11-13-2023

# Management of Atrazine, Glyphosate, and ALS-Inhibiting Herbicide-Resistant Palmer Amaranth (*Amaranthus palmeri* S. Watson) in Herbicide-Resistant and Food Garde White Field Corn

Ramandeep Kaur
*University of Nebraska-Lincoln*, rkaur9@huskers.unl.edu

MANAGEMENT OF ATRAZINE, GLYPHOSATE, AND ALS-INHIBITING HERBICIDE-RESISTANT PALMER AMARANTH (*Amaranthus palmeri* S. Watson) IN HERBICIDE-RESISTANT AND FOOD GARDE WHITE FIELD CORN

by

Ramandeep Kaur

A DISSERTATION

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Doctor of Philosophy

Major: Agronomy and Horticulture

(Weed Science)

Under the Supervision of Professor Amit J. Jhala

Lincoln, Nebraska

December, 2023

MANAGEMENT OF ATRAZINE, GLYPHOSATE, AND ALS-INHIBITING HERBICIDE-RESISTANT PALMER AMARANTH (*Amaranthus palmeri*) IN HERBICIDE- RESISTANT AND FOOD GARDE WHITE FIELD CORN

Ramandeep Kaur, Ph.D.

University of Nebraska, 2023

Advisor: Amit J. Jhala

A recent survey reported that Palmer amaranth (*Amaranthus palmeri S.Watson*) is the number one most difficult to control weed in Nebraska. A survey reported that about 6 million acres in Nebraska are infested with at least one glyphosate-resistant weed. Confirmation and widespread occurrence of atrazine, glyphosate, and ALS-inhibitor-resistant Palmer amaranth in Nebraska is one of biggest concerns for corn producers. Nebraska, the cornhusker state, is one of the leading corn producing states with the production of corn on about 9 to 10 million acres annually; and it ranks 1$^{st}$ in food grade white corn and 3$^{rd}$ in field corn production. Optimum corn yield depends on a number of factors including effective weed management that justify the need to develop management approach for control of multiple herbicide resistant Palmer amaranth. Field experiments were conducted 2020-2021 for assessing control and seed production of multiple herbicide-resistant Palmer amaranth in herbicide resistant and food grade white corn. Chapter 1 outlines Palmer amaranth biology, infestation with corn yield, multiple herbicide resistance and management approaches adopted by growers. Chapter 2 evaluates the herbicide programs for control of multiple herbicide resistant Palmer

amaranth in corn resistant to 2,4-d choline/glufosinate/glyphosate (Enlist corn). Chapter 3 determines the effect of plant height on control of multiple herbicide resistant Palmer amaranth in glyphosate/glufosinate resistant corn. Chapter 4 evaluates comparison of residual activity of pre-emergence herbicides for control and seed production of multiple herbicide resistant Palmer amaranth in food grade white corn. Chapter 5 determines the integrative effect of row spacing and herbicide programs for control and seed production of atrazine, glyphosate, and ALS-inhibitor-resistant Palmer amaranth in glyphosate/glufosinate resistant corn. Results of these projects provided guideline for growers for effective management of multiple herbicide-resistant Palmer amaranth in Enlist corn, glufosinate/glyphosate-resistant corn, and food grade white corn.

## ACKNOWLEDGEMENTS

Foremost of all, I express my heartfelt gratitude to the “Almighty God” for his benign blessing hand and bestowing a healthy, and protective environment throughout my carrier.

The sense of veneration and sincere gratitude through words hardly suffice my feelings of respect for my esteemed major advisor, Dr. Amit J. Jhala, for his sagacious guidance and ceaseless encouragement. His sense of dedication, search for perfection, calm endurance, moral support and endless efforts helped me to end this tireless venture with fruitful results and make this manuscript worthy of presentation. I shall forever be indebted to him for the things I learnt from him and for the trust he pays in me. I also extend my gratitude to my graduate committee members, Dr. Parminder S. Chahal, Dr. Yeyin Shi, Dr. Nevin C. Lawrence and Dr. Stevan Z. Knezevic for their time and praiseworthy guidance, cordial behavior and encouragement in this degree. I express my sincere thanks to Dr. Martha Mamo, Head Department of Agronomy and Horticulture for her encouragement and appreciation during this degree. I extend my sincere thanks to the staff and faculty of the department of Agronomy and Horticulture at the University of Nebraska-Lincoln for helping me in this journey.

I would acknowledge the Indian Council of Agricultural Research, Agricultural Education Division, Pusa, New Delhi, India for awarding Netaji Subhas- ICAR International fellowship for this degree. I am thankful to the Agricultural Research Division, University of Nebraska-Lincoln for awarding the John and Louise Skala fellowship for two years.

I am indebted to Irvin Schleufer for their constant technical help and support throughout the Ph.D. research. I would like to thank Jasmine Mausbach, Rachana Jhala, Rupinder Sandhu didi, Kiran Didi, Lisa Hilfikar, Dr. Kelsey Richters for their kindness and moral support. I want to acknowledge the guidance of Dr. Parminder S. Chahal, and Ian Rogers. I also would like to thank the members of the Jhala Lab for providing their assistance with projects. I also appreciate the chance to meet with my fellow graduate students at the University of Nebraska-Lincoln.

Finally, I express my deep love and gratitude for my parents Dr. Thakar Singh and Mrs. Kulwinder Kaur, who have been an inexhaustible source of inspiration to me and whose blessing, love, care, selfless sacrifices have brought cherished expectation true. Dictions not enough to express my deep sense of honor, love, support and affection for the smiling of my beloved younger brother Rajandeep Singh, my dearest sisters Dr. Amandeep Kaur and Dr. Balwinder Kaur and my best friends who hold a special place in my heart and life. Acknowledgement is inherently endless & incomplete, and I request indulgence from many kind and helpful people whom I could not name here. Needless to mention, errors and omissions are mine.

**TABLE OF CONTENTS**

## LIST OF TABLES

## LIST OF FIGURES

# CHAPTER 1 BACKGROUND

## INTRODUCTION

Palmer amaranth (*Amaranthus palmeri* S.Watson), a member of the *Amaranthaceae* family, can be characterized by rapid growth rate, prolific seed production, competitive ability, extended seedling emergence, and high water use efficiency (Chahal et al. 2015). By 1995, it was the most troublesome weed in Carolina in cotton; and it became number 7 most troublesome and economically damaging glyphosate-resistant weed species in corn in 2009 (Ward et al. 2013; Beckie 2006). A survey conducted in Northeast, Panhandle, southeast and west central districts of Nebraska in 2019-2020 showed that Palmer amaranth was number one problematic weed in corn, and it poses a major challenge across the state in corn-soybean production system, and about 80% of growers have at least one herbicide resistant weed species in their production system (McDonald et al. 2023). Though this species is native to the Southwestern United States, the human activities including seed and equipment transportation, and agriculture expansion in 20th century have promoted the spread of this problem weed in the Northern and Midwestern United States (Ward et al. 2013). The spread, threats and severity of Palmer amaranth in Nebraska were also discussed in an article in Omaha World Herald that showed the need for its management in corn-soybean production system.

Palmer amaranth leaves are rich in calcium, iron and vitamin A, however if these plants were grown under dry conditions, their leaves have high nitrate content that are detrimental for human and cattle consumption (Chahal et al. 2015). It germinates in optimum temperature range of 25 to 35C (Guo et al. 2003) and possess diaheliotropism (solar tracking) mechanism for entrapping higher incoming radiations for higher photosynthetic rate that led to make it aggressive and troublesome (Ehleringer and Forseth 1980).

**Palmer amaranth biology and seed production**

Palmer amaranth is a dioecious, broadleaf weed species with chromosome number (2n) varies from 32 to 34 (Gaines et al. 2012; Rayburn et al. 2005). It is obligate outcrosser (Franssen et al 2010), wind-pollinated and has seed production from unfertilized ovule known as apparent agamospermy (Chahal et al. 2015). Due to vigorous growth habit, and deep fibrous root system, Palmer amaranth poses a strong competition and gained an advantage for extracting nutrients, water, light and other resources compared with the row crops (Place et al. 2008).

Palmer amaranth is a prolific seed producer. A single female Palmer amaranth plant has capacity to produce 200,000 to 500,000 seeds per plant depending on competition with crop plants (Massinga et al. 2001). The seed production varies from location and time of emergence. In California, the seed production by a single Palmer amaranth plant was 200,000 to 600,000 seeds and their emergence was lies from March to June (Keeley et al. 1987). Plants that emerged later from July to October produced 80,000 seeds plant$^{-1}$ (Keeley et al. 1987). In Missouri, Palmer amaranth plants emergence in late May to early June produced more than 250,000 seeds plant$^{-1}$ (Sellers et al. 2003). In South Carolina, Palmer amaranth emerged between mid-June and late-July in soybean spaced 97 cm apart produced 211,000 seeds m$^{-2}$, while for narrow spaced soybean (19 cm) produced 139,000 seeds m$^{-2}$ (Jha et al. 2008). Weed seed yields were ranged from 1,800 to 91,000 seeds m$^{-2}$ for Palmer amaranth emerged when corn was at the four to seven leaf stage (Massinga et al. 2001). About a billion seed per hectare was recorded from Palmer amaranth (124,000 seeds) in peanut (*Arachis hypogaea* L.) with 5.2 plants m$^{-2}$ density (Burke et al. 2007).

**Palmer amaranth infestation and corn yield reduction**

Due to large emergence window, Palmer amaranth extends well into the corn growing season that provides extreme competition and results in large yield reductions (Crow et al. 2016). A three-year study in Kansas reported that Palmer amaranth emergence with corn reduced yield from 11 to 91% as density increased from 0.5 to 8 plants m$^{-1}$; and when Palmer amaranth emergence occurred at the four to seven leaf stage of corn, Palmer amaranth led to yield reductions of 7 to 35% at 0.5 to 8 plants m$^{-1}$ (Massinga et al. 2001). Similarly, Palmer amaranth reduced 1 to 44% corn forage yield when its density lies from 0.5 to 8 plants m$^{-1}$ of corn row, respectively (Massinga and Currie, 2002). For dryland corn production systems, Palmer amaranth at density of 1 to 6 plants m$^{-1}$ row resulted in yield loss from 18 to 38%, respectively (Liphadzi and dille, 2006).

**Multiple herbicide resistance (MHR) reports of Palmer amaranth**

By 2023, 269 weed species evolved resistance globally to 21 out of 31 herbicide sites of action. A total of 65 herbicide-resistant weed species were associated with corn production fields. Repeated use of herbicides belonging to similar sites of action is a major reason for the evolution of herbicide-resistant weeds. Additionally, the overreliance on glyphosate for weed control in glyphosate-resistant crops has triggered the evolution of glyphosate-resistant weeds species (Chahal et al. 2017). A total of nine weed species have been confirmed resistant to at least one herbicide in Nebraska (Jhala 2017). Multiple herbicide resistance (resistance to two or more herbicide sites of action) has also been reported in a few weed species (Ganie and Jhala 2017), and Palmer amaranth is one of them with resistance to 10 herbicide sites of action (Heap, 2023). The first report of multiple herbicide-resistant Palmer amaranth was reported in 2009 in Kansas, and it evolved resistant to atrazine, mesotrione, pyrasulfotole, tembotrione, thifensulfuron-methyl, and toprameozone in corn (Heap, 2023). By 2023, the presence of glyphosate-resistant Palmer amaranth has been reported in 30 states in the United States (Heap 2023). Jhala et al. (2014) indicated that growers from South Central Nebraska have reported failure to control Palmer amaranth following sequential application of atrazine, glyphosate, and acetolactate synthase (ALS)-inhibitors. Due to failure of managing multiple herbicide-resistant Palmer amaranth with present strategies, this study was planned to develop management tools of the three-way resistant Palmer amaranth in corn.

**Management of multiple herbicide-resistant Palmer amaranth**

Herbicide-resistant weeds become widespread throughout the United States (Price et al. 2012), and the use of herbicides is the most common and easiest approach for their management. In Nebraska, survey results showed that the most common PRE herbicides used in corn were atrazine/bicyclopyrone/mesotrione/*S*-metolachlor, acetochlor/clopyralid/mesotrione, and isoxaflutole/thiencarbazone-methyl. Other major corn herbicides were atrazine plus *S*-metolachlor (Dual II Magnum) and atrazine. These PRE herbicides in corn clearly shown the dominance of atrazine-based herbicides and premixes for early season management of weeds (McDonald et al. 2023). Similarly, in other studies, it was reported that acetochlor, alachlor, atrazine, dimethenamid-*P*, flumioxazin, fluthiacet-methyl, isoxaflutole, mesotrione, pyroxasulfone, *S*-metolachlor, and saflufenacil were the most used PRE herbicides that effectively controlled emerging ALS-inhibitor and glyphosate resistant Palmer amaranth (Legleiter and Johnson, 2013; Steckel 2014). Grichar et al. (2005) concluded that Palmer amaranth was controlled 95%, 78%, and 44% with acetochlor, atrazine, and flufenacet plus isoxaflutole, respectively, at 10 to 12 weeks after corn planting. He further elaborated that acetochlor, atrazine, and flufenacet plus isoxaflutole provided > 97% control for densities of Palmer amaranth those emerged at 8–10 plants $m^{-2}$. A separate study showed that atrazine plus isoxaflutole plus thiencarbazone methyl provided 91% control of Palmer amaranth 8 wk after PRE application compared to 81% control with atrazine removed from the mixture (Stephenson and Bond 2012).

As for POST herbicide management of Palmer amaranth, Legleiter and Johnson (2013) listed the commonly used options of growth regulators (2,4-D, dicamba, and diflufenzopyr), HPPD inhibitors (mesotrione, tembotrione, and topramezone), and PS II inhibitors (atrazine). Of these herbicides, 2,4-D and dicamba provided only POST activity, whereas atrazine, mesotrione, tembotrione, and topramezone were used as both PRE and POST control options of Palmer amaranth. Jones et al. (1998) found that a mixture of glufosinate with atrazine enhanced Palmer amaranth control over glufosinate. Bararpour et al. (2011) reported that HPPD-inhibiting herbicides can provide good control of Palmer when mixed with atrazine. Sarangi and Jhala (2018) conducted a survey in 2014-2015, the results shown that the most used POST herbicides were glyphosate, mesotrione/*S*-metolachlor plus glyphosate, and dicamba/diflufenzopyr. A follow up survey conducted by McDonald et al. (2023) in 2019-2020 concluded glyphosate, dicamba/diflufenzopyr and mesotrione as the best POST herbicide options for management of herbicide resistant Palmer amaranth. Acetochlor/*S*-metolachlor with a POST herbicide was one of best herbicide strategies to prevent Palmer amaranth emergence later in the season (Chahal et al. 2015).

There is a need to integrate chemical control with cultural and non-chemical approaches such as scouting of fields both prior to and after herbicide application, row width manipulation, use of diversified sites of action herbicide programs, cover cropping, crop rotation, herbicide resistant crop varieties, weed seed destruction practices for integrative management of multiple herbicide resistant Palmer amaranth. For instance, Price et al. (2012) reported that a high residue cereal cover crop in combination with broadcast PRE herbicide were necessary to manage multiple herbicide-resistant *Amaranthus* species. Similarly, a cereal rye cover cropping at rate of 846 g biomass $m^{-2}$ controlled Palmer amaranth by 90%. (Norsworthy et al. 2011). McDonald et al. (2021) concluded GR Palmer amaranth control was 83% with 38 cm row spacing compared to 76 cm (78%) 21 d after late POST. So, due to high yield reduction, seed production of MHR Palmer amaranth, poor control with available management tools were observed, thus, this study was conducted for the management of ALS, atrazine, and glyphosate-resistant Palmer amaranth in herbicide- resistant corn and food grade white corn with row width manipulation, herbicide resistant cultivar (Enlist technology) and diversified sites of action herbicide programs.

## OBJECTIVES

For management of multiple herbicide-resistant Palmer amaranth in corn, the research was conducted for last three years in a grower's field near Carleton, Nebraska. A diversified weed management program, use of premixes with effective multiple sites of action, crop rotation, and cultivation of multiple herbicide-resistant crop varieties are already published for herbicide resistant weeds in soybean. This research was conducted in corn to develop recommendations with new herbicide resistant cultivar (Enlist™ Corn), narrow row spacing and diversified weed management program by use of premixes with effective multiple sites of action for integrated management of multiple herbicide-resistant Palmer amaranth in herbicide-resistant corn and food grade white corn with the following objectives and rationale:

1. Enlist Corn is a new multiple herbicide-resistant corn (2,4-D choline, glyphosate, glufosinate, FOP herbicides) recently developed by industry. Published information on herbicide program for management of resistant Palmer amaranth in Enlist corn is scarce in literature. Thus, this experiment was conducted with the objective of enhancing the understanding and management of multiple herbicide resistant Palmer amaranth in Enlist corn.
2. Due to unavoidable weather conditions, sometimes it is not possible for growers to apply pre-emergence herbicide, hence, the post-emergence herbicide program must be needed for effective weed control. Information on post-emergence control of resistant Palmer amaranth in glyphosate/glufosinate -resistant corn is meagre and it needs to be formalized. Thus, this study was conducted with the objective to evaluate the effect of plant height on control and seed production of multiple herbicide resistant Palmer amaranth in herbicide- resistant corn.
3. Nebraska is the number one producer of food grade white corn; and the data on residual activity of pre-emergence herbicides in white corn for control of multiple herbicide-resistant Palmer amaranth is lacking in literature. Thus, this research experiment was conducted with the objective to compare residual activity of pre-emergence herbicides for control and seed production of multiple herbicide resistant Palmer amaranth in food grade white corn.

4. Corn row width manipulation is often a recommended cultural component of a sound integrated weed management program in addition to PRE and POST herbicide program for control of weed flora in different crops. The information regarding the effect of row spacing and herbicide programs for control of multiple herbicide resistant Palmer amaranth in glyphosate/glufosinate resistant corn is lacking. Thus, this study was conducted with the objective to generate an integrative cultural and chemical approach for management of multiple herbicide resistant Palmer amaranth along with enhancing corn productivity.

**LITERATURE CITED**

Bararpour MT, Oliver LR, Bell CG (2011) Comparisons of HPPD inhibitors for weed control programs in corn. Page 16 in 2011 Proceedings of the Southern Weed Science Society. Las Cruces, NM: Southern Weed Science Society.

Beckie HJ (2006) Herbicide resistant weeds: management tactics and practices. Weed Technol 20:793–814

Burke IC, Schroeder M, Thomas WE, Wilcut JW (2007) Palmer amaranth interference and seed production in peanut. Weed Technol 21:367– 371

Chahal PS, Aulakh J, Mithila J, Jhala AJ (2015) Herbicide-resistant Palmer amaranth (*Amaranthus palmeri* S. Wats) in the United States: impact, mechanism of resistance, and management. Pages 1–40 in: Price AJ, Kelton JA, Sarunaite L, eds, Herbicides, Agronomic Crops, and Weed Biology. New York, NY: Tech Scientific Publisher

Chahal PS, VK Varanasi, M Jugulam, and AJ Jhala (2017) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Nebraska: confirmation, EPSPS gene amplification, and response to POST corn and soybean herbicides. Weed Technol 31:80–93.

Crow WD, LE Steckel, TC Mueller, RM Hayes (2016) Management of large, glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in corn. Weed Technol 30:611–616

Ehleringer J, Forseth I (1980) Solar tracking by plants. Sci 210:1094– 1098

Franssen AS, Skinner DZ, Al-Khatib K, Horak MJ, Kulakow PA (2010) Interspecific hybridization and gene flow of ALS resistance in *Amaranthus* species. Weed Sci 49:598– 606

Gaines TA, Ward SM, Bekun B, Preston C, Leach JE, Westra P (2012) Interspecific hybridization transfers a previously unknown glyphosate resistance mechanism in *Amaranthus* species. Evol Appl 5:29–38

Ganie ZA, and Jhala AJ (2017) Multiple herbicide-resistant weeds and challenges ahead. https://cropwatch.unl.edu/multiple-herbicide-resistant-weeds-and-challenges-ahead

Grichar, WJ, Besler BA, Palrang DT (2005) Flufenacet and isoxaflutole combinations for weed control and corn (*Zea mays*) tolerance. Weed Technol 19:891–896

Guo PG, Al-Khatib K (2003) Temperature effects on germination and growth of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common water- hemp (*A. rudis*). Weed Sci 51:869–875

Heap I (2023) The International Herbicide-Resistant Weed Database. https://www.weedscience.org.

Jha P, Norsworthy JK, Bridges W, Riley MB (2008) Influence of glyphosate timing and row width on Palmer amaranth (*Amaranthus palmeri*) and pusley (*Richardia* spp.) demographics in glyphosate-resistant soybean. Weed Sci 56:408–415

Jhala AJ (2017) Status of herbicide-resistant weeds in Nebraska. https://cropwatch.unl.edu/2017/status-herbicide-resistant-weeds-nebraska

Jhala AJ, Sandell LD, Rana N, Kruger G, Knezevic SZ (2014) Confirmation and control of triazine and 4-hydroxyphenylpyruvate dioxygenase-inhibiting herbicide-resistant Palmer amaranth in Nebraska. Weed Technol 28:28-38

Jones CA, Chandler JM, Morrison JE, Seseman SA, Tingle CH (1998) Glufosinate combinations and row spacing for weed control in glufosinate-resistant corn. Weed Technol 15:141–147

Keeley PE, Carter CH, Thullen RJ (1987) Influence of planting date on growth of Palmer amaranth (*Amaranthus palmeri*). Weed Sci 35:199– 204.

Legleiter TR, Johnson B (2013) Palmer amaranth biology, identification, and management. https://www.extension.purdue.edu/extmedia/ws/ws-51-w.pdf

Liphadzi KB, Dille JA (2006) Annual weed competitiveness as affected by preemergence herbicide in corn. Weed Sci 54:156–165

Massinga RA, Currie RS (2002) Impact of Palmer amaranth (*Amaranthus palmeri*) on corn (*Zea mays*) grain yield and yield and quality of forage. Weed Technol 16:532–536

Massinga RA, Currie RS, Horak MJ, Boyer J (2001) Interference of Palmer amaranth in corn. Weed Sci 49:202–208

McDonald S, Sarangi D, Rees J, Jhala A (2023) A follow-up survey to assess stakeholders' perspectives on weed management challenges and current practices in Nebraska, USA. Agrosyst Geosci Environ 6. 10.1002/agg2.20425

McDonald ST, Striegel A, Chahal PS, Jha P, Rees JM, Proctor CA, Jhala AJ (2021) Effect of row spacing and herbicide programs for control of glyphosate-resistant

Palmer amaranth (*Amaranthus palmeri*) in dicamba/glyphosate-resistant soybean. Weed Technol 35:790–801

Norsworthy JK, McClelland M, Griffith G, Bangarwa SK, Still J (2011) Evaluation of cereal and Brassicaceae cover crops in conservation-tillage, enhanced, glyphosate-resistant cotton. Weed Technol 25:6–13

Place G, Bowman D, Burton M, Rutty T (2008) Root penetration through a high bulk density soil layer: differential response of a crop and weed species. Plant Soil 307:179–190

Price AJ, Balkcom KS, Duzy LM, Kelton JA (2012) Herbicide and cover crop residue integration for *Amaranthus* control in conservation agriculture cotton and implications for resistance management. Weed Technol 26:490–498

Rayburn AL, McCloskey R, Tatum TC, Bollero GA, Jeschke MR, Tranel PJ (2005) Genome size analysis of weedy *Amaranthus* species. Crop Sci 45:2557–2562

Sarangi D, Jhala AJ (2018) A statewide survey of stakeholders to assess the problem weeds and weed management practices in Nebraska. Weed Technol 32:642–655

Sellers BA, Smeda RJ, Johnson WG, Kendig JA, Ellersieck MR (2003) Comparative growth of six *Amaranthus* species in Missouri. Weed Sci 51:329–333

Steckel L (2014) Corn weed control. In: Rodes GN Jr, Mains C, Sims BD, Hayes RM, McClure A, Mueller TC, Blake B, Wiggins M, Senseman S, editors. Weed Control Manual for Tennessee. Knoxville, TN: University of Tennessee-Extension. p. 11–20

Stephenson DO and Bond JA (2012) Evaluation of thiencarbazone-methyland soxaflutole-based herbicide programs in corn. Weed Technol 26:37–42

Trucco ZD, Woodyard AJ, Walter JR, Tatum TC, Rayburn AL, Tranel PJ (2007) Non-hybrid progeny from crosses of dioecious Amaranths: implications for gene flow research. Weed Sci 55:119–122

Ward SM, Webster TM, and Steckel LE (2013) Palmer amaranth (*Amaranthus palmeri*): a review. Weed Technol 27:12–27

# CHAPTER 2

## EFFECT OF HERBICIDE PROGRAMS ON CONTROL AND SEED PRODUCTION OF MULTIPLE HERBICIDE-RESISTANT PALMER AMARANTH (*Amaranthus palmeri*) IN CORN RESISTANT TO 2,4-D CHOLINE/GLUFOSINATE/GLYPHOSATE

***This chapter is submitted:*** Kaur R, Rogers R, Lawrence N C, Shi Y, Chahal P S, Knezevic S Z, Jhala A J (2023) Effect of herbicide programs on control and seed production of multiple herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) in corn resistant to 2,4-D choline/glufosinate/glyphosate. ***Weed Technology***.

## ABSTRACT

Multiple herbicide-resistant (MHR) Palmer amaranth is among the most problematic summer annual broadleaf weeds in Nebraska and several other states in the United States. A new multiple herbicide-resistant corn (2,4-D choline/glufosinate/glyphosate-resistant corn, also known as Enlist corn), has been commercially available in the United States from the 2018 growing season. Growers are searching for herbicide programs that can be used for control and reducing seed production of MHR Palmer amaranth in Enlist corn. The objectives of this study were to evaluate herbicide programs applied PRE, early-POST (EPOST), or PRE followed by (fb) late-POST (LPOST) for management of MHR Palmer amaranth in Enlist corn and their effect on Palmer amaranth biomass, density, seed production, and corn yield. Field experiments were conducted near Carleton, Nebraska in 2020 and 2021 in a grower's field infested with acetolactate synthase-inhibitor/atrazine/glyphosate-resistant Palmer amaranth. Herbicides applied PRE such as flufenacet/isoxaflutole/thiencarbazone-methyl, acetochlor/clopyralid/flumetsulam, or acetochlor/clopyralid/mesotrione provided 75% to 99% control of MHR Palmer amaranth

30 d after PRE (DA-PRE). PRE fb LPOST herbicides resulted in 94% Palmer amaranth control, reduced weed density to 0 to 8 plants $m^{-2}$ and biomass to 2 to 14 g $m^{-2}$ compared to PRE-only (59% control, 0 to 15 plants $m^{-2}$, and 4 to 123 g $m^{-2}$) and EPOST-only programs (78% control, 6 to 30 plants $m^{-2}$, and 8 to 25 g $m^{-2}$). Similarly, Palmer amaranth seed production was reduced to 14,053 seeds $m^{-2}$ in PRE fb LPOST herbicide programs compared with PRE-only (325,491 seeds $m^{-2}$) and EPOST-only (376,751 seeds $m^{-2}$) programs based on contrast analysis. Relatively higher corn yield of 12,343 and 11,731 kg $ha^{-1}$ was obtained with PRE fb LPOST herbicide programs than PRE-only (10,837 and 11,512 kg $ha^{-1}$) and EPOST-only programs (10,850 and 10,031 kg $ha^{-1}$) in 2020 and 2021, respectively.

## INTRODUCTION

Palmer amaranth is among the most problematic summer annual broadleaf weeds across the mid-south, southeastern, and north central United States (Vencill et al., 2008; Webster 2005). In a survey conducted by the Weed Science Society of America, Palmer amaranth was ranked as the most troublesome weed in agronomic cropping systems in the United States (Van Wychen 2022). A widespread occurrence of Palmer amaranth is due to its unique biological attributes, including an extended period of emergence, aggressive growth rate, high photosynthetic rate, high water-use efficiency, considerable biomass accumulation, and prolific seed production (up to 0.6 million seeds per female plant) (Chahal et al. 2018b; Jha and Norsworthy 2009; Ward et al. 2013), and dioecious reproductive biology that increases the pollen-mediated gene flow and chances of spread of herbicide resistance alleles (Jhala et al. 2021). If not controlled, Palmer amaranth can cause a significant crop yield reduction. For example, a Palmer amaranth density of 3 plants $m^{-2}$ caused 60% yield loss in soybean (*Glycine max* L. Merill) in a study conducted in Arkansas (Klingaman and Oliver 1994). Bensch et al. (2003) reported 78% soybean yield loss at a density of 8 plants $m^{-2}$ in Kansas, and Massinga et al. (2001) showed that Palmer amaranth at 0.5–8 plants $m^{-1}$ row reduced corn yield from 11% to 91%. In addition to its biological characteristics, the evolution of herbicide-resistant Palmer amaranth populations in agronomic cropping systems has become a challenge for growers for effective management (Chahal et al. 2018a; Mausbach et al. 2021).

Palmer amaranth has evolved resistance to a number of herbicide sites of action (SOA), including acetolactate synthase (ALS) inhibitor, 5-enolpyruvyl shikimate-3-phosphate synthase (EPSPS), dinitroanilines, photosystem II, protoporphyrinogen oxidase (PPO)-inhibitor (Chahal et al. 2017; Garetson et al. 2019; Ward et al. 2013), 4-hydroxyphenyl pyruvate dioxygenase (HPPD)-inhibitor (Jhala et al. 2014; Chahal et al. 2015), synthetic auxins (Kumar et al. 2019), and very long chain fatty acid inhibitor (Brabham et al. 2019). A Palmer amaranth biotype resistant to glufosinate has been confirmed in Arkansas in 2021 (Barber et al. 2021) and dicamba-resistant Palmer amaranth in Tennessee (Foster and Steckel 2022). In addition to resistance to single herbicide SOA, there are reports of Palmer amaranth resistant to multiple herbicides belonging to different SOA. One of the most prevalent forms of multiple resistance in Palmer amaranth is resistance to glyphosate and ALS-inhibiting herbicides, which has been confirmed in eight states, including Michigan (Nandula et al. 2012; Sosnoskie et al. 2011) and Nebraska (Chahal et al. 2017; Jhala et al. 2014). In addition, Palmer amaranth resistant to atrazine, chlorsulfuron, 2,4-D, glyphosate, and mesotrione has been reported in Kansas (Kumar et al. 2019; 2020). Kohrt et al. (2016) confirmed Palmer amaranth resistant to ALS-inhibitor, atrazine, and glyphosate in Michigan. As of August 2023, Palmer amaranth has evolved resistance to ten herbicide SOA (Heap 2023).

Palmer amaranth has an extended emergence pattern from early May through August in the Midwest (Chahal et al. 2021) and from late April to early September in the southern United States (Liu et al. 2022), making it difficult to control with a single herbicide application (Keeley et al., 1987). Preemergence (PRE) herbicides generally lose their residual activity 20–40 d after application depending on the herbicide used and soil type; however, most postemergence (POST) herbicides commonly applied in corn have minimal to no soil residual activity (Jhala et al. 2015; Wiggins et al. 2015). The late-emerging Palmer amaranth often escapes POST herbicide application and produce seeds, leading to the replenishment of the soil seedbank for the next several seasons (Bagavathiannan and Norsworthy 2012). Therefore, herbicide programs should be focused on season-long control of Palmer amaranth to reduce seed production and infestation during subsequent crop seasons (Striegel and Jhala 2022). Though over-the top application of most foliar active POST herbicides is restricted up to a certain corn growth stage (Jhala 2017), some herbicides such as topramezone can be applied late in the season in corn (Anonymous 2021). In addition, soil residual herbicides such as acetochlor, dimethenamid-*P*, fluthiacet-methyl, or pyroxasulfone can be applied with foliar active POST herbicide in corn up to certain growth stages (Jhala 2023) to provide overlapping residual activity to control weeds such as Palmer amaranth with an extended emergence period (Sarangi and Jhala 2019).

A new MHR corn trait resistant to 2,4-D choline, glufosinate, and glyphosate, also known as Enlist corn, has been commercially available in the United States since 2018 growing season. In addition, this corn trait is also resistant to aryloxyphenoxypropionates, providing an opportunity to control volunteer corn in Enlist corn using quizalofop (Striegel et al. 2020). Corn resistant to 2,4-D choline was conferred by the insertion of a gene (AAD-12) that codes for an aryloxyalkanoate dioxygenase enzyme (Nandula 2019). It provides an opportunity for management of ALS-inhibitor-, atrazine-, and glyphosate-resistant Palmer amaranth with the aid of herbicide programs that can't be applied in conventional or glyphosate-resistant corn. The objectives of this study were to evaluate the effect of herbicide programs applied PRE, early-POST (EPOST), and PRE followed by late-POST (LPOST) for control of ALS-inhibitor/atrazine/glyphosate-resistant Palmer amaranth, and their effect on Palmer amaranth density, biomass, seed production, crop injury, and yield in Enlist corn in a multiyear field study conducted in a grower's field in Nebraska. We hypothesized that a season-long control of multiple herbicide-resistant Palmer amaranth would be achieved with reduced seed production in a PRE followed by a LPOST herbicide program.

# MATERIALS AND METHODS

## Field Experiments

Field experiments were conducted in 2020 and 2021 in a grower's field infested with ALS-inhibitor/atrazine/glyphosate-resistant Palmer amaranth near Carleton, NE (40.30°N, 97.67°W). The experiments were established under no-till conditions. The previous crops at the site were no-till soybean in 2019 and no-till corn in 2020. Palmer amaranth was the dominant summer weed at the experimental site and was confirmed resistant to ALS-inhibitor/atrazine/glyphosate (Chahal et al. 2017). The soil at the experimental site was silt loam (montmorillonitic, mesic, Pachic Argiustolls), with 19.0% sand, 63.0% silt, 18.0% clay, 6.0 pH, and 2.5% organic matter content. 2,4-D choline (Enlist ONE, Corteva Agriscience, Indianapolis, IN) was applied early spring for control of glyphosate-resistant marestail (*Conyza canadensis* L. Cronq.) present at the experimental site. The treatments were laid out in a randomized complete block design with four replications. The dimensions of an individual experimental plot were 3 m wide and 9 m long. Enlist E3 corn (8097 SXE Enlist Corn SmartStax) was planted at 67,500 seeds ha$^{-1}$ on May 12, 2020 and May 18, 2021. The experimental site was without supplemental irrigation. The precipitation received during the crop growing season for both years is listed in Table 2.1.

Herbicide programs included PRE-only, EPOST-only, and PRE fb LPOST with a total of 15 treatments, including a nontreated control and a weed-free control for comparison (Table 2.2). 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 a 140 L $ha^{-1}$ flow rate at 276 kPa at a constant speed of 4.8 km $h^{-1}$. Glufosinate was mixed with liquid ammonium sulfate at 3% vol/vol (Anonymous 2017) and was applied with XR 11005 flat-fan nozzles (TeeJet® Technologies). The PRE herbicides were applied 2 d after corn planting on May 14 in 2020 and on the day of corn planting on May 18 in 2021. Early POST herbicides were applied 36 d after corn planting on June 18, 2020, and 28 d after corn planting on June 16, 2021; and LPOST herbicides were applied on June 23, 2020, and on June 25, 2021. Recommended adjuvants were added with POST herbicides. EPOST and LPOST herbicides were applied when Palmer amaranth was 10–15 cm tall and 20-30 cm, respectively. The height of Palmer amaranth was variable because of its extended emergence pattern as new plants emerged.

**Data Collection**

Visual estimates of Palmer amaranth control were recorded 15 and 30 days after PRE (DA-PRE); 15 and 30 days after days after EPOST (DA-EPOST); and 15, 30, and 90 days after LPOST (DA-LPOST) using a scale 0% to 100%, with 0% meaning no Palmer amaranth control and 100% meaning complete control. Corn injury was assessed on a scale of 0% to 100% at 15 and 30 DA-PRE; 15 and 30 DA-EPOST; and 15 and 30 DA-LPOST with 0% meaning no corn injury and 100% meaning plant death. Palmer amaranth density was recorded by counting the number of Palmer amaranth plants in 0.5

$m^2$ quadrats from each plot 15 and 30 DA-PRE, 30 DA-EPOST, and 30 DA-LPOST. Aboveground biomass was collected from 0.5-$m^2$ quadrats $plot^{-1}$ 30 DA-EPOST and 15 DA-LPOST. Palmer amaranth plants were clipped at the soil surface, kept in paper bags, dried at 65 C in an oven until a constant weight was achieved, and weighed. Palmer amaranth seed production was recorded by placing 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 a series of standard laboratory sieves with mesh size 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 (Sosnoskie et al. 2014). The seeds were thoroughly cleaned, and the seed weight and number of seeds per $m^2$ were determined. At maturity, corn was harvested from the center two rows of each plot using a plot combine, weighed, and the moisture content was recorded. Grain yield was adjusted to 13% moisture content and converted into kilograms per hectare.

**Statistical Analysis**

Palmer amaranth control, density, and aboveground biomass, Palmer amaranth seed production, and corn yield data were subjected to ANOVA using PROC GLIMMIX in SAS version 9.4. Before analysis, data were subjected to PROC UNIVARIATE analysis for testing normality and homogeneity of variance with normal Q-Q plots and levene test, respectively. 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 data 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. Palmer amaranth density and biomass data were square-root transformed, and back-transformed values are presented. 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. Year and herbicide treatments were considered fixed effects in the model, while replications were considered a random effect. Orthogonal contrasts were considered to compare herbicide programs (PRE vs EPOST, PRE vs PRE fb LPOST, and EPOST vs PRE fb LPOST) at $P \leq 0.05$ for Palmer amaranth control at 15 and 30 DA-EPOST; 15, 30 and 90 DA-LPOST; Palmer amaranth seed production; and corn yield.

## RESULTS AND DISCUSSION

Year-by-treatment interactions for MHR Palmer amaranth control, aboveground biomass, and Palmer amaranth seed production were not significant ($P \geq 0.05$); therefore, data from both years were combined. Palmer amaranth density and corn yield were significant; therefore, data are presented separately for both years (2020 and 2021). No corn injury was observed from any herbicide program (data not shown), indicating that the herbicides evaluated in this study are safe to use in Enlist corn when applied according to label instructions.

**Temperature and Precipitation**

The average monthly temperature during the 2021 growing season was higher than in 2020 (Table 2.1). Apart from this average, monthly temperatures during the crop season in both years were similar. Below-average precipitation occurred in 2021, with 13.5 mm and 45.5 mm in June and July, respectively, whereas above-average precipitation was observed throughout the 2020 growing season (Table 2.1).

**Palmer amaranth Control**

Herbicides applied PRE in this study provided 96% to 99% control of MHR Palmer amaranth 15 DA-PRE, and 75% to 99% control 30 DA-PRE, without difference among them (Table 2.3). The residual activity of most herbicides applied PRE declined as the season progressed. For example, acetochlor/clopyralid/flumetsulam, and flufenacet/isoxaflutole/thiencarbazone-methyl controlled Palmer amaranth 44%-45% 90 DA-LPOST compared with 87% control with acetochlor/clopyralid/mesotrione (Table 2.3).

Among the E-POST herbicides, glufosinate-based herbicide programs provided better control compared with glyphosate-based programs. For example, 2,4-D choline + glufosinate controlled Palmer amaranth 90%; and glufosinate provided 83% control compared with 57% control with 2,4-D choline/glyphosate; and 62% control with 2,4-D choline (Table 2.3). The lower control with glyphosate-based programs can be explained by the presence of glyphosate-resistant Palmer amaranth at the study site. Chahal et al. (2017) reported 99% Palmer amaranth control 21 DA-POST with glufosinate in corn. It was clear that glufosinate applied alone or in a mixture with 2,4-D choline was better compared with 2,4-D choline applied alone for control of Palmer amaranth early in the season. As the season progressed, Palmer amaranth control with glufosinate alone was reduced to 66% compared with 85% control achieved with 2,4-D choline + glufosinate 90 DA-LPOST (Table 2.3). Glufosinate doesn't have soil residual activity therefore, was not able to control the late emerging flush of Palmer amaranth and 2,4-D in the mixture provided some residual activity (Table 2.3).

Herbicides applied PRE without a follow-up POST herbicide were not able to provide economically acceptable Palmer amaranth control compared with PRE fb LPOST herbicide programs later in the season, with the exception of acetochlor/clopyralid/mesotrione, which provided 87% control 90 DA-LPOST compared to 44% to 45% control with the remaining PRE-only herbicide treatments. This is because Palmer amaranth at the study site was resistant to ALS-inhibitor; thus, lower Palmer amaranth control was obtained with acetochlor/clopyralid/ flumetsulam, and flufenacet/isoxaflutole/thiencarbazone-methyl as both of these premixes have ALS-inhibitor; whereas Palmer amaranth was not resistant to acetochlor/clopyralid/mesotrione. A similar decline in residual activity of soil-applied PRE herbicides has been reported in soybean in multiyear field studies in Nebraska, where PRE herbicides resulted in 66% control of Palmer amaranth compared with 86% control by PRE fb POST herbicide programs 28 DA-POST (Sarangi and Jhala 2019). Liu et al. (2021) concluded that PRE fb LPOST herbicide programs resulted in 83% Palmer amaranth control 7 weeks after LPOST compared to 67% control with PRE-only program in glufosinate/glyphosate-resistant corn.

The PRE fb POST herbicide programs provided 94% to 99% control of MHR Palmer amaranth 15 DA-LPOST; and 87% to 97% control 90 DA-LPOST without difference among them (Table 2.3). This can be attributed to a higher Palmer amaranth control by the residual activity of PRE herbicides and a follow-up application of a POST herbicide controlled late-emerged Palmer amaranth. Among the PRE fb LPOST herbicide programs, acetochlor/clopyralid/mesotrione fb glufosinate provided the lowest (87%) MHR Palmer amaranth control 90 DA-LPOST (Table 2.3). Palmer amaranth control provided by the remaining PRE fb LPOST herbicide programs ranged from 93% to 97%. While Palmer amaranth is known for its extended emergence pattern, emergence is reported to be higher from early May to mid-July (Chahal et al. 2021), which is before crop canopy closure (Jha and Norsworthy 2009). Thus, the use of a PRE herbicide with diversified SOA would not only provide emerging crop seedlings with a weed-free start, but also result in reduced reliance on a POST herbicide (Norsworthy et al. 2012). Meyer et al. (2015) showed that auxin-based LPOST herbicides can be used as an option to control glyphosate-resistant Palmer amaranth in soybean; however, the evolution of 2,4-

D/dicamba-resistant Palmer amaranth in Kansas (Kumar et al. 2019) and dicamba-resistant Palmer amaranth in Tennessee (Foster and Steckel 2022) are concerning, and a reminder not to use the same herbicide or herbicides with the same SOA in the same field over multiple years.

Contrast analysis showed that PRE fb LPOST herbicide programs resulted in 94% Palmer amaranth control compared with 59% and 78% control with PRE and EPOST-only programs, respectively (Table 2.3). Similarly, Sarangi et al. (2017) reported 90% control of herbicide-resistant *Amaranthus* species in soybean with PRE fb LPOST herbicide programs. Several other studies have found greater control of *Amaranthus* species with PRE fb POST herbicide programs compared with PRE-only or EPOST-only programs (Aulakh and Jhala 2015; Johnson et al. 2012; Liu et al. 2021; Striegel and Jhala 2022).

**Palmer amaranth Density and Biomass**

Palmer amaranth density and biomass were affected by the herbicide programs compared with the nontreated control (Table 2.4). Palmer amaranth emergence was greater in 2020 compared with 2021, leading to greater Palmer amaranth density in 2020. For example, Palmer amaranth density in the nontreated control ranged from 61 to 149 plants $m^{-2}$ in 2020 compared with 43 to 72 plants $m^{-2}$ in 2020. This was most likely due to the availability of more moisture from higher precipitation in 2020 compared with 2021 growing season (Table 2.1). A greater density reduction was obtained in 2020 compared with 2021 at each evaluation timing.

At 30 DA-PRE, acetochlor/clopyralid/mesotrione reduced Palmer amaranth density to 0 and 5 plants $m^{-2}$ in 2020 and 2021, respectively, whereas on average in both years, acetochlor/clopyralid/flumetsulam, and flufenacet/isoxaflutole/thiencarbazone-methyl resulted in density of 10 to 66 and 2 to 47 plants $m^{-2}$, respectively (Table 2.4). As the season progressed, the efficacy of PRE herbicides was reduced, except acetochlor/clopyralid/mesotrione that reduced Palmer amaranth density to 0 to 2 plants $m^{-2}$ 30 DAEPOST. Among EPOST herbicide programs, 2,4-D choline had a Palmer amaranth density of 9 and 17 plants $m^{-2}$ in 2020 and 2021, respectively, whereas 2,4-D choline + glufosinate, and glufosinate applied alone recorded Palmer amaranth density of 6 and 9 plants $m^{-2}$ in 2021, respectively. Adequate soil moisture at the beginning of the season favors the germination of Palmer amaranth, and due to the lack of PRE herbicide, provided an opportunity for Palmer amaranth to emerge and compete with corn. Palmer amaranth was at a variable height when EPOST herbicides were applied, and it is known that the efficacy of auxinic herbicides, as well as glufosinate, can vary with weed height and density (Barnett et al. 2013; Jhala et al. 2017; Steckel et al. 1997).

Among PRE fb LPOST herbicide programs, acetochlor/clopyralid/mesotrione fb 2,4-D choline; acetochlor/clopyralid/flumetsulam fb glufosinate; or flufenacet/isoxaflutole/ thiencarbazone-methyl fb glufosinate reduced Palmer amaranth density 0 to 2, 0 to 8, and 0 to 12 plants $m^{-2}$ in both years 30 DA-EPOST; and reduced density up to 100% 30 DALPOST. Chahal and Jhala (2015) reported 83% density reduction of *Amaranthus* spp. with glufosinate applied EPOST fb LPOST 45 DA-LPOST in glufosinate-resistant soybean in Nebraska. Acetochlor/clopyralid/flumetsulam fb 2,4-D choline resulted in lower Palmer amaranth density (8 plants $m^{-2}$), most likely due to declining residual activity of the PRE herbicide and uneven Palmer amaranth height when 2,4-D choline was applied. The PRE fb LPOST herbicide programs recorded 0 to 8 Palmer amaranth plants $m^{-2}$ compared with 6 to 30 and 0 to 15 plants $m^{-2}$ with EPOST and PRE-only programs, respectively, 30 DA-LPOST. Thus, the LPOST herbicide caused a 50% density reduction compared with the most PRE-only herbicides. Norsworthy et al. (2016) and Aulakh and Jhala (2015) have explained that PRE fb LPOST programs were more sustainable compared with EPOST or PRE-only herbicide programs due to the integration of herbicides with multiple SOA. Miller and Norsworthy (2016) reported a lower density of Palmer amaranth with herbicide programs involving multiple SOA compared with a single herbicide SOA. Furthermore, repeated use of herbicides with the same SOA (e.g., 2,4-D or glufosinate) would select for the herbicide-resistant weed biotype. It is important to note that 2,4-D resistance has already been confirmed in Palmer amaranth from Kansas (Kumar et al. 2019) and in a biotype of waterhemp in Nebraska (Bernards et al. 2012). Therefore, a sequential application and repeated application of 2,4-D choline in Enlist corn and Enlist soybean should be avoided.

Aboveground biomass of Palmer amaranth followed a similar trend as density (Table 2.4). Lower Palmer amaranth biomass (5 g $m^{-2}$) was obtained with acetochlor/clopyralid/mesotrione applied PRE alone or fb 2,4-D choline 30 DA-EPOST. Some PRE and EPOST-only herbicides showed higher Palmer amaranth biomass (acetochlor/clopyralid/flumetsulam, flufenacet/isoxaflutole/ thiencarbazone-methyl, glyphosate/2,4-D choline, and 2,4-D choline). This might be due to reduced efficacy of the applied residual herbicide and Palmer amaranth more than 15 cm tall at the time of EPOST herbicide application. PRE fb LPOST herbicide programs recorded Palmer amaranth biomass of 5 to 22 g $m^{-2}$ and were comparable to EPOST herbicide programs, with the exception of acetochlor/clopyralid/mesotrione fb glufosinate (48 g $m^{-2}$).

Averaged across herbicide programs, acetochlor/clopyralid/mesotrione applied PRE as well as PRE fb LPOST herbicide programs resulted in 90% to 99% reduction of Palmer amaranth biomass 15 DA-LPOST. Shyam et al. (2021) reported 99% Palmer amaranth biomass reduction with PRE fb LPOST herbicides in 2,4-D choline/glufosinate/glyphosate–resistant soybean. Sarangi and Jhala (2019) showed high biomass reduction of Palmer amaranth in soybean with PRE fb POST herbicides ranging from 96% to 100%. Thus, a PRE herbicide with multiple SOA fb 2,4-D choline/glufosinate has consistently provided greater than 90% Palmer amaranth density and biomass reduction. To maintain the effectiveness of any herbicide program, however, it will be crucial to follow application timings with appropriate crop and weed growth stages as described on the product label. For example, the 2,4-D choline label suggests applying when broadleaf weeds are less than 15 cm (Anonymous 2022); therefore, if it is applied late, Palmer amaranth control can be compromised.

**Corn Yield**

Year-by-treatment interaction was significant; therefore, yield data are presented separately for both years (Table 2.5). Corn yield in 2020 was higher compared to 2021 due to higher precipitation in 2020 that provided sufficient moisture for better corn growth and development as it was a dryland site. Several herbicide programs resulted in similar grain yield in the range of 11,080 kg ha$^{-1}$ to 12,910 kg ha$^{-1}$ and 10,282 kg ha$^{-1}$ to 12,417 kg ha$^{-1}$, respectively, in 2020 and 2021 growing seasons. Averaged across herbicide programs, PRE fb LPOST herbicide programs and PRE-only herbicide such as acetochlor/clopyralid/mesotrione, or acetochlor/clopyralid/flumetsulam and weed-free resulted in greater corn yield compared to nontreated control in both years (Table 2.5). Similarly, Jones et al. (2001) concluded that PRE fb POST herbicide programs produced 8,890 to 9,570 kg ha$^{-1}$ grain yield compared with glufosinate (8,300 kg ha$^{-1}$) and nontreated control (5,810 kg ha$^{-1}$) in multi-year studies in glufosinate-resistant corn in Texas. The lowest yield (8,750 kg ha$^{-1}$ and 5,792 kg ha$^{-1}$ in 2020 and 2021, respectively) was obtained in the nontreated control, which was comparable to 2,4-D choline without a PRE herbicide (9,391 and 9,107 kg ha$^{-1}$ in 2020 and 2021, respectively), indicating that if Palmer amaranth is the predominant weed in a corn field, using an EPOST-only program will not provide season long control and result in significant yield reduction due to weed-crop competition. There was no difference in corn yield between PRE fb LPOST programs (11,731 to 12,343 kg $ha^{-1}$) and PRE-only herbicides (10,837 to 11,512 kg $ha^{-1}$), with the exception of flufenacet/isoxaflutole/thiencarbazone-methyl in 2020 (10,247 kg $ha^{-1}$). Liu et al. (2021) reported that no difference in corn yield was observed with PRE-only and PRE fb POST herbicide programs, and it ranged from 9,207 to 10,215 kg $ha^{-1}$.

**Palmer amaranth Seed Production**

Palmer amaranth seed production was affected by herbicide programs (Table 2.5). The highest Palmer amaranth seed production (1,077,652 seeds $m^{-2}$) resulted from glufosinate applied alone compared with the nontreated control (939,687 seeds $m^{-2}$) (Table 2.5). Miranda et al. (2021) reported that Palmer amaranth seed production per plant decreased as Palmer amaranth density increased, and concluded that the highest seed production (376,000 seeds $plant^{-1}$) was found at the lowest density of 0.2 plants $m^{-1}$ row, and that it declined by 12%, 28%, 55%, and 75% when density increased to 0.3, 0.5, 1, and 2 plants $m^{-1}$ row, respectively. Palmer amaranth density in this study was 43 to 149 plants $m^{-2}$ in the nontreated control compared with 0 to 15, 6 to 30, and 0 to 24 plants $m^{-2}$ in PRE-only, EPOST-only, and PRE fb LPOST herbicide programs, respectively. Therefore, lower seed production in the nontreated control compared with the glufosinate applied EPOST was due to higher inter-plant competition in the nontreated control. Acetochlor/clopyralid/mesotrione applied PRE without a follow-up POST herbicide resulted in no Palmer amaranth seed production (Table 2.5), compared with flufenacet/isoxaflutole/ thiencarbazone-methyl applied PRE-only and acetochlor/clopyralid/flumetsulam applied PRE-only, which produced about 0.5 million seeds $m^{-2}$. This might be due to acetochlor/clopyralid/ mesotrione provided better control and reduced Palmer amaranth density compared with later two treatments.

Averaged across herbicide programs, PRE fb LPOST herbicide programs had Palmer amaranth seed production of 14,053 seeds $m^{-2}$ compared with PRE-only (325,491 seeds $m^{-2}$) and EPOST-only (376,751 seeds $m^{-2}$) programs. Thus, a PRE fb a LPOST herbicide program has a better chance of reducing Palmer amaranth seed production compared with relying on a single herbicide application. Striegel and Jhala (2022) reported that Palmer amaranth seed production was 1,634 seeds $plant^{-1}$ with PRE fb POST herbicide programs compared with 7,544 seeds $plant^{-1}$ with a single POST herbicide. Similarly, Norsworthy et al. (2016) concluded that the inclusion of PRE herbicides with diversified SOA fb glufosinate/glyphosate resulted in 97% to 99.9% reduction in Palmer amaranth seed production compared to a glyphosate–only treatment.

## PRACTICAL IMPLICATIONS

Results of this study indicated that PRE fb LPOST herbicide programs are available for season-long control and reduce seed production of MHR Palmer amaranth in Enlist corn. Phenoxy herbicides such as 2,4-D or dicamba can be applied in any type of corn, but only up to 20-cm (8 inch) corn height; however, 2,4-D choline (Enlist ONE) can be applied up to the V8 growth stage or 76-cm (30-inch) height in Enlist corn

(Anonymous 2022). If corn is taller than 30 inches, 2,4-D choline should be applied using drop nozzles aligned in such a way that spraying does not reach into the whorl of Enlist corn plants. Annual broadleaf weeds are best controlled by 2,4-D choline when they are small (less than 13 cm), and no more than two POST applications of 2,4-D choline should be applied per year (Anonymous 2022). If 2,4-D choline is applied sequentially in Enlist corn, the interval between applications must be a minimum of 12 days. Enlist corn adoption will likely be higher in the future, due to its resistance to aryloxyphenoxypropionates which will allow the use of FOPs (for example, quizalofop) as a in Enlist corn for controlling glyphosate/glufosinate-resistant corn volunteers (Striegel et al. 2020). This is particularly important in states such as Nebraska where continuous corn is a common practice in the south-central region and quizalofop can also control grass weeds. Apart from using Enlist corn technology and herbicides with different SOA, integrative approaches such as cover cropping, diverse crop rotations, weed seed destruction practices need to be incorporated for persistent control of MHR Palmer amaranth and reducing seedbank additions in a corn-soybean rotation.

**LITERATURE CITED**

Anonymous (2017) Liberty herbicide product label. EPA Reg. No. 264-829. Research Triangle Park, NC: Bayer Crop Science 29 p

Anonymous (2021) Impact® herbicide product label. EPA Reg. No. 5481-524. Los Angeles, CA: AMVAC. 4 p

Anonymous (2022) Enlist ONE herbicide product label. EPA Reg. No. 62719-695. Indianapolis, IN: Corteva agriscience. 2 p

Aulakh JS, Jhala AJ (2015) Comparison of glufosinate-based herbicide programs for broad-spectrum weed control in glufosinate-resistant soybean. Weed Technol 29:419–430

Bagavathiannan MV, Norsworthy JK (2012) Late-season seed production in arable weed communities: management implications. Weed Sci 60:325–334

Barber T, Norsworthy J, Butts T (2021) Arkansas Palmer amaranth found resistant to field rates of glufosinate. https://arkansascrops.uada.edu/posts/weeds/zz-68882.aspx. Accessed: September 5, 2023

Barnett KA, Culpepper SA, York AC, Steckel LE (2013) Palmer amaranth control by glufosinate plus flometuron applied post emergence to WideStrike cotton. Weed Technol 27:291–297

Bensch CN, Horak MJ, Peterson D (2003) Interference of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*) in soybean. Weed Sci 51:37–43

Bernards M, Crespo R, Kruger G, Gaussoin R, Tranel P (2012) A waterhemp (*Amaranthus tuberculatus*) population resistant to 2,4-D Weed Sci 60:379–384

Brabham C, Norsworthy JK, Houston MM, Varanasi VK, Barber T (2019) Confirmation of S-metolachlor resistance in Palmer amaranth (*Amaranthus palmeri*). Weed Technol 33:720–726

Chahal PS, Aulakh J, Mithila J, Jhala AJ (2015) Herbicide-resistant Palmer amaranth (*Amaranthus palmeri* S. Wats) in the United States: impact, mechanism of resistance, and management. Pages 1–40 in: Price AJ, Kelton JA, Sarunaite L, eds, Herbicides, Agronomic Crops, and Weed Biology. New York, NY: Tech Scientific Publisher

Chahal PS, Barnes ER, Jhala AJ (2021) Emergence pattern of Palmer amaranth (*Amaranthus palmeri*) influenced by tillage timings and residual herbicides. Weed Technol 35:433-439

Chahal PS, Ganie ZA, Jhala AJ (2018a) Overlapping residual herbicides for control of photosystem (PS) II- and 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibitor-resistant Palmer amaranth (*Amaranthus palmeri* S. Watson) in glyphosate-resistant maize. Front Plant Sci 8:1–11

Chahal PS, Irmak S, Jugulam M, Jhala AJ (2018b) Evaluating effect of degree of water stress on growth and fecundity of Palmer amaranth (*Amaranthus palmeri*) using soil moisture sensors. Weed Science 66:738–745

Chahal PS, Jhala AJ (2015) Herbicide programs for control of glyphosate resistant volunteer corn in glufosinate-resistant soybean. Weed Technol 29:431–443

Chahal PS, Varanasi VK, Jugulam M, Jhala AJ (2017) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Nebraska: confirmation, EPSPS gene amplification, and response to POST corn and soybean herbicides. Weed Technol 31:80–93

Foster D, Steckel L (2022) Confirmation of dicamba-resistant Palmer amaranth in Tennessee. Weed Technol 36:777–780

Garetson R, Singh V, Singh S, Dotray P, Bagavathiannan M (2019) Distribution of herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) in row crop production systems in Texas. Weed Technol 33:355–365

Heap I (2023) The International Herbicide-Resistant Weed Database. https://www.weedscience.org. Accessed: September 15, 2023

Jha P, Norsworthy JK (2009) Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a natural seed bank. Weed Sci 57:644–651

Jhala (2023) Soil residual herbicide options after corn emergence. https://cropwatch.unl.edu/2020/soil-residual-herbicide-options-after-corn-emergence Accessed: September 25, 2023

Jhala (2017) Consider corn growth stage when applying postemergence herbicides. https://cropwatch.unl.edu/2017/consider-corn-growth-stage-when-applying-postemergence-herbicides. Accessed: August 31, 2023

Jhala AJ, Malik MS, Willis JB (2015) Weed control and crop tolerance of micro-encapsulated acetochlor applied sequentially in glyphosate-resistant soybean. Can J Plant Sci 95:973–981

Jhala AJ, Norsworthy JK, Ganie ZA, Sosnoskie LM, Beckie HJ, Mallory-Smith CA, Liu J, Wei W, Wang J, Stoltenberg DE (2021) Pollen-mediated gene flow and transfer of resistance alleles from herbicide-resistant broadleaf weeds. Weed Technology 35:173-187

Jhala AJ, Sandell LD, Rana N, Kruger GR, Knezevic SZ (2014) Confirmation and control of triazine and 4-hydroxyphenylpyruvate dioxygenase-inhibiting herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) in Nebraska. Weed Technol 28:28–38

Jhala AJ, Sandell LD, Sarangi D, Kruger GR, Knezevic SZ (2017) Control of glyphosate-resistant common waterhemp (*Amaranthus rudis*) in glufosinate resistant soybean. Weed Technol 31:32–45

Jones C, Chandler J, Morrison J, Senseman S, Tingle C (2001) Glufosinate combinations and row spacing for weed control in glufosinate-resistant corn (*Zea mays*). Weed Technol 15:141–147

Johnson G, Breitenbach F, Behnken L, Miller R, Hoverstad T, Gunsolus J (2012) Comparison of herbicide tactics to minimize species shifts and selection pressure in glyphosate-resistant soybean. Weed Technol 26:189–194

Keeley PE, Carter CH, Thullen RJ (1987) Influence of planting date on growth of Palmer amaranth (*Amaranthus palmeri*). Weed Sci 35:199–204

Klingaman TE, Oliver LR (1994) Palmer amaranth (*Amaranthus palmeri*) interference in soybeans (*Glycine max*). Weed Sci 42:523–527

Kohrt JR, Sprague CL, Nadakuduti SS, Douches D (2016) Confirmation of a three-way (glyphosate, ALS, and atrazine) herbicide-resistant population of Palmer amaranth (*Amaranthus palmeri*) in Michigan. Weed Sci 65:327–338

Kumar V, Liu R, Boyer G, Stahlman PW (2019) Confirmation of 2,4-D resistance and identification of multiple resistance in a Kansas Palmer amaranth (*Amaranthus palmeri*) population. Pest Manag Sci 75:2925–2933

Kumar V, Liu R, Stahlman PW (2020) Differential sensitivity of Kansas Palmer amaranth populations to multiple herbicides. Agron J 112:2152–2163

Liu R, Kumar V, Jha P, Stahlman PW (2022) Emergence pattern and periodicity of Palmer amaranth (*Amaranthus palmeri*) populations from southcentral Great Plains. Weed Technol 36:110–117

Liu R, Kumar V, Jhala A, Jha P, Stahlman PW (2021) Control of glyphosate- and mesotrione-resistant Palmer amaranth in glyphosate-and glufosinate-resistant corn. Agron J 113:5362–5372

Massinga RA, Currie RS, Horak MJ, Boyer J Jr (2001) Interference of Palmer amaranth in corn. Weed Sci 49:202–208

Mausbach J, Irmak S, Sarangi D, Lindquist J, Jhala AJ (2021) Control of acetolactate synthase inhibitor/glyphosate resistant Palmer amaranth (*Amaranthus palmeri*) in isoxaflutole/glufosinate/glyphosate-resistant soybean. Weed Technol 35:779–785

Meyer CJ, Norsworthy JK, Young BG, Steckel LE, Bradley KW, Johnson WG, Loux MM, Davis VM, Kruger GR, Bararpour MT, Ikley JT, Spaunhorst DJ, Butts TR (2015) Herbicide program approaches for managing glyphosate resistant Palmer amaranth (*Amaranthus palmeri*) and waterhemp (*Amaranthus tuberculatus* and *Amaranthus rudis*) in future soybean-trait technologies. Weed Technol 29:716–729

Miller MR, Norsworthy JK (2016) Evaluation of herbicide programs for use in a 2,4-D–resistant soybean technology for control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*). Weed Technol 30:366–376

Miranda J, Jhala A, Bradshaw J, Lawrence N (2021) Palmer amaranth (*Amaranthus palmeri*) interference and seed production in dry edible bean. Weed Technol 35:995–1006

Nandula VK (2019) Herbicide resistance traits in maize and soybean: current status and future outlook. Plants 8:337. https://www.mdpi.com/2223-7747/8/9/337. Accessed: September 1, 2023

Nandula VK, Reddy KN, Koger CH, Poston DH, Rimando AM, Duke SO, Bond JA, Ribeiro DN (2012) Multiple resistance to glyphosate and pyrithiobac in Palmer amaranth (*Amaranthus palmeri*) from Mississippi and response to flumiclorac. Weed Sci 60:179–188

Norsworthy JK, Korres NE, Walsh MJ, Powles SB (2016) Integrating herbicide programs with harvest weed seed control and other fall management practices for the control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*). Weed Sci 64:540–550

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60:31–62

Sarangi D, Jhala AJ (2019) Palmer amaranth (*Amaranthus palmeri*) and velvetleaf (*Abutilon theophrasti*) control in no-tillage conventional (non–genetically engineered) soybean using overlapping residual herbicide programs. Weed Technol 33:95–105

Sarangi D, Sandell LD, Kruger GR, Knezevic SZ, Irmak S, Jhala AJ (2017) Comparison of herbicide programs for season-long control of glyphosate resistant common waterhemp (*Amaranthus rudis*) in soybean. Weed Technol 31:53–66

Shyam C, Chahal PS, Jhala AJ, Jugulam M (2021) Management of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in 2,4-D choline, glufosinate, and glyphosate-resistant soybean. Weed Technol 35:136–143

Sosnoskie LM, Kichler JM, Wallace RD, Culpepper AS (2011) Multiple resistance in Palmer amaranth to glyphosate and pyrithiobac confirmed in Georgia. Weed Sci 59:321–325

Sosnoskie LM, Webster TM, Grey TL, Culpepper AS (2014) Severed stems of *Amaranthus palmeri* are capable of regrowth and seed production in *Gossypium hirsutum*. Ann Appl Biol 165:147–154

Steckel GJ, Wax LM, Simmons FW, Phillips WH II (1997) Glufosinate efficacy on annual weeds is influenced by rate and growth stage. Weed Technol 11:484–488

Striegel A, Jhala AJ (2022) Economics of reducing Palmer amaranth seed production in dicamba/glufosinate/glyphosate-resistant soybean. Agron J 114:2518–2540

Striegel, A, NC Lawrence, SZ Knezevic, JT Krumm, G Hein, AJ Jhala (2020) Control of glyphosate/glufosinate-resistant volunteer corn in corn resistant to aryloxyphenoxypropionates. Weed Technol 34:309–317

Van Wychen L (2022) Survey of the most common and troublesome weeds in broadleaf crops, fruits & vegetables in the United States and Canada. Weed Science Society of America National Weed Survey Dataset. https://wssa.net/wp-content/uploads/2022-Weed-Survey-Broadleaf-crops.xlsx. Accessed: September 1, 2023

Vencill WK, Grey TL, Culpepper AS, Gaines C, Westra P (2008) Herbicide-resistance in the Amaranthaceae. J Plant Dis Prot 21:41–44

Ward SM, Webster TM, and Steckel LE (2013) Palmer amaranth (*Amaranthus palmeri*): a review. Weed Technol 27:12–27

Webster TM (2005) Weed survey–southern states: broadleaf crops subsection. Pages 291-306 *in* Proceedings of the Southern Weed Science Society Meeting. Champaign, IL: Southern Weed Science Society

Wiggins M S, McClure MA, Hayes RM, Steckel LE (2015) Integrating cover crops and post herbicides for glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) control in corn. Weed Technol 29:412–418

Table 2.1. Monthly mean air temperature and total precipitation during the 2020 and 2021 growing seasons along with the 30-yr average at the experiment site near Carleton, Nebraska.

| Month | Mean air temperature[a] | | | Total precipitation[a] | | |
|---|---|---|---|---|---|---|
| | 2020 | 2021 | 30-yr average | 2020 | 2021 | 30-yr average |
| | ---------------------------C--------------------------- | | | -------------------------mm---------------------- | | |
| 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 the National Oceanic and Atmospheric Administration.

Table 2.2. Herbicides, application timings, and rates used for control of acetolactate synthase inhibitor/atrazine/glyphosate-resistant Palmer amaranth in a 2,4-D choline/glufosinate/glyphosate-resistant corn in field experiments conducted near Carleton, Nebraska in 2020 and 2021.

| Herbicide program[a] | Trade name | Application timing[b] | Rate g ae or ai $ha^{-1}$ | Manufacturer |
|---|---|---|---|---|
| Acetochlor/clopyralid/mesotrione | Resicore | PRE | 2,300 | Corteva Agriscience |
| Acetochlor/clopyralid/flumetsulam | Surestart II | PRE | 890 | Corteva Agriscience |
| Flufenacet/isoxaflutole/thiencarbazone-methyl | TriVolt | PRE | 536 | Bayer CropScience |
| Glyphosate/2,4-D choline | Enlist DUO | EPOST | 1,630 | Corteva Agriscience |
| 2,4-D choline | Enlist ONE | EPOST | 1,060 | Corteva Agriscience |
| Glufosinate | Liberty | EPOST | 656 | BASF Corp. |
| 2,4-D choline + glufosinate | Enlist ONE + Liberty | EPOST | 800 + 656 | Corteva Agriscience + BASF Corp. |
| Acetochlor/clopyralid/mesotrione fb 2,4-D choline | Resicore fb Enlist ONE | PRE fb LPOST | 2,300 fb 800 | Corteva Agriscience |
| Acetochlor/clopyralid/flumetsulam fb 2,4-D choline | Surestart II fb Enlist ONE | PRE fb LPOST | 1,190 fb 800 | Corteva Agriscience |
| Flufenacet/isoxaflutole/thiencarbazone-methyl fb 2,4-D choline | TriVolt fb Enlist ONE | PRE fb LPOST | 536 fb 800 | Bayer CropScience, Corteva Agriscience |
| Acetochlor/ clopyralid/mesotrione fb glufosinate | Resicore fb Liberty | PRE fb LPOST | 2,300 fb 656 | Corteva Agriscience, BASF Corp. |
| Acetochlor/clopyralid/flumetsulam fb glufosinate | Surestart II fb Liberty | PRE fb LPOST | 1,190 fb 656 | Corteva Agriscience, BASF Corp. |
| Flufenacet/isoxaflutole/thiencarbazone-methyl fb glufosinate | TriVolt fb Liberty | PRE fb LPOST | 536 fb 656 | Bayer CropScience, BASF Corp. |

[a] Glufosinate treatments were mixed with liquid ammonium sulfate (N PAK AMS, Winfield United, WI) at 3% vol/vol.
[b] Abbreviations: PRE, preemergence; EPOST, early POST; fb, followed by; LPOST, late POST; POST, postemergence.

Table 2.3. Control of multiple herbicide-resistant Palmer amaranth affected by herbicide programs in a 2,4-D choline/ glufosinate/glyphosate-resistant corn in field experiments conducted at Carleton, Nebraska, during the 2020 and 2021 growing seasons.

| Herbicide program | Timing[a] | Palmer amaranth control[a,b,c] | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 15 DA-PRE | 30 DA-PRE | 15 DA-EPOST | 30 DA-EPOST | 15 DA-LPOST | 30 DA-LPOST | 90 DA-LPOST |
| | | % | | | | | | |
| Nontreated control | - | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Weed free | - | 99 | 99 | 99 | 99 | 99 | 99 | 99 |
| Acetochlor/clopyralid/mesotrione (2,300 g ai $ha^{-1}$) | PRE | 96 a | 97 a | 90 a | 90 a | 99 a | 89 ab | 87 ab |
| Acetochlor/clopyralid/flumetsulam (890 g ai $ha^{-1}$) | PRE | 97 a | 79 a | 41 f | 49 d | 91 c | 58 e | 44 d |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (536 g ai $ha^{-1}$) | PRE | 97 a | 75 a | 43 f | 40 d | 87 b | 40 f | 45 d |
| Glyphosate/ 2,4-D choline (1,630 g ae $ha^{-1}$) | EPOST | - | - | 57 e | 71 b | 89b | 82b | 82 b |
| 2,4-D choline (1,060 g ae $ha^{-1}$) | EPOST | - | - | 62 d | 60 c | 77c | 68 d | 80 b |
| Glufosinate (656 g ai $ha^{-1}$) | EPOST | - | - | 83 b | 57 c | 88 b | 73 c | 66 c |
| 2,4-D choline (800 g ae $ha^{-1}$) + glufosinate (656 g ai $ha^{-1}$) | EPOST | - | - | 90 a | 78 b | 95 a | 84 b | 85 b |
| Acetochlor/ clopyralid/mesotrione (2,300 g ai $ha^{-1}$) fb 2,4-D choline (800 g ae $ha^{-1}$) | PRE fb LPOST | 98 a | 99 a | 93 a | 97 a | 99 a | 89 b | 97 a |
| Acetochlor/clopyralid/flumetsulam (1,190 g ai $ha^{-1}$) fb 2,4-D choline (800 g ae $ha^{-1}$) | PRE fb LPOST | 98 a | 86 a | 78 b | 73 b | 95 a | 92 a | 95 a |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (536 g ai $ha^{-1}$) fb 2,4-D choline (800 g ae $ha^{-1}$) | PRE fb LPOST | 97 a | 83 a | 72 c | 69 c | 96 a | 87 b | 94 a |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Acetochlor/clopyralid/mesotrione (2,300 g ai $ha^{-1}$) fb glufosinate (656 g ai $ha^{-1}$) | PRE fb LPOST | 99 a | 99 a | 99 a | 98 a | 94 a | 89 b | 87 ab |
| Acetochlor/ clopyralid/flumetsulam (1,190 g ai $ha^{-1}$) fb glufosinate (656 g ai $ha^{-1}$) | PRE fb LPOST | 98 a | 83 a | 92 a | 92 a | 99 a | 95 a | 95 a |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (536 g ai $ha^{-1}$) fb glufosinate (656 g ai $ha^{-1}$) | PRE fb LPOST | 99 a | 79 a | 93 a | 93 a | 99 a | 93 b | 93 a |
| P-value | | 0.725 | 0.157 | 0.0004 | 0.0001 | 0.8633 | 0.005 | 0.0004 |
| **Contrast analysis**[d] | | | | | | | | |
| PRE vs EPOST | | | | 58 vs 73 [e] | 60 vs 67 [NS] | 92 vs 87 [NS] | 62 vs 77 [NS] | 59 vs 78 [NS] |
| PRE vs PRE fb LPOST | | | | 58 vs 88 [e] | 60 vs 87 [e] | 92 vs 97 [NS] | 62 vs 91 [e] | 59 vs 94 [e] |
| EPOST vs PRE fb LPOST | | | | 73 vs 88 [NS] | 67 vs 87 [e] | 87 vs 97 [e] | 77 vs 91 [e] | 78 vs 94 [e] |

[a] Abbreviations: -, not applicable, DA-PRE, days after PRE application; DA-EPOST, days after early-POST application; DA-LPOST, days after late-POST application; EPOST, early POST; fb, followed by; LPOST, late POST; NS, not significant.

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

[c] Means presented within each column with no common letter (s) are significantly different as per Fisher Protected LSD at $P \leq 0.05$.

[d] A priori orthogonal contrasts.

[e] $P < 0.0001$.

Table 2.4. Multiple herbicide-resistant Palmer amaranth density and above-ground biomass as affected by the herbicide programs in a 2,4-D/glyphosate/glufosinate-resistant corn in field experiments conducted in Carleton, Nebraska, during the 2020 and 2021 growing seasons.[a,b]

| Herbicide program | Timing[a] | Palmer amaranth density [a,b,c] | | | | | | | Palmer amaranth biomass[a,c,d] | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 15 DA-PRE | | 30 DA-PRE | | 30 DA-EPOST | | 30 DA-LPOST | 30 DA-EPOST | 15 DA-LPOST |
| | | number $m^{-2}$ | | | | | | | g $m^{-2}$ | |
| | | 2020 | 2021 | 2020 | 2021 | 2020 | 2021 | 2021 | | |
| Nontreated control | | 149 a | 43 a | 108 a | 55 a | 61 a | 53 a | 72 a | 94 a | 143 a |
| Weed free | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Acetochlor/clopyralid/mesotrione (2,300 g ai $ha^{-1}$) | PRE | 6 c | 0 b | 5 b | 0 d | 2 c | 0 e | 0 e | 5 d | 4 e |
| Acetochlor/clopyralid/flumetsulam (890 g ai $ha^{-1}$) | PRE | 3 c | 0 b | 66 a | 14 c | 14 a | 9 bc | 12 b | 40 b | 123 ab |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (536 g ai $ha^{-1}$) | PRE | 2 c | 0 b | 47 a | 9 c | 22 a | 11 bc | 15 b | 26 b | 72 b |
| Glyphosate/2,4-D choline (1,630 g ae $ha^{-1}$) | EPOST | 47 b | 46 a | 33 a | 30 b | 25 a | 10 bc | 18 b | 36 b | 25 c |
| 2,4-D choline (1,060 g ae $ha^{-1}$) | EPOST | 59 b | 45 a | 30 a | 33 b | 9 b | 17 b | 22 b | 55 b | 21 cd |
| Glufosinate (656 g ai $ha^{-1}$) | EPOST | 69 b | 45 a | 34 a | 33 b | 41 a | 9 bc | 30 ab | 22 c | 8 cd |
| 2,4-D choline (800 g ae $ha^{-1}$) + glufosinate (656 g ai $ha^{-1}$) | EPOST | 45 b | 40 a | 36 a | 18 b | 42 a | 6 c | 6 c | 13 c | 12 d |
| Acetochlor/ clopyralid/mesotrione (2,300 g ai $ha^{-1}$) fb 2,4-D choline (800 g ae $ha^{-1}$) | PRE fb LPOST | 2 c | 0 b | 3 b | 0 d | 2 c | 0 e | 0 e | 5 d | 3 e |
| Acetochlor/clopyralid/flumetsulam (1,190 g ai $ha^{-1}$) fb 2,4-D choline (800 g ae $ha^{-1}$) | PRE fb LPOST | 3 c | 0 b | 24 a | 10 bc | 7 b | 7 c | 8 c | 17 c | 14 d |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Flufenacet/isoxaflutole/thiencarbazone-methyl (536 g ai ha$^{-1}$) fb 2,4-D choline (800 g ae ha$^{-1}$) | PRE fb LPOST | 4 c | 0 b | 15 b | 10 bc | 10 ab | 2 d | 2 d | 22 c | |
| Acetochlor/clopyralid/mesotrione (2,300 g ai ha$^{-1}$) fb glufosinate (656 g ai ha$^{-1}$) | PRE fb LPOST | 0 d | 0 b | 2 b | 2 cd | 3 c | 5 c | 1 d | 48 b | 2 e |
| Acetochlor/ clopyralid/flumetsulam (1,190 g ai ha$^{-1}$) fb glufosinate (656 g ai ha$^{-1}$) | PRE fb LPOST | 3 c | 0 b | 19 ab | 11 bc | 8 b | 0 e | 0 e | 19 c | 2 e |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (536 g ai ha$^{-1}$) fb glufosinate (656 g ai ha$^{-1}$) | PRE fb LPOST | 0 d | 0 b | 23 a | 2 cd | 12 ab | 0 e | 0 e | 17 c | 2 e |
| P-value | | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | < 0.0001 | < 0.0001 | < 0.0001 |

[a] Abbreviations: DA-PRE, days after PRE application; DA-EPOST, days after early-POST application; DA-LPOST, days after late-POST application; EPOST, early POST; fb, followed by; LPOST, late POST.
[b] Year by treatment interaction for Palmer amaranth density was significant; therefore, data are presented separately for both years (2020 and 2021).
[c] Means presented within each column with no common letter(s) are significantly different as per Fisher Protected LSD.Year by treatment for Palmer amaranth biomass was non-significant; therefore, data were pooled across both years.
[d] Year by treatment interaction for Palmer amaranth biomass was non-significant; therefore, data of both years were combined.

Table 2.5. Corn yield and Palmer amaranth seed production affected by herbicide programs in a 2,4-D–, glyphosate-, and glufosinate-resistant corn in field experiment conducted at Carleton, Nebraska during the 2020 and 2021 growing seasons.[a]

| Herbicide program | Timing[a] | Corn yield [b,c] | | Palmer amaranth seed production[c,d,e] |
|---|---|---|---|---|
| | | kg ha$^{-1}$ | | seeds m$^{-2}$ |
| | | 2020 | 2021 | |
| Nontreated control | | 8,750 d | 5,792 e | 939,687 b |
| Weed-free | | 11,216 ab | 10,623 abcd | 0 |
| Acetochlor/clopyralid/mesotrione (2,300 g ai ha$^{-1}$) | PRE | 11,080 a | 12,161 a | 0 |
| Acetochlor/clopyralid/flumetsulam (890 g ai ha$^{-1}$) | PRE | 11,183 abc | 11,124 abcd | 464,937 c |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (536 g ai ha$^{-1}$) | PRE | 10,247 bcd | 11,250 abc | 511,537 c |
| Glyphosate/2,4-D choline (1,630 g ae ha$^{-1}$) | EPOST | 10,205 bcd | 10,586 abcd | 168,956 d |
| 2,4-D choline (1,060 g ae ha$^{-1}$) | EPOST | 9,391 cd | 9,107 d | 138,089 d |
| Glufosinate (656 g ai ha$^{-1}$) | EPOST | 12,066 ab | 9,554 cd | 1,077,652 a |
| 2,4-D choline (800 g ae ha$^{-1}$) + glufosinate (656 g ai ha$^{-1}$) | EPOST | 11,739 ab | 10,876 abcd | 122,308 d |
| Acetochlor/ clopyralid/mesotrione (2,300 g ai ha$^{-1}$) fb 2,4-D choline (800 g ae ha$^{-1}$) | PRE fb LPOST | 12,910 a | 12,417 a | 0 |
| Acetochlor/clopyralid/flumetsulam (1,190 g ai ha$^{-1}$) fb 2,4-D choline (800 g ae ha$^{-1}$) | PRE fb LPOST | 12,882 a | 11,860 ab | 42,944 e |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (536 g ai ha$^{-1}$) fb 2,4-D choline (800 g ae ha$^{-1}$) | PRE fb LPOST | 12,569 a | 11,077 abcd | 12,012 e |
| Acetochlor/clopyralid/mesotrione (2,300 g ai ha$^{-1}$) fb glufosinate (656 g ai ha$^{-1}$) | PRE fb LPOST | 11,241 abc | 10,282 abcd | 29,362 e |

| | | | | |
|---|---|---|---|---|
| Acetochlor/clopyralid/flumetsulam (1,190 g ai ha$^{-1}$) fb glufosinate (656 g ai ha$^{-1}$) | PRE fb LPOST | 12,383 ab | 12,353 a | 0 |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (536 g ai ha$^{-1}$) fb glufosinate (656 g ai ha$^{-1}$) | PRE fb LPOST | 12,070 ab | 12,399 a | 0 |
| P-value | | <.0001 | <.0001 | <.0001 |
| **Contrast analysis**[f] | | | | |
| PRE vs EPOST | | 10,837 vs 10,850 [NS] | 11,512 vs 10,031 [g] | 325,491 vs 376,751 [g] |
| PRE vs PRE fb LPOST | | 10,837 vs 12,343 [g] | 11,512 vs 11,731 [NS] | 325,491 vs 14,053 [g] |
| EPOST vs PRE fb LPOST | | 10,850 vs 12,343 [g] | 10,031 vs 11,731 [g] | 376,751 vs 14,053 [g] |

[a] Abbreviations: EPOST, early POST; fb, followed by; LPOST, late POST; NS, not significant; POST, postemergence.

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

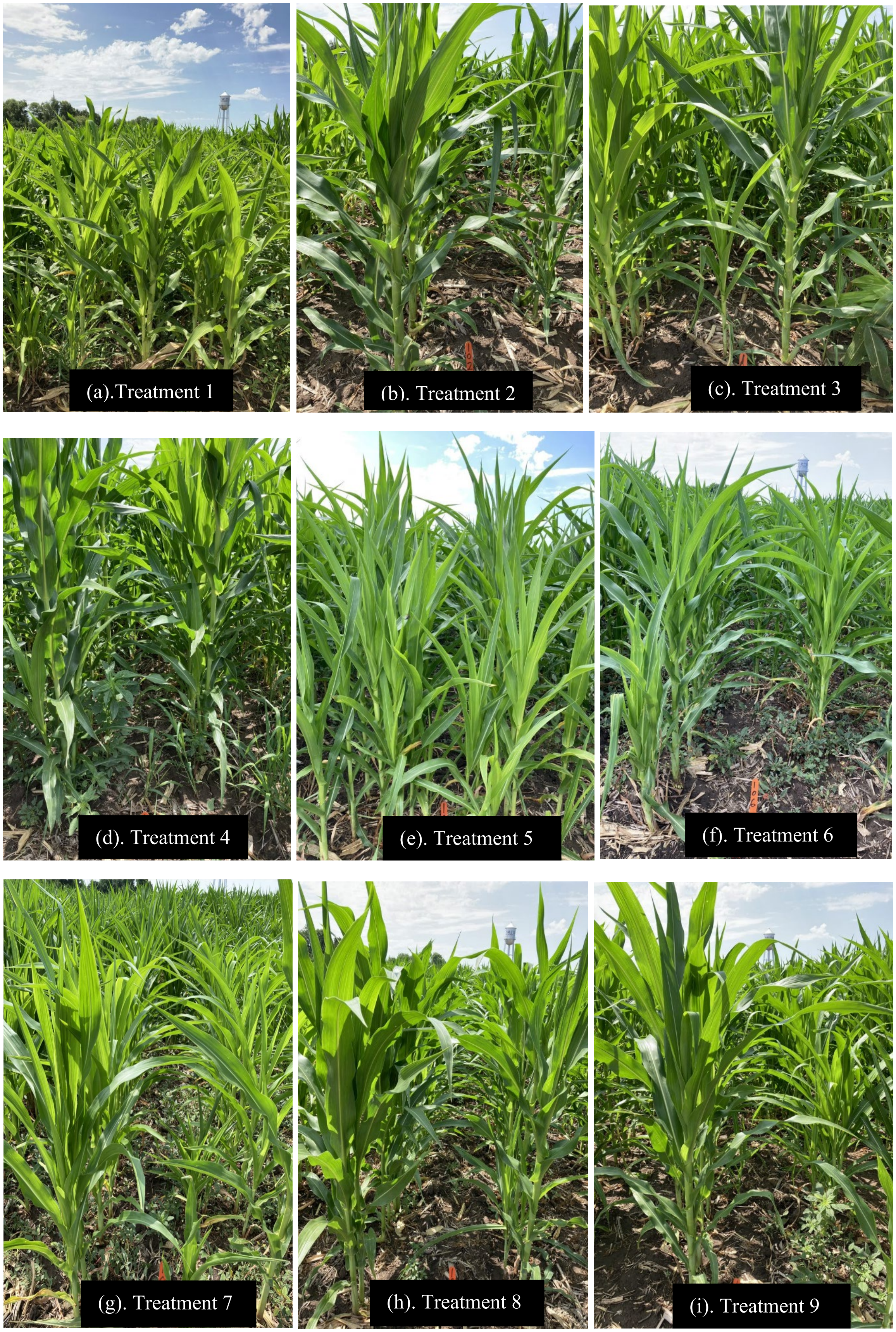
[c] Means presented within each column with no common letter(s) are significantly different as per Fisher Protected LSD test at $P \leq 0.05$.

[d] Year by treatment interaction for Palmer amaranth seed production was non-significant; therefore, data were pooled across both years.

[e] Treatments with 0 Palmer amaranth seed production were excluded from the analysis.

[f] A priori orthogonal contrasts.

[g] $P < 0.0001$


(a).Treatment 1
(b). Treatment 2
(c). Treatment 3
(d). Treatment 4
(e). Treatment 5
(f). Treatment 6
(g). Treatment 7
(h). Treatment 8
(i). Treatment 9

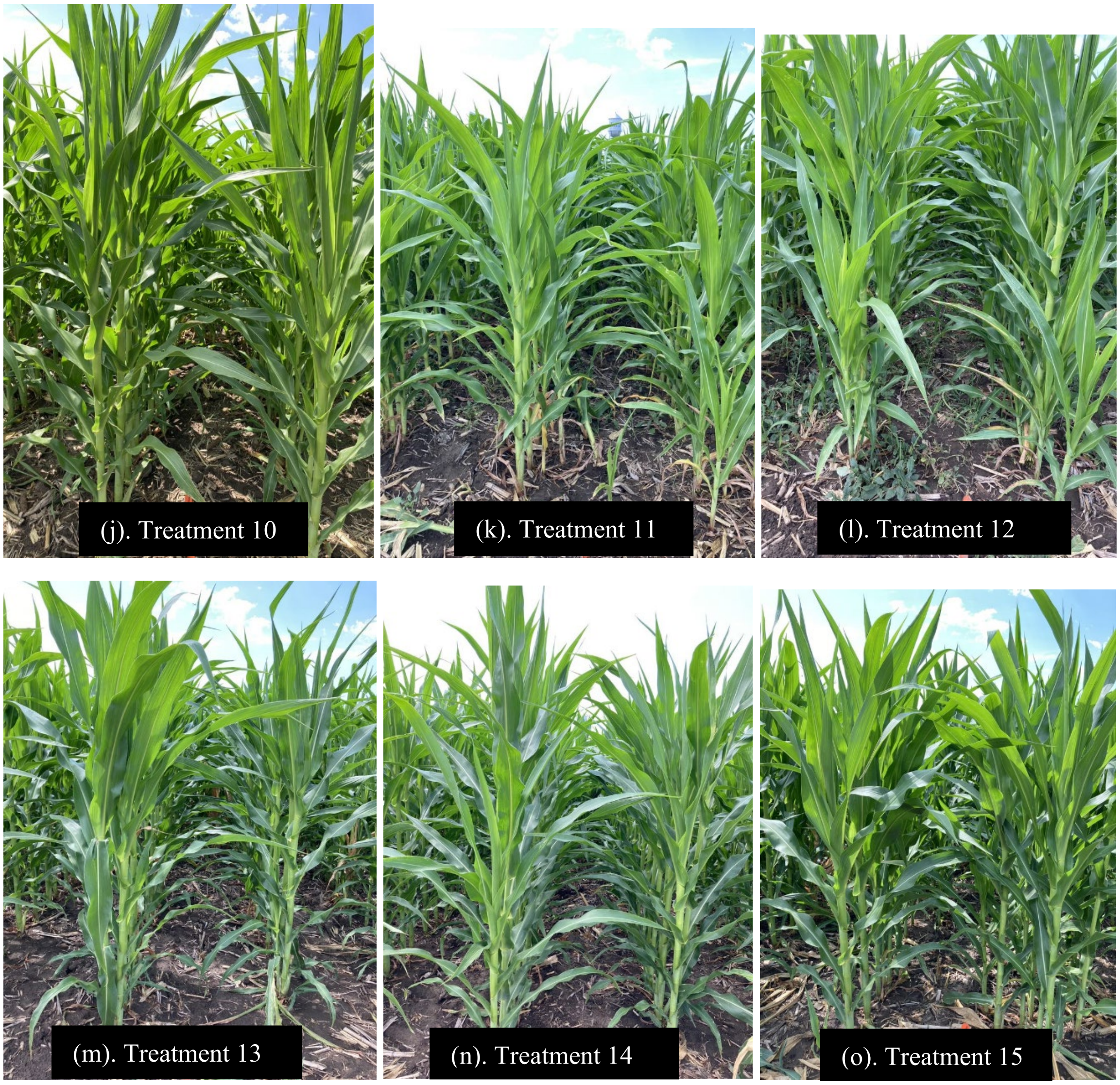



Figure 2.1. (a-o); herbicide programs in Enlist corn 15 d after LPOST

# CHAPTER 3

# EFFECT OF PLANT HEIGHT ON CONTROL OF MULTIPLE HERBICIDE-RESISTANT PALMER AMARANTH (*Amaranthus palmeri*) IN GLUFOSINATE/GLYPHOSATE-RESISTANT CORN

***This chapter is submitted:*** Kaur R, Chahal P S, Shi Y, Lawrence N C, Knezevic S Z, Jhala A J (2023) Effect of plant height on control of multiple herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) in glufosinate/glyphosate-resistant corn. ***Frontiers in Agronomy***.

## ABSTRACT

Multiple herbicide-resistant (MHR) Palmer amaranth is a troublesome weed in several crops across the United States, 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.

## INTRODUCTION

Corn (*Zea mays* L.) is the most widely cultivated crop in the United States, 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 (Gossett et al., 1992), with evolved resistance to trifluralin. 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 United States. 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 has 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 United States depending on the location. 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; Korres et al., 2019; Ward et al., 2013). 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 $plant^{-1}$ (Burke et al., 2007; Keeley et al., 1987). 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.

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 (Bollman et al., 2008; Stephenson and Bond, 2012; Sutton et al., 2002; Swanton et al., 2007; 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 (Chahal et al., 2015; Jhala et al., 2014; 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 (Barnett et al., 2013; Cahoon et al., 2015b; Corbett et al., 2004). The efficacy of glufosinate is compromised when it is applied to Palmer amaranth taller than 12 cm (Coetzer et al., 2002; Culpepper et al., 2010; Steckel et al., 1997). It can be mixed with dicamba or glyphosate for POST control of Palmer amaranth (Cahoon et al., 2015a; Norsworthy et al., 2012), and glufosinate mixed with dicamba was effective for controlling ≥ 20 cm tall Palmer amaranth 12 d after application in XtendFlex cotton (*Gossypium hirsutum* L.) in North Carolina (Vann et al., 2017; Merchant et al. 2013). Similarly, Merchant et al. (2014) elaborated the greater control of 20 cm tall Palmer amaranth by sequential applications of glufosinate plus 2,4-D compared with sequential applications of 2,4-D alone.

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. 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, this study was planned 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.

## MATERIALS AND METHODS

### 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 $ha^{-1}$. An 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 3.1).

**Data Collection**

Palmer amaranth control was estimated visually using a 0% to 100% scale, with 0% meaning no control and 100% meaning 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 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.

**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 interaction was 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 interaction of replication by herbicide treatment, column, and column by 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 weed-free treatment was excluded from the Palmer amaranth seed production analysis.

## 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 ranges from 10% to 15 % were recorded with acetochlor/mesotrione, dimethenamid-*P*/topramezone, and acetochlor/clopyralid/mesotrione at 30 DAEPOST (data not shown).

### 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 3.2). 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% 14 d after application. Herbicides applied E-POST 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% 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.

**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 3.3). 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 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.

At 30 DALPOST, later in the season, the efficacy of glufosinate for 10-15 cm Palmer amaranth varies, and 24 Palmer amaranth plants m$^{-2}$ were recorded in both years. However, 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 fb glufosinate provided 100% Palmer amaranth control when applied to less than 12 cm tall plants. Dicamba/tembotrione resulted in the least Palmer amaranth density (24 plants/m$^{-2}$) when applied to 20-30 cm tall plants in 2020, whereas in 2021, atrazine/bicyclopyone/mesotrione/*S*–metolachlor, glufosinate, dicamba/ tembotrione, and dicamba reduced density up to 82% to 95%.

**Palmer amaranth biomass**

The interaction of herbicide by Palmer amaranth height on Palmer amaranth biomass was significant ($P < 0.0001$), with most 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 3.4). 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.

**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 3.5), 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 dimethenamaid-*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 3.5). 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.

**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 3.6). 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 (Burke et al., 2007; MacRae et al., 2013; Massinga et al., 2001). 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) 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 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.

## PRACTICAL IMPLICATIONS

Nebraska is one of the largest corn-producing states in the United States. 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.

## LITERATURE CITED

Anonymous (2020). Diflexx herbicide product label. EPA Reg. No. 264-1173. Research Triangle Park, NC: Bayer Crop Science, 3-6.

Barnett, K. A., Culpepper, A. S., York, A. C., and Steckel, L. E. (2013). Palmer amaranth (*Amaranthus palmeri*) control by glufosinate plus fluometuron applied postemergence to WideStrike cotton. *Weed Technol.* 27, 291–297.

Bensch, C. N., Horak, M. J., and Peterson, D. (2003). Interference of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*) in soybean. *Weed Sci.* 51, 37–43.

Bollman, J. D., Boerboom, C. M., Becker, R. L., and Fritz, V. A. (2008). Efficacy and tolerance to HPPD-inhibiting herbicides in sweet corn. *Weed Technol.* 20, 267–274.

Bond, J. A., Oliver, L. R., and Stephenson, D. O. IV (2006). Response of Palmer amaranth (*Amaranthus palmeri*) accessions to glyphosate, fomesafen, and pyrithiobac. *Weed Technol.* 20, 885–892.

Burke, I., Schroeder, M., Thomas, W. E., and Wilcut, J. W. (2007). Palmer amaranth interference and seed production in peanut. *Weed Technol.* 21, 367–371.

Cahoon, C. W., York, A. C., Jordan, D. L., Everman, W. J., Seagroves, R. W., Culpepper, A. S., and Eure, P. M. (2015a). Palmer amaranth (*Amaranthus palmeri*) management in dicamba-resistant cotton. *Weed Technol.* 29, 758–770.

Cahoon, C. W., York, A. C., Jordan, D. L., Seagroves, R. W., Everman, W. J., and Jennings, K. M. (2015b). Sequential and co-applications of glyphosate and glufosinate in cotton. *J. Cotton Sci.* 19, 337–350.

Caverzan, A., Piasecki, C., Chavarria, G., Stewart, C. N., and Vargas, L. (2019). Defenses against ROS in crops and weeds: the effects of interference and herbicides. *Int. J. Mol. Sci.* 20, 1086.

Chahal, P. S., Aulakh, J. S., Jugulam, M., and Jhala, A. J. (2015). Herbicide-resistant Palmer amaranth (*Amaranthus palmeri* S. Wats.) in the United States: Mechanisms of resistance, impact, and management. Pages 1-29 in Price, A., Kelton, J. and Sarunaite, L., eds., Herbicides, agronomic crops and weed biology.

Coetzer, E., Al-Khatib, K., and Peterson, D. E. (2002). Glufosinate efficacy on *Amaranthus* species in glufosinate-resistant soybean (*Glycine max*). *Weed Technol.* 16, 326–331.

Corbett, J. L., Askew, S. D., Thomas, W. E., and Wilcut, J. W. (2004). Weed efficacy evaluations for bromoxynil, glufosinate, glyphosate, pyrithiobac, and sulfosate. *Weed Technol*, 18, 443–453.

Crow, W., Steckel, L., Hayes, R., and Mueller, T. (2015). Evaluation of POST-Harvest Herbicide Applications for Seed Prevention of Glyphosate-Resistant Palmer amaranth (*Amaranthus palmeri*). *Weed Technol.* 29, 405-411.

Culpepper, A. S., Grey, T. L., Vencill, W. K., Kichler, J. M., Webster, T. M., Brown, S. M., York, A. C., Davis, J. W., and Hanna, W. W. (2006). Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) confirmed in Georgia. *Weed Sci.* 54:620–626.

Culpepper, A. S., Webster, T. M., Sosnoskie, L. M., and York, A. C. (2010). Glyphosate resistant Palmer amaranth in the United States. Pages 195–212 in Nandula VK, ed., Glyphosate Resistance in Crops and Weeds: History, Development, and Management. Hoboken, NJ: Wiley.

Gossett, B. J., Murdock, E. C., and Toler, J. E. (1992). Resistance of Palmer amaranth (*Amaranthus palmeri*) to the dinitroaniline herbicides. *Weed Technol.* 6, 587–591.

Gower, S. A., Loux, M. M., and Harrison, S. K. (2002). Effect of planting date, residual herbicide, and post emergence application timing on weed control and grain yield in glyphosate tolerance corn (*Zea mays*). *Weed Technol.* 27, 63-71.

Heap, I. (2023). The international herbicide-resistant Weed Database. Available at: www.weedscience.org

Horak, M. J., and Loughin, T. M. (2000). Growth analysis of four Amaranthus species. *Weed Sci.* 48, 347–355.

Jha, P. and Norsworthy, J. K. (2009). Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a natural seed bank. *Weed Sci.* 57, 644–651.

Jhala, A. J., Sandell, L. D., Rana, N., Kruger, G. R., and Knezevic, S. Z. (2014). Confirmation and control of triazine and 4-hydroxyphenylpyruvate dioxygenase-inhibiting herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) in Nebraska. *Weed Technol.* 28, 28–38.

Keeley, P. E., Carter, C. H., and Thullen, R. J. (1987). Influence of planting date on growth of Palmer amaranth (*Amaranthus palmeri*). *Weed Sci.* 35, 199–204.

Klingaman, T. E. and Oliver, L. R. (1994). Palmer amaranth (*Amaranthus palmeri*) interference in soybeans (*Glycine max*). *Weed Sci.* 42, 523–527.

Korres, N.E., Norsworthy, J. K., and Mauromoustakos, A. (2019). Effects of Palmer amaranth (*Amaranthus palmeri*) establishment time and distance from the crop row on biological and phenological characteristics of the weed: implications on soybean yield. *Weed Sci.* 67, 126–135.

Kumar, V., Liu, R., Boyer, G., and Stahlman, P. W. (2019). Confirmation of 2, 4-D resistance and identification of multiple resistance in a Kansas Palmer amaranth (*Amaranthus palmeri*) population. *Pest Manage. Sci.* 75, 2925–2933.

Kumar, V., Liu, R., and Stahlman, P. W. (2020). Differential sensitivity of Kansas Palmer amaranth populations to multiple herbicides. *Agron. J.* 112, 2152–2163.

Liu, R., Kumar, V., Jhala, A., Jha, P., and Stahlman, P. W. (2021). Control of glyphosate- and mestrione-resistant Palmer amaranth in glyphosate- and glufosinate-resistant corn. *Agron. J.* 113, 5362-5372.

MacRae, A. W., Webster, T., Sosnoskie, L., Culpepper, A. S., and Kichler, J. (2013). Cotton yield loss potential in response to length of Palmer amaranth (*Amaranthus palmeri*) interference. *J. Cotton Sci.* 17:227–232.

Mahoney, D. J., Jordan, D. L., Hare, A. T., Roma-Burgos, N., Jennings, K. M., Leon, R. G., Vann, M. C., Everman, W. J., and Cahoon, C. W. (2021). The influence of soybean population and POST herbicide application timing on in-season and subsequent-season Palmer amaranth (*Amaranthus palmeri*) control and economic returns. *Weed Technol.* 35, 106–112.

Massinga, R. A., Currie, R. S., Horak, M. J., and Boyer, J. Jr. (2001). Interference of Palmer amaranth in corn. *Weed Sci.* 49:202–208.

McDonald, S. T., Striegel A., Chahal, P. S., Jha, P., Rees, J. M., Proctor, C. A., and Jhala, A. J. (2021). Effect of row spacing and herbicide programs for control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in dicamba/glyphosate-resistant soybean. *Weed Technol.* 35, 790–801.

Merchant, R. M., Sosnoskie, L. M., Culpepper, A. S., Steckel, L. E., York, A. C., Braxton, L. B., and Ford, J. C. (2013). Weed response to 2, 4-D, 2, 4-DB, and dicamba applied alone or with glufosinate. *J Cotton Sci.* 17, 212–218.

Merchant, R. M., Culpepper, A. S., Eure, P. M., Richburg, J. S., and Braxton, L. B. (2014). Salvage Palmer amaranth programs can be effective in cotton resistant to glyphosate, 2,4-D, and glufosinate. *Weed Technol.* 28, 316–322.

Meyer, C. J. and Norsworthy, J. K. (2019). Influence of weed size on herbicide interactions for Enlist™ and Roundup Ready® Xtend® technologies. *Weed Technol.* 33, 569–577.

Meyer, C. J. and Norsworthy, J. K. (2020). Timing and application rate for sequential applications of glufosinate are critical for maximizing control of annual weeds in liberty link soybean. *Int. J. Agron.* 2020, 1-7.

Miranda, J., Jhala, A., Bradshaw, J., and Lawrence, N. (2022). Palmer amaranth (*Amaranthus palmeri*) interference and seed production in dry edible bean. *Weed Technol.* 35, 995-1006.

Norsworthy, J. K., Ward, S. M., Shaw, D. R., Llewellyn, R. S., Nichols, R. L., Webster, T. M., Bradley, K. W., Frisvold, G., Powles, S. B., Burgos, N. R., Witt, W. W., and Barrett, M. (2012). Reducing the risks of herbicide resistance: best management practices and recommendations. *Weed Sci.* 60, 31–62.

Priess, G. L., Popp, M. P., Norsworthy, J. K., Mauromoustakos, A., Roberts, T. L., and Butts T. R. (2022). Optimizing weed control using dicamba and glufosinate in eligible crop systems. *Weed Technol.* 36, 468–480.

Shyam, C., Chahal P. S., Jhala, A. J., and Jugulam, M. (2021). Management of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in 2,4-D choline, glufosinate, and glyphosate-resistant soybean. *Weed Technol.* 35, 136–143.

Steckel, G. J., Wax, L. M., Simmons, F. W., and Phillips, W. H. (1997). Glufosinate efficacy on annual weeds is influenced by rate and growth stage. *Weed Technol.* 11, 484–488.

Stephenson, D. O., and Bond, J. A. (2012). Evaluation of thiencarbazone-methyl- and isoxaflutole-based herbicide programs in corn. *Weed Technol.* 26, 37–42.

Sutton, P., Richards, C., Buren, L., and Glasgow, L. (2002). Activity of mesotrione on resistant weeds in maize. *Pest Manag. Sci.* 58, 981–984.

Swanton, C. J., Gulden, R. H., and Chandler, K. (2007). A rationale for atrazine stewardship in corn. *Weed Sci.* 55, 75–78.

Vann, R. A., York, A. C., Cahoon, C. W., Buck, T. B., Askew, M. C., and Seagroves, R. W. (2017). Effect of delayed dicamba plus glufosinate on Palmer amaranth control and XtendFlex cotton yield. *Weed Technol.* 31, 633–640.

Walsh, M. J., Stratford, K., Stone, K., and Powles, S. B. (2012). Synergistic effects of atrazine and mesotrione on susceptible and resistant wild radish (*Raphanus raphanistrum*) populations and the potential for overcoming resistance to triazine herbicides. *Weed Technol.* 26, 341–347.

Ward, S. M., Webster, T. M., and Steckel, L. E. (2013). Palmer amaranth (*Amaranthus palmeri*): a review. *Weed Technol.* 27, 12–27.

[USGS] United States Geological Survey (2016). Estimated agricultural use for glyphosate, 1992–2013.

Table 3.1. 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] Abbreviations: 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.

Table 3.2. 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 e | 0 e | 0 f | 0 f | 0 f | 0 f | 0 g | 0 g | 0 f | 0 f | 0 e | 0 e |
| 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 om 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] Abbreviations: DAEPOST, days after early-POST application; DALPOST, days after late-POST application.

Table 3.3. 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 d | 0 d | 0 e | 0 e | 0 e | 0 e | 0 f | 0 f |
| 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] Abbreviations: DAEPOST, days after early-POST application; DALPOST, days after late-POST application.

Table 3.4. 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 d | 0 e | 0 l | 0 l |
| 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 om 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] Abbreviations: DAEPOST, days after early-POST application; DALPOST, days after late-POST application.

Table 3.5. 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.

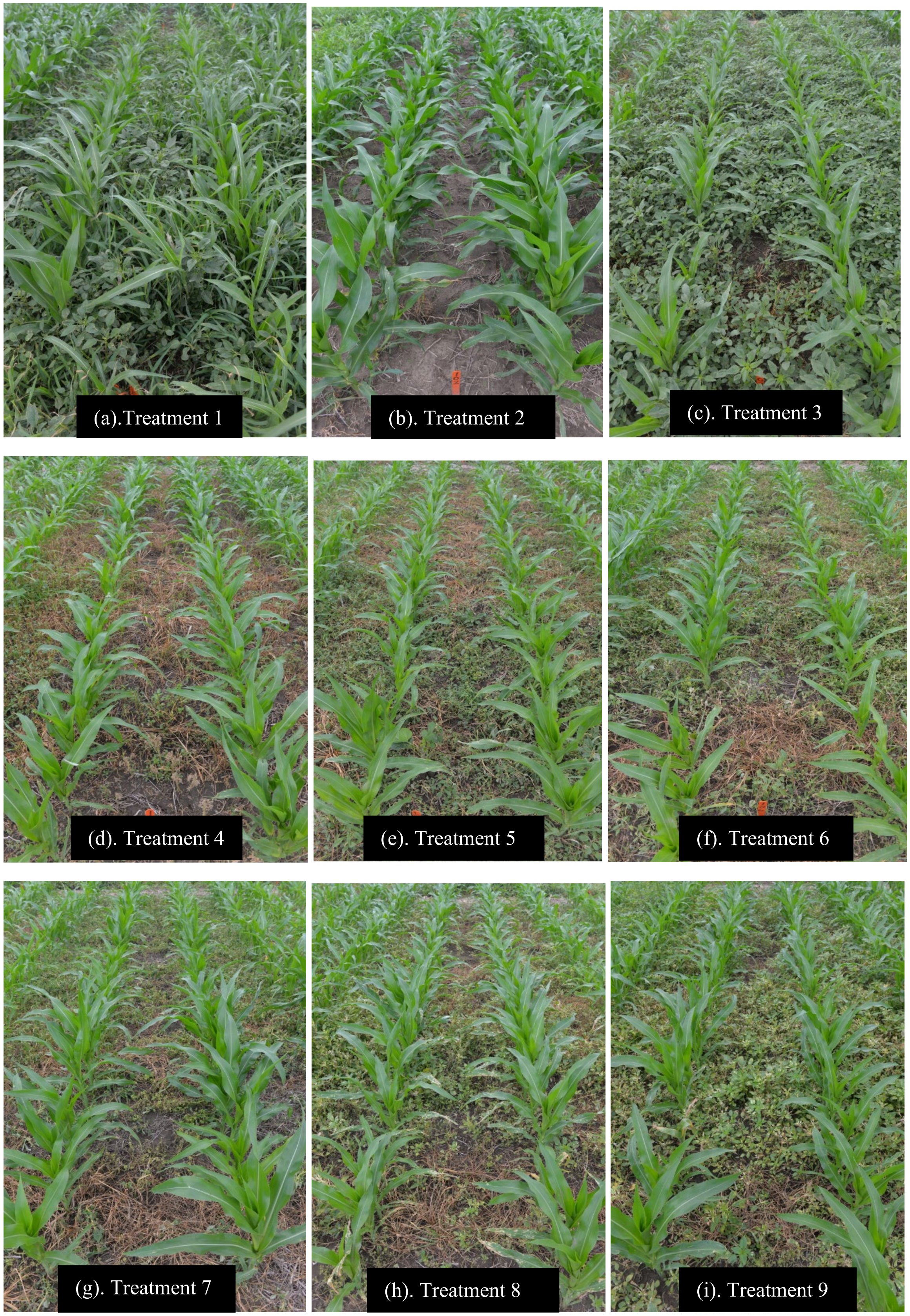
[b] Means presented within each column with no common letter(s) are significantly different according to estimated mean with Sidak adjustments and Tukey P-value.

Table 3.6. 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.


(a).Treatment 1
(b). Treatment 2
(c). Treatment 3
(d). Treatment 4
(e). Treatment 5
(f). Treatment 6
(g). Treatment 7
(h). Treatment 8
(i). Treatment 9

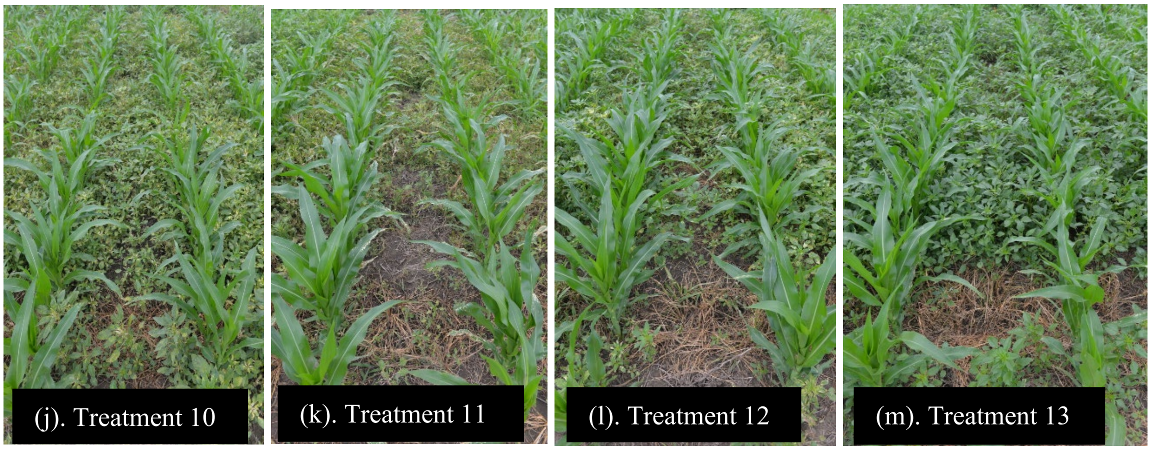



Figure 3.1. (a-m); Effect of POST herbicide programs on 10-15 cm Palmer amaranth height in glyphosate/glufosinate-resistant corn 15 d after EPOST

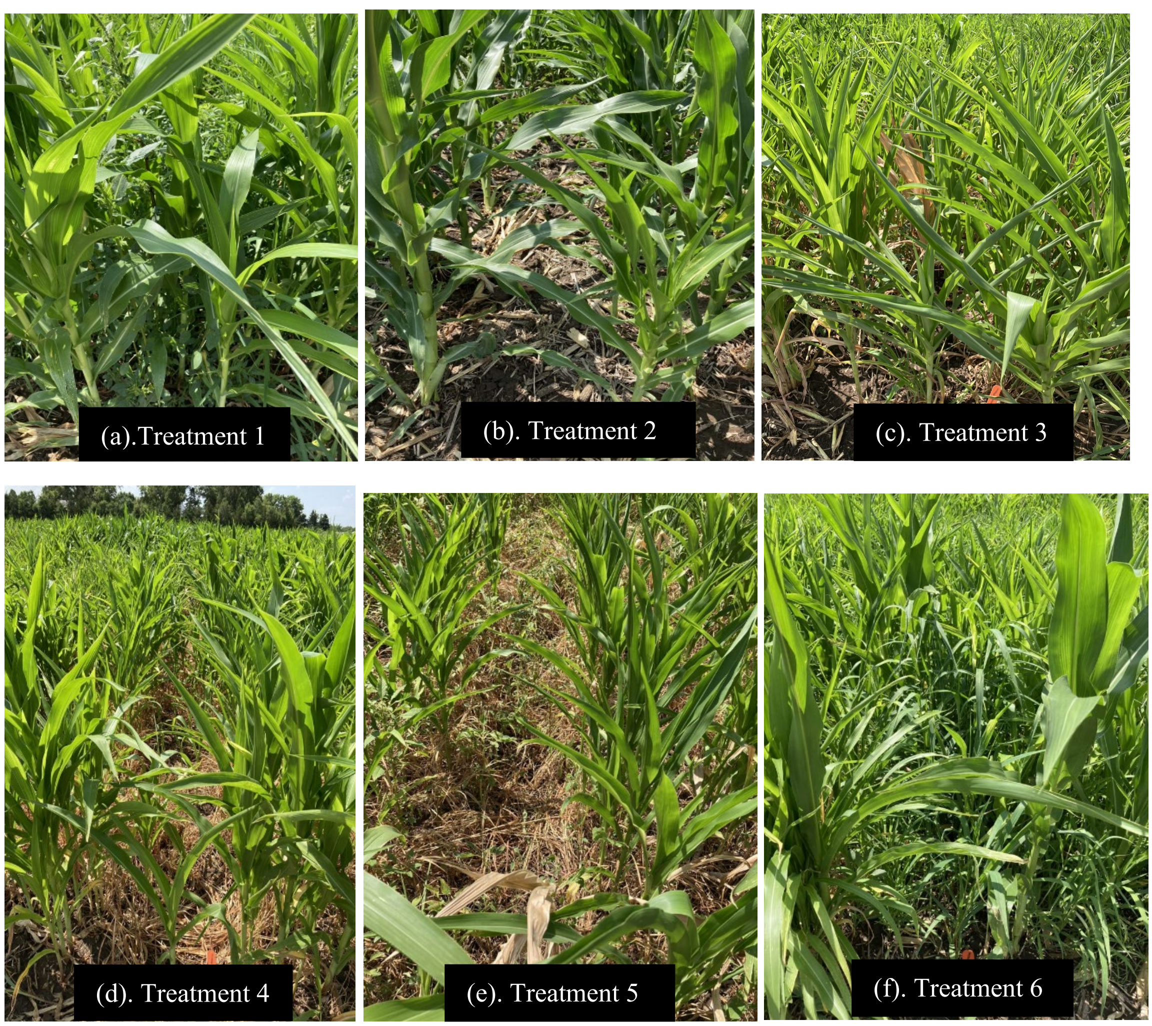



Figure 3.2. (a-m); Effect of POST herbicide programs on 20-30 cm Palmer amaranth height in glyphosate/glufosinate-resistant corn 15 d after LPOST

# CHAPTER 4

# COMPARISON OF RESIDUAL ACTIVITY OF PRE-EMERGENCE HERBICIDES FOR CONTROL AND SEED PRODUCTION OF MULTIPLE HERBICIDE-RESISTANT PALMER AMARANTH IN FOOD GRADE WHITE CORN

***This chapter is submitted:*** Kaur R, Chahal P S, Shi Y, Lawrence N C, Knezevic S Z, Jhala A J (2023) Comparison of residual activity of pre-emergence herbicides for control and seed production of multiple herbicide-resistant Palmer amaranth in food grade white corn. ***Agrosystems, Geosciences & Environment***.

## ABSTRACT

Nebraska is the number-one producer of food grade white corn 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 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 (ALS) inhibitor/atrazine/glyphosate-resistant Palmer amaranth control and their effect on Palmer amaranth density, biomass, seed production as well as grain yield in food grade white corn. Field experiments were conducted during summer 2020 and 2021 in a grower's field infested with ALS-inhibitor/atrazine/glyphosate-resistant Palmer amaranth near Carleton, Nebraska, USA. 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% to 95% Palmer amaranth. Acetochlor/clopyralid/mesotrione and

atrazine/bicyclopyrone/mesotrione/*S*-metolachlor provided 96% to 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 yield of 12,139 kg $ha^{-1}$ and 12,093 kg $ha^{-1}$ in 2020 and 2021, respectively was 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 PRE residual herbicides are available for early season control of Palmer amaranth in food grade white corn.

## INTRODUCTION

Nebraska ranks first in non-genetically modified (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). Over the last several years, the demand for non–genetically engineered food products have increased in the United States, with an average growth of 70% each year (Bain and 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 Palmer amaranth (*Amaranthus palmeri* S. Watson) is a concern for white corn growers in a no-till production system. Palmer amaranth's faster growth habit, high C4 photosynthetic rate, continued emergence throughout the season, issues of multiple herbicide-resistance, and prolific seed production allows it to replenish its weed seed bank quickly and makes it troublesome in agronomic crop production fields (Horak and 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-meter row of cotton (*Gossypium hirsutum* L.) in Texas, 3 plants per meter row of soybean [*Glycine max* (L.) Merr.] in Arkansas, and 0.5 plant per meter row of corn in Kansas reduced crop yield by 13%, 17%, and 11%, respectively (Klingaman and 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).

As of September 2023, 523 weed biotypes have evolved resistance to at least one herbicide globally; among these, 131 were reported in the United States (Heap, 2023). 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), 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 (Nandula et al., 2012; Sosnoskie et al., 2011). In total, Palmer amaranth has been found resistant to ten sites of action (Heap, 2023). Thus, effective weed management of Palmer amaranth is of the utmost importance, including integration of herbicides with different sites of action and residual activity.

Herbicide-resistant weeds become widespread throughout the United States (Prince et al. 2012). The use of residual herbicides is the cornerstone of a diversified herbicide program that combines multiple sites of action for management of these weeds (Norsworthy et al. 2012). Pre-emergence (PRE) herbicides benefit growers in several ways by reducing early season weed interference and often improving season-long Palmer amaranth control (Culpepper and York, 1998; Keeling et al., 2006; Reddy, 2001; Toler et al., 2002). Diuron, fluometuron, fomesafen, pendimethalin, prometryn, and pyrithiobac can be applied PRE in cotton for effective control of Palmer amaranth (York and 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 and groundwater contamination from extensive use of atrazine (Foy and 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 in grass crops such as corn and sorghum (Peterson et al., 2016; Vink et al., 2012). Mesotrione and isoxaflutole have been shown to be effective for control of *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). One study in Nebraska reported that an overlapping residual herbicide program was effective to control PS II and HPPD inhibitor-resistant Palmer amaranth in corn (Chahal et al., 2018). However, the residual activity of PRE herbicides in food grade white corn for control of MHR Palmer amaranth was questionable, and this information 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 evaluate and compare the residual activity of PRE herbicides with different sites of action for early season control of ALS-inhibitor/atrazine/glyphosate-resistant Palmer amaranth and their effect on Palmer amaranth density, biomass, seed production, and grain yield of food grade white corn.

## MATERIALS AND METHODS

### Study site

Field experiments were conducted during the summer in 2020 and 2021 in a grower's field located near Carleton, Nebraska, USA (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 a pH of 6.0. The experimental site was infested primarily with ALS/atrazine/glyphosate-resistant Palmer amaranth. 2,4-D choline (Enlist ONE) was used for control of glyphosate-resistant horseweed/marestail (*Conyza canadensis* L. Cronq.) in early spring 2 weeks before planting corn in this study.

**Experimental design and herbicide treatments**

The research site had been under a continuous no-till glyphosate-resistant corn-soybean rotation for the last eight 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 4 corn rows per plot were spaced 76 cm apart. Fifteen PRE herbicides and a nontreated control were included for comparison (Table 4.2). 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 $h^{-1}$.

**Data collection**

Palmer amaranth control ratings were recorded visually at 15, 30, 45, 60, 75, and 90 days after PRE (DAPRE) herbicide applied using a scale of 0% to 100%, with 0% representing no Palmer amaranth control and 100% representing complete control. 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 were 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 size 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 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, weighted, and the yield was adjusted to 13% moisture content and converted into kg $ha^{-1}$.

**Statistical analysis**

Palmer amaranth control, density, aboveground biomass, and corn yield data were subjected to ANOVA using PROC GLIMMIX in SAS (SAS Institute, Cary, NC). Normality and homogeneity of error variances were confirmed by using PROC UNIVARIATE, with normal Q-Q plots and levene test. Palmer amaranth control data were log-transformed using 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.

## RESULTS AND DISCUSSION

Year-by-treatment interactions for Palmer amaranth control, density, biomass, and seed production were non-significant ($P \geq 0.05$); and year-by-treatment interaction for corn yield was significant; therefore, corn yield data are presented separately for 2020 and 2021. Temperature and precipitation for PRE applications were optimum for both years (Table 4.1). There was no corn injury from any PRE herbicide applied in this study; therefore, these herbicides are safe to use in food grade white corn if applied as per label directions.

### Palmer amaranth control

The PRE herbicides evaluated in this study, except for atrazine, provided 90% to 99% control of MHR Palmer amaranth 15 and 30 DAPRE (Table 4.3). Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor, atrazine/*S*-metolachlor, isoxaflutole/thiencarbazone-methyl, acetochlor/atrazine, acetochlor/mesotrione, flufenacet/isoxaflutole/thiencarbazone-methyl, acetochlor/clopyralid/mesotrione and dimethenamid-*P*/saflufenacil controlled MHR Palmer amaranth 99% 15 DAPRE (Table 4.3). 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 greater than 95% control of Palmer amaranth 28 DAPRE. Chahal et al (2017) determined that saflufenacil provided 65% control of Palmer amaranth 21 DAPRE. Meyer et al. (2016) reported that mesotrione and isoxaflutole applied PRE were effective for control of *Amaranthus* spp. Striegel and Jhala (2022) indicated that acetochlor plus dicamba plus metribuzin, acetochlor/fomesafen plus dicamba, dicamba plus flumioxazin, and imazethapyr/pyroxasulfone/saflufenacil applied PRE provided 94%–98% control of herbicide-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% to 95% control of MHR Palmer amaranth (Table 4.3). 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 *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 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% to 92% control of MHR Palmer amaranth 75 DAPRE and 90 DAPRE (Table 4.3). Inman et al (2020) reported that acetochlor plus diuron plus fomesafen applied PRE provided 79% Palmer amaranth control at 2-3 weeks after planting. Chahal et al. (2018) concluded that pyroxasulfone plus safluefenacil and/or saflufenacil plus dimethenamid-*P* (PRE), followed by glyphosate plus topramezone plus dimethenamid-*P* plus atrazine, glyphosate plus diflufenzopyr plus dicamba plus pyroxasulfone, glyphosate plus diflufenzopyr plus pendimethalin and/or glyphosate plus diflufenzopyr plus dicamba plus atrazine (POST) at 3 weeks after POST provided 95–98% Palmer amaranth season-long control in glyphosate-resistant corn. Striegel and Jhala (2022) elaborated on the use of PRE herbicides for control of Palmer amaranth (94 to 98% 35 DAPRE) in dicamba/glufosinate/glyphosate-resistant soybean and concluded that PRE herbicides have a positive effect on net income and 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).

**Palmer amaranth density and biomass**

Palmer amaranth density and biomass were affected by PRE herbicides (Table 4.4). In this study, the MHR Palmer amaranth population ranged from 27 to 92 plants $m^{-2}$ in the nontreated control. 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, respectively, 15 DAPRE (Table 4.4). These were followed by isoxaflutole, acetochlor/flumetsulam/clopyralid, saflufenacil, pyroxasulfone, dimethenamid-*P* and fluthiacet-methyl/pyroxasulfone (1 to 4 Palmer amaranth plants $m^{-2)}$. At 30 DAPRE, almost all residual herbicides recorded 1 to 3 plants $m^{-2}$ with the exception of atrazine (15 plants $m^{-2}$) and atrazine/bicyclopyone/mesotrione/*S*-metolachlor (11 plants $m^{-2}$). Striegel and Jhala (2021) reported that PRE herbicide resulted in reducing herbicide 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 residual herbicides for control of Palmer amaranth in cotton.

At 45 DAPRE, acetochlor/mesotrione, and acetochlor/clopyralid/mesotrione recorded the lowest density (2 plants $m^{-2}$) of Palmer amaranth. 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 $m^{-2}$ density of MHR Palmer amaranth, respectively. Inman et al. (2020) elaborated on the importance of PRE herbicides for controlling herbicide-resistant Palmer amaranth and their role in reducing early-season weed interference by at least 79%. The acetochlor/clopyralid/mesotrione, atrazine/bicyclopyone/mesotrione/*S*-metolachlor, and acetochlor/mesotrione plots recorded 2 to 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 Palmer amaranth density to 2 to 3 plants $m^{-2}$. The remaining herbicide programs recorded 4 to 17 Palmer amaranth plants $m^{-2}$ compared with the nontreated control. Janak and Grichar (2016) reported > 95% Palmer amaranth reduction with saflufenacil plus dimethenamid-*P* in corn at 95 DAPRE in 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 to 10 g $m^{-2}$ MHR Palmer amaranth biomass 30 DAPRE (Table 4). Striegal and Jhala (2022) reported that PRE herbicide provided 95% to 100% biomass reduction of herbicide-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 to 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 applications; thus, there was higher MHR Palmer amaranth biomass that indicated the importance of follow-up programs in weed management. Mausbach et al (2021) concluded that PRE herbicides with multiple sites of action followed by glufosinate provided at least 87% reduction of MHR Palmer amaranth density and biomass reduction until 14 DALPOST.

**Corn yield**

Year-by-treatment interaction was significant ($P \leq 0.05$); therefore, yield data were presented separately for both years (Table 4.5). Acetochlor/clopyralid/mesotrione had 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. Several PRE herbicides resulted in similar corn yield in the range of 8,968 to 11,746 kg ha$^{-1}$ (Table 4.5). The remaining herbicides resulted in similar corn yield ranging from 9,302 to 10,557 and 8,902 to 10,290 kg ha$^{-1}$ in 2020 and 2021, respectively, except for atrazine. Shyam et al. (2021) reported similar yield with PRE herbicides in soybean, while 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 herbicide-resistant Palmer amaranth in Arkansas, Indiana, Nebraska, Illinois, and Tennessee. McDonald et al. (2021) focused on the importance of PRE herbicide programs in dicamba/glyphosate resistant soybean for early-season control of MHR Palmer amaranth and concluded that PRE fb EPOST (655 to 925 kg ha$^{-1}$) had higher yield than POST-only programs (564 kg ha$^{-1}$).

**Palmer amaranth seed production**

Palmer amaranth seed production was affected by PRE herbicides (Table 4.5). The highest MHR Palmer amaranth seed production (2,503,706 seeds $m^{-2}$) resulted from atrazine and the nontreated control (2,464,016 seeds $m^{-2}$). 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 2 to 11 plants $m^{-2}$ apart from 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 reported 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 of Palmer amaranth seed production. This might be because there was no POST herbicide applied in this study. 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 Palmer amaranth seed production declined to 0-325 seeds $plant^{-1}$ when PRE herbicide was used compared with POST-only programs (85–4,786 seeds $plant^{-1}$) in soybean and further reduced to 0 seeds $plant^{-1}$ when a PRE herbicide was followed by a POST herbicide with residual activity.

# CONCLUSIONS

Because food grade white corn is not genetically engineered, 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, PRE herbicides should be carefully selected to provide early season control of MHR Palmer amaranth for higher white corn productivity. From the PRE herbicides evaluated in this study, acetochlor/clopyralid/mesotrione was very effective for managing MHR Palmer amaranth control (92%), 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 is extended unusual cold/hot/dry/wet weather conditions after application (Anonymous, 2017). Although not tested in this study, there are number of post-emergence herbicides that can be applied when residual activity of PRE herbicide declines after 30-40 days for control of weeds such as Palmer amaranth and waterhemp. A follow-up application of a post-emergence herbicide reduces the crop-weed competition and results in higher grain yield of white corn compared with only PRE herbicide application at planting. Apart from the use of PRE herbicide with multiple effective sites of action, it is important to scout fields and include cultural practices such as reduced row spacing and cover crops that can provide early season Palmer amaranth suppression.

## LITERATURE CITED

Anonymous (2017). Resicore herbicide product label. EPA Reg. No. 62719-693. Dow AgroSciences LLC; Corteva agriscience 2–5 p.

Bain, C., & Selfa, T. (2017). Non-GMO vs organic labels: purity or process guarantees in a GMO contaminated landscape. *Agriculture Human Values, 34*, 805–818.

Chahal, P. S., Ganie, Z. A., & Jhala, A. J. (2018). Overlapping residual herbicides for control of photosystem II and 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitor-resistant Palmer amaranth (*Amaranthus palmeri* S. Watson) in glyphosate-resistant maize. *Frontiers in Plant Science*, *8*, 2231. https://doi.org/10.3389/fpls.2017.02231

Chahal, P. S., Varanasi, V. K., Jugulam, M., & Jhala, A. J. (2017). Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Nebraska: confirmation, EPSPS gene amplification, and response to POST corn and soybean herbicides. *Weed Technology*, *31*, 80–93.

Culpepper, A., Whitaker, J., MacRae, A., & York, A. (2008). Distribution of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Georgia and North Carolina during 2005 and 2006. *Journal of Cotton Science*, *12*, 306–310.

Culpepper, A. S., & York, A. C. (1998). Weed management in glyphosate-tolerant cotton. *Journal of Cotton Science*, *2*, 174–185.

Culpepper, A. S., Grey, T. L., Vencill, W. K., Kichler, J. M., Webster, T. M., Brown, S. M., York, A. C., Davis, J. W., & Hanna, W. W. (2006). Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) confirmed in Georgia. *Weed Science*, *54*, 620–626.

Delye, C., Jasieniuk, M., & Le Corre, V. (2013). Deciphering the evolution of herbicide resistance in weeds. *Trends in Genetics*, *29*, 649–658.

Foy, C. L., & Witt, H. L. (1997). SAN 582, alachlor, and metolachlor control triazine-resistant (TR) smooth pigweed (*Amaranthus hybridus*) in no-till corn (*Zea mays*). *Weed Technology*, *11*, 623–625.

Hay, M. M. (2017). Control of Palmer amaranth (*Amaranthus palmeri*) and common waterhemp (*Amaranthus rudis*) in double crop soybean and with very long chain fatty acid inhibitor herbicides. M.Sc thesis. Manhattan, KS: Kansas State University. Pp 1–39.

Heap I. (2023). The International Herbicide-Resistant Weed Database. https://www.weedscience.org.

Horak, M. J., & Loughin, T. M. (2000). Growth analysis of four *Amaranthus* species. *Weed Science*, *48*, 347–355.

Inman, M. D., Joran, D. L., Vann, M. C., Hare, A. T., Yotk, A. C., & Cahoob, C. W. (2020). Influence of timing of Palmer amaranth control in dicamba-resistant cotton on yield and economic return. *Weed Technology*, *34*, 682–688.

Janak, T. W. & Grichar W. J. (2016). Weed control in corn (*Zea mays* L.) as influenced by preemergence herbicides. *International Journal of Agronomy*. Article ID 2607671:1–9

http://dx.doi.org/10.1155/2016/2607671

Jhala, A. J., Sandell, L. D., Rana, N., Kruger, G. R., & Knezevic, S. Z. (2014). Confirmation and control of triazine and 4-hydroxyphenylpyruvate dioxygenase-inhibiting herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) in Nebraska. *Weed Technology*, *28*, 28–38.

Jhala AJ, Norsworthy JK, Ganie ZA, Sosnoskie LM, Beckie HJ, Mallory-Smith CA, Liu J, Wei W, Wang J, Stoltenberg DE (2021) Pollen-mediated gene flow and transfer of resistance alleles from herbicide-resistant broadleaf weeds. *Weed Technology,* 35:173–187.

Johnson, W. G., Chahal, G. S., & Regeh, D. L. (2012). Efficacy of various corn herbicides applied preplant incorporated and preemergence. *Weed Technology*, *26*, 220–229.

Keeling, J. W., Dotray, P. A., & Everitt, J. D. (2006). Importance of residual herbicides in Roundup Ready and Liberty Link systems. p. 222. In Proc. South. Weed Sci. Soc., San Antonio, TX. 23–25 Jan. 2006. South. Weed. Sci. Soc., Champaign, IL.

Klingaman, T. E., & Oliver, L. R. (1994). Palmer amaranth (*Amaranthus palmeri*) interference in soybeans (*Glycine max*). *Weed Science*, *42*, 523–527.

Kohrt, J. R., & Sprague, C. L. (2017) Herbicide management strategies in field corn for a three-way herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) population. *Weed Technology*, *31*, 364–372.

Malvar, R. A., Revilla, P., Moreno-Gonzalez, J., Butron, A., Sotelo, J., & Ordas, A. (2008). White maize: genetics of quality and agronomic performance. *Crop Science*, *48*, 1373–1381.

Massinga, R. A., Currie, R. S., Horak, M. J., Boyer, J. (2001). Interference of Palmer amaranth in corn. *Weed Science*, *49*, 202–208.

Mausbach, J., Irmak, S., Sarangi, D., Lindquist, J., & Jhala, A. J. (2021). Control of acetolactate synthase inhibitor/glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in isoxaflutole/glufosinate/glyphosate-resistant soybean. *Weed Technology*, *35*, 779–785.

McDonald, S. T., Striegel, A., Chahal, P. S., Jha, P., Rees, J. M., Proctor, C. A., & Jhala, A. J. (2021). Effect of row spacing and herbicide programs for control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in dicamba/glyphosate-resistant soybean. *Weed Technology*, *35*, 790–801.

Meyer, J. C., Norsworthy, J. K., Young, B. G., Steckel, L. E., Kevin, B. W., Johnson, W. G., Loux, M. M., Davis, V. M., Kruger, G. R., Bararpour, M. T., Ikley, J. T., Spaunhorst, D. J., & Butts, T. R. (2016). Early-season Palmer amaranth and waterhemp control from pre-emergence programs utilizing HPPD-inhibiting and auxinic herbicides in soybean. *Weed Technology*, *30*, 67–75.

Miranda, J. W. A., Jhala, A. J., Bradshaw, J., & Lawrence, N. C. (2022). Palmer amaranth (*Amaranthus palmeri*) interference and seed production in dry edible bean. Weed Technol 35: 995–1006.

Morgan, G. D., Baumann, P. A., & Chandler, J. M. (2001). Competitive impact of Palmer amaranth (*Amaranthus palmeri*) on cotton (*Gossypium hirsutum*) development and yield. *Weed Technology*, *15*, 408–412.

Nandula, V. K., Reddy, K. N., Kroger, C. H., Poston, D. H., Rimando, A. M., & Duke, S. O. (2012). Multiple resistance to glyphosate and pyrithiobac in Palmer amaranth (*Amaranthus palmeri*) from Mississippi and response to flumiclorac. *Weed Science*, *60*, 179–188.

Norsworthy, J. K., Ward, S. M., Shaw, D. R., Llewellyn, R. S., Nichols, R. L., Webster, T. M., Bradley, K. W., Frisvold, G., Powles, S. B., Burgos, N. R., Witt, W. W., & Barrett, M. (2012). Reducing the risks of herbicide resistance: best management practices and recommendations. *Weed Science*, *60*, 31–62.

Parks, R. J., Curran, W. S., Roth, G. W., Hartwig, N. L., & Calvin, D. D. (1996). Herbicide susceptibility and biological fitness of triazine-resistant and susceptible common lambsquarters (*Chenopodium album*). *Weed Science*, *44*, 517–522.

Peterson, M. A., McMaster, S. A., Riechers, D. E., Skelton, J., & Stahlman, P. W. (2016). 2, 4-D past, present, and future: a review. *Weed Technology*, *30*, 303–345.

Prince, J. M., Shaw, D. R., Givens, W. A., Owen, M. D. K., Weller, S. C., Young, B. G., Wilson, R. G., & Jordan, D. L. (2012). Benchmark study: IV. Survey of grower practices for managing glyphosate resistant weed populations. *Weed Technology*, *26*, 543–548.

Reddy, K. N. (2001). Broadleaf weed control in ultra-narrow row bromoxynil-resistant cotton (*Gossypium hirsutum*). *Weed Technology*, *15*, 497–504.

Sarangi, D. & Jhala, A. J. (2019). Palmer Amaranth (*Amaranthus palmeri*) and Velvetleaf (*Abutilon theophrasti*) Control in No-Tillage Conventional (Non– genetically engineered) Soybean Using Overlapping Residual Herbicide Programs. *Weed Technology*, *33*, 95–105.

Sarangi, D., Sandell L. D., Kruger, G. R., Knezevic, S. Z., Irmak, S., & Jhala, A. J. (2017). Comparison of herbicide programs for season-long control of glyphosateresistant common waterhemp (*Amaranthus rudis*) in soybean. *Weed Technology*, *31*, 53–66.

Sellers, B. A., Smeda, R. J., Johnson, W. G., Kendig, J. A., & Ellersieck, M. R. (2003). Comparative growth of six *Amaranthus* species in Missouri. Weed Sci 51:329–333

Sheng, S., Li, T., Liu, R. (2018). Corn phytochemicals and their health benefits. *Food Science Human Wellness*, *7*, 185–195.

Shyam, C., Chahal, P. S., Jhala, A. J., & Jugulam, M. (2021). Management of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in 2,4-D–, glufosinate-, and glyphosate-resistant soybean. *Weed Technology*, *35*, 136–143.

Sosnoskie, L. M., Kichler, J. M., Wallace, R. D., & Culpepper, A. S. (2011). Multiple resistance in Palmer amaranth to glyphosate and pyrithiobac confirmed in Georgia. *Weed Science*, *59*, 321–325.

Sprague, C. L., Stoller, E. W., & Hart, S. E. (1997). Preemergence broadleaf weed control and crop tolerance in imidazolinone-resistant and susceptible corn (*Zea mays*). *Weed Technology*, *11*, 118–122.

Striegel, A., & Jhala, A. J. (2022). Economics of reducing Palmer amaranth seed production in dicamba/glufosinate/glyphosate resistant soybean. *Agronomy Journal*, *114*, 2518–2540.

Sutton, P., Richards, C., Buren, L., & Glasgow, L. (2002). Activity of mesotrione on resistant weeds in maize. *Pest Management Science*, *58*, 981–984.

Sylvia (2018) White corn nutrition and uses. https://www.healthbenefitstimes.com/white-corn/

Toler, J. E., Murdock, E. C., & Keeton, A. (2002). Weed management systems for cotton (*Gossypium hirsutum*) with reduced tillage. *Weed Technology*, *16*, 773–780.

USDA-NASS (United States Department of Agriculture – National Agriculture Statistics Service) (2020) Available at https://www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-us/.

Vink, J. P., Soltani, N., Robinson, D. E., Tardif, F. J., Lawton, M. B., & Sikkema, P. H. (2012). Glyphosate-resistant giant ragweed (*Ambrosia trifida*) control in dicamba-tolerant soybean. *Weed Technology*, *26*, 422–428.

Volenberg, D. S., Stoltenberg, D. E., Boerboom, C. M. (2000). Solanum ptycanthum resistance to acetolactate synthase inhibitors. *Weed Science*, *48*, 399–401.

Ward, S. M., Webster, T. M., & Steckel, L. E. (2013). Palmer amaranth (*Amaranthus palmeri*): a review. *Weed Technology*, *27*, 12–27.

Whitaker, J. R., York, A. C., Jordan, D. L., Culpepper, A. S., & Sosnoskie, L. M. (2011). Residual herbicides for Palmer amaranth control. *Journal of Cotton Science*, *15*, 89–99.

York, A. C., & Culpepper, A. S. (2009). Weed Management in Cotton. p. 68-125. In 2009 Cotton Information. Publ. AG-417. North Carolina Coop. Ext. Serv., Raleigh, NC.

Table 4.1. Monthly mean air temperature and total precipitation during the 2020 and 2021 growing seasons, along with the 30-yr average, at the experiment site near Carleton, Nebraska.[a]

| Month | Mean air temperature | | | Total precipitation | | |
|---|---|---|---|---|---|---|
| | 2020 | 2021 | 30-yr average | 2020 | 2021 | 30-yr average |
| | -----------------------C------------------------- | | | ----------------------mm--------------------------- | | |
| 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 4.2. 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, Nebraska in 2020 and 2021.

| Herbicide program | Trade name | Rate | Manufacturer |
|---|---|---|---|
| | | g ai ha$^{-1}$ | |
| Atrazine/bicyclopyone/mesotrione/*S*-metolachlor | Acuron | 2,400 | Syngenta |
| Atrazine | Atrazine | 1,200 | Syngenta |
| Fluthiacet-methyl/pyroxasulfone | Anthem MAXX | 150 | FMC |
| Isoxaflutole | Balance Flaxx | 52.5 | Bayer CropScience |
| Atrazine/*S*-metolachlor | Bicep II Magnum | 2,770 | Syngenta |
| Isoxaflutole/thiencarbazone-methyl | Corvus | 129 | Corteva Agriscience |
| Acetochlor/atrazine | Degree Xtra | 3,960 | Bayer CropScience |
| Acetochlor/mesotrione | Harness Max | 2,700 | Bayer CropScience |
| Flufenacet/isoxaflutole/thiencarbazone-methyl | TriVolt | 610 | Bayer CropScience |
| Acetochlor/clopyralid/ mesotrione | Resicore | 2,300 | 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. |

[a] Abbreviation: ai, active ingredient.

Table 4.3. Multiple herbicide-resistant Palmer amaranth control as affected by pre-emergence herbicides in food grade white corn in field experiments conducted at Carleton, Nebraska, during the 2020 and 2021 growing seasons.

| Herbicide program | Palmer amaranth control[a,b,c] | | | | | |
|---|---|---|---|---|---|---|
| | 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 **(**2,400 g ai ha$^{-1}$) | 99 a | 99 a | 91 a | 96 ab | 85 abc | 85 abc |
| Atrazine (1,200 g ai ha$^{-1}$) | 42 cd | 64 e | 29 f | 38 h | 10 h | 12h |
| Fluthiacet-methyl/pyroxasulfone (150 g ai ha$^{-1}$) | 90 ab | 92 cd | 72 cd | 80 d | 53 e | 54 fg |
| Isoxaflutole (52.5 g ai ha$^{-1}$) | 95 ab | 95 abc | 73 cd | 76 e | 38 f | 37 g |
| Atrazine/*S*-metolachlor (2,770 g ai ha$^{-1}$) | 99 a | 99 a | 73 cd | 67 ef | 59 e | 57 f |
| Isoxaflutole/thiencarbazone-methyl (129 g ai ha$^{-1}$) | 99 a | 95 abc | 71 cd | 72 e | 44 e | 44 g |
| Acetochlor/atrazine (3,960 g ai ha$^{-1}$) | 99 a | 98 ab | 81 b | 75 e | 79 d | 79 e |
| Acetochlor/mesotrione (2,700 g ai ha$^{-1}$) | 99 a | 99 a | 90 a | 90 b | 87 ab | 87 ab |
| Flufenacet/Isoxaflutole/thiencarbazone-methyl (610 g ai ha$^{-1}$) | 99 a | 97 abc | 75 c | 59 f | 58 e | 60 f |
| Acetochlor/clopyralid/ mesotrione (2,300 g ai ha$^{-1}$) | 99 a | 99 a | 95 a | 99 a | 92 a | 92 a |
| Acetochlor/flumetsulam/ clopyralid (890 g ai ha$^{-1}$) | 95 ab | 97 abc | 81 b | 59 f | 55 e | 55 fg |
| Dimethenamid-*P* (736 g ai ha$^{-1}$) | 95 ab | 95 abc | 71 cd | 56 fg | 27 g | 27 gh |
| Saflufenacil (62.4 g ai ha$^{-1}$) | 95 ab | 99 a | 81 b | 88 bc | 83 bc | 82 cd |
| Dimethenamid-*P*/saflufenacil (780 g ai ha$^{-1}$) | 99 a | 99 a | 89 a | 81 d | 79 d | 80 de |
| Pyroxasulfone (179 g ai ha$^{-1}$) | 95 ab | 97 abc | 75 c | 47 gh | 41 ef | 41 g |
| P-value | < 0.0001 | < 0.0001 | < 0.0001 | < 0.0001 | < 0.0001 | < 0.0001 |

[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 Fisher Protected LSD.
[c] Abbreviations: DA-PRE, days after pre-emergence herbicide application.

Table 4.4. Multiple herbicide-resistant Palmer amaranth density and above-ground biomass affected by pre-emergence herbicides in food grade white corn in field experiments conducted in Carleton, Nebraska, during the 2020 and 2021 growing seasons.

| Herbicide program | Palmer amaranth density [a, b, c] | | | | | Palmer amaranth biomass [a, b, c] | |
|---|---|---|---|---|---|---|---|
| | 15DA-PRE | 30DA-PRE | 45DA-PRE | 60DA-PRE | 75DA-PRE | 30DA-PRE | 60DA-PRE |
| | number $m^{-2}$ | | | | | g $m^{-2}$ | |
| Nontreated control | 92 a | 42 a | 27 ab | 36 a | 33 a | 106 a | 134 a |
| Atrazine/bicyclopyone/mesotrione/*S*-metolachlor (2,400 g ai $ha^{-1}$) | 0 f | 11 d | 4 gh | 4 fg | 2 f | 13 bcd | 12 bcd |
| Atrazine (1,200 g ai $ha^{-1}$) | 59 b | 15 cd | 17 bcd | 23 b | 17 b | 29 b | 63 b |
| Fluthiacet-methyl/pyroxasulfone (150 g ai $ha^{-1}$) | 4 cde | 3 ef | 6 fg | 9 ef | 10 d | 24 bc | 32 bc |
| Isoxaflutole (52.5 g ai $ha^{-1}$) | 1 e | 3 ef | 6 fg | 10 ef | 9 d | 25 bc | 51 bc |
| Atrazine/*S*-metolachlor (2,770 g ai $ha^{-1}$) | 0 f | 2 f | 10 de | 12 de | 5 ef | 20 bc | 22 bc |
| Isoxaflutole/thiencarbazone-methyl (129 g ai $ha^{-1}$) | 0 f | 2 f | 5 fg | 7 f | 3 f | 22 bc | 30 bc |
| Acetochlor/atrazine (3,960 g ai $ha^{-1}$) | 0 f | 2 f | 8 efg | 7 f | 6 e | 13 bcd | 18 bcd |
| Acetochlor/mesotrione (2,700 g ai $ha^{-1}$) | 0 f | 3 ef | 2 h | 5 fg | 7 e | 4 cd | 30 bcd |
| Flufenacet/Isoxaflutole/thiencarbazone-methyl (610 g ai $ha^{-1}$) | 0 f | 2 f | 6 fg | 15 c | 11 c | 15 bc | 66 bc |
| Acetochlor/clopyralid/mesotrione (2,300 g ai $ha^{-1}$) | 0 f | 3 ef | 2 h | 2 g | 2 f | 6 cd | 5 d |
| Acetochlor/flumetsulam/clopyralid (890 g ai $ha^{-1}$) | 1 e | 2 f | 6 fg | 17 c | 6 e | 14 bc | 32 bc |
| Dimethenamid-*P* (736 g ai $ha^{-1}$) | 2 de | 3 ef | 14 bc | 16 c | 6 e | 37 bc | 34 bc |
| Saflufenacil (62.4 g ai $ha^{-1}$) | 1 e | 3 ef | 7 f | 7 f | 4 ef | 9 bcd | 17 bcd |
| Dimethenamid-*P*/saflufenacil (780 g ai $ha^{-1}$) | 0 f | 1 f | 4 gh | 10 e | 3 f | 10 bcd | 8 cd |
| Pyroxasulfone (179 g ai $ha^{-1}$) | 1 e | 3 ef | 4 gh | 19 c | 6 e | 10 bc | 41 bc |
| P-value | $< 0.0001$ | $< 0.0001$ | $< 0.0001$ | $< 0.0001$ | $< 0.0001$ | 0.0009 | $< 0.0001$ |

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

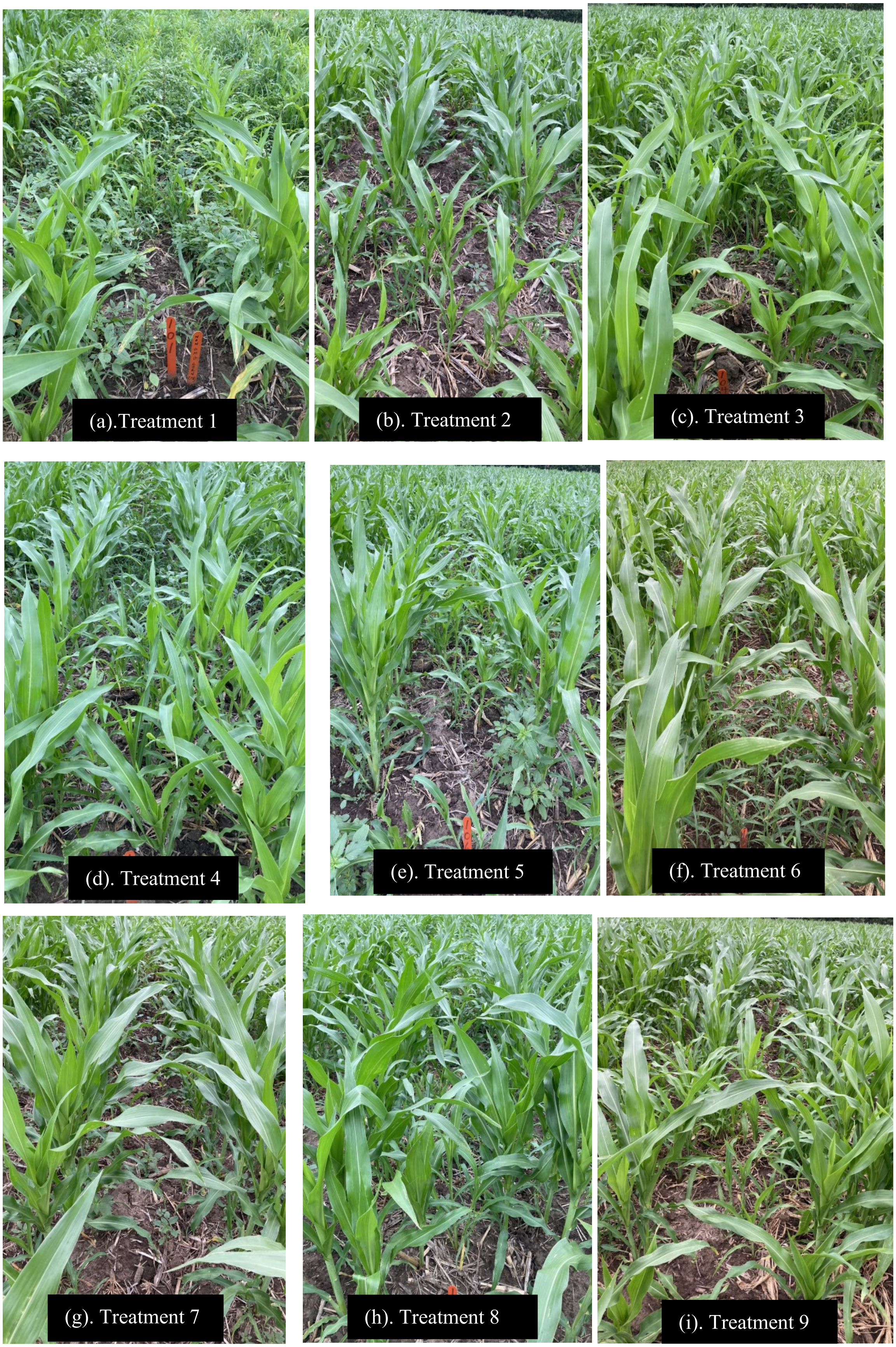
[b] Means presented within each column with no common letter(s) are significantly different as per Fisher's Protected LSD test at $P \leq 0.05$.

[c] Abbreviations: DA-PRE, days after pre-emergence herbicide application.

Table 4.5. Food grade white corn yield and Palmer amaranth seed production affected by pre-emergence herbicides in field experiments conducted at Carleton, Nebraska, during the 2020 and 2021 growing seasons.

| Herbicide program | Corn yield [a, b] | | Palmer amaranth seed production [a,b] |
|---|---|---|---|
| | 2020 | 2021 | |
| | kg $ha^{-1}$ | | seeds $m^{-2}$ |
| Nontreated control | 2,651 g | 7,735 f | 2,464,016 a |
| Atrazine/bicyclopyone/mesotrione/*S*-metolachlor **(**2,400 g ai $ha^{-1}$) | 11,063 abc | 11,213 abc | 100,407 fg |
| Atrazine (1,200 g ai $ha^{-1}$) | 5,854 f | 9,318 def | 2,503,706 a |
| Fluthiacet-methyl/pyroxasulfone (150 g ai $ha^{-1}$) | 10,001 b-e | 10,836 a-d | 411,829 cde |
| Isoxaflutole (52.5 g ai $ha^{-1}$) | 9,558 de | 10,223 b-e | 692,872 bc |
| Atrazine/*S*-metolachlor (2,770 g ai $ha^{-1}$) | 10,000 b-e | 9,673 cde | 166,012 ef |
| Isoxaflutole/thiencarbazone-methyl (129 g ai $ha^{-1}$) | 11,255 ab | 9,404 de | 325,233 d-f |
| Acetochlor/atrazine (3,960 g ai $ha^{-1}$) | 9,302 e | 10,010 b-e | 586,459 bcd |
| Acetochlor/mesotrione (2,700 g ai $ha^{-1}$) | 10,643 bcd | 11,570 ab | 324,221 d-f |
| Flufenacet/Isoxaflutole/thiencarbazone-methyl (610 g ai $ha^{-1}$) | 9940 cde | 8,902 ef | 605,565 bcd |
| Acetochlor/clopyralid/mesotrione (2,300 g ai $ha^{-1}$) | 12,139 a | 12,093 a | 32,894 g |
| Acetochlor/flumetsulam/clopyralid (890 g ai $ha^{-1}$) | 9,398 de | 9,558 de | 278,606 ef |
| Dimethenamid-*P* (736 g ai $ha^{-1}$) | 9,794 cde | 10,290 b-e | 393,030 def |
| Saflufenacil (62.4 g ai $ha^{-1}$) | 10,103 b-e | 10,719 a-d | 180,780 ef |
| Dimethenamid-*P*/saflufenacil (780 g ai $ha^{-1}$) | 10,557 b-e | 10,859 a-d | 217,185 ef |
| Pyroxasulfone (179 g ai $ha^{-1}$) | 10,145 b-e | 10,720 a-d | 755,880 b |
| P-value | < 0.0001 | < 0.0001 | < 0.0001 |

[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 Fisher's Protected LSD test at $P \leq 0.05$.


(a).Treatment 1
(b). Treatment 2
(c). Treatment 3
(d). Treatment 4
(e). Treatment 5
(f). Treatment 6
(g). Treatment 7
(h). Treatment 8
(i). Treatment 9

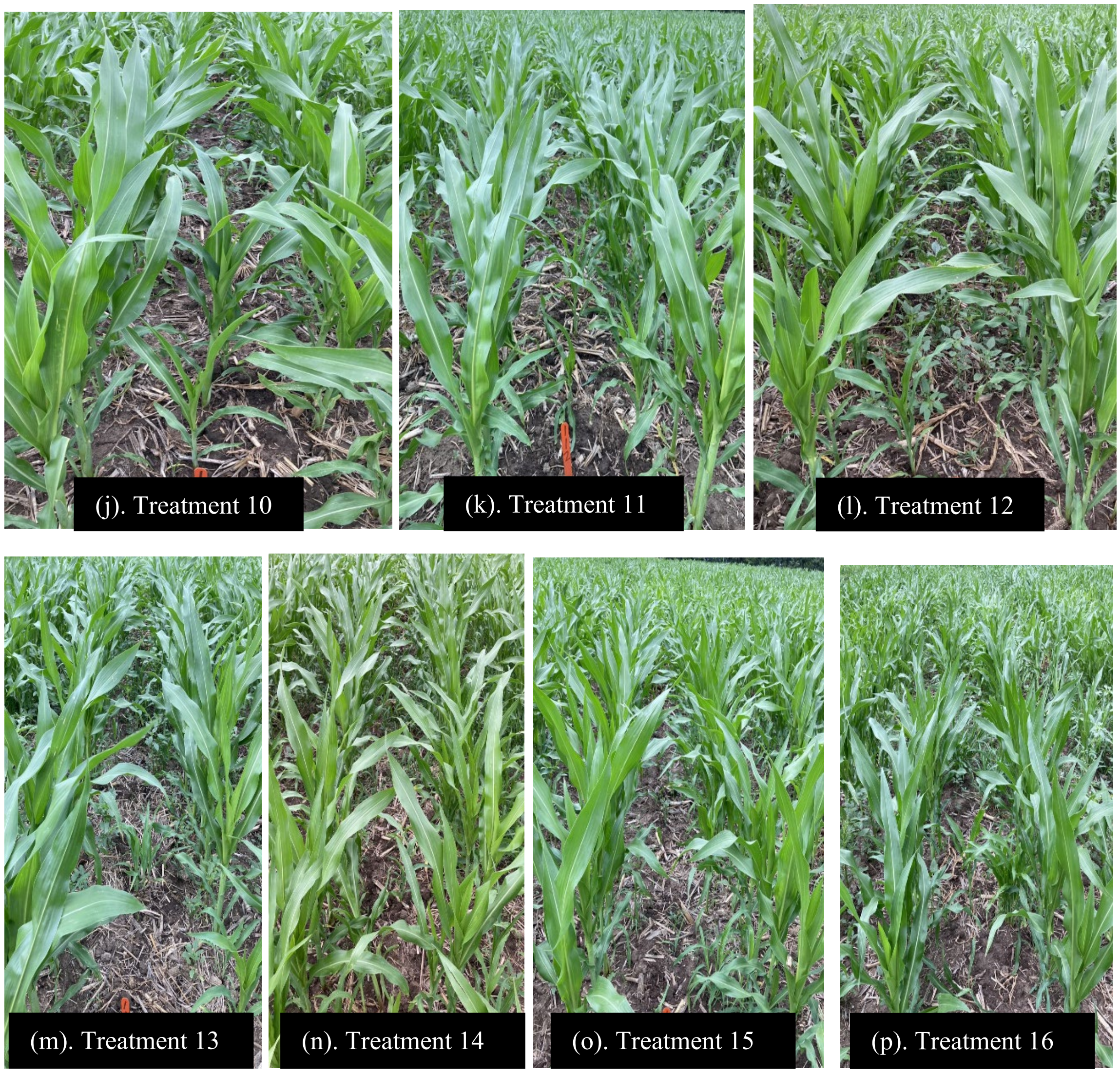



Figure 4.1. (a-p); Effect of PRE herbicide programs on control of multiple herbicide resistant Palmer amaranth in white field corn 30 d after PRE

# CHAPTER 5

# EFFECT OF ROW SPACING AND HERBICIDE PROGRAMS ON CONTROL OF MULTIPLE HERBICIDE-RESISTANT PALMER AMARANTH (*Amaranthus palmeri*) PHOTOSYNTHETICALLY ACTIVE RADIATION IN GLYPHOSATE/GLUFOSINATE-RESISTANT CORN

## ABSTRACT

Multiple herbicide-resistant (MHR) Palmer amaranth has been ranked as the most problem weed in corn production fields in Nebraska. Integration of narrow row spacing with herbicide might augment control of MHR Palmer amaranth. The objectives of this study were to determine the effects of row spacing and herbicide programs for MHR Palmer amaranth control, density, biomass, and seed production as well as corn injury, photosynthetically active radiation (PAR) interception, and grain yield in glyphosate/glufosinate-resistant corn. Field experiments were conducted during the summer 2020 and 2021 in a grower's field infested with population of MHR Palmer amaranth near Carleton, Nebraska. Herbicide- by- row spacing interactions were significant for all variables. Herbicides applied PRE controlled MHR Palmer amaranth 81% to 99%, and 79% to 99% 30 d after PRE (DAPRE) with 38- and 76- cm, respectively. Flufenacet/isoxaflutole/ thiencarbazone-methyl fb glufosinate, acetochlor/mesotrione applied PRE or fb glufosinate, acetochlor/clopyralid/flumetsulam fb glufosinate, and glufosinate fb dicamba/tembotrione controlled MHR Palmer amaranth ≥90% till 90 DALPOST. Glufosinate fb dicamba/tembotrione and acetochlor/mesotrione fb glufosinate with 38- and- 76 cm row spacing, flufenacet/isoxaflutole/thiencarbazone-methyl fb glufosinate, and acetochlor/clopyralid/flumetsulam fb glufosinate with 38 cm

row spacing recorded no MHR Palmer amaranth plants $m^{-2}$ 30 DALPOST. Acetochlor/mesotrione applied PRE recorded 0 g $m^{-2}$ MHR Palmer amaranth biomass at 30 DAPRE with 38- and- 76 cm row spacing. Acetochlor/mesotrione PRE or fb glufosinate, acetochlor/clopyralid/flumetsulam fb glufosinate, flufenacet/isoxaflutole/thiencarbazone-methyl fb glufosinate, glufosinate fb dicamba/tembotrione, and acetochlor/mesotrione applied PRE recorded 0 to 3 g $m^{-2}$ MHR Palmer amaranth biomass with both row spacing compared with 125 to 131 g $m^{-2}$ in the nontreated control at 30 DAEPOST. Later in the season, acetochlor/mesotrione fb glufosinate, and glufosinate fb dicamba/tembotrione with 38- and- 76 cm row spacing; acetochlor/clopyralid/flumetsulam fb glufosinate, and flufenacet/isoxaflutole/thiencarbazone-methyl fb glufosinate with 38 cm row spacing recorded 0 g $m^{-2}$ MHR Palmer amaranth biomass 30 DALPOST. No corn injury was observed from the tested herbicide programs in this study. Herbicide programs with narrow row spacing having higher PAR interception. Highest corn yield (13,222 to 13,596 kg $ha^{-1}$) was obtained with acetochlor/clopyralid/flumetsulam fb glufosiante with 38 cm row spacing. No MHR Palmer amaranth seed production was observed with acetochlor/mesotrione fb glufosinate, and glufosinate fb dicamba/tembotrione with both row spacing; acetochlor/clopyralid/flumetsulam fb glufosiante with 38 cm row spacing, flufenacet/isoxaflutole/thiencarbazone-methyl fb glufosinate with 76 cm row spacing.

## INTRODUCTION

Palmer amaranth (*Amaranthus palmeri* S. Watson) is a dioecious summer annual broadleaf weed belonging to the *Amaranthus* genus. Palmer amaranth is native to the southwestern United States, and northern Mexico (Crow et al. 2016). Similar to corn (*Zea* *mays* L.), Palmer amaranth uses $C_4$ photosynthetic pathways, photosynthesizing at a rapid rate than $C_3$ plants, resulting in greater growth rate, and potential to grow up to 3.5 cm $d^{-1}$ (Horak and Loughin 2000). Palmer amaranth has the highest plant dry weight, leaf area, height, growth rate (0.10 to 0.21 cm per growing degree day), and water-use efficiency compared to other *Amaranthus* species (Horak and Longhin 2000). Palmer amaranth's prolific seed production makes it a pervasive weed in agronomic fields (Bensch et al. 2003; Massinga et al. 2001; Smith et al. 2000). Keeley et al. (1987) reported that Palmer amaranth could produce 200,000 to 600,000 seeds per female plant depending on density, and competition with other weeds and crop. A survey conducted in 2015 across the state of Nebraska reported Palmer amaranth as the sixth most troublesome weed to manage in agronomic crops (Sarangi and Jhala 2018); however, McDonald et al. (2023) reported Palmer amaranth as number one most troublesome weed across the state in a survey conducted in 2019-2020.

As of 2023, a total of 269 weed species have evolved resistance to 21 of the 31 available herbicide sites of action (SOA) (Heap 2023). Glyphosate-resistant (GR) Palmer amaranth has been confirmed in 30 states (Heap 2023), including Nebraska (Chahal et al. 2017; Vieira et al. 2018). A population of dicamba-resistant Palmer amaranth was identified in Tennessee in 2020 (Foster and Steckel 2022), and glufosinate-resistant Palmer amaranth in Arkansas (Barber et al. 2021). Multiple herbicide-resistant (MHR) Palmer amaranth populations have been reported in multiple states; for example, Schwartz-Lazaro et al. (2017) confirmed Palmer amaranth resistant to glyphosate, acetolactate synthase (ALS), protoporphyrinogen oxidase (PPO), and microtubule-inhibiting herbicides in Arkansas. Jhala et al. (2014) reported atrazine and HPPD-inhibiting herbicide-resistant Palmer amaranth in Nebraska. Kumar et al. (2019) confirmed Palmer amaranth resistant to atrazine, chlorsulfuron, 2,4-D, glyphosate, and mesotrione in Kansas. Thus, management of multiple herbicide-resistant Palmer amaranth is a challenge for agronomic crop producers.

Agronomic and weed management strategies have been identified that can provide effective control of MHR weeds. Herbicides are the principal tool of most effective weed control programs (Harker and O'Donovan 2013; Norsworthy et al. 2012). Since the occurrence of herbicide-resistant weeds, there has been a need for research on the effectiveness of non-chemical management practices that could potentially augment weed control, as evidenced by consultants describing their top priority of weed management research being that of cultural weed control practices (Riar et al. 2013). Practices such as crop rotation, and the use of narrow row spacing or increased crop density, promote crop competitiveness−reduce weed growth, fecundity, and the weed seedbank (Harder et al. 2007; Jha et al. 2008; Walsh and Powles 2007; Yelverton and Coble 1991). Studies in agronomic crops reported that narrow row spacing could reduce weed seed production compared to conventional row spacing in corn (Teasdale 1998), and GR soybean [*Glycine max* (L.) Merr], glufosinate-resistant soybean, and sweet potato [*Ipomoea batatas* (L.)] (Bell et al. 2015; Meyers et al. 2010; Whitaker et al. 2010). Norris et al. (2002) reported greater weed control in GR soybean in 38 cm row spacing compared with 76 cm. Similarly, in corn, with narrow spacing (38 cm) resulted up to 60% reduction in weed biomass compared with 76 cm row spacing (Jha et al. 2016). End-of season weed biomass decreased (Hock et al. 2006), weed control increased (Young et al. 2001), and weed survival decreased (Norsworthy et al. 2007) in narrow-row (19 cm) versus wide-row (76 cm) soybean.

Previous studies have shown that increasing light interception can increase corn yield (Karlen and Camp 1985; Parvez et al. 1989). Less interplant shading, less competition for light early in the season, earlier canopy closure, and increased crop competitiveness were achieved with narrow row spacing in corn (Camp et al. 1985). Few studies concluded that decreasing row spacing from the conventional spacing (90 to 108 cm) to narrow spacing (50 to 75 cm) may increase corn production. The response to row spacing was linked to a difference in the amount of photosynthetically active radiation (PAR) able to penetrate the crop canopy. At the V2–V3 soybean growth stage, 98% and 45% of the available PAR was able to penetrate soybean canopy in 76- and 19-cm row spacing, respectively (Steckel and Sprague 2004). Flenet et al. (1996) showed that the crop canopy is more efficient at capturing radiation when the crop is planted in narrower row spacing. When row spacing is reduced, and plant population remains constant, plant spacing is equidistant, which increases light interception in corn (Teasdale 1995).

Herbicide applications to manage difficult-to-control weeds should be implemented as a part of a diverse integrated weed management program (Shaner 2014), and should contain multiple components, such as overlapping residual herbicides (Chahal et al. 2018; Sarangi and Jhala 2018; Sosnoskie and Culpepper 2014; Steckel et al. 2002). Herbicides with different SOAs are needed in a PRE followed by a POST herbicide programs, and in subsequent seasons to delay the evolution of herbicide resistant weeds (Norsworthy et al. 2012). The use of soil-residual herbicides not only can increase the number of SOAs used in an herbicide program but can also offer extended weed control compared to POST herbicides (i.e., glyphosate or glufosinate) that lack residual activity (Taylor-Lovell et al. 2002; Wiesbrook et al. 2001). The efficacy of soil-residual herbicides is highly dependent on either rainfall or irrigation received within 10 days after application, which places the herbicide molecules into soil solution where they can be taken up as weeds germinate and emerge (Krausz et al. 2001; Stewart et al. 2010). The incorporation of a soil-residual herbicide into herbicide programs has been reported to effectively control Palmer amaranth (Riar et al. 2011). McDonald et al. (2021) reported that most PRE followed by (fb) early-POST (EPOST) herbicide programs provided 84% to 97% control of Palmer amaranth in dicamba/GR soybean compared to most EPOST fb late post (LPOST) programs, excluding dicamba in single, and sequential application (82% to 95% control).

Glyphosate was ranked as the most used POST herbicide in GR corn-soybean cropping systems in Nebraska in a survey conducted in 2015 (Sarangi and Jhala 2018) and 2019-2020 (McDonald et al. 2023). Since the commercialization of GR crops, glyphosate has been extensively used for POST weed control in GR corn/soybean fields across the Midwest. Glyphosate inhibits the EPSPS enzyme, a component of the shikimate pathway. Glyphosate prevents the biosynthesis of the aromatic amino acids phenylalanine, tyrosine, and tryptophan, resulting in the death of glyphosate-sensitive plants due to the accumulation of shikimate (Herrmann and Weaver 1999; Steinrucken and Amrhein 1980). A statewide survey in 2015 reported 5.2% of total crop area was planted with glufosinate-resistant crops in Nebraska (Sarangi and Jhala 2018) compared to 80% in a 2019-2020 survey (McDonald et al. 2023). Glyphosate and glufosinate-resistant corn were commercialized respectively in 1997, and 1998, but they were not rapidly adopted by growers (Dill 2005). In recent years, glufosinate/glyphosate-resistant corn is popular among growers particularly for control of GR weeds (Livingston et al. 2015).

Failure to control Palmer amaranth with acetolactate synthase (ALS) inhibitor, atrazine, and glyphosate was observed in a grower's field in southcentral Nebraska (Chahal et al. 2017). The field was under GR corn–soybean rotation in a no-till production system with reliance on ALS-inhibitor, atrazine, and glyphosate for weed management. It is important to develop an integrated approach for the management of MHR Palmer amaranth for recommendation to growers. The objectives of this study were to determine the effects of row spacing (38- or 76- cm), and herbicide programs for ALS-inhibitor/atrazine/glyphosate-resistant Palmer amaranth control, density, biomass and seed production as well as corn injury, PAR interception, and grain yield in glyphosate/glufosinate-resistant corn in a grower's field in Carleton, Nebraska. We hypothesized that control of MHR Palmer amaranth would be achieved with the combined approach of narrow row spacing, and a PRE followed by a POST herbicide program.

## MATERIALS AND METHODS

### Study Site and Experimental Design

Field experiments were conducted in a grower's field infested with ALS-inhibitor/atrazine/glyphosate-resistant Palmer amaranth near Carleton, Nebraska (40.30°N, 97.67°W) during the summer 2020, and 2021. The soil at the research site was silt loam (montmorillonitic, mesic, Pachic Argiustolls), with a pH of 6.0, 19% sand, 63%

silt,18% clay, and 2.5% organic matter content. Palmer amaranth was the dominant weed at the experimental site with sporadic presence of green foxtail (*Setaria viridis* P. Beauv.), and Johnson grass [*Sorghum halepense* (L.) Pers.]. The experiments were conducted under no-till conditions and followed GR corn-soybean rotation. 2,4-D choline (Enlist ONE) was applied in early spring for control of glyphosate-resistant marestail (*Conyza canadensis* L. Cronq.) present at the research site. Glufosinate/glyphosate-resistant corn cultivar 'DKC 60-87 RIB' was planted on May 12, 2020, and May 18, 2021 at 87,500 seeds $ha^{-1}$. The same seeding rate was used for 38 cm row spacing plots having 8 rows per plot. Two row spacing (38 or 76 cm), and herbicide programs (PRE-only, EPOST-only, PRE fb POST, EPOST fb LPOST) were laid out in a factorial arrangement of randomized complete block design (RCBD) (Table 5.1). An incomplete blocking factor was added to simplify the field operation of planting corn in 38 cm and 76 cm row spacing and reduce field traffic to avoid soil compaction (McDonald et al. 2021). Experimental plots were 3 m wide (four corn rows spaced 76 cm apart; eight corn rows spaced 38 cm apart) and 9 m long.

The PRE herbicides were applied 2 d after corn planting (May 14) in 2020 and on the day of planting (May 18) in 2021. Early POST herbicides were applied 36 d after planting (DAP) corn on June 18, 2020, and 28 DAP on June 16, 2021; and LPOST herbicides were applied 5 d after EPOST (DAEPOST) on June 23, 2020, and 8 DAEPOST herbicides on 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) based on label requirements, and 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$^{-1}$ (Anonymous 2017) and was applied with XR 11005 flat-fan nozzles (TeeJet® Technologies). Recommended adjuvants were added with POST herbicides (Table 5.1).

**Data Collection**

Palmer amaranth control was visually assessed 15, 30, 45, and 90 d after herbicide application using a scale 0% to 100%, with 0% representing no Palmer control, and 100% representing complete control. Likewise, corn injury was assessed on a scale of 0% to 100%, with 0% meaning no corn injury, and 100% meaning complete plant death at 15 and 30 d after PRE and POST herbicides applied. Palmer amaranth density was recorded 30- DAPRE, 30- DAEPOST, and 30- DALPOST by counting the Palmer amaranth plants in 0.5 m$^2$ quadrats from each plot and converting to plants per square meter. Aboveground biomass of Palmer amaranth was collected from 0.5 m$^2$ quadrats plot$^{-1}$ at 30 DAPRE, 30 DAEPOST, and 30 DALPOST. Palmer amaranth biomass samples were clipped at the soil surface, oven-dried at 65 C for 7 d, until a constant weight was achieved, and weighed. Line Quantum Sensor (Model MQ-200) was used to measure photosynthetically active radiation (PAR) interception on clear sunny days at 10.00 am; and it was recorded for 30 DAPRE, 30 DAEPOST, and 15 DALPOST. The sensor was placed 20 cm above the corn canopy that automatically set to record the total PAR incoming radiations [PAR (I)]. The reflected PAR from the canopy [PAR (R)] was measured at the same position by inverting the sensor. For PAR transmitted to ground [PAR (T)], the instrument was horizontally lowered down the canopy and the sensor was placed near the selected plant to measure the PAR at the bottom. The readings for PAR

(I), PAR (T) and PAR (R) were recorded from three plants in each plot from middle two or four rows in each plot, respectively, for 76- and 38-cm row spacing and average values were presented. PAR interception was calculated using an equation (Zhu et al. 2012):

$$\text{PAR interception (\%)} = \frac{\text{PAR (I) - PAR (T) - PAR (R)}}{\text{PAR (I)}}$$

Where, PAR (I) = Total PAR incoming above the canopy, $Wm^{-2}$

PAR (T) = PAR transmitted to ground, $Wm^{-2}$

PAR (R) = PAR reflected from the canopy, $Wm^{-2}$

The final values were expressed in percent PAR interception.

Corn yield was taken from the center two or four rows in each plot (for 76- and 38-cm row spacing, respectively) using a plot combine (Gleaner K2; AGCO, Duluth, GA), weighted, adjusted to 13% moisture content, and converted into kg $ha^{-1}$. Palmer amaranth seed production was estimated at the end of season. Palmer amaranth seed heads were stripped from stems of female plant 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 0.50 mm sieve was processed with a seed cleaner that used air to remove the floral chaff from seeds (Sosnoskie et al. 2014). Seeds were thoroughly cleaned, and seed weight and the number of seeds per female Palmer amaranth plant were recorded.

**Statistical Analysis**

Statistical analysis was performed in SAS version 9.4 (SAS Institute, Cary, NC) using “proc glimmix”. Year by-herbicide, and year-by-herbicide-by-row spacing interactions were evaluated, and if significant, data were analyzed separately by year. In the models separated by year, the interaction of herbicide treatment, and row spacing were considered fixed effects whereas the interaction of replication by herbicide treatment, column, and column by row spacing were considered random effects. Palmer amaranth control and PAR interception data were log-transformed and fit to generalized linear mixed (GLIMMIX) models using beta (link = "complementary log-log") response distributions based on the residual pseudo-likelihood (PL) technique. Nontreated control was excluded from Palmer amaranth control analysis due to 0% value.

Palmer amaranth density, aboveground biomass, and seed production data were square root transformed and fit to GLIMMIX models using the gaussian (link = "identity") distribution based on the restricted maximum likelihood technique. Estimates were then back transformed. Corn yield data were fitted to GLIMMIX models using the gaussian (link = "identity") distribution based on the restricted maximum likelihood technique at convergence values. Before analysis, data were subjected to PROC UNIVARIATE analysis for testing normality, and homogeneity of variance using normal Q-Q plot, and levene test, respectively. ANOVA was conducted with Type III tests of fixed effects, and treatment comparisons were made with Tukey-Kramer test, and Sidak confidence-level adjustment was used during analysis. Contrast analysis was performed for Palmer amaranth seed production to compare herbicide programs (PRE, EPOST, EPOST fb LPOST, and PRE fb LPOST) at specific row spacing.

## RESULTS AND DISCUSSION

Year-by-herbicide programs-by-row spacing interactions were significant ($P<0.0001$) for Palmer amaranth control and density 15 and 30 DAPRE, and corn yield; therefore, data were presented separately by year. Data of remaining experimental variables were combined for both years as year-by- treatment interactions were not significant (P > 0.05). No corn injury was observed from the tested herbicide programs (data not shown), indicating that evaluated herbicides are safe to use in glyphosate/glufosinate-resistant corn if applied as per label direction.

**Palmer amaranth control**

Herbicide applied PRE controlled Palmer amaranth 22% to 99%, and 95% to 99% in 2020 and 2021 at 15 DAPRE, respectively (Table 5.2). In 2020, Palmer amaranth control was comparatively better with 76 cm row spacing than 38 cm. In 2021, all the PRE herbicides performed similar (≥ 95%) with both row spacing. At 30 DAPRE, acetochlor/mesotrione provided 96% to 99% Palmer amaranth control with 36 cm as well as 76 cm row spacing in both years, whereas flufenacet/isoxaflutole/thiencarbazone-methyl provided 81% to 99% control, and 79% to 98% control by acetochlor/clopyralid/flumetsulam. A similar Palmer amaranth control was observed with 38- and- 76 cm row spacing in both years, except for acetochlor/clopyralid/flumetsulam where control was 88% to 96% with 38 cm, and 79% to 95% with 76 cm row spacing in 2020. McDonald et al. (2021) reported that there was no considerable effect of row spacing until 21 DAPRE; and from the PRE programs, flumioxazin/metribuzin/pyroxasulfone and imazethapyr/pyroxasulfone/saflufenacil provided > 90% control in dicamba/glyphosate-resistant soybean in multi-year study in Nebraska. Bell et al. (2015) determined that Palmer amaranth control was 99% to 100% 21 DAP with *S*-metolachlor plus metribuzin applied PRE. Similarly, Striegel et al. (2020), and Shyam et al. (2021) reported PRE herbicides with multiple effective sites of action provided respectively, 82%–98% and 85%–97% Palmer amaranth control 14 DAPRE Palmer amaranth control in soybean.

Among EPOST herbicides, glufosinate fb dicamba/tembotrione and tembotrione plus acetochlor provided Palmer amaranth control ≥ 95%, and ≥80%, respectively, in 2020 with both row spacings, whereas, in 2021, glufosinate with 76 cm row spacing, and acetochlor plus glufosinate with 38 cm row spacing controlled MHR Palmer amaranth by 93%, and 82%, respectively, at 15 DAPRE. Palmer amaranth control from PRE herbicides varied from 47% to 99% in 2020, and 84% to 96% in 2021 (Table 5.2). At 30 DAEPOST, acetochlor/mesotrione fb glufosinate, glufosinate fb dicamba/tembotrione, flufenacet/isoxaflutole/thiencarbazone-methyl fb glufosinate with 38- and-76 cm row spacing controlled Palmer amaranth ≥ 90% in both years. Acetochlor/clopyralid/flumetsulam fb glufosinate provided 94% control of Palmer amaranth with 76 cm row spacing in 2020, and 93% to 96% in 2021 with both row spacings. Wilson et al. (2007) noted that glufosinate applied EPOST, and mid-POST to two-and six-leaf stage of the crop provided > 90% control of *Amaranthus* spp. 15 DAT in narrow-row cotton (*Gossypium hirsutum* L.). Similarly, Bell et al. (2015) reported the POST-only herbicides 42 DAP with a 45- or 90- cm row spacing had less Palmer amaranth control (53% to 68%) compared with the 19-cm row spacing (85%), likely because of earlier canopy closure in the narrow row spacing.

At 30 DALPOST, the interaction of herbicide program-by-row spacing, and main effect of row spacing for Palmer amaranth control was not significant for both years (Table 5.3). Tembotrione plus acetochlor, flufenacet/isoxaflutole/thiencarbazone-methyl fb glufosinate, glufosinate fb dicamba/tembotrione, and acetochlor/mesotrione fb glufosinate controlled Palmer amaranth 85% to 99% in 2020; however, in 2021, acetochlor/ mesotrione applied PRE or fb glufosinate, flufenacet/isoxaflutole/thiencarbazone-methyl fb glufosinate, acetochlor/clopyralid/flumetsulam fb glufosinate, and glufosinate fb dicamba/tembotrione provided 88% to 95% control. Kohrt and Sprague (2017) concluded that acetochlor fb glufosinate, atrazine + mesotrione + *S*-metolachlor fb atrazine + tembotrione, atrazine + isoxaflutole fb acetochlor + glufosinate, and dimethenamid-*P* + saflufenacil fb dicamba + diflufenzopyr + tembotrione + glyphosate provided ≥ 91% control of Palmer amaranth 14 DAPOST in corn in field studies in Michigan. Whereas Jhala et al. (2014) reported that mesotrione plus atrazine, tembotrione, glufosinate, and dicamba applied POST controlled Palmer amaranth > 92% 21 DAT in Nebraska.

At 45 DALPOST, the interaction of herbicide program-by-row spacing was not significant, and among the herbicide programs, flufenacet/isoxaflutole/thiencarbazone-methyl applied PRE or fb glufosinate, acetochlor/mesotrione applied PRE or fb glufosinate, acetochlor/clopyralid/flumetsulam applied PRE fb glufosinate, acetochlor plus glufosinate applied EPOST, and glufosinate fb dicamba/tembotrione controlled Palmer amaranth ≥ 90%. Crow et al. (2016) reported that tembotrione and thiencarbazone plus dicamba applied POST at V5-V6 stage in corn provided 98% control of Palmer amaranth 28 d after application. Jones et al (2001) concluded that glufosinate in follow up programs provided 94% to 95% control of Palmer amaranth 42 DAT; and row spacing (51 cm and 102 cm) had little effect on Palmer amaranth control in corn. As the season progressed, the efficacy of the most EPOST-only herbicides reduced compared with other follow up programs. At end of season, acetochlor/mesotrione applied PRE fb glufosinate, flufenacet/isoxaflutole/thiencarbazone-methyl fb glufosinate, acetochlor/clopyralid/flumetsulam fb glufosinate, and glufosinate fb dicamba/tembotrione provided 90% to 99% control of MHR Palmer amaranth 90 DALPOST. Kohrt and Sprague (2017) reported that glufosinate fb glufosinate, and atrazine + mesotrione + *S*-metolachlor + glyphosate applied EPOST provided 88% to 95% control of Palmer amaranth at harvest in corn.

Palmer amaranth control was higher in 38 cm row spacing (78%) than 76 cm (70%) 90 DALPOST. Jones et al (2001) concluded that row spacing influenced weed control only a few times, and on a general note, weed control in narrow-row corn (51 cm) was numerically equal to or better than conventional row spacing (102 cm). In soybean, McDonald et al. (2021) reported GR Palmer amaranth control was 83% with 38 cm row spacing compared to 78% control in 76 cm 21 DALPOST. Similarly, Singh et al. (2023) in a meta-analysis on this topic reported that effect of row spacing was more consistent for weed suppression in soybean compared with corn.

**Palmer amaranth density and biomass**

MHR Palmer amaranth density and biomass was affected by herbicide programs, and row spacing (Table 5.4, 5.5 and 5.6). MHR Palmer amaranth population varied from 31 to 165 plants $m^{-2}$ and 65 to 174 g $m^{-2}$ in the nontreated control. At 30 DAPRE, acetochlor/mesotrione recorded the lowest density of MHR Palmer amaranth (1 to 5 plants $m^{-2}$ and 0 g $m^{-2}$) at both row spacing. Chahal and Jhala (2018) reported mesotrione plus *S*-metolachlor plus atrazine, acetochlor plus clopyralid plus flumetsulam, saflufenacil plus dimethenamid-*P* and pyroxasulfone plus fluthiacet-ethyl plus atrazine applied PRE provided 55% to 83% and 9% to 45% Palmer amaranth density at 21 d after PRE and biomass reduction 28 d after POST in glufosinate- and glyphosate-resistant corn, respectively.

Furthermore, the application of acetochlor/mesotrione applied PRE or fb glufosinate, flufenacet/isoxaflutole/thiencarbazone-methyl fb glufosinate, acetochlor/clopyralid/flumetsulam fb glufosinate, and glufosinate fb dicamba/tembotrione were provided consistently lowest Palmer amaranth density and biomass of 0 to 4 plants $m^{-2}$ and 0 to 2 g $m^{-2}$ with 38 cm row spacing, 0 to 5 plants $m^{-2}$ and 0 to 3 g $m^{-2}$ with 76 cm row spacing 30 DAEPOST; 0 to 2 plants $m^{-2}$ and 0 to 2 g $m^{-2}$ with 38 cm row spacing and 0 to 8 plants $m^{-2}$ and 0 to 8 g $m^{-2}$ with 76 cm row spacing 30 DALPOST (Table 5.5 and 5.6). Lower Palmer amaranth density and biomass in narrow row spacing than conventional row spacing indicated the early canopy coverage, availability of less space, nutrients, light, and other resources for late emerging Palmer amaranth plants. Singh et al. (2023) in a meta-analysis concluded narrow row spacing reduced weed density and biomass by 34% and 55%; and its effects with weed parameters were more predominate in soybean compared to corn (Hock et al. 2006). Bradley (2006) reported the non-significant reduction of weed density and biomass for narrow spacing in corn. Hay et al. (2019) reported that the similar density of pigweed (840–850 plants $m^{-2}$) was recorded with both row spacing in nontreated control; however lower biomass (302 g $m^{-2}$) was reported with narrow row spacing than 76 cm (392 g $m^{-2}$) in soybean; and they concluded narrow row spacing could be considered as an additional integrated strategy to provide pigweed growth suppression in soybeans. Chahal and Jhala (2015) concluded that common waterhemp [(*Amaranthus tuberculatus* (Moq.) Sauer] density and biomass reduction were 83% and 92% to 95% at 45 DALPOST with glufosinate applied in sequential applications in glufosinate-resistant soybean. Mausbach et al (2021) determined that herbicide applied PRE fb glufosinate in isoxaflutole/glufosinate/glyphosate-resistant soybean reduced MHR Palmer amaranth density and biomass by >87% at 14 DAEPOST and ≥80% at 14 DALPOST, respectively. Similar findings were also confirmed by Norsworthy et al (2016). Shyam et al. (2021) reported 98-99% density and biomass reduction with glufosinate applied EPOST followed by LPOST in 2,4-D choline/glufosinate/ glyphosate–resistant soybean. Thus, the combination of narrow row spacing with follow up program is best option for the management of MHR Palmer amaranth density and biomass.

**Photosynthetically active radiations (PAR) Interception**

PAR interception influences the leaf photosynthesis efficiency, and Palmer amaranth density, growth, and seed production which in turn affects corn growth and yield. The interaction of herbicide program-by- row spacing was significant for PAR interception (Table 5.7). In the nontreated control, 91% PAR interception was recorded in 76 cm row spacing compared with 88% in 38 cm 30 DAPRE; however, later in the season, PAR interception was 95% in 38 cm row spacing compared with 90%–93% in 76 cm row spacing 30 DAEPOST and 15 DALPOST. Thus, MHR Palmer amaranth biomass was higher at 30 DAPRE with 38 cm spacing (108 g $m^{-2}$) than 76 cm (65 g $m^{-2}$); later on it was higher with 76 cm row spacing (131 and 174 g $m^{-2}$) than 38 cm (125 and 161 g $m^{-2}$), so corn yield of 38 cm row spacing was higher than 76 cm (Table 5.8). This showed the response to row spacing was linked to a difference in the amount of photosynthetically active radiation able to penetrate the crop canopy. Similarly, Knezevic et al. (2003) concluded that crop planted in narrow spacing had competitive advantage over weeds in capturing solar radiation than conventional sown crop. Among all of the herbicide programs, acetochlor/clopyralid/flumetsulam fb glufosinate, and flufenacet/isoxaflutole/theincarbazone-methyl with 38 cm row spacing recorded comparatively higher PAR interception (90%) compared to other combinations. This showed the advantage of narrow row spacing over conventional spacing through more production of carbohydrates in initial phase, and their subsequent translocation towards sink. Flenet et al. (1996) reported the crop canopy is more efficient at capturing radiation when the crop is planted in narrower row spacing. Similarly, Teasdale (1995) concluded that when row spacing is reduced (76 cm to 38 cm), and plant population remains constant, plant spacing is equidistant, which increases light interception in corn. In soybean, Steckel and Sprague (2004) determined that 98% and 45% of the available PAR was able to penetrate canopy in 76- and 19-cm row spacing at the V2–V3 soybean growth stage, respectively.

At 30 DAEPOST, all the herbicide programs with 38 cm row spacing recorded ≥ 94%, whereas, with 76 cm row spacing, flufenacet/isoxaflutole/theincarbazone-methyl, thiencarbazone-methyl/tembotrione plus acetochlor, tembotrione plus acetochlor, acetochlor/mesotrione fb glufosinate, and glufosinate fb dicamba/tembotrione recorded ≤88% PAR interception. This might be due to the early canopy closure in narrow spacing and thus, due to shading and high intercrop-competition, Palmer amaranth emergence was least in narrow spacing than conventional spacing as later one have wider space availability for later emergent populations of Palmer amaranth. Similar trend was observed at 15 DALPOST for all herbicide programs with 38 cm row spacing. However, acetochlor/mesotrione, acetochlor/clopyralid/flumetsulam, acetochlor plus glufosinate, tembotrione plus acetochlor, acetochlor/clopyralid/flumetsulam fb glufosinate, and glyphosate fb glyphosate with 76 cm row spacing recorded ≥90% PAR interception, Besancon et al (2017) concluded no significant differences were observed between row spacing for the light interception in beginning, or rate at which the canopy was closing in sorghum, however, differences ($P \leq 0.05$) were observed at Rocky Mount, North Carolina when canopy closure were lower for 76-cm rows compared to 38-cm rows. Other authors reported no or limited row spacing effect on canopy closure, the difference in photosynthetic active radiation intercepted not exceeding 10% between 38 cm, 56 cm, and 76 cm row spacing in corn (Norsworthy and Oliveira 2004; Tharp and Kells 2001). In contrast, some studies reported maximum photosynthetic active radiation was intercepted in 38 cm row spacing than 76 cm row spacing in corn (Ottman and Wetch 1989; Westgate et al. 1997).

**Corn yield**

Year by herbicide program by row spacing interaction was significant for corn yield. Higher corn yield was recorded with 38 cm row spacing than 76 cm spacing in both years (Table 5.8). Maximum corn yield was recorded in 38 cm row spacing with acetochlor/clopyralid/flumetsulam fb glufosinate (13,596 kg $ha^{-1}$ and 13,222 kg $ha^{-1}$) in 2020 and 2021, respectively. This might be due to early canopy closure in narrow spacing and less inter-competition between corn and Palmer amaranth, thus higher yield were observed in this narrow spacing and PRE fb POST program. Furthermore, acetochlor/clopyralid/flumetsulam fb glufosinate, glufosinate fb dicamba/tembotrione (12,561 kg $ha^{-1}$) or acetochlor plus glufosinate (12,384 kg $ha^{-1}$) with 38 cm row spacing provided similar corn yield in 76 cm row spacing of weed free (13,363 kg $ha^{-1}$), acetochlor/mesotrione (13,249 kg $ha^{-1}$), acetochlor/clopyralid/flumetsulam (12,532 kg $ha^{-1}$), flufenacet/isoxaflutole/theincarbazone-methyl fb glufosinate (13,133 kg $ha^{-1}$) and glufosinate fb dicamba/tembotrione (12,584 kg $ha^{-1}$) in 2020. Similarly, in 2021, acetochlor/clopyralid/flumetsulam fb glufosinate in 38 cm row spacing provided similar yield with flufenacet/isoxaflutole/theincarbazone-methyl applied PRE or acetochlor/mesotrione fb glufosinate and acetochlor/clopyralid/flumetsulam fb glufosinate with 76 cm row spacing (12,175 kg $ha^{-1}$, 12,468 kg $ha^{-1}$ and 13,170 kg $ha^{-1}$), respectively. Higher corn yield in 38 cm row spacing nontreated control in both years compared with its 76 cm row spacing showed the benefit of narrow row spacing over conventional spacing. Johnson and Hoverstad (2002) reported the positive impacts of row spacing in corn, whereas, Estenshade et al. (2001) and Tharp and Kells (2001) concluded non-significant effect of row spacing with corn yield. Dalley et al. (2004) reported mixed effect of narrow spacing with corn and soybean yield; and he concluded there were various factors responsible for the mixed results, for instance; weather situations (hails/rains), degree of weed infestation and herbicide spray application techniques and timings. Wax and Pendleton (1968) reported soybean yield increase of 10%, 18%, and 20% in 76 cm, 50 cm, and 25 cm row spacing compared with the 101 cm row spacing in field experiments conducted in Illinois. Besancon et al. (2017) reported grain sorghum planted in narrow rows (19 cm) increased yield on average by 1.8 to 2.8 Mg $ha^{-1}$ compared to conventional spacing in North Carolina.

A PRE fb LPOST application of acetochlor/clopyralid/flumetsulam fb glufosinate with 38 cm row spacing (13,596 and 13,222 kg $ha^{-1}$) provided equal or higher corn yield with 76 cm row spacing in weed free (13,363 and 10,480 kg $ha^{-1}$). Similarly, EPOST fb LPOST application of glufosinate fb dicamba/tembotrione with 38 cm row spacing (12,561 and 10,646 kg $ha^{-1}$) provided similar corn yield than weed free with 76 cm row spacing in both years. This indicates the integrative effect of row spacing and follow up herbicide program for higher yield. Bell et al. (2015) reported the 45 cm row spacing had greater soybean grain yield (3,070 kg $ha^{-1}$) than 90 cm row spacing (2,120 kg $ha^{-1}$, respectively), and use of a PRE herbicide at planting improved soybean grain yield in Arkansas. On the contrary, Jones et al (2001) concluded that decreasing row spacing (102 cm to 51 cm) while maintaining same plant populations did not necessarily increase corn yield.

**Palmer amaranth Seed Production**

The interaction of herbicide program by row spacing for Palmer amaranth seed production was significant ($P < 0.0001$). A single female Palmer amaranth plant produced 106,378 to 174,051 seeds in the nontreated control (Table 5.9). Acetochlor/mesotrione fb glufosinate and glufosinate fb dicamba/tembotrione with both row spacings, acetochlor/clopyralid/flumetsulam fb glufosiante with 38 cm row spacing, flufenacet/isoxaflutole/thiencarbazone-methyl fb glufosinate with 76 cm row spacing were most effective herbicide programs with no Palmer amaranth seed production. Acetochlor/mesotrione applied PRE, and flufenacet/isoxaflutole/thiencarbazone-methyl fb glufosinate in 38 cm row spacing recorded Palmer amaranth seed production of 1,750 and 2,943 seeds $plant^{-1}$; that were comparable with 3,345 and 9,666 seeds $plant^{-1}$ in acetochlor/mesotrione applied PRE and acetochlor/clopyralid/flumetsulam fb glufosiante with 78 cm row spacing, respectively. This showed the advantage of narrow row spacing in combination with herbicides over conventional row spacing. Bell et al. (2015) reported that averaged across the row spacing in soybean study, Palmer amaranth seed production of 2,700 to 10,800 seeds $m^{-2}$ was recorded in PRE herbicides compared to 7,700-1,67,500 seeds $m^{-2}$ with EPOST herbicides. Further, they elaborated that impact of row spacing on Palmer amaranth seed production was less apparent than the influence of herbicide programs.

A single EPOST application of acetochlor plus glufosinate, and thiencarbazone-methyl/tembotrione plus acetochlor were least effective in reducing seed production regardless of row spacing. Flufenacet/isoxaflutole/thiencarbazone-methyl applied PRE with both row spacings, EPOST application of tembotrione plus acetochlor in 78 cm row spacing, glyphosate fb glyphosate (EPOST fb LPOST) with both row spacing produced 12,073 to 47,986 seeds $plant^{-1}$ compared with the nontreated control (106,378-174,051 seeds $plant^{-1}$). Contrast analysis comparing Palmer amaranth seed production was significant with the lowest Palmer amaranth seed production in PRE fb LPOST programs with both row spacing (981 seeds $plant^{-1}$ with 38-cm and 3222 seeds $plant^{-1}$ with 76-cm) than PRE, EPOST and EPOST fb LPOST herbicide programs, that indicating the importance of PRE programs and narrow row spacing in herbicide-resistant corn (Table 5.9). Similarly, the beneficial impacts of PRE fb POST herbicide application with narrow spacing were more prominent than PRE or POST-only or POST fb POST herbicide applications (Singh et al. 2023).

## PRACTICAL IMPLICATIONS

Palmer amaranth resistant to ALS-inhibitor/atrazine/glyphosate-resistant is difficult to control in corn production fields in Nebraska. It is important to incorporate a cultural approach for integrated management of MHR Palmer amaranth. Results of this study suggest that PRE fb LPOST applications of flufenacet/isoxaflutole/thiencarbazone-methyl fb glufosinate, acetochlor/mesotrione fb glufosinate, acetochlor/clopyralid/flumetsulam fb glufosiante, EPOST application of glufosinate fb dicamba/tembotrione, and PRE application of acetochlor/mesotrione provided ≥ 90% Palmer amaranth control, 0 to 2 and 0 to 8 Palmer amaranth plants $m^{-2}$, 0 to 2 g $m^{-2}$ and 0 to 9 g $m^{-2}$ Palmer amaranth biomass, 94–96% and 88–94% PAR interception, 9,239–13,596 kg $ha^{-1}$ and 9,241–13,249 kg $ha^{-1}$ corn yield, 0–2,943 seeds $plant^{-1}$ and 0–9,666 seeds $plant^{-1}$ with 38 cm- and- 76 cm row spacing, respectively. The use of narrow row spacing and PRE fb POST herbicide programs in herbicide resistant corn provided higher levels of Palmer amaranth control than most of PRE or EPOST-only herbicide programs, except acetochlor/mesotrione. Singh et al. (2023) reported the overall benefit of narrow row spacing in reduction of weed density (34%), weed biomass (55%), and weed seed production (45%) and increasing crop yield (11%) than 76-cm row spacing. Herbicide programs should be selected carefully that include herbicides with diversifying SOA that would reduce the evolution of herbicide-resistant weeds and their seed production. Thus, from this research, it can be concluded that integration of narrow row spacing with herbicide application provides an advantage for augmenting herbicide efficacy for the multiple-herbicide Palmer amaranth management.

**LITERATURE CITED**

Barber t, Norsworthy J and Butts T (2021) Arkansas Palmer Amaranth found resistant to field rates of glufosinate. https://www.uaex.uada.edu/farm-ranch/pest-management/weed/weed-science-highlights-blog/glufosinate-resistant-pigweed.aspx. Accessed: October 07, 2023

Bell HD, Norsworthy JK, Scott RC, Popp M (2015) Effect of row spacing, seeding rate, and herbicide program in glufosinate-resistant soybean on Palmer amaranth management. Weed Technol 29:390–404

Bensch CN, Horak MJ, Peterson D (2003) Interference of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*) in soybean. Weed Sci 51:37–43

Besancon T, Heiniger R, Weisz R, Everman W (2017) Grain sorghum and Palmer Amaranth (*Amaranthus palmeri*) response to herbicide programs and agronomic practices. Weed Technol. 31:781–792

Bradley KW (2006) A review of the effects of row spacing on weed management in corn and soybean. Crop Manag 5:1–10

Camp CR, Karlen DL, Lambert JR (1985) Irrigation scheduling and row configurations for corn in the Southeastern Coastal Plain. Trans Am Soc Agric Eng 28:1159–1165.

Chahal P, Jhala A (2018) Economics of management of photosystem II- and HPPD-inhibitor-resistant Palmer amaranth in corn. Agron J. 110. DOI:10.2134/agronj2017.12.0703.

Chahal PS, Ganie ZA, Jhala AJ (2018) Overlapping residual herbicides for control of photosystem (PS) II- and 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibitor-resistant Palmer amaranth (*Amaranthus palmeri* S. Watson) in glyphosate-resistant maize. Front Plant Sci 8:2231

Chahal PS, Jhala AJ (2015) Herbicide programs for control of glyphosate-resistant volunteer corn in glufosinate-resistant soybean. Weed Technol 29:431–443

Chahal PS, Varanasi VK, Jugulam M, Jhala AJ (2017) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Nebraska: confirmation, EPSPS gene amplification, and response to POST corn and soybean herbicides. Weed Technol 31:80–93

Crow WD, Steckel LE, Mueller TC, Hayes RM (2016) Management of Large, Glyphosate-Resistant Palmer Amaranth (*Amaranthus palmeri*) in Corn. Weed Technol 30:611–616

Dalley CD, Kells JJ, Renner KA (2004) Effect of glyphosate application timing and row spacing on corn (*Zea mays*) and soybean (*Glycine max*) yields. Weed 756 Technol 18:165–176

Dill GM (2005) Glyphosate-resistant crops: history, status, and future. Pest Manag Sci 61:219–224

Esbenshade WR, Curran WS, Roth GW, Hartwig NL, Orzolek MD (2001) Effect of row spacing and herbicides on burcucumber (*Sicyos angulatus*) control in herbicide-resistant corn (*Zea mays*). Weed Technol 15:348–354

Flenet F, Kiniry JR, Board JE, Westgate ME, Reicosky DC (1996) Row spacing effects on light extinction coefficients of corn, sorghum, soybean, and sunflower. Agron J 88:185–190

Foster D and Steckel L (2022) Confirmation of dicamba-resistant Palmer amaranth in Tennessee. Weed Technol 36:777–780

Harder DB, Sprague CL, Renner KA (2007) Effect of soybean row width and population on weeds, crop yield, and economic return. Weed Technol 21:744–752

Harker KN, O'Donovan JT (2013) Recent weed control, weed management, and integrated weed management. Weed Technol 27:1–11

Hay MM, Dille JA, Peterson DE (2019) Integrated pigweed (*Amaranthus* spp.) management in glufosinate-resistant soybean with a cover crop, narrow row widths, row-crop cultivation, and herbicide program. Weed Technol 33:710–719

Heap I (2023) International survey of herbicide resistant weeds. https://www.weedscience.org/Home.aspx

Herrmann KM, Weaver LM (1999) The shikimate pathway. Annu Rev Plant Physiol Plant Mol Biol 50:473–503

Hock SM, Knezevic SZ, Martin AR, Lindquist JL (2006) Soybean row spacing and weed emergence time influence weed competitiveness and competitive indices. Weed Sci 54:38–46

Horak MJ, Loughin TM (2000) Growth analysis of four *Amaranthus* species. Weed Sci 48:347–355

Jha P, Kumar V, Godera R K, Chauhan B S (2016) Weed management using crop competition in the United States: A review. Crop Prot 95:31–37

Jha P, Norsworthy JK, Bridges W, Riley MB (2008) Influence of glyphosate timing and row width on Palmer amaranth (*Amaranthus palmeri*) and pusley (*Richardia* spp.) demographics in glyphosate-resistant soybean. Weed Sci 56:408–415

Jhala AJ, Sandell LD, Rana N, Kruger GR, Knezevic SZ (2014) Confirmation and control of triazine and 4-hydroxyphenylpyruvate dioxygenase-inhibiting herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) in Nebraska. Weed Technol 28:28–38

Johnson GA, Hoverstad TR (2002) Effect of row spacing and herbicide application timing on weed control and grain yield in corn (*Zea mays*). Weed Technol 16:548–553

Jones C, Chandler J, Morrison J, Senseman S, Tingle C (2001) Glufosinate combinations and row spacing for weed control in glufosinate-resistant corn (*Zea mays*). Weed Technol. 15:141–147

Karlen DL, Camp CR (1985) Row spacing, plant population, and water management effects on corn in the in the Atlantic coastal plain. Agron J 77:393–398

Keeley PE, Carter CH, Thullen RJ (1987) Influence of planting date on growth of palmer amaranth (*Amaranthus palmeri*). Weed Sci 35(2):199–204

Knezevic SZ, Evans SP, Mainz M (2003) Row spacing influences the critical timing for weed removal in soybean (*Glycine max*). Weed Technol 805 17:666–673

Kohrt, JR, Sprague CL (2017) Herbicide management strategies in field corn for a three-way herbicide-resistant Palmer Amaranth (*Amaranthus palmeri*) population. Weed Technol 31: 364–372

Krausz RF, Young BG, Kapusta G, Matthews JL (2001) Influence of weed competition and herbicides on glyphosate resistant soybean (*Glycine max*). Weed Technol 15:530–53

Kumar V, Liu R, Boyer G, Stahlman PW (2019) Confirmation of 2,4-D resistance and identification of multiple resistance in a Kansas Palmer amaranth (*Amaranthus palmeri*) population. Pest Manag Sci 75:2925–2933

Livingston M, Fernandez-Cornejo J, Unger J, Osteen C, Schimmelpfennig D, Park T, Lambert D (2015) The economics of glyphosate resistance management in corn and soybean production, ERR-184, U.S. Department of Agriculture, Economic Research Service.

Massinga RA, Currie RS, Horak MJ, Boyer Jr J (2001) Interference of Palmer amaranth in corn. Weed Sci 49:202–208

Mausbach J, Irmak S, Sarangi D, Lindquist J, Jhala AJ (2021) Control of acetolactate synthase inhibitor/glyphosate resistant Palmer amaranth (*Amaranthus palmeri*) in isoxaflutole/glufosinate/ glyphosate-resistant soybean. Weed Technol. 35: 779–785

McDonald S, Sarangi D, Rees J, Jhala A (2023) A follow-up survey to assess stakeholders' perspectives on weed management challenges and current practices in Nebraska, USA. Agrosyst Geosci Environ 6. 10.1002/agg2.20425

McDonald ST, Striegel A, Chahal PS, Jha P, Rees JM, Proctor CA, Jhala AJ (2021) Effect of row spacing and herbicide programs for control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in dicamba/glyphosate-resistant soybean. Weed Technol 35:790–801

Meyers SL, Jennings KM, Schultheis JR, Monks DW (2010) Interference of Palmer amaranth (*Amaranthus palmeri*) in sweetpotato. Weed Sci 58:199–203

Norris JL, Shaw DR, Snipes CE (2002) Influence of row spacing and residual herbicides on weed control in glufosinate-resistant soybean (*Glycine max*). Weed Technol 16:319–325

Norsworthy JK and Oliveria MJ (2004) Comparison of the critical period for weed control in wide- and narrow-row corn. Weed Sci 52:802–807

Norsworthy JK, Jha P, Bridges W (2007) Sicklepod (*Senna obtusifolia*) survival and fecundity in wide- and narrow-row glyphosate-resistant soybean. Weed Sci 55:252–259

Norsworthy JK, Korres NE, Walsh MJ, Powles SB (2016) Integrating herbicide programs with harvest weed seed control and other fall management practices for the control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*). Weed Sci 64:540–550

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60:31–62

Ottman MJ, Welch LF (1989) Planting patterns and radiation interception, plant nutrient concentration, and yield in corn. Agron J 81:167–174

Parvez AQ, Gardner FP, Boote KJ (1989) Determinate- and indeterminate-type soybean cultivar responses to pattern, density, and planting date. Crop Sci 29:150–157

Riar DS, Norsworthy JK, Griffith GM (2011) Herbicide programs for enhanced glyphosate-resistant and glufosinate-resistant cotton (*Gossypium hirsutum*). Weed Technol 25:526–534

Riar DS, Norsworthy JK, Steckel LE, Stephenson DO IV, Eubank TW, Scott RC (2013) Assessment of weed management practices and problem weeds in the midsouth United States-soybean: a consultant's perspective. Weed Technol 27:612–622

Sarangi D, Jhala AJ (2018) A statewide survey of stakeholders to assess the problem weeds and weed management practices in Nebraska. Weed Technol 32:642–655

Schwartz-Lazaro LM, Norsworthy JK, Scott RC, Barber LT (2017) Resistance of two Arkansas Palmer amaranth populations to multiple herbicide sites of action. Crop Prot 96:158–163

Shaner DL (2014) Lessons learned from the history of herbicide resistance. Weed Sci 62:427–431

Shyam C, Chahal PS, Jhala AJ, Jugulam M (2021) Management of glyphosate resistant Palmer amaranth (*Amaranthus palmeri*) in 2,4-D choline, glufosinate, and glyphosate-resistant soybean. Weed Technol 35:136–143

Singh M, Thapa R, Singh N, Mirsky S, Acharya B, Jhala A (2023) Does narrow row spacing suppress weeds and increase yields in corn and soybean? A meta-analysis. Weed Sci 50: 1–54

Smith DT, Baker RV, Steele GL (2000) Palmer amaranth (*Amaranthus palmeri*) impacts on yield, harvesting, and ginning in dryland cotton (*Gossypium hirsutum*). Weed Technol 14:122–126

Sosnoskie LM, Culpepper AS (2014) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) increases herbicide use, tillage, and hand-weeding in Georgia cotton. Weed Sci 62:393–402

Sosnoskie LM, Webster TM, Grey TL, Culpepper AS (2014) Severed stems of *Amaranthus palmeri* are capable of regrowth and seed production in *Gossypium hirsutum*. Ann Appl Biol 165:147–154

Steckel LE, Sprague CL (2004) Late-season common waterhemp (*Amaranthus rudis*) interference in narrow- and wide-row soybean. Weed Technol 18:947–952

Steckel LE, Sprague CL, Hager AG (2002) Common waterhemp (*Amaranthus rudis*) control in corn (*Zea mays*) with single preemergence and sequential applications of residual herbicides. Weed Technol 16:755–761

Steinrucken HC, Amrhein N (1980) The herbicide glyphosate is a potent inhibitor of 5-enolpyruvyl-shikimic acid-3-phosphate synthase. Biochem Biophys Res Commun 94:1207–1212

Stewart CL, Nurse RE, Hamill AS, Sikkema PH (2010) Environment and soil conditions influence pre- and postemergence herbicide efficacy in soybean. Weed Technol 24:234–243

Striegel A, Eskridge KM, Lawrence NC, Knezevic SZ, Kruger GR, Proctor CA, Hein GL, Jhala AJ (2020) Economics of herbicide programs for weed control in conventional, glufosinate, and dicamba/glyphosate-resistant soybean across Nebraska. Agron J 112:5158–5179

Taylor-Lovell S, Wax LM, Bollero G (2002) Preemergence flumioxazin and pendimethalin and postemergence herbicide systems for soybean (*Glycine max*). Weed Technol 16:502–511

Teasdale JR (1995) Influence of narrow row/high population corn (*Zea mays*) on weed control and light transmittance. Weed Technol 9:113–118

Teasdale JR (1998) Influence of corn (*Zea mays*) population and row spacing on corn and velvetleaf (*Abutilon theophrasti*) yield. Weed Sci 31:81–85

Tharp BE, Kells JJ (2001) Effect of glufosinate-resistant corn (Zea mays) population and row spacing on light interception, corn yield, and common lambsquarters (*Chenopodium album*) growth. Weed Technol 15:413–418

Vieira BC, Samuelson SL, Alves GS, Gaines TA, Werle R (2018) Distribution of glyphosate-resistant *Amaranthus* spp. in Nebraska. Pest Manag Sci 74: 2316–2324

Walsh MJ, Powles SB (2007) Management strategies for herbicide-resistant weed populations in Australian dryland crop production systems. Weed Technol 21:332–338

Wax LM, Pendleton JW (1968) Effect of row spacing on weed control in soybeans. Weed Sci 16:462−465

Westgate ME, Forcella F, Reicosky DC, Somsen J (1997) Rapid canopy closure for maize production in the northern US corn belt: radiation-use efficiency and grain yield. Field Crops Res 49:249–258

Whitaker JR, York AC, Jordan DL, Culpepper AS (2010) Palmer amaranth (*Amaranthus palmeri*) control in soybean with glyphosate and conventional herbicide systems. Weed Technol 24:403–410

Wiesbrook ML, Johnson WG, Hart SE, Bradley PR, Wax LM (2001) Comparison of weed management systems in narrow-row, glyphosate and glufosinate-resistant soybean (*Glycine max*). Weed Technol 15: 122–128

Wilson D, York A, Jordan D (2007) Effect of row spacing on weed management in glufosinate-resistant Cotton. Weed Technol 21:489–495.

Yelverton FH, Coble HD (1991) Narrow row spacing, and canopy formation reduces weed resurgence in soybeans (*Glycine max*). Weed Technol 5:169–174

Young BG, Young JM, Gonzini LC, Hart SE, Wax LM, Kapusta G (2001) Weed management in narrow- and wide-row glyphosate-resistant soybean (*Glycine max*). Weed Technol 15:112–121

Zhu X, Tang L, Zhang W, Cao MY, Cao WX, Zhu Y (2012) Transfer characteristics of canopy photo-synthetically active radiation in different rice cultivars under different cultural conditions. Sci Agr Sinica 45: 34–43

Table 5.1. Herbicides, and application timings rates and products used for control of acetolactate synthase inhibitors/atrazine/ glyphosate-resistant Palmer amaranth in glyphosate/glufosinate -resistant corn in field experiments conducted near Carleton, Nebraska in 2020 and 2021

| Herbicide program | Trade name | Application timing[a] | Rate [a] | Manufacturer | Adjuvants [a,b] |
|---|---|---|---|---|---|
| | | | g ae or ai $ha^{-1}$ | | |
| Flufenacet/isoxaflutole/thiencarbazone-methyl | TriVolt | PRE | 610 | Bayer CropScience | - |
| Acetochlor/mesotrione | Harness max | PRE | 2,160 | Bayer CropScience | - |
| Acetochlor/clopyralid/flumetsulam | Triple flex | PRE | 1,020 | Monsanto | - |
| Acetochlor+glufosinate | Warrant+Liberty | EPOST | 656 + 1,260 | BASF Corp, Bayer CropScience | AMS |
| Thiencarbazone-methyl/tembotrione +acetochlor | Capreno+Warrant | EPOST | 91 + 1,260 | Bayer CropScience | AMS+COC |
| Tembotrione+acetochlor | Laudis+Warrant | EPOST | 92 + 1,260 | Bayer CropScience | AMS+MSO |
| Flufenacet/isoxaflutole/thiencarbazone-methyl fb glufosinate | TriVolt fb Liberty | PRE fb LPOST | 610 fb 656 | BASF Corp | AMS |
| Acetochlor/mesotrione fb glufosinate | Harness max fb Liberty | PRE fb LPOST | 2,160 fb 656 | Bayer CropScience, BASF Corp | AMS |
| Acetochlor/clopyralid/flumetsulam fb glufosinate | Triple flexx fb Liberty | PRE fb LPOST | 1,020 fb 656 | Monsanto, BASF Corp | AMS |
| Glyphosate fb glyphosate | Roundup powermax fb Roundup powermax | EPOST fb LPOST | 1,580 fb 1580 | Bayer CropScience | AMS |
| Glufosinate fb dicamba/tembotrione | Liberty fb DiFlexx Duo | EPOST fb LPOST | 656 fb 900 | BASF Corp, Bayer CropScience | AMS, WC+DRA (Intact) |

[a] Abbreviations: ai, active ingredient; ae, acid equivalent; AMS, ammonium sulfate (N-Pak AMS Liquid, Winfield United, LLC., St. Paul, MN 55164); COC, crop oil concentrate (Agri-Dex®; Helena Chemical Co., Collierville, TN); DRA, drift reducing agent (Intact, Precision Laboratories, Waukegan, IL 60085); MSO, methylated seed oil; EPOST, early POST-emergence; fb, followed by; LPOST, late POST-emergence; WC, water conditioner (Class Act Ridion, Winfield United, Arden Hills, MN, 55126).

[b] AMS at 3% vol/vol, DRA at 0.5% vol/vol, and COC, MSO, WC at 1% vol/vol were mixed with herbicide treatments based on label recommendations

Table 5.2. Interaction of herbicide programs and row spacing (38 cm or 76 cm) for control of multiple herbicide-resistant Palmer amaranth in glyphosate/glufosinate -resistant corn in field experiments conducted at Carleton, NE, during the 2020 and 2021 growing seasons

| Herbicide program | Application timing | Palmer amaranth control [ab] | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 15 DAPRE [c, d] | | | | 30 DAPRE [c, d] | | | | 15 DAEPOST [c] | | | | 30 DAEPOST [c] | | | |
| | | 2020 | | 2021 | | 2020 | | 2021 | | 2020 | | 2021 | | 2020 | | 2021 | |
| | | 38 cm | 76 cm | 38 cm | 76 cm | 38 cm | 76 cm | 38 cm | 76 cm | 38 cm | 76 cm | 38 cm | 76 cm | 38 cm | 76 cm | 38 cm | 76 cm |
| | | % | | | | | | | | | | | | | | | |
| Nontreated control | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Weed free | | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a | 99 a |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (610 g ai $ha^{-1}$) | PRE | 22 e | 23 e | 99 a | 95 ab | 81 cd | 84 bcd | 95 ab | 95 ab | 64 hij | 47 ij | 91 bc | 85 c-f | 76 f-i | 67 g-i | 84 d-g | 80 d-h |
| Acetochlor/mesotrione (2,160 g ai $ha^{-1}$) | PRE | 85 bc | 64 c | 99 a | 99 a | 98 ab | 99 a | 96 ab | 99 a | 81 cde | 82 d | 94 abc | 94 bc | 85 cd | 80 e | 86 d-g | 89 de |
| Acetochlor/clopyralid/flumetsulam (1,020 g ai $ha^{-1}$) | PRE | 49 e | 51 cd | 99 a | 99 a | 96 ab | 95 ab | 98 ab | 97 ab | 63 hij | 65 ij | 88 c-f | 84 c-f | 70 f-i | 70 f-i | 84 d-g | 81 d-h |
| Acetochlor (656 g ai $ha^{-1}$)+glufosinate (1,260 g ai $ha^{-1}$) | EPOST | - | - | - | - | - | - | - | - | 75 f-i | 72 e-i | 82 de | 75 gh | 61 ij | 66 ghi | 75 e | 64 ijk |
| Thiencarbazone-methyl/tembotrione (91 g ai $ha^{-1}$) +acetochlor (1,260 g ai $ha^{-1}$) | EPOST | - | - | - | - | - | - | - | - | 77 f-i | 63 g-i | 59 ij | 10 j-l | 49 ij | 44 ij | 42 ijk | 20 ijk |
| Tembotrione (92 g ai $ha^{-1}$)+acetochlor (2,160 g ai $ha^{-1}$) | EPOST | - | - | - | - | - | - | - | - | 80 e | 86 d | 32 ijk | 25 jk | 85 cd | 84 cde | 43 ijk | 58 ijk |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (610 g ai $ha^{-1}$) fb glufosinate (656 g ai $ha^{-1}$) | PRE fb LPOST | 73 d | 95 ab | 99 a | 99 a | 99 a | 96 ab | 95 ab | 99 a | 83 cde | 90 abc | 95 abc | 96 abc | 90 ab | 99 a | 92 abc | 97 ab |
| Acetochlor/mesotrione (2,160 g ai $ha^{-1}$) fb glufosinate (656 g ai $ha^{-1}$) | PRE fb LPOST | 99 a | 99 a | 99 a | 99 a | 98 ab | 98 ab | 99 a | 96 ab | 99 a | 99 a | 92 abc | 95 abc | 99 a | 99 a | 92 abc | 97 ab |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Acetochlor/clopyralid/flumetsulam (1,020 g ai $ha^{-1}$) fb glufosinate (656 g ai $ha^{-1}$) | PRE fb LPOST | 89 b | 90 ab | 99 a | 99 a | 88 c | 79 cde | 95 ab | 95 ab | 95 ab | 99 a | 88 cde | 92 abc | 71 f-i | 94 abc | 96 ab | 93 abc |
| Glyphosate (1,580 g ai $ha^{-1}$) fb glyphosate (1,580 g ai $ha^{-1}$) | EPOST fb LPOST | - | - | - | - | - | - | - | - | 50 f-i | 50 f-i | 56 ij | 40 ij | 55 ij | 60 ghi | 65 h | 46 f-i |
| Glufosinate (656 g ai $ha^{-1}$) fb dicamba/tembotrione (900 g ai $ha^{-1}$) | EPOST fb LPOST | - | - | - | - | - | - | - | - | 95 ab | 96 ab | 79 fg | 93 abc | 95 ab | 95 ab | 93 abc | 95 ab |
| P-value [year*treatment* row spacing] | | <0.0001 | | <0.0001 | | <0.0001 | | <0.0001 | | <0.0001 | | <0.0001 | | <0.0001 | | <0.0001 | |

[a] Data for each year 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.

[c] Abbreviations: DAPRE, days after PRE application; DAEPOST, days after early-POST application; LPOST, late-POST application.

[d] POST herbicides were not applied at the time 15 DAPRE and 30 DAPRE.

Table 5.3. Multiple herbicide-resistant Palmer amaranth control as affected by herbicide programs and row spacing (38 cm or 76 cm) in glyphosate/glufosinate -resistant corn in field experiments conducted in Carleton, NE, during the 2020 and 2021 growing seasons

| Herbicide program | Application timing | Palmer amaranth control [a, b] | | | |
|---|---|---|---|---|---|
| | | % | | | |
| | | 30 DALPOST [c] | | 45 DALPOST [cd] | 90 DALPOST [cd] |
| | | 2020 | 2021 | 2021 | 2021 |
| Nontreated control | | 0 | 0 | 0 | 0 |
| Weed free | | 99 a | 99 a | 99 a | 99 a |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (610 g ai ha$^{-1}$) | PRE | 70 bc | 82 bc | 95 a | 87 b |
| Acetochlor/mesotrione (2,160 g ai ha$^{-1}$) | PRE | 82 ab | 88 ab | 97 a | 90 a |
| Acetochlor/clopyralid/flumetsulam (1,020 g ai ha$^{-1}$) | PRE | 70 bc | 83 bc | 95 a | 75 c |
| Acetochlor (656 g ai ha$^{-1}$)+glufosinate (1,260 g ai ha$^{-1}$) | EPOST | 63 c | 68 cd | 90 a | 75 c |
| Thiencarbazone-methyl/tembotrione (91 g ai ha$^{-1}$)+acetochlor (1,260 g ai ha$^{-1}$) | EPOST | 48 c | 31 e | 53 c | 53 cd |
| Tembotrione (92 g ai ha$^{-1}$) +acetochlor (2,160 g ai ha$^{-1}$) | EPOST | 85 ab | 50 de | 63 c | 43 d |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (610 g ai ha$^{-1}$) fb glufosinate (656 g ai ha$^{-1}$) | PRE fb LPOST | 94 a | 94 ab | 99 a | 99 a |
| Acetochlor/mesotrione (2,160 g ai ha$^{-1}$) fb glufosinate (656 g ai ha$^{-1}$) | PRE fb LPOST | 99 a | 95 ab | 99 a | 99 a |
| Acetochlor/clopyralid/flumetsulam (1,020 g ai ha$^{-1}$) fb glufosinate (656 g ai ha$^{-1}$) | PRE fb LPOST | 82 ab | 94 ab | 99 a | 94 a |
| Glyphosate (1,580 g ai ha$^{-1}$) fb glyphosate (1,580 g ai ha$^{-1}$) | EPOST fb LPOST | 58 c | 56 de | 78 b | 53 cd |
| Glufosinate (656 g ai ha$^{-1}$) fb dicamba/tembotrione (900 g ai ha$^{-1}$) | EPOST fb LPOST | 95 a | 94 ab | 95 a | 94 a |
| **Row Spacing** | | | | | |
| 38 cm | | 74 | 73 | 82 | 78 |
| 76 cm | | 72 | 70 | 81 | 70 |
| Herbicide P-value | | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| Row spacing P-value | | 0.4770 | 0.4559 | 0.5356 | 0.0532 |
| P-value [treatment*row spacing] | | 0.7067 | 0.6865 | 0.9506 | 0.1199 |

[a] Data for each year 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.
[c] Abbreviations: DALPOST, days after late-POST application; EPOST, early-POST application; LPOST, late-POST application.
[d] 45- and- 90 DALPOST visual control rating data is only available for 2021.

Table 5.4. Multiple herbicide-resistant Palmer amaranth density as affected by interaction of herbicide programs and row spacing (38 cm or 76 cm) at 30 DAPRE in glyphosate/glufosinate -resistant corn in field experiments conducted in Carleton, NE, during the 2020 and 2021 growing seasons

| Herbicide program | Application timing | Palmer amaranth density [a, b] number $m^{-2}$ | | | |
|---|---|---|---|---|---|
| | | 2020 | | 2021 | |
| | | 38 cm | 76 cm | 38 cm | 76 cm |
| Nontreated control | | 165 a | 92 ab | 65 ab | 85 a |
| Weed free | | 0 e | 0 e | 0 d | 0 d |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (610 g ai $ha^{-1}$) | PRE | 66 b | 25 bc | 6 cd | 6 cd |
| Acetochlor/mesotrione (2,160 g ai $ha^{-1}$) | PRE | 1 e | 2 e | 5 cd | 2 d |
| Acetochlor/clopyralid/flumetsulam (1,020 g ai $ha^{-1}$) | PRE | 11 d | 14 d | 4 cd | 4 cd |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (610 g ai $ha^{-1}$) fb glufosinate (656 g ai $ha^{-1}$) | PRE fb LPOST | 12 d | 12 d | 6 cd | 2 d |
| Acetochlor/mesotrione (2,160 g ai $ha^{-1}$) fb glufosinate (656 g ai $ha^{-1}$) | PRE fb LPOST | 1 e | 2 e | 2 d | 4 cd |
| Acetochlor/clopyralid/flumetsulam (1,020 g ai $ha^{-1}$) fb glufosinate (656 g ai $ha^{-1}$) | PRE fb LPOST | 33 bc | 47 b | 6 cd | 6 cd |
| P-value [year*treatment*row spacing] | | <0.0001 | | <0.0001 | |

[a] Year by treatment 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] Abbreviations: DAPRE, days after PRE application; EPOST, early-POST application; LPOST, late-POST application.

Table 5.5. Multiple herbicide-resistant Palmer amaranth density as affected by interaction of herbicide programs and row spacing (38 cm or 76 cm) at 15- and 30- DAEPOST, 15- and 30- DALPOST in glyphosate/glufosinate-resistant corn in field experiments conducted in Carleton, NE, during the 2020 and 2021 growing seasons

| Herbicide program | Application timing | Palmer amaranth density [a, b] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | number $m^{-2}$ | | | | | | | |
| | | 15 DAEPOST [c] | | 30 DAEPOST [c] | | 15 DALPOST [c] | | 30 DALPOST [c] | |
| | | 38 cm | 76 cm | 38 cm | 76 cm | 38 cm | 76 cm | 38 cm | 76 cm |
| Nontreated control | | 83 ab | 84 ab | 75 ab | 90 a | 53 b | 54 b | 31 bc | 47 ab |
| Weed free | | 0 h | 0 h | 0 e | 0 e | 0 d | 0 d | 0 e | 0 e |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (610 g ai $ha^{-1}$) | PRE | 6 fg | 2 gh | 17 c | 9 cd | 6 cd | 11 c | 5 cd | 11 cd |
| Acetochlor/mesotrione (2,160 g ai $ha^{-1}$) | PRE | 0 h | 6 fg | 2 de | 2 de | 8 cd | 8 cd | 2 de | 2 de |
| Acetochlor/clopyralid/flumetsulam (1,020 g ai $ha^{-1}$) | PRE | 11 efg | 16 efg | 8 cd | 18 c | 12 c | 11 c | 7 cd | 11 cd |
| Acetochlor (656 g ai $ha^{-1}$)+glufosinate (1,260 g ai $ha^{-1}$) | EPOST | 19 efg | 30 def | 12 c | 25 c | 40 bc | 11 c | 9 cd | 18 cd |
| Thiencarbazone-methyl/tembotrione (91 g ai $ha^{-1}$) +acetochlor (1,260 g ai $ha^{-1}$) | EPOST | 23 def | 83 ab | 45 bc | 46 bc | 17 c | 41 bc | 12 cd | 17 cd |
| Tembotrione (92 g ai $ha^{-1}$)+acetochlor (2,160 g ai $ha^{-1}$) | EPOST | 45 cd | 35 de | 40 bc | 45 bc | 59 b | 36 bc | 9 cd | 25 bcd |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (610 g ai $ha^{-1}$) fb glufosinate (656 g ai $ha^{-1}$) | PRE fb LPOST | 4 g | 2 gh | 3 de | 0 e | 4 cd | 0 d | 0 e | 8 cd |
| Acetochlor/mesotrione (2,160 g ai $ha^{-1}$) fb glufosinate (656 g ai $ha^{-1}$) | PRE fb LPOST | 3 gh | 6 fg | 0 e | 3 de | 0 d | 0 d | 0 e | 0 e |
| Acetochlor/clopyralid/flumetsulam (1,020 g ai $ha^{-1}$) fb glufosinate (656 g ai $ha^{-1}$) | PRE fb LPOST | 2 gh | 6 fg | 0 e | 5 d | 0 d | 0 d | 0 e | 3 d |
| Glyphosate (1,580 g ai $ha^{-1}$) fb glyphosate (1,580 g ai $ha^{-1}$) | EPOST fb LPOST | 63 bc | 100 a | 32 bc | 34 bc | 111 a | 82 ab | 65 a | 67 a |
| Glufosinate (656 g ai $ha^{-1}$) fb dicamba/tembotrione (900 g ai $ha^{-1}$) | EPOST fb LPOST | 12 efg | 1 gh | 4 d | 1 de | 13 c | 0 d | 0 e | 0 e |
| P-value (treatment*row spacing) | | <0.0001 | | <0.0001 | | <0.0001 | | <0.0001 | |

[a] Year by treatment for Palmer amaranth density was non-significant, therefore, data were combined 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] Abbreviations: DAEPOST, days after early-POST application; DALPOST, days after late-POST application; EPOST, early-POST application; LPOST, late-POST application.

Table 5.6. Interaction of herbicide programs and row spacing (38 cm or 76 cm) on Palmer amaranth above-ground biomass in glyphosate/glufosinate -resistant corn in field experiment conducted at Carleton, NE, 2020 and 2021 growing seasons

| Herbicide program | Application timing | Palmer amaranth biomass [a, b, c, d] | | | | | |
|---|---|---|---|---|---|---|---|
| | | g m$^{-2}$ | | | | | |
| | | 30 DAPRE | | 30 DAEPOST | | 30 DALPOST | |
| | | 38 cm | 76 cm | 38 cm | 76 cm | 38 cm | 76 cm |
| Nontreated control | | 108 a | 65 b | 125 a | 131 a | 161 a | 174 a |
| Weed free | | 0 e | 0 e | 0 d | 0 d | 0 e | 0 e |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (610 g ai ha$^{-1}$) | PRE | 38 bc | 39 bc | 24 bc | 41 bc | 10 de | 20 c |
| Acetochlor/mesotrione (2,160 g ai ha$^{-1}$) | PRE | 0 e | 0 e | 2 d | 3 d | 2 de | 2 de |
| Acetochlor/clopyralid/flumetsulam (1,020 g ai ha$^{-1}$) | PRE | 10 de | 6 de | 11 bc | 25 bc | 49 bc | 53 bc |
| Acetochlor (656 g ai ha$^{-1}$)+glufosinate (1,260 g ai ha$^{-1}$) | EPOST | - | - | 8 cd | 17 bc | 88 ab | 107 ab |
| Thiencarbazone-methyl/tembotrione (91 g ai ha$^{-1}$)+acetochlor (1,260 g ai ha$^{-1}$) | EPOST | - | - | 11 bc | 78 ab | 64 abc | 117 a |
| Tembotrione (92 g ai ha$^{-1}$)+acetochlor (2,160 g ai ha$^{-1}$) | EPOST | - | - | 30 bc | 37 bc | 49 bc | 8 de |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (610 g ai ha$^{-1}$) fb glufosinate (656 g ai ha$^{-1}$) | PRE fb LPOST | 9 de | 4 de | 0 d | 0 d | 0 e | 8 de |
| Acetochlor/mesotrione (2,160 g ai ha$^{-1}$) fb glufosinate (656 g ai ha$^{-1}$) | PRE fb LPOST | 0 e | 0 e | 0 d | 0 d | 0 e | 0 e |
| Acetochlor/clopyralid/flumetsulam (1,020 g ai ha$^{-1}$) fb glufosinate (656 g ai ha$^{-1}$) | PRE fb LPOST | 17 d | 8 de | 0 d | 0 d | 0 e | 9 de |
| Glyphosate (1,580 g ai ha$^{-1}$) fb glyphosate (1,580 g ai ha$^{-1}$) | EPOST fb LPOST | - | - | 65 ab | 75 ab | 28 c | 34 c |
| Glufosinate (656 g ai ha$^{-1}$) fb dicamba/tembotrione (900 g ai ha$^{-1}$) | EPOST fb LPOST | - | - | 1 d | 0 d | 0 e | 0 e |
| P-value [treatment* row spacing] | | 0.0026 | | <0.0001 | | <0.0001 | |

[a] Year by herbicide by row spacing was non-significant; therefore, data were combined for both years.

[b] Data were square-root transformed before analysis; however back-transformed values are presented based om 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] Abbreviations: DAPRE, days after PRE application; DAEPOST, days after early-POST application; DALPOST, days after late-POST application; EPOST, early-POST application; LPOST, late-POST application.

Table 5.7. Interaction of herbicide programs and row spacing (38 cm or 76 cm) on photosynthetically active radiations (PAR) interception in glyphosate/glufosinate -resistant corn in field experiment conducted at Carleton, NE, 2020 and 2021 growing seasons

| Herbicide program | Application timing | PAR interception [a, b, c, d] | | | | | |
|---|---|---|---|---|---|---|---|
| | | % | | | | | |
| | | 30 DAPRE | | 30 DAEPOST | | 15 DALPOST | |
| | | 38 cm | 76 cm | 38 cm | 76 cm | 38 cm | 76 cm |
| Nontreated control | | 88 a | 91 a | 95 ab | 93 abc | 95 ab | 90 cd |
| Weed free | | 88 a | 82 b | 94 ab | 94 ab | 94 ab | 91 bc |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (610 g ai $ha^{-1}$) | PRE | 90 a | 89 a | 94 ab | 85 e | 95 ab | 89 cd |
| Acetochlor/mesotrione (2,160 g ai $ha^{-1}$) | PRE | 88 a | 88 a | 96 a | 95 ab | 94 ab | 94 ab |
| Acetochlor/clopyralid/flumetsulam (1,020 g ai $ha^{-1}$) | PRE | 89 a | 89 a | 95 ab | 95 ab | 95 ab | 94 ab |
| Acetochlor (656 g ai $ha^{-1}$)+glufosinate (1,260 g ai $ha^{-1}$) | EPOST | 86 ab | 89 a | 95 ab | 95 ab | 95 ab | 94 ab |
| Thiencarbazone-methyl/tembotrione (91 g ai $ha^{-1}$)+acetochlor (1,260 g ai $ha^{-1}$) | EPOST | 89 a | 88 a | 95 ab | 85 e | 95 ab | 88 d |
| Tembotrione (92 g ai $ha^{-1}$)+acetochlor (2,160 g ai $ha^{-1}$) | EPOST | 88 a | 87 ab | 96 a | 88 d | 95 ab | 90 cd |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (610 g ai $ha^{-1}$) fb glufosinate (656 g ai $ha^{-1}$) | PRE fb LPOST | 87 ab | 87 ab | 95 ab | 90 c | 95 ab | 88 d |
| Acetochlor/mesotrione (2,160 g ai $ha^{-1}$) fb glufosinate (656 g ai $ha^{-1}$) | PRE fb LPOST | 87 ab | 87 ab | 94 ab | 85 e | 96 a | 88 d |
| Acetochlor/clopyralid/flumetsulam (1,020 g ai $ha^{-1}$) fb glufosinate (656 g ai $ha^{-1}$) | PRE fb LPOST | 90 a | 89 a | 95 ab | 92 abc | 96 a | 92 abc |
| Glyphosate (1,580 g ai $ha^{-1}$) fb glyphosate (1,580 g ai $ha^{-1}$) | EPOST fb LPOST | 89 a | 88 a | 94 ab | 90 c | 96 a | 88 d |
| Glufosinate (656 g ai $ha^{-1}$) fb dicamba/tembotrione (900 g ai $ha^{-1}$) | EPOST fb LPOST | 87 ab | 87 ab | 94 ab | 85 e | 95 ab | 93 abc |
| P-value [treatment*row spacing] | | <0.0001 | | <0.0001 | | <0.0001 | |

[a] Year by herbicide by row spacing was non-significant; therefore, data were combined for both years.

[b] Data were log transformed before analysis; however back-transformed values are presented based om 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] Abbreviations: DAPRE, days after PRE application; DAEPOST, days after early-POST application; DALPOST, days after late-POST application; EPOST, early-POST application; LPOST, late-POST application.

Table 5.8. Interaction effect of herbicide program and row spacing (38 cm or 76 cm) on corn yield in glyphosate/glufosinate - resistant corn in field experiment conducted at Carleton, NE, 2020 and 2021 growing seasons

| Herbicide program | Application timing | Corn yield [a, b, c] | | | |
|---|---|---|---|---|---|
| | | kg ha$^{-1}$ | | | |
| | | 2020 | | 2021 | |
| | | 38 cm | 76 cm | 38 cm | 76 cm |
| Nontreated control | | 8,900 kj | 8,359 k | 7,032 kl | 5,999 l |
| Weed free | | 11,362 e-i | 13,363 ab | 9,726 fgh | 10,480 d-g |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (610 g ai ha$^{-1}$) | PRE | 11,091 f-i | 11,012 f-i | 11,552 bcd | 12,175 abc |
| Acetochlor/mesotrione (2,160 g ai ha$^{-1}$) | PRE | 11,915 c-h | 13,249 abc | 9,239 hi | 10,936 de |
| Acetochlor/clopyralid/flumetsulam (1,020 g ai ha$^{-1}$) | PRE | 11,994 b-h | 12,532 a-e | 9,415 ghi | 9,882 e-h |
| Acetochlor (656 g ai ha$^{-1}$)+glufosinate (1,260 g ai ha$^{-1}$) | EPOST | 12,384 a-f | 11,718 e-h | 9,207 hi | 10,014 e-h |
| Thiencarbazone-methyl/tembotrione (91 g ai ha$^{-1}$)+acetochlor (1,260 g ai ha$^{-1}$) | EPOST | 10,703 hi | 12,132 b-g | 9,241 hi | 6,693 kl |
| Tembotrione (92 g ai ha$^{-1}$)+acetochlor (2,160 g ai ha$^{-1}$) | EPOST | 10,803 ghi | 11,919 c-h | 7,468 jk | 8,597 i |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (610 g ai ha$^{-1}$) fb glufosinate (656 g ai ha$^{-1}$) | PRE fb LPOST | 11,225 e-i | 13,133 a-d | 11,227 cd | 10,819 def |
| Acetochlor/mesotrione (2,160 g ai ha$^{-1}$) fb glufosinate (656 g ai ha$^{-1}$) | PRE fb LPOST | 11,324 e-i | 10919 ghi | 11,211 cd | 12,468 ab |
| Acetochlor/clopyralid/flumetsulam (1,020 g ai ha$^{-1}$) fb glufosinate (656 g ai ha$^{-1}$) | PRE fb LPOST | 13,596 a | 11,851 d-h | 13,222 a | 13,170 a |
| Glyphosate (1,580 g ai ha$^{-1}$) fb glyphosate (1,580 g ai ha$^{-1}$) | EPOST fb LPOST | 10,198 ij | 10,993 ghi | 8,370 ij | 9112 hi |
| Glufosinate (656 g ai ha$^{-1}$) fb dicamba/tembotrione (900 g ai ha$^{-1}$) | EPOST fb LPOST | 12,561 a-e | 12,584 a-e | 10,646 def | 9,241 hi |
| P-value [year*treatment*row spacing] | | 0.0009 | | <0.0001 | |

[a] Year by treatment 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 according to estimated mean with Sidak adjustments and Tukey P-value.
[c] Abbreviations: EPOST, early-POST application; LPOST, late-POST application.

Table 5.9. Interaction of herbicide programs and row spacing (38 cm or 76 cm) on Palmer amaranth seed production in glyphosate/glufosinate -resistant corn in field experiment conducted at Carleton, NE, 2020 and 2021 growing seasons

| Herbicide program | Application timing | Palmer amaranth seed production [a, b, c] | |
|---|---|---|---|
| | | number $plant^{-1}$ | |
| | | 38 cm | 76 cm |
| Nontreated control | | 174,051 ab | 106,378 abc |
| Weed free | | 0 f | 0 f |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (610 g ai $ha^{-1}$) | PRE | 27,436 cd | 12,073 d |
| Acetochlor/mesotrione (2,160 g ai $ha^{-1}$) | PRE | 1,750 e | 3,345 e |
| Acetochlor/clopyralid/flumetsulam (1,020 g ai $ha^{-1}$) | PRE | 69,073 abc | 71,891 cd |
| Acetochlor (656 g ai $ha^{-1}$)+glufosinate (1,260 g ai $ha^{-1}$) | EPOST | 198,388 a | 112097 ab |
| Thiencarbazone-methyl/tembotrione (91 g ai $ha^{-1}$)+acetochlor (1,260 g ai $ha^{-1}$) | EPOST | 66,994 abc | 140,734 a |
| Tembotrione (92 g ai $ha^{-1}$)+acetochlor (2,160 g ai $ha^{-1}$) | EPOST | 63,242 abc | 40,810 cd |
| Flufenacet/isoxaflutole/thiencarbazone-methyl (610 g ai $ha^{-1}$) fb glufosinate (656 g ai $ha^{-1}$) | PRE fb LPOST | 2,943 e | 0 f |
| Acetochlor/mesotrione (2,160 g ai $ha^{-1}$) fb glufosinate (656 g ai $ha^{-1}$) | PRE fb LPOST | 0 f | 0 f |
| Acetochlor/clopyralid/flumetsulam (1,020 g ai $ha^{-1}$) fb glufosinate (656 g ai $ha^{-1}$) | PRE fb LPOST | 0 f | 9,666 e |
| Glyphosate (1,580 g ai $ha^{-1}$) fb glyphosate (1,580 g ai $ha^{-1}$) | EPOST fb LPOST | 44,619 c | 47,986 cd |
| Glufosinate (656 g ai $ha^{-1}$) fb dicamba/tembotrione (900 g ai $ha^{-1}$) | EPOST fb LPOST | 0 f | 0 f |
| P-value [treatment* row spacing] | | <.0001 | <.0001 |
| **Contrasts** | | | |
| PRE vs EPOST | | 32,753 vs 1,09,541** | 29,103 vs 97,880 * |
| PRE vs PRE fb LPOST | | 32,753 vs 981* | 29,103 vs 3,222 ** |
| PRE vs EPOST fb LPOST | | NS | NS |

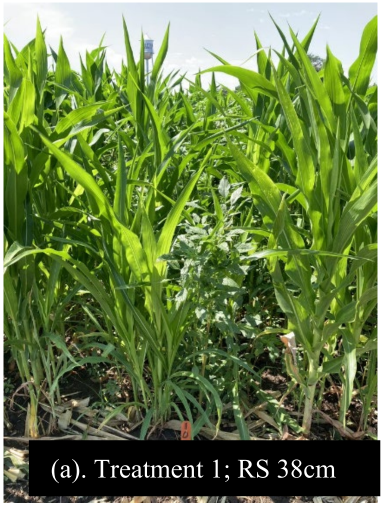
| | | |
|---|---|---|
| EPOST vs PRE fb LPOST | 1,09,541 vs 981* | 97,880 vs 3,222 * |
| EPOST vs EPOST fb LPOST | 109,541 vs 22,310 * | 97,880 vs 23,993 * |
| PRE fb LPOST vs EPOST fb LPOST | 9,81 vs 22,310 ** | 3,222 vs 23,993 ** |

[a] Data were square-root transformed before analysis; however back-transformed values are presented based om 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.

[c] Abbreviations: EPOST, early-POST application; LPOST, late-POST application.

[d] a priori contrasts; * = significant (P<0.0001); ** = significant (P<0.05); NS = non-significant (P>0.05)


(a). Treatment 1; RS 38cm


(b). Treatment 1; RS 76cm


(c). Treatment 2; RS 38cm


(d). Treatment 2; RS 76cm


(e). Treatment 3; RS 38cm


(f). Treatment 3; RS 76cm

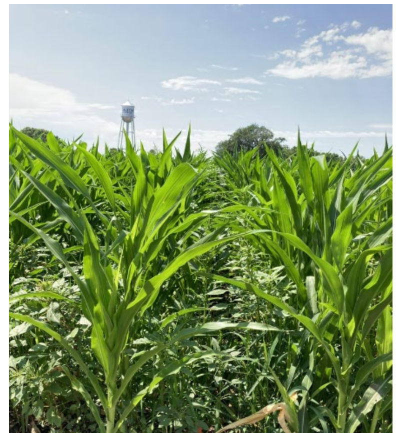

(g). Treatment 4; RS 38cm


(h). Treatment 4; RS 76cm


(i). Treatment 5; RS 38cm

(j). Treatment 5; RS 76cm

(k). Treatment 6; RS 38cm



(l). Treatment 6; RS 76cm

(m). Treatment 7; RS 38cm

(n). Treatment 7; RS 76cm

(o). Treatment 8; RS 38cm

(p). Treatment 8; RS 76cm

(q). Treatment 9; RS 38cm

(r). Treatment 9; RS 76cm

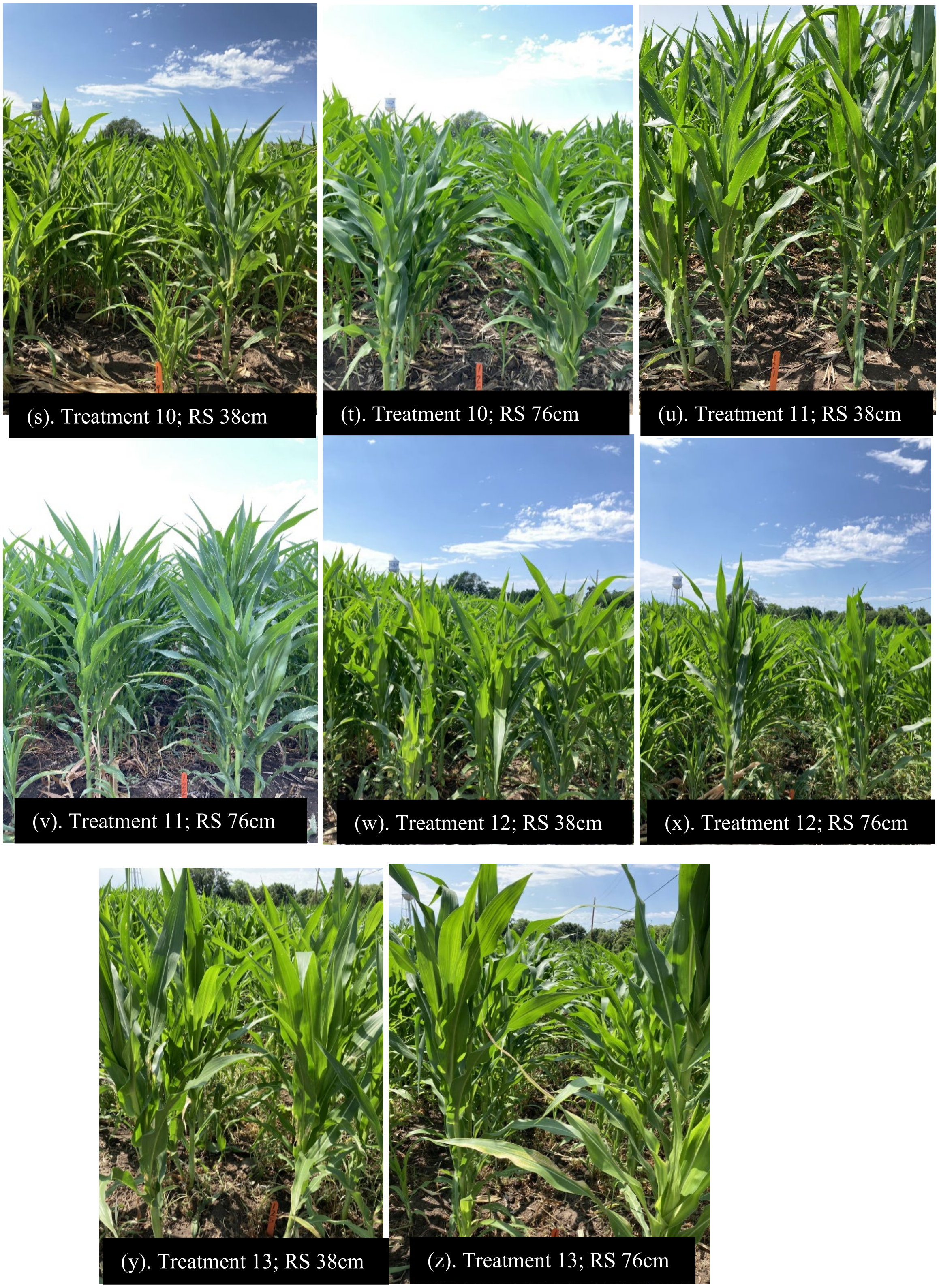



Figure 5.1. (a-z); Effect of herbicide programs and row spacing (RS) on control of multiple herbicide resistant Palmer amaranth in glyphosate/glufosinate-resistant corn 15 d after LPOST