no corn injury from any PRE herbicide applied in this study (data not shown); therefore, these herbicides are safe to use in food-grade white corn.

3.1 | Palmer amaranth control

All PRE herbicides evaluated in this study, except for atrazine, provided 90%–99% control of MHR Palmer amaranth 15 and 30 DAPRE (Table 3). A study conducted in soybean by Hay (2017) in Kansas, along with Sarangi and Jhala (2019) in Nebraska, reported that saflufenacil plus dimethenamid-*P* provided >95% control of ALS-inhibitor-resistant Palmer amaranth 28 DAPRE. Chahal et al. (2017) observed that saflufenacil provided 65% control of glyphosate-resistant Palmer amaranth 21 DAPRE. Meyer et al. (2016) reported that mesotrione and isoxaflutole applied to PRE were effective for control of glyphosate-resistant *Amaranthus* spp. Striegel and Jhala (2022) indicated that acetochlor plus dicamba plus metribuzin, acetochlor/fomesafen plus dicamba, dicamba plus

TABLE 2 Monthly mean air temperature and total precipitation during the 2020 and 2021 growing seasons, along with the 30-year average at the experiment site near Carleton, NE.[a]

	Mean air temperature (°C)			Total precipitation (mm)		
Month	**2020**	**2021**	**30-year average**	**2020**	**2021**	**30-year average**
March	6.1	7.5	4.6	147.8	147.1	45.2
April	9.2	10.0	10.6	37.8	73.7	66.3
May	15.0	15.8	16.4	80.3	81.5	135.4
June	24.7	23.9	22.3	147.6	13.5	115.1
July	24.7	24.2	24.9	424.2	45.5	105.2
August	23.6	24.7	23.7	42.9	105.1	94.0
September	17.8	21.4	19.1	87.63	46.7	66.0

[a]Data were obtained from National Oceanic and Atmospheric Administration (NOAA 2020 & 2021).

TABLE 3 Multiple herbicide-resistant Palmer amaranth control was affected by pre-emergence herbicides in food-grade white corn in field experiments conducted at Carleton, NE, during the 2020 and 2021 growing seasons.

	Palmer amaranth control[a,b]					
Herbicide program	**15DA-PRE (%)**	**30DA-PRE (%)**	**45DA-PRE (%)**	**60DA-PRE (%)**	**75DA-PRE (%)**	**90DA-PRE (%)**
Nontreated control	0	0	0	0	0	0
Atrazine/bicyclopyone/mesotrione/*S*-metolachlor (2400 g ai ha^{-1})	99a	99a	91a	96ab	85abc	85abc
Atrazine (1200 g ai ha^{-1})	42cd	64e	29f	38h	10h	12h
Fluthiacet-methyl/pyroxasulfone (150 g ai ha^{-1})	90ab	92cd	72cd	80d	53e	54fg
Isoxaflutole (52.5 g ai ha^{-1})	95ab	95abc	73cd	76e	38f	37g
Atrazine/*S*-metolachlor (2770 g ai ha^{-1})	99a	99a	73cd	67ef	59e	57f
Isoxaflutole/thiencarbazone-methyl (129 g ai ha^{-1})	99a	95abc	71cd	72e	44e	44g
Acetochlor/atrazine (3960 g ai ha^{-1})	99a	98ab	81b	75e	79d	79e
Acetochlor/mesotrione (2700 g ai ha^{-1})	99a	99a	90a	90b	87ab	87ab
Flufenacet/Isoxaflutole/thiencarbazone-methyl (610 g ai ha^{-1})	99a	97abc	75c	59f	58e	60f
Acetochlor/clopyralid/ mesotrione (2300 g ai ha^{-1})	99a	99a	95a	99a	92a	92a
Acetochlor/flumetsulam/ clopyralid (890 g ai ha^{-1})	95ab	97abc	81b	59f	55e	55fg
Dimethenamid-*P* (736 g ai ha^{-1})	95ab	95abc	71cd	56fg	27g	27gh
Saflufenacil (62.4 g ai ha^{-1})	95ab	99a	81b	88bc	83bc	82cd
Dimethenamid-*P*/saflufenacil (780 g ai ha^{-1})	99a	99a	89a	81d	79d	80de
Pyroxasulfone (179 g ai ha^{-1})	95ab	97abc	75c	47gh	41ef	41g
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Abbreviations: ai, active ingredient; DA-PRE, days after pre-emergence herbicide application.

[a]Year by treatment for Palmer amaranth control was non-significant; therefore, data were combined across both years (2020 and 2021).

[b]Means presented within each column with no common letter(s) are significantly different as per Tukey Kramer's pairwise comparison test.

flumioxazin, and imazethapyr/pyroxasulfone/saflufenacil provided 94%–98% control of herbicide-resistant glyphosate-resistant Palmer amaranth at 35 DAPRE in dicamba/glufosinate/glyphosate-resistant soybean.

At 45 DAPRE, atrazine/bicyclopyrone/mesotrione/*S*-metolachlor, acetochlor/mesotrione, acetochlor/clopyralid/mesotrione, and dimethenamid-*P*/saflufenacil provided 89%–95% control of MHR Palmer amaranth. These were followed by acetochlor/atrazine, acetochlor/flumetsulam/clopyralid, and saflufenacil (81%). Sarangi et al. (2017) elaborated on the effective use of very long-chain fatty acid-inhibiting herbicides for the residual control of glyphosate-resistant *Amaranthus* spp. The residual activity of some PRE herbicides in this study declined as the season progressed; for instance, flufenacet/isoxaflutole/thiencarbazone-methyl provided 59% control of Palmer amaranth 60 DAPRE. This

might be due to lower persistence of the applied residual herbicide and late-season emergence of Palmer amaranth. Chahal et al. (2018) reported that PS-II- and HPPD-inhibitor-resistant Palmer amaranth control from PRE herbicides was <26% at 6 weeks after POST in glyphosate-resistant corn. However, in this study, atrazine/bicyclopyrone/mesotrione/*S*-metolachlor and acetochlor/clopyralid/mesotrione controlled Palmer amaranth >96% 60 DAPRE. This demonstrated the efficacy of these residual herbicides through their persistence and by reducing interplant competition between the corn and Palmer amaranth.

Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor, acetochlor/mesotrione, and acetochlor/clopyralid/mesotrione consistently provided 85%–92% control of MHR Palmer amaranth 75 DAPRE and 90 DAPRE (Table 3). Inman et al. (2020) reported that acetochlor plus diuron plus fomesafen applied PRE provided 79% glyphosate-resistant Palmer amaranth control at 2–3 weeks after planting. Striegel and Jhala (2022) elaborated on the use of PRE herbicides for control of glyphosate-resistant Palmer amaranth (94%–98% 35 DAPRE) in dicamba/glufosinate/glyphosate-resistant soybean and concluded that PRE herbicides have a positive effect on soybean yield. Thus, if MHR Palmer amaranth is a major weed in growers' field, the use of PRE herbicides with multiple effective sites of action is almost mandatory for early season control to avoid competition with crops (Ward et al., 2013).

3.2 | Palmer amaranth density and biomass

Palmer amaranth density and biomass were affected by PRE herbicides (Table 4). In this study, the MHR Palmer amaranth population ranged from 27 to 92 plants m^{-2} in the nontreated control from 15 to 75 DAPRE. Atrazine/bicyclopyone/mesotrione/*S*-metolachlor, atrazine/*S*-metolachlor, isoxaflutole/thiencarbazone-methyl, acetochlor/atrazine, acetochlor/mesotrione, flufenacet/isoxaflutole/thiencarbazone-methyl, acetochlor/clopyralid/mesotrione, and dimethenamid-*P*/saflufenacil recorded no MHR Palmer amaranth plants compared to 59 and 92 plants m^{-2} with atrazine and the nontreated control 15 DAPRE. These were followed by isoxaflutole, acetochlor/flumetsulam/clopyralid, saflufenacil, pyroxasulfone, dimethenamid-*P*, and fluthiacet-methyl/pyroxasulfone (1–4 Palmer amaranth plants m^{-2}). At 30 DAPRE, almost all residual herbicides recorded 1–3 plants m^{-2} apart from atrazine (15 plants m^{-2}) and atrazine/bicyclopyone/mesotrione/*S*-metolachlor (11 plants m^{-2}). Striegel and Jhala (2022) reported that PRE herbicide reduced glyphosate-resistant Palmer amaranth density to 0–1 plant m^{-2} compared with nontreated plots (26 plants m^{-2}). Whitaker et al. (2011) concluded that diuron, fluometuron, fomesafen, pendimethalin, prometryn, and pyrithiobac were effective PRE herbicides for control of glyphosate-resistant Palmer amaranth in cotton.

At 45 DAPRE, acetochlor/mesotrione and acetochlor/clopyralid/mesotrione recorded the lowest Palmer amaranth density (2 plants m^{-2}). These were followed by atrazine/bicyclopyrone/mesotrione/*S*-metolachlor, dimethenamid-*P*/saflufenacil, and pyroxasulfone (4 plants m^{-2}). The dimethenamid-*P* and atrazine treatments had 14 and 17 plants m^{-2} of MHR Palmer amaranth, respectively. Inman et al. (2020) elaborated on the importance of PRE herbicides for controlling glyphosate-resistant Palmer amaranth and their role in reducing early season weed interference by 79%. The acetochlor/clopyralid/mesotrione, atrazine/bicyclopyone/mesotrione/*S*-metolachlor, and acetochlor/mesotrione plots recorded 2–5 Palmer amaranth plants m^{-2} 60 DAPRE. Furthermore, at 75 DAPRE, atrazine/bicyclopyrone/mesotrione/*S*-metolachlor, acetochlor/clopyralid/mesotrione, isoxaflutole/thiencarbazone-methyl, and dimethenamid-*P*/saflufenacil reduced MHR Palmer amaranth density to 2–3 plants m^{-2}. The remaining herbicide programs recorded 4–17 Palmer amaranth plants m^{-2} compared with the nontreated control. Janak and Grichar (2016) reported >95% glyphosate-resistant Palmer amaranth reduction with saflufenacil plus dimethenamid-*P* at 95 DAPRE in corn at Texas.

Palmer amaranth biomass was in consensus with the control estimates and density. Jhala et al. (2014) and Kohrt and Sprague (2017) reported agreement between control estimates and biomass of Palmer amaranth with herbicide programs. In this study, acetochlor/mesotrione, acetochlor/clopyralid/mesotrione, saflufenacil, dimethenamid-*P*/saflufenacil, and pyroxasulfone recorded 4–10 g m^{-2} MHR Palmer amaranth biomass 30 DAPRE (Table 4). Striegal and Jhala (2022) reported that PRE herbicide provided 95%–100% biomass reduction of glyphosate-resistant Palmer amaranth in dicamba/glyphosate/glufosinate-resistant soybean.

At 60 DAPRE, acetochlor/clopyralid/mesotrione, dimethenamid-*P*/saflufenacil, and atrazine/bicyclopyone/mesotrione/*S*-metolachlor resulted in 5–12 g m^{-2} Palmer amaranth biomass compared with 134 g m^{-2} in the nontreated control. These were followed by saflufenacil and acetochlor/atrazine (17–18 g m^{-2}); however, the remaining herbicides had biomass ranging from 22 to 66 g m^{-2}. This study focused only on PRE herbicides; thus, there was higher MHR Palmer amaranth biomass that indicated the importance of follow-up programs for season-long weed management. Mausbach et al. (2021) concluded that PRE herbicides with multiple sites of action followed by glufosinate provided at least 87% reduction of ALS inhibitor/glyphosate-resistant Palmer amaranth density and biomass reduction up to 60 DAPRE.

TABLE 4 Multiple herbicide-resistant Palmer amaranth density and above-ground biomass were affected by pre-emergence herbicides in food-grade white corn in field experiments conducted in Carleton, NE, during the 2020 and 2021 growing seasons.

	Palmer amaranth density [a,b]					Palmer amaranth biomass [a,b]	
Herbicide program	**15DA-PRE (number m^{-2})**	**30DA-PRE (number m^{-2})**	**45DA-PRE (number m^{-2})**	**60DA-PRE (number m^{-2})**	**75DA-PRE (number m^{-2})**	**30DA-PRE (g m^{-2})**	**60DA-PRE (g m^{-2})**
Nontreated control	92a	42a	27ab	36a	33a	106a	134a
Atrazine/bicyclopyone/mesotrione/*S*-metolachlor (2400 g ai ha^{-1})	0f	11d	4gh	4fg	2f	13bcd	12bcd
Atrazine (1200 g ai ha^{-1})	59b	15cd	17bcd	23b	17b	29b	63b
Fluthiacet-methyl/pyroxasulfone (150 g ai ha^{-1})	4cde	3ef	6fg	9ef	10d	24bc	32bc
Isoxaflutole (52.5 g ai ha^{-1})	1e	3ef	6fg	10ef	9d	25bc	51bc
Atrazine/*S*-metolachlor (2770 g ai ha^{-1})	0f	2f	10de	12de	5ef	20bc	22bc
Isoxaflutole/thiencarbazone-methyl (129 g ai ha^{-1})	0f	2f	5fg	7f	3f	22bc	30bc
Acetochlor/atrazine (3960 g ai ha^{-1})	0f	2f	8efg	7f	6e	13bcd	18bcd
Acetochlor/mesotrione (2700 g ai ha^{-1})	0f	3ef	2h	5fg	7e	4cd	30bcd
Flufenacet/Isoxaflutole/thiencarbazone-methyl (610 g ai ha^{-1})	0f	2f	6fg	15c	11c	15bc	66bc
Acetochlor/clopyralid/mesotrione (2300 g ai ha^{-1})	0f	3ef	2h	2g	2f	6cd	5d
Acetochlor/flumetsulam/clopyralid (890 g ai ha^{-1})	1e	2f	6fg	17c	6e	14bc	32bc
Dimethenamid-*P* (736 g ai ha^{-1})	2de	3ef	14bc	16c	6e	37bc	34bc
Saflufenacil (62.4 g ai ha^{-1})	1e	3ef	7f	7f	4ef	9bcd	17bcd
Dimethenamid-*P*/saflufenacil (780 g ai ha^{-1})	0f	1f	4gh	10e	3f	10bcd	8cd
Pyroxasulfone (179 g ai ha^{-1})	1e	3ef	4gh	19c	6e	10bc	41bc
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0009	<0.0001

Abbreviations: ai, active ingredient; DA-PRE, days after pre-emergence herbicide application.

[a]Year by treatment interaction for Palmer amaranth density and biomass was non-significant; therefore, data were combined across both years.

[b]Means presented within each column with no common letter(s) are significantly different as per Tukey Kramer's pairwise comparison test.

TABLE 5 Food-grade white corn yield and Palmer amaranth seed production affected by pre-emergence herbicides in field experiments conducted at Carleton, NE, during the 2020 and 2021 growing seasons.

Herbicide program	Corn yield [a,b]		Palmer amaranth seed production [a,b] (seeds m^{-2})
	2020 (kg ha^{-1})	2021 (kg ha^{-1})	
Nontreated control	2651g	7735f	2,464,016a
Atrazine/bicyclopyone/mesotrione/*S*-metolachlor (2400 g ai ha^{-1})	11,063abc	11,213abc	100,407fg
Atrazine (1200 g ai ha^{-1})	5854f	9318def	2,503,706a
Fluthiacet-methyl/pyroxasulfone (150 g ai ha^{-1})	10,001b-e	10,836a-d	411,829cde
Isoxaflutole (52.5 g ai ha^{-1})	9558de	10,223b-e	692,872bc
Atrazine/*S*-metolachlor (2770 g ai ha^{-1})	10,000b-e	9673cde	166,012ef
Isoxaflutole/thiencarbazone-methyl (129 g ai ha^{-1})	11,255ab	9404de	325,233d-f
Acetochlor/atrazine (3960 g ai ha^{-1})	9302e	10,010b-e	586,459bcd
Acetochlor/mesotrione (2700 g ai ha^{-1})	10,643bcd	11,570ab	324,221d-f
Flufenacet/isoxaflutole/thiencarbazone-methyl (610 g ai ha^{-1})	9940cde	8902ef	605,565bcd
Acetochlor/clopyralid/mesotrione (2300 g ai ha^{-1})	12,139a	12,093a	32,894g
Acetochlor/flumetsulam/clopyralid (890 g ai ha^{-1})	9398de	9558de	278,606ef
Dimethenamid-*P* (736 g ai ha^{-1})	9794cde	10,290b-e	393,030def
Saflufenacil (62.4 g ai ha^{-1})	10,103b-e	10,719a-d	180,780ef
Dimethenamid-*P*/saflufenacil (780 g ai ha^{-1})	10,557b-e	10,859a-d	217,185ef
Pyroxasulfone (179 g ai ha^{-1})	10,145b-e	10,720a-d	755,880b
p-value	<0.0001	<0.0001	<0.0001

Abbreviation: ai, active ingredient.

[a]Year by treatment interaction for corn yield was significant; therefore, data were presented separately for both years.

[b]Means presented within each column with no common letter(s) are significantly different as per Tukey Kramer's pairwise comparison test.

3.3 | Palmer amaranth seed production

Palmer amaranth seed production was affected by PRE herbicides (Table 5). The highest MHR Palmer amaranth seed production (2,503,706 seeds from 17 plants m^{-2}) resulted from atrazine and the nontreated control (2,464,016 seeds from 33 plants m^{-2}). This is because Palmer amaranth in this field is highly resistant to atrazine; therefore, atrazine was not effective. Palmer amaranth density in this study was 33 plants m^{-2} in the nontreated control compared with all PRE herbicides (2–11 plants m^{-2}) except atrazine (17 plants m^{-2}). Miranda et al. (2022) concluded that the highest seed production of 376,000 seeds per plant was produced when 0.2 Palmer amaranth plants m^{-1} row of dry bean, and that this number decreased by 12%, 28%, 55%, and 75% when Palmer amaranth density increased to 0.3, 0.5, 1, and 2 plants m^{-1} row, respectively.

Minimal seed production was noted in acetochlor/clopyralid/mesotrione (32,894 seeds m^{-2}) and atrazine/bicyclopyone/mesotrione/*S*-metolachlor (100,407 seeds m^{-2}). This might be because of lower Palmer amaranth density in these treatments (2 plants m^{-2}), and thus, less intraspecific competition among the MHR Palmer amaranth plants. None of the programs resulted in a 100% reduction in Palmer amaranth seed production. This might be because there was no POST herbicide applied in this study. Kaur et al. (2023) concluded that the lowest MHR Palmer seed production was observed with POST application of dicamba and atrazine/bicyclopyone/mesotrione/*S*-metolachlor in corn. Thus, a PRE fb a POST herbicide program has a better chance of reducing MHR Palmer amaranth seed production compared with relying only on PRE herbicide. Striegel and Jhala (2022) reported that glyphosate-resistant Palmer amaranth seed production declined to 0–325 seeds $plant^{-1}$ when PRE herbicide was used compared with POST-only programs (85–4786 seeds $plant^{-1}$) in soybeans and further reduced to 0 seeds $plant^{-1}$ when a PRE herbicide was followed by a POST herbicide with residual activity.

3.4 | Corn yield

Year-by-treatment interaction was significant ($p \leq 0.05$); therefore, yield data were presented separately for both years (Table 5). Acetochlor/clopyralid/mesotrione recorded the highest corn yield of 12,139 and 12,093 kg ha^{-1} in 2020 and 2021, respectively, which was similar to isoxaflutole/thiencarbazone-methyl (11,255 kg ha^{-1}) and

atrazine/bicyclopyone/mesotrione/*S*-metolachlor (11,063 kg ha^{-1}) in 2020; and acetochlor/mesotrione (11,570 kg ha^{-1}), atrazine/bicyclopyone/mesotrione/*S*-metolachlor (11,213 kg ha^{-1}), dimethenamid-*P*/saflufenacil (10,859 kg ha^{-1}), fluthiacet-methyl/pyroxasulfone (10,836 kg ha^{-1}), saflufenacil (10,719 kg ha^{-1}), and pyroxasulfone (10,720 kg ha^{-1}) in 2021. The remaining herbicides resulted in corn yield ranging from 9302 to 10,557 and 8902 to 10,290 kg ha^{-1} in 2020 and 2021, respectively, except for atrazine. Meyer et al. (2016) reported that isoxaflutole plus *S*-metolachlor plus metribuzin, *S*-metolachlor plus mesotrione, and flumioxazin plus pyroxasulfone were the most effective PRE herbicides for higher productivity in soybean by managing glyphosate-resistant Palmer amaranth in Arkansas, Indiana, Nebraska, Illinois, and Tennessee.

4 | CONCLUSIONS

Because food-grade white corn is not genetically engineered, the non-selective herbicides such as glyphosate or glufosinate cannot be used. MHR Palmer amaranth control in no-till food-grade white corn is difficult due to limited POST herbicide options; therefore, the PRE herbicides should be carefully selected to provide early season control of MHR Palmer amaranth for higher food-grade white corn productivity. From the PRE herbicides evaluated in this study, acetochlor/clopyralid/mesotrione was very effective for managing MHR Palmer amaranth (92% control), density (2 plants m^{-2}), biomass (5 g m^{-2}), and seed production (32,894 seeds m^{-2}) in corn. Although no corn injury was observed in this study, a premix of acetochlor/clopyralid/mesotrione may result in corn injury if there are extended unusual cold/hot/dry/wet weather conditions after application (Anonymous, 2017).

AUTHOR CONTRIBUTIONS

Ramandeep Kaur: Data curation; formal analysis; investigation; methodology; validation; writing—original draft. **Parminder S. Chahal**: Writing—review and editing. **Yeyin Shi**: Writing—review and editing. **Nevin C. Lawrence**: Writing—review and editing. **Stevan Z. Knezevic**: Writing—review and editing. **Amit J. Jhala**: Conceptualization; funding acquisition; project administration; resources; software; supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Amit J. Jhala https://orcid.org/0000-0001-8599-4996

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