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Control of acetolactate synthase-inhibiting herbicide-resistant Palmer amaranth (*Amaranthus palmeri*) with sequential applications of dimethenamid-*P* in dry edible bean

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Abstract

Biotypes of Palmer amaranth that are resistant to acetolactate synthase (ALS) inhibitor are becoming widespread in western Nebraska. There are limited effective postemergence (POST) herbicides labeled for ALS-inhibitor-resistant Palmer amaranth control in dry edible bean. The objective of this study was to evaluate the efficacy of dimethenamid-*P* in a sequential preemergence (PRE) fb followed by (fb) POST program at two POST application timings, the first and third trifoliate stages (V1 and V3, respectively), for controlling ALS-inhibitor-resistant Palmer amaranth in dry edible bean. A field study was conducted in 2019, 2020, and 2021 in Scottsbluff, NE. PRE-alone applications of pendimethalin + dimethenamid-*P* provided inconsistent Palmer amaranth control. Dimethenamid-*P* applied POST following a PRE application of pendimethalin + dimethenamid-*P* provided effective (>90%) Palmer amaranth control at 4 wk after V3 only at the V1 application timing in 2019. In 2020 and 2021 dimethenamid-*P* applied POST at V1 and V3 following a PRE application of pendimethalin + dimethenamid-*P* provided 99% and 98% Palmer amaranth control at 4 wk after V3, and 98% and 94% Palmer amaranth control at harvest, respectively. Palmer amaranth biomass was reduced by 95% to 99% and by 96% to 98% compared with the -nontreated control when dimethenamid-*P* was applied POST at V1 and V3, respectively, following a PRE application of pendimethalin + dimethenamid-*P* in 2020 and 2021. Application of a mixture of dimethenamid-*P* with imazamox + bentazon POST provided similar results to those of the fomesafen-containing treatments and dimethenamid-*P* alone POST. Dimethenamid-*P* applied POST following a PRE application of pendimethalin + dimethenamid-*P* resulted in similar yield as the fomesafen-containing treatments. If fomesafen is not an option due to the crop rotation interval restriction, using dimethenamid-*P* in a sequential PRE fb POST program is the only effective alternative to control ALS-inhibitor–resistant Palmer amaranth in Nebraska. The use of dimethenamid-*P* in a sequential PRE fb POST program, alone or mixed with foliar-active herbicides should be considered by dry edible bean growers who are dealing with ALS-inhibitor-resistant Palmer amaranth.

Introduction

Dry edible bean is the legume most directly consumed by people worldwide and is a major source of protein for human nutrition (Schmutz et al. 2014; Urrea et al. 2009). The United States produces more than 1.3 million tons of dry edible beans annually (Lucier and Davis 2020; Soltani et al. 2018a). Dry edible bean is a specialty crop in Nebraska and one of the major cash crops in western Nebraska and the High Plains region (Beiermann et al. 2021c; Urrea et al. 2009). Nebraska ranks fourth in dry edible bean production in the United States, representing an annual value of more than $94 million, wherein more than 70% of the dry edible bean production occurs in the Nebraska panhandle region (Lucier and Davis 2020; Soltani et al. 2018a; Thomas et al. 2001). Weed competition with dry edible bean can result in a significant yield loss because dry edible bean is a weak competitor with weeds, primarily because of its slow growth rate and short stature (Adjesiwor et al. 2020; Beiermann et al. 2021a). The potential yield loss in dry edible beans in the United States and Canada, if weeds are left unmanaged, is estimated be 71.4%, compared to 50% and 52.1% in corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.), respectively (Soltani et al. 2016, 2017, 2018a). The 71.4% yield loss estimated by

Soltani et al. (2018a) would represent a financial loss to the dry edible bean industry of more than $622 and $100 million annually in the United States and Canada, respectively.

The most common weed species in dry edible bean production in the United States include barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], common cocklebur (*Xanthium strumarium* L.), common lambsquarters (*Chenopodium album* L.), common ragweed (*Ambrosia artemisiifolia* L.), common sunflower (*Helianthus annuus* L.), foxtails (*Setaria* spp.), nightshades (*Solanum* spp.), redroot pigweed (*Amaranthus retroflexus* L.), velvetleaf (*Abutilon theophrasti* Medik.), and waterhemp [*Amaranthus tuberculatus* (Moq.) J. D. Sauer] (Burnside et al. 1998; Soltani et al. 2014; Wilson 2005; Wilson et al. 1980). Similar weed species are commonly reported in dry edible bean production areas in Nebraska; however, Palmer amaranth is a recent arrival to western Nebraska (Lawrence 2017; Sarangi and Jhala 2018a) and is not reported in most other states and counties that produce dry edible beans (CABI 2020). However, Palmer amaranth is spreading outside of its native range in North America; the U.S. Department of Agriculture estimated that 81% of land in the United States is suitable for Palmer amaranth establishment, and there is a high probability that Palmer amaranth could cause significant damage to agricultural fields, resulting in negative economic, environmental, and societal impacts (USDA-APHIS 2020).

Palmer amaranth is a dioecious, broadleaf, summer annual, and extremely competitive species in the Amaranthaceae family that infests agricultural fields in the United States (Ward et al. 2013). Palmer amaranth has a fluctuating emergence pattern that is affected by light, moisture, and temperature; it can germinate rapidly, completely germinating in 1 d under ideal conditions (Jha et al. 2010; Jha and Norsworthy 2009; Spaunhorst 2016; Steckel et al. 2004); and has a unique long emergence period that varies geographically based on the length of the local growing season. In the southeastern United States, Palmer amaranth emerges from May to September, and in the Midwest it emerges from May to August (McDonald et al. 2021). Palmer amaranth has evolved resistance to many herbicide modes of action (Heap 2021). In Nebraska, there is confirmed resistance to acetolactate synthase (ALS), hydroxyphenylpyruvate dioxygenase, triazine, photosystem II (PS II), and glyphosate (5-enolpyruvylshikimate-3-phosphate synthase) herbicides (Chahal et al. 2017). Because of herbicide resistance, extended emergence pattern, high fecundity, and fast growth rate, Palmer amaranth has become one of the most troublesome weeds in row crops in the United States (Chahal et al. 2015; Chandi et al. 2012; Korres et al. 2019). Palmer amaranth interference reduced corn, soybean, and peanut (*Arachis hypogaea* L.) yield by 91% at 8 plants m^{-1} row crop (Massinga et al. 2001), 68% at 10 plants m^{-1} row crop (Klingaman and Oliver 1994), and 67% at 5.2 plants m^{-1} row crop (Burke et al. 2007), respectively. Its interference in dry edible bean reduced yield by 77% at 2 plants m^{-1} row crop and a 5% yield reduction has been estimated to occur at only 4 plants 100 m^{-2} (Miranda et al. 2022).

ALS inhibitor-resistant biotypes of Palmer amaranth are widespread and found mainly in western Nebraska where crops are irrigated (Beiermann et al. 2021b; Lawrence 2017). There are effective preplant-incorporated (PPI) and preemergence (PRE) herbicides in dry edible bean for ALS inhibitor-resistant pigweed (*Amaranthus* spp.) species control in Nebraska (Knezevic et al. 2020); however, PRE and PPI herbicides provide weed control only for the early season (Beiermann et al. 2021a; Steckel et al. 2002). In contrast, postemergence (POST) herbicide options are limited, and ALS inhibitor-resistant pigweed species control is challenging (Beiermann et al. 2021c). Halosulfuron, imazamox, and imazethapyr are commonly used herbicides; however, they are not effective for controlling Palmer amaranth once ALS inhibitor-resistant biotypes become present in the field. Bentazon, a PS II-inhibitor herbicide applied POST is ineffective against pigweed species (Beiermann et al. 2021a; Chahal et al. 2017). Currently, the only effective POST herbicide for ALS inhibitor-resistant pigweed species control in dry edible bean is fomesafen (Wilson 2005); however, with the recent label update of fomesafen, corn planting is prohibited in western Nebraska for 18 mo after application (Anonymous 2021). Corn is the most widely used rotational crop following dry edible beans in western Nebraska; therefore, fomesafen is no longer an option for control of ALS inhibitor-resistant Palmer amaranth for most dry edible bean growers in the region.

A need exists for effective herbicide programs in dry edible bean to control ALS-inhibitor-resistant Palmer amaranth in western Nebraska. One effective option to manage weeds with extended periods of emergence and resistance to multiple herbicides, such as Palmer amaranth, is to use sequential herbicide applications, PRE followed by (fb) POST, of soil-residual herbicides to create overlapping control of emerging seedlings and achieve season-long control (Chahal et al. 2018; Goodrich et al. 2018; Jhala et al. 2015; McCloskey 2001; Steckel et al. 2002). It is essential that POST application of soil-residual herbicides occur while PRE applied soil-residual herbicides are still active in the soil to prevent weed escapes between application timings. Dimethenamid-*P*, a very-long-chain fatty acid (VLCFA) synthesis inhibitor (classified as a Group 15 herbicide by the Weed Science Society of America) herbicide labeled for POST use in dry edible bean, has the potential to effectively control Palmer amaranth in dry edible bean (Anonymous 2019; Knezevic et al. 2020; Sarangi and Jhala 2019; Soltani et al. 2018b; Wilson and Sbatella 2014). In fact, Kohrt and Sprague (2017b), Mueller and Steckel (2011), and Steckel et al. (2002) concluded that the use of VLCFA synthesis inhibitor herbicides is critically important for the management of herbicide-resistant Palmer amaranth and waterhemp since their residual activity may provide control throughout the season.

Dimethenamid-*P* is a soil-residual herbicide within the chloroacetamide chemical family that provides excellent dry edible bean crop safety and effectively controls a wide range of annual grass weeds, nutsedges, and small-seeded broadleaf weeds such as common lambsquarters and pigweed species that include triazine- and ALS inhibitor-resistant biotypes in several crops (Sarangi and Jhala 2019; Soltani et al. 2006, 2014). Limited research has been conducted with sequential PRE fb POST application programs of soil-residual herbicides in dry edible bean. The objective of this study was to evaluate dimethenamid-*P* efficacy applied sequentially PRE fb POST at two POST application timings, first trifoliate (V1) and third trifoliate (V3) growth stages, for control of ALS-inhibitor-resistant Palmer amaranth in dry edible bean.

Materials and Methods

Site Description

A field study was initiated in 2019 at the University of Nebraska-Lincoln Panhandle Research and Extension Center in Scottsbluff, Nebraska (41.893°N, 103.680°W) with additional treatments in the field experiments conducted in 2020 and 2021. However, due to multiple significant hail events occurring in mid-August 2019, causing total crop loss, only ALS inhibitor-resistant Palmer amaranth control and density data were presented from 2019. Soil type was a Tripp fine sandy loam (coarse silty, mixed, superactive, mesic Aridic Haplustolls; NCSS 2006; USDA-NRCS 2019) with a pH range from 7.8 to 8.3 and organic matter of 1.5% to 1.7%. The experiment area had natural populations of common lambsquarters, hairy nightshade (*Solanum physalifolium* Rusby), green foxtail [*Setaria viridis* (L.) P. Beauv.], and Palmer amaranth. Around 60% of Palmer amaranth population present at the experiment area is resistant to ALS-inhibiting herbicides; however, the proportion of resistant Palmer amaranth is spatially highly variable. The preceding crop in the experiment area had been sugar beet (*Beta vulgaris* L.) for several years.

Treatments and Experimental Design

This study was designed as a randomized complete block design with four replications. The dry edible bean cultivar 'La Paz' (ADM Seedwest, Decatur, IL) was planted on June 7, 2019, the cultivar 'SV6139GR' (Seminis, St. Louis, MO) was planted on May 26, 2020, and the cultivar 'Cowboy' (ADM Seedwest) was planted on June 1, 2021. All dry edible bean cultivars are pinto with type II (upright indeterminate) growth habits. Dry edible beans were planted at a density of 210,000 seeds ha^{-1} using a row spacing of 0.56 m, a standard row spacing for dry edible bean in the western United States. The plots consisted of four rows, 9.1 m in length. Nitrogen was applied at 112 kg ha^{-1} and P_2O_5 was applied at 45 kg ha^{-1} with a dry fertilizer applicator prior to experiment establishment. Glyphosate was applied at a rate of 1,261 g ae ha^{-1} + ammonium sulfate (AMS; WinField United, Arden Hills, MN) at 3% vol/vol + nonionic surfactant (NIS; WinField United) at 0.25% vol/vol within 1 d after dry edible bean planting to control emerged weeds. Irrigation was provided season-long using an overhead lateral-move irrigation system.

In the initial field experiment conducted in 2019, all treatments received a PRE application of pendimethalin + dimethenamid-*P*. Treatments consisted of PRE alone, PRE fb dimethenamid-*P* at V1, PRE fb dimethenamid-*P* at V3, PRE fb imazamox + bentazon + fomesafen at V1, and PRE fb imazamox + bentazon + fomesafen at V3. In the field experiments in 2020 and 2021, all treatments containing an herbicide received a PRE application of pendimethalin + dimethenamid-*P*. Treatments consisted of PRE alone, PRE fb imazamox + bentazon at V1, PRE fb imazamox + bentazon at V3, PRE fb dimethenamid-*P* at V1, PRE fb dimethenamid-*P* at V3, PRE fb imazamox + bentazon + dimethenamid-*P* at V1, PRE fb imazamox + bentazon + dimethenamid-*P* at V3, PRE fb imazamox + bentazon + fomesafen at V1, and PRE fb imazamox + bentazon + fomesafen at V3. Herbicide rates used for the PRE and POST application timings are shown in Table 1. A nontreated control was included in 2020 and 2021 for a comparison with other PRE fb POST herbicide programs and was considered as a weedy treatment.

Herbicides applied PRE were incorporated into the soil with 12.5 mm of irrigation within 24 h after application (Table 2). Herbicides applied POST with residual activity into the soil were incorporated within 24 h after their application with 6.25 mm of irrigation (Table 2). AMS at 18 g L^{-1} and methylated seed oil (MSO; WinField United) at 1.5% vol/vol were used with all POST applications that included imazamox, bentazon, or fomesafen. Herbicides were applied with a CO_2-pressurized backpack sprayer equipped with four TeeJet 11002 AIXR nozzles (Spraying Systems Co., Wheaton, IL) spaced at 0.51 m, calibrated to deliver 140 L ha^{-1} of spray solution at a pressure of 160 kPa and at a constant speed of 4.8 km h^{-1}.

Data Collection

Palmer amaranth visual control (%) was assessed every 2 wk after V3 treatment (WAV3) until harvest on a scale of 0% to 100%, where 0% represents no control and 100% represents complete control. Palmer amaranth density was recorded every two WAV3 until harvest by randomly placing two 0.5 m^2 quadrants in each plot. At harvest, density was assessed, and aboveground Palmer amaranth biomass was also recorded from the same quadrats. Palmer amaranth aboveground biomass was oven-dried at 60 C for 1 wk before weighed. To simplify the presentation of results, Palmer amaranth control and density at 4WAV3 were presented for 2019, 2020, and 2021 for appropriate comparison between treatments. Additionally, for 2020 and 2021, Palmer amaranth density and control at harvest were presented. Assessments of control, density, and biomass at harvest occurred on September 2, 2020, and September 1, 2021. Dry edible bean was harvested September 17, 2020, and September 10, 2021, by hand pulling all plants from 6.1 m of row from the center rows. Hand-pulled dry edible bean plants were later threshed with a Zurn 150 plot combine (ZURN USA Inc., Brooklyn Park, MN) serving as a stationary thresher. Weight and moisture per plot were recorded by an H2 Classic GrainGage (Juniper Systems & HarvestMaster Inc., Logan, UT) installed on the combine. Yields were adjusted to a 15% standard moisture. Dry edible bean yield was not assessed in 2019 because hail events produced total crop failure.

Statistical Analysis

Data were analyzed using R software version 4.0.2 (R Core Team 2020). Visual estimated Palmer amaranth control, Palmer amaranth dry biomass, and yield data were analyzed using a linear mixed model (LMM) with the *lmer* function in the LME4 package version 1.1-23 (Bates et al. 2015) along with ANOVA at the 5% level of significance. Palmer amaranth control (%) data for the nontreated control were excluded from the analysis because the values were 0% (Sarangi and Jhala 2018b). Improvement in normality and homogeneity for Palmer amaranth control residuals was gained through arcsine square root transformation, whereas for Palmer amaranth, dry biomass was gained through square root transformation; therefore, data were analyzed with arcsine square root or square root transformation. However, back-transformed mean values and their standard errors are presented for better interpretation (Onofri et al. 2010). Palmer amaranth density was analyzed using a generalized linear mixed-effect model (GLMM) with Poisson error distribution using the *glmer* function in the LME4 package version 1.1-23 (Bates et al. 2015) along with ANOVA at the 5% level of significance. The ANOVA was performed using the *Anova* function in the CAR package version 3.010 (Fox and Weisberg 2019). For LMM models, Type III Wald *F*-tests were conducted in the ANOVA, while Type III Wald chi-square tests were conducted in the ANOVA for GLMM models. Data from the 2019 growing season were analyzed separately from 2020 and 2021 growing seasons because treatments were not similar, where herbicide treatment was considered as fixed effect and replications were considered as random effects. For 2020 and 2021 growing seasons, herbicide treatment, year, and treatment by year interaction were considered fixed effects, and replications within years were considered as random effects. Treatment by year interaction was tested for each response variable to evaluate variability across years. ANOVA assumptions of normality and homogeneity of variance were tested by plotting residuals for the models assuming normal distributions

Table 1. Information on herbicides evaluated in dry edible bean for ALS-inhibitor-resistant Palmer amaranth control in field experiments conducted in 2019, 2020 and 2021.[a]

Common name	Trade name	Rate		Manufacturer
		PRE	POST	
		——g ai ha^{-1}——		
Pendimethalin	Prowl H_2O®	1,070	—	BASF Corporation, 26 Davis Drive, Research Triangle Park, NC 27709
Dimethenamid-*P*	Outlook®	685	420	BASF Corporation
Imazamox[b]	Raptor®	—	35	BASF Corporation
Bentazon[b]	Basagran®	—	675	BASF Corporation
Fomesafen[b]	Reflex®	—	280	Syngenta Crop Protection, 9 Davis Dr, Research Triangle, NC 27709

[a]Abbreviations: ALS, **acetolactate synthase**; POST, postemergence; PRE, preemergence.
[b]Herbicides applied POST included 18 g ammonium sulfate L^{-1} and 1.5% vol/vol methylated seed oil.

Table 2. Dates of PRE and POST application timings of herbicides evaluated in dry edible bean for ALS-inhibitor-resistant Palmer amaranth control in field experiments conducted in 2019, 2020 and 2021.[a]

Year	Date of application		
		POST[c]	
	PRE[b]	First trifoliate (V1)	Third trifoliate (V3)
2019	June 10	July 1	July 10
2020	May 28	June 15	June 22
2021	June 2	June 17	June 28

[a]Abbreviations: ALS, acetolactate synthase; POST, postemergence; PRE, preemergence.
[b]Herbicides applied PRE were incorporated into the soil with 12.5 mm of irrigation.
[c]Herbicides applied POST were incorporated into the soil with 6.25 mm of irrigation.

(Kniss and Streibig 2018; Onofri et al. 2010). Whenever a significant herbicide treatment and/or a treatment by year effect was found, means were separated using estimated marginal means (a.k.a. least squares means) using the *emmeans* function in the 'EMMEANS' package version 1.5.1 (Lenth 2020), and the 5% Fisher's protected LSD test was calculated using the *cld* function in the MULTCOMP package version 1.4-14 (Hothorn et al. 2008).

Results and Discussion

Year by treatment interactions for Palmer amaranth control at 4 WAV3 and at harvest in 2020 and 2021 were not significant at $\alpha = 0.05$; therefore, data at 4 WAV3 and at harvest from both years were combined and results were presented as an average control over 2 yr by assessment date. Year by treatment interactions for Palmer amaranth density at 4 WAV3 and at harvest were significant at $\alpha = 0.05$; there were greater densities in 2020 than in 2021. Therefore, data at 4 WAV3 and at harvest from both years were analyzed separately. Given that Palmer amaranth densities were different between 2020 and 2021 and to simplify results, Palmer amaranth biomass at harvest and dry edible bean yield were also analyzed separately because they may have been influenced by Palmer amaranth densities; therefore, results were presented for each year for these response variables.

Weather

Average temperatures in 2019 were lower than the 30-yr average; specifically, the average temperature in May was 24% lower compared with the 30-yr average (Table 3). In July and August 2019, temperatures were similar to the 30-yr average. Overall, in 2020 and 2021, average temperatures were greater than the 30-yr average by 5% and 6%, respectively (Table 3). In 2019, recorded rainfall was around 23% greater than the 30-yr average. In 2020 and 2021, rainfall was not as high as in 2019, both years were very dry compared with the 30-yr average, around 46% and 33% less rainfall, respectively (Table 3). Normal planting dates for dry edible bean in the region occur between mid-May to the first days in June to assure that the crop senesces before the first frost (Beiermann et al. 2021a). Because of frequent rainfall events, dry edible bean planting in 2019 was delayed until June 7th, which is late in the season compared with normal planting dates in the region. Planting in 2020 and 2021 occurred between the window of normal planting dates in the region. As irrigation was supplied during the three growing seasons, rainfall had minimal influence on study results, with the exception of delaying planting in 2019.

Palmer Amaranth Control

Dimethenamid-*P* + pendimethalin applied PRE alone provided 0% Palmer amaranth control at 4 WAV3 in 2019; while in 2020 and 2021, the PRE-alone application provided 96% control of Palmer amaranth (Table 4). Dimethenamid-*P* applied POST at V1 following the PRE application of dimethenamid-*P* + pendimethalin provided 95% control of Palmer amaranth; however, when dimethenamid-*P* was applied POST at V3, control was 70% at 4 WAV3 in 2019. Even though in 2019 the POST application of dimethenamid-*P* only provided effective (> 90%) control of Palmer amaranth when applied at V1, in 2020 and 2021, both POST application timings, V1 and V3, provided >98% Palmer amaranth control at 4 WAV3, similar to the fomesafen-containing treatments (Table 4). In 2020 and 2021, imazamox + bentazon applied POST at V1 provided the lowest Palmer amaranth control at 4 WAV3. However, when dimethenamid-*P* was mixed with imazamox + bentazon in the POST application, the control of Palmer amaranth increased to >97%.

Dimethenamid-*P* applied POST at V1 and V3, following PRE application of dimethenamid-*P* + pendimethalin, provided >94% control of Palmer amaranth at harvest in 2020 and 2021, which was similar to the control provided by the fomesafen-containing treatments (Table 5). Palmer amaranth control provided by the PRE-alone application of dimethenamid-*P* + pendimethalin declined from 96% at 4 WAV3 to 86% at harvest. The PRE-alone application of dimethenamid-*P* + pendimethalin along with imazamox + bentazon applied POST at V1 (91%) provided the lowest Palmer amaranth control at harvest. Imazamox + bentazon applied POST at V3 (99%) provided similar control as the fomesafen-containing treatments. As not all the Palmer amaranth populations

Table 3. Average monthly temperature and total rainfall during 2019, 2020, and 2021 growing seasons compared to the 30-yr average at the University of Nebraska Panhandle Research and Extension Center, Scottsbluff, NE.[a]

	Average temperature				Total rainfall			
Month	2019	2020	2021	30-yr average	2019	2020	2021	30-yr average
	C				mm			
May	10.0	13.9	12.8	13.1	99.8	55.4	34.5	73
June	18.5	21.4	22.4	19.1	47.2	31.0	25.1	63
July	22.9	23.5	24.0	22.9	57.2	35.4	84.6	47
August	21.7	23.2	21.6	21.7	84.8	0	11.2	36
September	18.2	15.8	18.2	16.6	23.9	14.7	15.5	35
Season (May–September)	18.3	19.6	19.8	18.7	312.9	136.5	170.9	254

[a]Temperature and rainfall data were obtained from the High Plains Regional Climate Center weather station (ID: Scottsbluff 2NW) located within 1 km of the field experiment site (https://hprcc.unl.edu/).

Table 4. ALS-inhibitor-resistant Palmer amaranth control and density at 4 WAV3 for 2019, 2020, and 2021 growing seasons.[a]

		Control[b]		Density[b]		
Herbicide treatment[a]	Application timing	2019	2020–2021	2019	2020	2021
		% (± SE)		plants m^{-2} (± SE)		
Nontreated control	—	NA	—	NA	24.9 (4) a	24 (2) a
Pendimethalin + dimethenamid-*P* (PRE)	PRE	0 (1) c	96 (1) bc	13 (3) a	4 (1) c	2.5 (1) c
PRE fb imazamox + bentazon	PRE fb V1	NA	95 (1) c	NA	2 (1) cd	8 (1) b
PRE fb imazamox + bentazon	PRE fb V3	NA	98 (1) abc	NA	9 (2) b	0.25 (0.25) d
PRE fb dimethenamid-*P*	PRE fb V1	95 (1) a	99 (1) ab	1.4 (0.6) bc	1.7 (0.7) cd	0.5 (0.3) d
PRE fb dimethenamid-*P*	PRE fb V3	70 (1) b	98 (1) abc	16.2 (3.5) a	0.5 (0.3) d	0.5 (0.3) d
PRE fb imazamox + bentazon + dimethenamid-*P*	PRE fb V1	NA	97 (1) abc	NA	3.3 (1) c	3.5 (1) c
PRE fb imazamox + bentazon + dimethenamid-*P*	PRE fb V3	NA	99 (1) ab	NA	0.5 (0.3) d	4 (1) c
PRE fb imazamox + bentazon + fomesafen	PRE fb V1	98 (1) a	99 (1) a	3.3 (1.1) b	0.1 (0.1) d	1.8 (0.6) cd
PRE fb imazamox + bentazon + fomesafen	PRE fb V3	99 (1) a	99 (1) a	0.2 (0.2) c	0.1 (0.1) d	0.5 (0.3) d

[a]Abbreviations: ALS, acetolactate synthase; fb, followed by; NA, not applicable as the treatment was not included in 2019; PRE, pendimethalin + dimethenamid-*P* applied preemergence; SE, standard error of the mean; V1, first trifoliate growth stage; V3, third trifoliate growth stage; 4 WAV3, 4 wk after V3 stage.
[b]Means (± SE) with no common letter(s) within the same column are significantly different at the LSD 5% level.

present in the study area were resistant to ALS-inhibiting herbicides, imazamox + bentazon applied POST provided >91% Palmer amaranth control. Additionally, the Palmer amaranth control provided by imazamox + bentazon at V1 increased to 97% with dimethenamid-*P* in the mix.

Equivalent results of a PRE-alone program as in 2020 and 2021 were reported by Kohrt and Sprague (2017a), when 83% to 98% control of glyphosate, atrazine, and ALS-inhibitor-resistant Palmer amaranth was achieved when S-metolachlor + atrazine, and S-metolachlor + mesotrione were used in a PRE-alone program in corn. On the other hand, inconsistent control provided by PRE-alone programs as observed in 2019 were previously reported in the literature. Liu et al. (2021b) and Chahal et al. (2018) reported ineffective control (62% to 72% and 12% to 15%, respectively) of multiple herbicide–resistant Palmer amaranth in corn when PRE-alone treatments were used. Inconsistent Palmer amaranth control provided by PRE-alone programs was attributed to the degradation of the residual activity of soil-residual herbicides as the soybean season advanced (Sarangi and Jhala 2019; Shyam et al. 2021).

Comparable sequential PRE fb POST program results were reported by Steckel et al. (2002) and Jhala et al. (2015). Steckel et al. (2002) reported that sequential PRE fb POST applications of S-metolachlor and acetochlor, when POST applications were mixed with dicamba to control emerged weeds, provided more than 83% and 89% control of waterhemp in corn, respectively. Similarly, Jhala et al. (2015) reported >90% control of waterhemp when acetochlor was mixed with glyphosate in the PRE and POST applications, in a PRE fb early-POST (V2 to V3) and late-POST (V4 to V5) program in soybean. Comparable sequential PRE fb POST program results without foliar-active herbicides in the POST application timing were reported by Moomaw et al. (1983) and Goodrich et al. (2018). Moomaw et al. (1983) reported in corn that sequential PRE fb POST applications of metolachlor + cyanazine fb metolachor and alachlor + cyanazine fb alachlor effectively controlled redroot pigweed. Likewise, in sorghum (*Sorghum bicolor* L. Moench), pyroxasulfone applied POST 2 wk after its PRE application provided 94% to 96% waterhemp control (Goodrich et al. 2018).

Palmer Amaranth Density and Biomass

Palmer amaranth control data were reflected in the density and biomass data. In 2019, the PRE-alone application of dimethenamid-*P* + pendimethalin along with dimethenamid-*P* applied POST at V3, resulted in the greatest Palmer amaranth density at 4 WAV3 with 13 and 16 plants m^{-2}, respectively (Table 4). However, Palmer amaranth density at 4 WAV3 was similar to that of the fomesafen-containing treatments, when dimethenamid-*P* was applied POST at V1 (1 plant m^{-2}). In 2020 and 2021, the nontreated control resulted in the greatest density at 4 WAV3. Within the herbicide treatments, imazamox + bentazon applied POST resulted in the greatest Palmer amaranth density at 4 WAV3 in

Table 5. ALS-inhibitor-resistant Palmer amaranth control, density, and biomass at harvest for 2020 and 2021 growing seasons.[a]

Herbicide treatment[a]	Application timing	Control[b]	Density[b]		Biomass[b]	
		2020–2021	2020	2021	2020	2021
		% (± SE)	——plants m^{-2} (± SE)—		————g m^{-2} (± SE)———	
Nontreated control	—	—	36.1 (3.4) a	28.8 (2.7) a	2,430 (454) a	1,060 (213) a
Pendimethalin + dimethenamid-*P* (PRE)	PRE	86 (1) c	1.0 (0.5) b	4.2 (1.0) c	3 (15) b	114 (70) b
PRE fb imazamox + bentazon	PRE fb V1	91 (1) bc	1.5 (0.6) b	11 (1.7) b	9 (28) b	25 (33) bc
PRE fb imazamox + bentazon	PRE fb V3	99 (1) a	0.2 (0.2) b	0.5 (0.4) e	0.1 (2) b	0.1 (1) c
PRE fb dimethenamid-*P*	PRE fb V1	98 (1) ab	0.2 (0.2) b	0.7 (0.4) de	111 (97) b	2 (10) bc
PRE fb dimethenamid-*P*	PRE fb V3	94 (1) abc	0.5 (0.3) b	0.5 (0.4) e	92 (89) b	22 (31) bc
PRE fb imazamox + bentazon + dimethenamid-*P*	PRE fb V1	97 (1) ab	0 (0) b	5.2 (1.1) c	0 (0) b	18 (28) bc
PRE fb imazamox + bentazon + dimethenamid-*P*	PRE fb V3	99 (1) a	0.2 (0.2) b	0.5 (0.4) e	0.2 (4) b	0.2 (3) c
PRE fb imazamox + bentazon + fomesafen	PRE fb V1	99 (1) a	0.2 (0.2) b	1.2 (0.6) de	5 (20) b	10 (21) bc
PRE fb imazamox + bentazon + fomesafen	PRE fb V3	99 (1) a	0 (0) b	2.5 (0.8) cd	0 (0) b	0.1 (2) c

[a]Abbreviations: ALS, acetolactate synthase; fb, followed by; PRE, pendimethalin + dimethenamid-*P* applied preemergence; SE, standard error of the mean; V1, first trifoliate growth stage; V3, third trifoliate growth stage.
[b]Means (± SE) with no common letter(s) within the same column are significantly different at the LSD 5% level.

both years, 2020 and 2021, with 9 plants m^{-2} when applied at V3 in 2020 and 8 plants m^{-2} when applied at V1 in 2021 (Table 4). The PRE-alone application of dimethenamid-*P* + pendimethalin resulted in the second greatest Palmer amaranth density at 4 WAV3 in both years 2020 and 2021 with 4 and 2.5 plants m^{-2}, respectively. Dimethenamid-*P* applied POST at V1 and V3 resulted in similar Palmer amaranth densities at 4 WAV3 as the fomesafen-containing treatments in both years 2020 and 2021. Imazamox + bentazon + dimethenamid-*P* applied POST at both V1 and V3 resulted in similar Palmer amaranth density at 4 WAV3 as the fomesafen-containing treatment in 2021; however, in 2020, only the V1 application timing of imazamox + bentazon + dimethenamid-*P* resulted in similar Palmer amaranth density as the fomesafen-containing treatments.

The nontreated control demonstrated the greatest density and biomass accumulation of Palmer amaranth at harvest in 2020 and 2021; however, densities were greater in 2020 by 20%, and dry biomass was 56% greater (Table 5). Although there were more statistical differences in Palmer amaranth density between herbicide treatments at the 4 WAV3 assessment date in 2020, at harvest all herbicide treatments resulted in similar Palmer amaranth densities and biomass accumulation. There were higher Palmer amaranth densities (0.1 to 4 plants m^{-2}) in the herbicide treatments at 4 WAV3 in 2020 than at harvest time (0 to 1.5 plants m^{-2}). This likely occurred due to the crop canopy closure that controlled the small flushes of Palmer amaranth via shading as the season progressed, resulting in Palmer amaranth densities of fewer than 1.5 plants m^{-2} in all herbicide treatments. Palmer amaranth biomass was reduced to 111 and 92 g m^{-2} (i.e., 95% and 96% reduction relative to the nontreated control) when dimethenamid-*P* was applied alone POST at V1 and V3, respectively.

Similar to 2020, in 2021 all herbicide treatments resulted in reduced densities and dry biomass accumulation of Palmer amaranth at harvest (Table 5); however, there were more statistical differences among treatments. Within the treatments containing an herbicide, similar to the 4 WAV3 assessment date, imazamox + bentazon applied POST at V1 provided the greatest Palmer amaranth density (11 plants m^{-2}), where density was reduced by 62% compared with the nontreated control. The best-performing treatments for reducing Palmer amaranth densities were imazamox + bentazon applied POST at V3, dimethenamid-*P* applied POST at V1 and V3, imazamox + bentazon + dimethenamid-*P* applied POST at V3, and imazamox + bentazon + fomesafen applied POST at V1, which reduced Palmer amaranth densities to 0.5, 0.7, 0.5, 0.5, and 1.2 plants m^{-2}, respectively, compared with the nontreated control (29 plants m^{-2}). Palmer amaranth biomass was more reduced when imazamox + bentazon (25 g m^{-2}), imazamox + bentazon + dimethenamid-*P* (18 g m^{-2}), and imazamox + bentazon + fomesafen (10 g m^{-2}) were all applied POST at V3. Palmer amaranth biomass provided by dimethenamid-*P* applied POST at V1 or V3, respectively, was similar to the aforementioned treatments. Palmer amaranth biomass was reduced to 2 and 22 g m^{-2} when dimethenamid-*P* was applied POST at V1 and V3, respectively.

Consistent Palmer amaranth and pigweeds species biomass and density reductions provided by sequential PRE fb POST programs of VLCFA-inhibiting herbicides were previously reported in the literature. Moomaw et al. (1983) reported in corn that sequential PRE fb POST applications of metolachlor + cyanazine fb metolachor and alachlor + cyanazine fb alachlor reduced redroot pigweed density to 0.9 and 0.7 plants m^{-2}, respectively. Sarangi and Jhala (2019) reported that PRE fb POST programs in soybean including VLCFA-inhibiting herbicides resulted in 96% to 100% Palmer amaranth biomass reduction compared with the nontreated control. Similarly, Jhala et al. (2015) reported reductions of waterhemp density and biomass to ≤2 plants m^{-2} and ≤12 g m^{-2} when acetochlor was mixed with glyphosate in the PRE and POST applications, in a PRE fb early-POST (V2 to V3) and late-POST (V4 to V5) program in soybean.

Differences in the POST application timing of imazamox + bentazon + fomesafen and imazamox + bentazon suggest that imazamox, bentazon, or fomesafen provide poor residual control (Table 5). Dimethenamid-*P* applied POST at V3 resulted in high Palmer amaranth density at 4 WAV3 in 2019, but the application timing was too late to overlap residual control with the PRE herbicides. In 2020, we did not observe Palmer amaranth flushes after the PRE application; consequently, the PRE-alone treatment as well as the sequential PRE fb POST programs, resulted statistically in the same density and biomass accumulation. However, in 2021, we did have Palmer amaranth flushes after the PRE application; however, those Palmer amaranth flushes occurred after the V3 application timing. Consequently, in 2020 and 2021, dimethenamid-*P* applied POST at V1 and V3 performed equally as the fomesafen-containing treatments, providing similar reductions in Palmer amaranth density and biomass. Mixing dimethenamid-*P* with imazamox + bentazon POST also performed similarly to the fomesafen-containing treatments and dimethenamid-*P* alone POST.

Table 6. Dry edible bean yield for 2020 and 2021 growing seasons.[a]

Herbicide treatment[a]	Application timing	Dry edible bean yield[b] 2020	2021
		kg ha^{-1} (± SE)	
Nontreated control	—	88 (367) d	1,100 (476) c
Pendimethalin + dimethenamid-*P* (PRE)	PRE	5,210 (367) ab	4,330 (476) b
PRE fb imazamox + bentazon	PRE fb V1	4,330 (367) bc	4,730 (476) ab
PRE fb imazamox + bentazon	PRE fb V3	4,190 (367) c	5,720 (476) a
PRE fb dimethenamid-*P*	PRE fb V1	4,370 (367) abc	5,220 (476) ab
PRE fb dimethenamid-*P*	PRE fb V3	4,870 (367) abc	5,300 (476) ab
PRE fb imazamox + bentazon + dimethenamid-*P*	PRE fb V1	4,350 (367) abc	5,020 (476) ab
PRE fb imazamox + bentazon + dimethenamid-*P*	PRE fb V3	5,260 (367) a	5,500 (476) ab
PRE fb imazamox + bentazon + fomesafen	PRE fb V1	5,160 (367) ab	5,760 (476) a
PRE fb imazamox + bentazon + fomesafen	PRE fb V3	4,640 (367) abc	4,780 (476) ab

[a]Abbreviations: fb, followed by; PRE, pendimethalin + dimethenamid-*P* applied preemergence; SE, standard error of the mean; V1, first trifoliate growth stage; V3, third trifoliate growth stage.
[b]Means (± SE) with no common letter(s) within the same column are significantly different at the LSD 5% level.

The poor Palmer amaranth control from dimethenamid-*P* applied POST at V3 in 2019 may have been caused by multiple factors, but it was primarily due to the dissipation or degradation of the PRE soil-residual herbicides prior to Palmer amaranth emergence. Average temperatures were cooler between dry edible bean planting and the V3 application timing in 2019 (19.2 C) by 1.1 C and 3.3 C compared with 2020 and 2021, respectively. The cooler temperatures in 2019 might have contributed to the delay in the reach of dry edible bean growth stages, due to lower growing degree day accumulation, during that delay the PRE soil-residual activity could have dissipated. Additionally, Liu et al. (2021a) reported that Palmer amaranth populations from western Nebraska had between two to four emergence flushes, which occurred from early May to early June, when the mean temperature was ≥21 C. In 2019, weather conditions may have been ideal for Palmer amaranth emergence within the V1 and V3 timeframe as average temperatures were >21 C. While in 2020 and 2021 average temperatures were >21 C earlier in the season, which may have caused earlier Palmer amaranth emergence in both years. The longevity of soil-residual herbicides may vary year to year along with the timing of Palmer amaranth emergence, depending on environmental conditions that are difficult to predict.

Dry Edible Bean Yield

The nontreated control had the lowest dry edible bean yield in both 2020 and 2021 (Table 6). All the treatments containing an herbicide in 2020 and 2021 resulted in greater dry edible bean yield compared with the nontreated control. In 2020, within the herbicide treatments, imazamox + bentazon applied POST at V3 provided the lowest dry edible bean yield (4,190 kg ha^{-1}), whereas the greatest yield was provided by imazamox + bentazon + dimethenamid-*P* applied POST at V3 (5,260 kg ha^{-1}), which was similar to the fomesafen-containing treatments and dimethenamid-*P* applied POST at V1 (4,370 kg ha^{-1}) and V3 (4,870 kg ha^{-1}). In 2021, within the treatments containing an herbicide, the PRE-alone application of dimethenamid-*P* + pendimethalin provided the lowest dry edible bean yield (4,330 kg ha^{-1}). The greatest yield was provided by imazamox + bentazon applied POST at V3 (5,720 kg ha^{-1}) and imazamox + bentazon + fomesafen applied POST at V1 (5,760 kg ha^{-1}), which were similar to what was provided by dimethenamid-*P* and imazamox + bentazon + dimethenamid-*P* both applied POST at V1 and V3.

Dry edible bean yield was reduced by 98% and 81% in the nontreated controls compared to the top-yielding treatments in both years 2020 and 2021, respectively. Soltani et al. (2018a) estimated that the potential yield loss in dry edible beans in Nebraska if weeds are left unmanaged would be 59%. However, Palmer amaranth was not widespread across Nebraska when Soltani et al. (2018a) reported the aforementioned yield loss, and Palmer amaranth yield loss may be more severe than other weed species commonly found within dry edible bean. In 2020 and 2021, dry edible bean yield potential was protected by dimethenamid-*P* applied POST at V1 and V3 resulting in similar yields as the fomesafen-containing treatments (Table 6).

Even when there were few yield differences among treatments containing an herbicide (Table 6), differences in Palmer amaranth biomass can relate to seed production. Previous studies reported a strong positive correlation between Palmer amaranth biomass and seed production, suggesting that as biomass increases, so does seed production (Mahoney et al. 2021; Miranda et al. 2022; Schwartz et al. 2016; Spaunhorst et al. 2018; Webster and Grey 2015). Liu et al. (2021b) and Norsworthy et al. (2016) concluded that late-emerging Palmer amaranth plants have negligible effects on crop yields; however, if those plants are left uncontrolled, even if they are small, they can set seeds into the soil and carry to future issues. For instance, late-emerging Palmer amaranth plants reported in cotton (*Gossypium hirsutum* L.) fields in Texas were able to produce 1,390 seeds m^{-2} (Werner et al. 2020). Given the high seed production of late-emerging Palmer amaranth plants, it is highly important to control every single plant for managing soil seedbank and reduce their persistence in a long-term weed management perspective.

Conclusion and Practical Implications

ALS-inhibitor resistance is segregating within the Palmer amaranth population present in the experiment area; consequently, imazamox + bentazon efficacy varied year to year depending on the timing of POST herbicide applied with respect to density and biomass. Although imazamox + bentazon controlled Palmer amaranth, resistance is a concern as several Palmer amaranth biotypes are ALS inhibitor-resistant worldwide (Heap 2021). Dimethenamid-*P* applied POST following a PRE application of dimethenamid-*P* + pendimethalin provided equivalent Palmer amaranth density and biomass reduction as when dimethenamid-*P* was mixed with imazamox + bentazon, or when fomesafen was applied, except in 2019 when the V3 application timing failed to provide adequate control, likely due to environmental conditions that influenced the degradation of the PRE soil-residual herbicides and the Palmer amaranth emergence. If the Palmer amaranth population were completely resistant to ALS-inhibiting herbicides, treatments containing dimethenamid-*P* applied POST would still have provided adequate control of Palmer amaranth while treatments of imazamox + bentazon applied alone would likely have provided poor control. If fomesafen is not an option due to the crop rotation interval restriction, dimethenamid-*P* applied sequentially PRE fb POST or POST after the application of an effective PRE program is the only remaining effective option for ALS inhibitor-resistant Palmer amaranth management in dry edible bean. Although dimethenamid-*P* applied alone in a sequential PRE fb POST program provided >90% Palmer amaranth control, it is suggested that this herbicide be applied in a mixture with other herbicides to mitigate herbicide resistance. The use of dimethenamid-*P* in a sequential PRE fb POST program, alone or in a mixture with foliar-active herbicides should be considered by dry edible bean growers who are managing ALS inhibitor-resistant Palmer amaranth.

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