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Optimizing weed management in chickpea through planting date and fall-applied residual herbicides

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Research Article

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Nomenclature:
Carfentrazone; dimethenamid; pendimethalin; pyridate; pyroxasulfone; sulfentrazone; common mallow, *Malva neglecta* L.; kochia, *Bassia scoparia* L.; redroot pigweed, *Amaranthus retroflexus* L.; chickpea, *Cicer arietinum* L.

Keywords:
Chickpea; crop injury; early planting; fall application; weed count

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Abstract

Chickpea provides significant diversification benefits for semiarid cropping systems. However, the crop's slow emergence and open canopy growth habit make it a poor competitor against rapidly growing weeds during the early season. In 2022 and 2023, field experiments were conducted at two sites, the Montana State University (MSU) Southern Agricultural Research Center, in Huntley, and the MSU Post Agronomy Farm, in Bozeman, to evaluate broadleaf weed management by integrating planting date and fall-applied,soil-active herbicides to chickpea. Application of dimethenamid at 950 g ai ha^{-1} + pendimethalin at 1.68 kg ai ha^{-1}, and carfentrazone + sulfentrazone at 238 g ai ha^{-1} resulted in better protection of yield against weeds and provided longer residual activity for control of kochia, redroot pigweed, and common mallow by reducing weed density to 10 to 20 plants m^{-2} compared with 50 to 70 plants m^{-2} in an untreated check. Pyridate (700 g ai ha^{-1}) applied postemergence was required with these treatments to eliminate escaped weeds. Early planting provided an additional biomass reduction compared to late planting due to the crop emergence before or around the same time as the weeds. Planting date had no effect on weed density or grain yield in plots that received dimethenamid + pendimethalin and carfentrazone + sulfentrazone, suggesting that these herbicides can extend the planting date window. These herbicide programs and early planting can be integrated with other weed management tactics for additional weed management options in chickpea.

Introduction

Crop diversification is essential for sustainable agriculture, yet semiarid cropping systems in the U.S. Great Plains are dominated by a simplified dryland wheat-fallow rotation (Lenssen et al. 2007) that helps store water during the fallow period (Hansen et al. 2012). However, a significant challenge of the wheat-fallow rotation is the dominance of weeds, which can result in substantial losses of water and soil resources (Hansen et al. 2012; McVay et al. 2013). Weed management during the wheat phase of the rotation is usually achieved through multiple applications of broad-spectrum postemergence herbicides. Unfortunately, the overuse of herbicides has led to the selection of herbicide-resistant weed biotypes (Tidemann et al. 2023). Diversifying the wheat-fallow rotation with chickpea can disrupt the weed life cycle (Lenssen et al. 2007) and boost soil conservation (Zhang et al. 2024). Also, rotating herbicides with different modes of action used alone or in tank mixtures can help delay the selection of resistant biotypes (Beckie 2007; Kumar and Jha 2015).

Chickpea production in the U.S. Great Plains contributes US$172.2 million in revenue from 148,000 ha, of which Montana's share was US$72 million from 70,000 ha in 2023 (USDA-NASS 2023). Chickpea has been shown to increase the wheat protein content by 16% and grain yield of subsequent wheat by 21%, and overall farm profitability by 81%, in pulse crop stubbles compared with wheat stubbles (Miller et al. 2002). However, weed competition poses a major concern in chickpea production due to the crop's slow germination and early growth, and open canopy growth habit (Campbell 2016). Weeds can outcompete the chickpea crop, leading to resource losses, poor crop stand, and management challenges (Schwinghamer and Van Acker 2008; Yenish 2007).

Given these challenges, exploring effective weed management strategies in chickpea cultivation is essential. A promising weed management approach is the timely planting of chickpea, which can enhance crop growth and competitiveness against weeds (Jha et al. 2017). This helps in improving crop-weed competition by taking advantage of temperature, photoperiod, and soil moisture (Shamsi 2010). The optimum planting date is crucial for managing resource loss and crop-weed competition, which can be influenced by local weather conditions and weed abundance (Tidemann et al. 2023). When properly implemented, planting date manipulation can influence crop-weed competition in an asymmetric manner for the crop, providing chickpea with a head start against the early flushes of weeds (Kwabiah 2004). While timely planting is crucial, effective weed management in conventional chickpea cultivation often necessitates the strategic use of herbicides, especially in environments with variable precipitation and challenging growing conditions (Norsworthy et al. 2012).

Preemergence herbicides face activation challenges in semiarid climates due to limited precipitation. Also, widely used herbicides such as carfentrazone + sulfentrazone can inadvertently damage chickpea planted at shallow depths and in soil with a high pH. Residual preemergence-applied herbicides can be timed with fall precipitation to enhance activation and minimize crop damage (Kumar and Jha 2015). Additionally, soil-active herbicides applied before weed emergence can be strategically employed in the fall, following wheat harvest and fallow field preparation, to maximize activation potential (Kumar and Jha 2015; Schmidt et al. 2001). Other benefits of applying herbicides in the fall include reduced grower workload, timely planting of chickpea in the spring, and minimizing the need for extensive field scouting later in the season. However, weed control with residual herbicides can be inconsistent depending on environmental conditions (Carey and Defelice 1991). In the dryland wheat-pulse crop rotations of the U.S. Great Plains, the strategic use of optimum planting dates and fall-applied soil-residual herbicides remains underused, despite their potential to address critical agronomic challenges. By integrating these practices, growers could significantly improve weed management, crop productivity, and system sustainability, ultimately maximizing the benefits of wheat-chickpea rotations in this region. To address this knowledge gap, we conducted trials at two locations in Montana to assess preemergence herbicides in combination with different planting dates as a tool to manage weeds in spring-planted dryland chickpea.

Materials and Methods

Site Description

Field experiments were conducted in 2022 and 2023 at two separate locations in Montana: the Montana State University Southern Agricultural Research Center (SARC), in Huntley (45.924°N, 108.245°W), and the Montana State University Post Agronomy Farm (PAF), in Bozeman (45.404°N, 111.0929°W). Average monthly air temperature and precipitation data were collected from the local weather station at each experimental site and are presented in Tables 1 and 2 (NOAA 2024). The soil type, organic matter, and soil pH at both sites are listed in Table 3 (USDA-NRCS 2023). Kochia and redroot pigweed were the dominant weed species at SARC. Wild mustard (*Sinapis arvensis* L.) and common mallow were the dominant weed species at PAF. The treatment list was designed as follows: half of the treatments were preemergence herbicides applied alone, and the other half consisted of preemergence followed by postemergence applications. This was designed to evaluate the residual activity of preemergence herbicides alone and to determine whether a postemergence herbicide treatment would be required.

Experimental Design

Experiments were conducted under dryland, no-till conditions in a split-plot design with four replications with plot sizes of 8 m long by 3 m wide at both sites. The main plots were planting schedules, and the subplots were herbicide treatments. Residual preemergence herbicides were applied at the recommended label rates during the last week of October each year before ground freeze (Table 4). The applications were timed with precipitation for maximum activation and an average of 0.3 to 0.6 cm of rain fell within a week of herbicide application each year, which facilitated activation. In the following spring, chickpea cultivar Orion inoculated with *rhizobium* was planted (3.5- to 5-cm depth) using a small-plot no-till drill at 40 plants m^{-2} (225 kg ha^{-1}) in the first week of May for early planting and in the third week of May for late planting. Chickpea plants were managed based on standard agronomic practices throughout the season to optimize yield. The postemergence herbicide pyridate (Tough 5 EC; Belchim, Wilmington, DE) at 700 g ae ha^{-1} was applied when plants were 5 to 10 cm tall. All herbicides were applied using a CO_2-pressurized backpack sprayer equipped with extended-range flat-fan XR8003 nozzles (TeeJet Technologies, Glendale Heights, IL) set to deliver 93 L ha^{-1} at 276 kPa. Chickpea was fertilized with diammonium phosphate according to soil test reports and Montana State University recommendations for chickpea production (McVay et al. 2013).

Data Collection

Chickpea establishment was recorded by taking stand counts from two random 1-m row lengths in each plot 14 d after crop emergence (DAE). Concurrently, crop phytotoxicity symptoms, including yellowing, necrosis, and burning, were visually evaluated. Weed density was counted twice from a 0.5-m × 0.5-m area within each plot, initially at 28 DAE when weeds were 5 to 10 cm tall, and subsequently at 28 d after postemergence application (28 DAT) each year at both locations. Weed biomass at 28 DAT was measured at chickpea flowering from two 0.5-m × 0.5-m quadrats per plot each year. The biomass samples were weighed after being oven-dried at 60 C for 24 h. Chickpea was harvested with a small-plot combine in the last week of October in both years, and all samples were cleaned and air-dried to determine grain weight, moisture percentage, and test weight.

Statistical Analyses

Data were subjected to a linear mixed model using the *lME4* function from the lMER package in R Studio version 4.0 (Bates et al. 2015). Herbicide treatments, planting dates, and experiment sites were included as fixed effects in the model, whereas year and replications were treated as random effects. The assumptions of normality, independence, and equal variance were assessed for each analysis using diagnostic plots and ANOVA tables. No data transformations were required because the assumptions were met in all cases. If the interaction effect of site or year was significant, data were analyzed and presented separately. When differences between sites were nonsignificant, data were combined for the sites. Estimated marginal means were calculated for each herbicide treatment and planting date combination, and comparisons were

Table 1. Average monthly air temperature and total precipitation from October to September during the 2022 and 2023 growing seasons and long-term averages at the SARC location.

Month	Average monthly temperature			Total monthly precipitation		
	1998–2023	2021–2022	2022–2023	1998–2023	2021–2022	2022–2023
	C			mm		
October	9.3	9.6	10.0	43.7	32.3	38.6
November	2.1	4.1	−4.6	60.2	26.4	19.3
December	−2.8	−6.3	−11.6	51.8	19.3	13.0
January	−4.2	−4.9	−2.9	26.9	6.4	6.4
February	−1.9	−4.6	−4.6	23.6	13.0	13.0
March	2.2	2.1	−3.7	32.5	16.4	19.3
April	7.4	3.1	6.5	30.7	23.2	45.0
May	12.9	12.1	15.4	17.8	15.2	41.6
June	18.1	17.3	17.9	17.3	30.9	47.2
July	22.7	23.3	21.8	18.0	13.3	13.0
August	21.8	22.7	22.1	16.3	11.4	14.9
September	15.8	18.3	17.4	25.9	19.3	26.9

Table 2. Average monthly air temperature and total precipitation from October to September during the 2022 and 2023 growing seasons and long-term averages at the PAF location.

Month	Average monthly temperature			Total monthly precipitation		
	1998–2023	2021–2022	2022–2023	1998–2023	2021–2022	2022–2023
	C			mm		
October	7.5	9.5	9.2	46.7	38.1	67.3
November	0.3	4.9	−4.4	62.5	5.6	29.0
December	−4.4	−0.8	−4.4	72.9	37.8	28.7
January	−3.9	−2.7	−3.7	23.1	16.5	24.6
February	−3.4	−6.4	−3.3	24.4	15.0	23.4
March	1.9	0.2	−2.3	32.5	18.3	59.9
April	6.2	4.9	5.4	37.8	55.9	13.0
May	10.9	11.9	13.8	20.6	114.8	24.6
June	15.3	14.9	14.7	16.8	57.7	115.8
July	20.1	20.5	19.3	13.5	19.6	43.2
August	19.2	20.8	20.2	16.0	22.1	35.6
September	14.4	16.9	17.3	23.4	14.2	22.1

Table 3. Dates of agronomic practices and soil properties of the two experimental locations in Montana.[a]

Agronomic practice	Southern Agricultural Research Center		Post Agronomy Farm	
	2021–2022	2022–2023	2021–2022	2022–2023
Fall herbicide application	October 27, 2022	October 21, 2023	October 30, 2022	October 26. 2022
Early planting	May 6, 2022	April 27, 2023	April 20, 2022	May 1. 2023
Late planting	May 20, 2022	May 16, 2023	May 5, 2022	May 20, 2023
POST herbicide application	June 26, 2022	June 12, 2023	June 27, 2022	June 6. 2023
Chickpea harvesting	August 10, 2022	September 14, 2023	September 13. 2022	September 18, 2023
Soil type	Fort Collins clay loam		Amsterdam silt loam	
Soil classification	fine-loamy, mixed, superactive, mesic Aridic Haplustalf		fine-silty, mixed, superactive, frigid Typic Haplustolls	
Organic Matter	1.2%		1.9-2.2%	
pH	7.8–8.0		7.6–8.0	

[a]Abbreviation: POST, Postemergence.

Table 4. Herbicides, rates used, and trade name and manufacturer information.[a]

Herbicide	Trade name	Rate	Manufacturer[b]
		g ai ha^{-1}	
Carfentrazone + sulfentrazone	Spartan Charge	238	FMC
Dimethamid + pendimethalin	Outlook + Prowl H2O	950 + 2,130	BASF
Pyroxasulfone	Zidua SC	126	BASF
Pyridate	Tough 5EC	700	Belchim

[a]All treatments contained crop oil concentrate (Kalo, Inc., Overland Park, KS) at 10 ml L^{-1}.
[b]Manufacturer locations: BASF, Research Triangle Park, NC; Belchim, Wilmington, DE; FMC, Philadelphia, PA.

conducted using Fisher's protected LSD test with a significance level of $\alpha < 0.05$. The estimated marginal means (EMMEANS) package was used for the estimation of marginal means and post hoc comparisons.

Results and Discussion

Effect of Planting Date and Herbicides on Weed Density and Biomass

Compared with an untreated check, weed density and biomass were reduced as a result of herbicide applications and planting date

Table 5. Overall ANOVA for effects of herbicide application and panting date on weed density, biomass, and grain yield.[a,b]

		Weed density				Weed biomass		Grain yield	
		28 DAE		28 DAT		28 DAT			
Source of variation	Df	*F*-value	P-value	*F*-value	P-value	*F*-value	P-value	*F*-value	P-value
Whole plot									
Planting date	1	2.4	NS	7.4	**	8.3	**	7.6	**
PD × Year	1	1.1	NS	1.9	NS	1.2	NS	1.6	NS
PD × Site	1	5.2	*	6.8	**	7.3	**	6.7	**
PD × Site × Year	1	8.9	**	7.1	**	8.8	**	4.5	***
Error	5								
Split plot									
Herbicides treatment	5	11.6	***	13.8	***	8.9	**	10.2	**
HT × PD	5	8.8	**	5.9	**	8.3	**	6.4	**
HT × Year	5	1.7	NS	0.9	NS	1.2	NS	1.3	NS
HT × Site	5	8.3	**	7.3	**	8.1	**	6.1	**
HT × PD × Site	5	12.4	***	14.8	***	11.3	***	8.9	**
HT × PD × Year	5	3.9	*	4.3	*	3.7	*	4.5	*
HT × PD × Site × Year	5	2.4	NS	1.8	NS	2.9	NS	1.9	NS
Error	52								

[a]Abbreviations: DAE, days after crop emergence; DAT, days after postemergence application; Df, degrees of freedom; HT, herbicide treatment; NS, nonsignificant; PD, planting date.
[b]P-values are as follows: NS, P > 0.1; *, P < 0.05; **, P< 0.01; ***, P < 0.05.

Table 6. Effect of herbicides and planting date on redroot pigweed density and biomass at the Southern Agricultural Research Center.[a,b,c]

		Redroot pigweed density				Redroot pigweed biomass	
Herbicide	Planting date	28 DAE		28 DAT		28 DAT	
		plants m^{-2}				kg ha^{-1}	
Untreated check	Early	32 (±3.4)	c	39 (±6.4)	d	148 (±17.8)	e
	Late	39 (±4.1)	d	49 (±4.8)	e	187 (±10.1)	f
Pyroxasulfone	Early	22 (±3.3)	b	30 (±5.4)	c	89 (±13.5)	c
	Late	29 (±4.8)	c	38 (±6.1)	c	118 (±16.4)	cd
Pyroxasulfone fb pyridate[3]	Early	20 (±4.2)	b	15 (±3.6)	ab	60 (±12.4)	b
	Late	27 (±4.7)	c	22 (±4.2)	c	69 (±10.9)	bc
Dimethamid + pendimethalin	Early	12 (±2.3)	a	8 (±3.5)	a	38 (±12.1)	ab
	Late	13 (±2.9)	a	16 (±2.4)	ab	52 (±8.9)	b
Dimethamid + pendimethalin fb pyridate[3]	Early	6 (±1.8)	a	3 (±1.8)	a	18 (±5.2)	a
	Late	10 (±2.2)	a	6 (±2.2)	a	34 (±6.2)	ab
Carfentrazone + sulfentrazone	Early	8 (±1.5)	a	10 (±2.7)	ab	37 (±6.4)	ab
	Late	9 (±2.8)	a	14 (±3.2)	ab	43 (±7.8)	b
Carfentrazone + sulfentrazone fb pyridate[3]	Early	5 (±1.2)	a	4 (±2.7)	a	20 (±3.1)	a
	Late	10 (±3.1)	a	8 (±2.7)	a	31 (±2.7)	ab
P-value		<0.001		<0.001		<0.001	

[a]Abbreviations: DAE, days after emergence; DAT, days after postemergence application; fb, followed by.
[b]Means within a column with same letters are not significantly different based on Fisher's protected LSD test (α = 0.05).
[c]Pyridate was applied in the spring when weeds were 5 to 10 cm tall.

(P <0.001) (Table 5). The year (P < 0.001) and site (P < 0.001) exhibited significant interaction in the model; thus, the data were analyzed and presented separately for each year and site (Table 5). At SARC, the interaction of planting date and herbicides affected the density and biomass of redroot pigweed in 2022 and kochia in 2023 (P < 0.001). At PAF in 2022, wild mustard density and biomass were not affected by herbicide or planting date (P = 0.32), whereas in 2023, differences were observed by the interaction of planting date and herbicides in reducing common mallow density and biomass (P < 0.001, data not shown).

Southern Agricultural Research Center Observations

Redroot Pigweed

In 2022, early planting resulted in a significantly lower pigweed density of 32 plants m^{-2} in untreated control plots compared to late planting, when the density was 39 plants m^{-2} (Table 6). Similarly, a stand-alone treatment with pyroxasulfone provided suppression of redroot pigweed of up to 22 plants m^{-2} after the early planting, which was better than suppression (29 plants m^{-2}) after the late planting (Table 6). Dimethenamid + pendimethalin and carfentrazone + sulfentrazone provided consistent residual activity, with a redroot pigweed density count of up to 5 to 13 plants m^{-2}, levels that were similar after both early and late plantings, indicating that the planting date did not affect weed suppression in the treated plots (Table 6). Later in the season (28 DAT), the residual activity of pyroxasulfone was exhibited when redroot pigweed density was 30 plants m^{-2} with 89 kg ha^{-1} biomass after the early planting treatment, compared with 38 plants m^{-2} and 118 kg ha^{-1} biomass in plots that were planted late (Table 6). Pyridate followed in the spring on the fall treated plots of fall pyroxasulfone helped in reducing redroot pigweed count by up to 15 plants m^{-2} and a biomass of 60 kg ha^{-1} in plots that were planted early, compared to late-planted plots when redroot pigweed density was up to 22

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Table 7. Effect of herbicides and planting date on kochia density and biomass at the Southern Agricultural Research Center.[a–c]

Herbicide	Planting date	Kochia density				Kochia biomass	
		28 DAE		28 DAT		28 DAT	
		plants m^{-2}				kg ha^{-1}	
Untreated check	Early	48 (±6.1)	d	62 (±4.7)	d	176 (±16.5)	e
	Late	62 (±4.7)	e	70 (±6.8)	e	198 (±11.8)	f
Pyroxasulfone	Early	24 (±7.4)	bc	30 (±6.5)	c	108 (±19.5)	c
	Late	29 (±6.8)	c	38 (±8.1)	c	124 (±16.7)	cd
Pyroxasulfone fb pyridate[3]	Early	26 (±4.5)	bc	20 (±4.7)	b	51 (±18.4)	b
	Late	30 (±3.5)	c	29 (±5.7)	c	76 (±13.4)	b
Dimethamid + pendimethalin	Early	8 (±2.7)	a	10 (±3.5)	a	38 (±12.1)	ab
	Late	12 (±3.5)	a	15 (±4.9)	ab	46 (±14.4)	ab
Dimethamid + pendimethalin fb pyridate[3]	Early	6 (±2.9)	a	4 (±2.8)	a	17 (±4.8)	a
	Late	15 (±5.4)	a	8 (±3.2)	a	31 (±8.7)	a
Carfentrazone + sulfentrazone	Early	10 (±2.7)	a	5 (±2.7)	a	29 (±9.4)	a
	Late	14 (±3.5)	a	10 (±4.4)	a	36 (±7.8)	b
Carfentrazone + sulfentrazone fb pyridate[3]	Early	8 (±2.7)	a	7 (±2.7)	a	18 (±2.7)	a
	Late	16 (±2.7)	a	12 (±2.7)	a	25 (±2.7)	a
P-value		<0.001		<0.001		<0.001	

[a]Abbreviations: DAE, days after emergence; DAT, days after postemergence application; fb, followed by.
[b]Means within a column with same letters are not significantly different based on Fisher's protected LSD test (α = 0.05).
[c]Pyridate was applied in the spring when weeds were 5 to 10 cm tall.

plants m^{-2}, and biomass was 69 kg ha^{-1} (Table 6). The addition of a postemergence herbicide was necessary because the efficacy of pyroxasulfone was reduced later in the season. Dimethenamid + pendimethalin and carfentrazone + sulfentrazone provided consistent suppression of redroot pigweed with a count of 8 to 16 plants m^{-2} and a biomass of 38 to 52 kg ha^{-1} throughout the season. The addition of pyridate as a postemergence treatment resulted in an even further reduction in redroot pigweed density by up to 3 to 8 plants m^{-2} and a biomass of 18 to 34 kg ha^{-1}, figures that were similar for both early and late plantings (Table 6). The addition of a postemergence herbicide to these treatments was needed to control weeds that escaped the preemergence herbicides to ensure there would be no weed seed bank replenishment.

Kochia

In 2023 at the SARC location, compared with an untreated check, kochia density and biomass were both reduced as a result of herbicide treatment and planting date ($P < 0.001$; data not shown). An early planting provided kochia suppression of up to 48 plants m $^{-2}$ in the untreated check plots compared with the late planting, when kochia density was 62 plants m^{-2} (Table 7). During early chickpea growth (28 DAE), a stand-alone treatment with pyroxasulfone provided good residual activity in suppressing kochia density to 24 plants m^{-2} when chickpea was planted early compared with 29 kochia plants m^{-2} when chickpea was planted late (Table 7). The combination of dimethenamid + pendimethalin and carfentrazone + sulfentrazone, which has multiple modes of action, led to a reduction in kochia plants of up to 6 to 16 plants m^{-2}, with no difference between early and late planting dates (Table 7).

Later in the season (28 DAT), the residual activity of pyroxasulfone was reduced, as evidenced by up to 30 kochia plants m^{-2} and a biomass of 108 kg ha^{-1} after the early planting, and up to 38 plants m^{-2} and a biomass of 124 kg ha^{-1} from late-planted plots (Table 7). Pyridate applied postemergence after a preemergence application of pyroxasulfone helped in achieving a kochia count of 20 plants m^{-2} with 51 kg ha^{-1} biomass in plots planted early, and up to 29 plants m^{-2} with 76 kg ha^{-1} biomass suppression in plots planted late (Table 7). The addition of a postemergence treatment was necessary because pyroxasulfone loses efficacy later in the season. Dimethenamid + pendimethalin and carfentrazone + sulfentrazone provided consistent suppression of kochia by up to 5 to 15 plants m^{-2} and a biomass of 29 to 46 kg ha^{-1} throughout the season. The addition of a postemergence herbicide to these treatments resulted in a further reduction in weed density of up to 4 to 12 plants m^{-2} and 17 to 31 kg ha^{-1} biomass, figures that were similar in both early and late planting scenarios (Table 7). The addition of a postemergence herbicide to these treatments was needed to control weeds that escaped the preemergence herbicide application to ensure no weed seed bank replenishment.

Post Agronomy Farm Observations

Common Mallow

Compared with an untreated check, the density and biomass of common mallow were both reduced as a result of herbicide treatment and planting date ($P < 0.001$). The untreated check that was planted early exhibited better suppression of common mallow by up to 44 plants m^{-2} compared with the late planting, for which common mallow density was up to 67 plants m^{-2} (Table 8). During the start of the season (28 DAE), pyroxasulfone provided residual activity by suppressing common mallow to 20 to 26 plants m^{-2}, which was similar from both planting date treatments (Table 8). The combination of dimethenamid + pendimethalin and carfentrazone + sulfentrazone provided a consistent residual activity in reducing common mallow by up to 7 to 14 plants m^{-2} with similar levels in plots that were planted both early and late (Table 8). Later in the season (28 DAT), the residual activity of pyroxasulfone was reduced, and was exhibited in a common mallow count of up to 25 plants m^{-2} with 49 kg ha^{-1} biomass in plots planted early, and up to 32 plants m^{-2} and 68 kg ha^{-1} biomass in plots that were planted late (Table 8). This can be attributed to the size differential between crop plants planted early (large) and late (small) (personal observation) exerting different competitiveness. The addition of a postemergence treatment to pyroxasulfone helped in reducing common mallow density by up to 14 plants m^{-2} and 36 kg ha^{-1} biomass in plots planted early, and to 20 plants m^{-2}

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Table 8. Effect of herbicides and planting date on common mallow density and biomass at the Post Agronomy Farm.[a–c]

Herbicide	Planting date	Common mallow density				Common mallow biomass	
		28 DAE		28 DAT		28 DAT	
		plants m^{-2}				kg ha^{-1}	
Untreated check	Early	44 (±5.8)	d	56 (±8.8)	e	81 (±12.2)	d
	Late	67 (±4.7)	e	71 (±6.7)	f	96 (±14.4)	e
Pyroxasulfone	Early	20 (±4.5)	bc	25 (±4.7)	c	49 (±8.7)	bc
	Late	26 (±2.7)	bc	32 (±2.8)	cd	68 (±7.2)	cd
Pyroxasulfone fb pyridate[3]	Early	22 (±2.8)	bc	14 (±2.7)	ab	36 (±4.7)	b
	Late	25 (±2.7)	bc	20 (±3.9)	bc	44 (±6.6)	c
Dimethamid + pendimethalin	Early	10 (±2.8)	a	12 (±3.7)	ab	30 (±4.8)	b
	Late	14 (±3.2)	ab	17 (±4.8)	b	41 (±2.1)	bc
Dimethamid + pendimethalin fb pyridate[3]	Early	8 (±1.9)	a	3 (±1.4)	a	20 (±3.4)	a
	Late	14 (±3.0)	ab	7 (±2.6)	a	24 (±9.4)	b
Carfentrazone + sulfentrazone	Early	7 (±1.1)	a	10 (±2.4)	ab	27 (±4.5)	ab
	Late	9 (±2.7)	a	15 (±3.1)	b	32 (±3.6)	ab
Carfentrazone + sulfentrazone fb pyridate[3]	Early	8 (±2.7)	a	5 (±2.7)	a	22 (±2.7)	a
	Late	13 (±2.7)	ab	9 (±2.7)	a	19 (±2.7)	ab
P-value		<0.001		<0.001		<0.001	

[a]Abbreviations: DAE, days after emergence; DAT, days after postemergence application; fb, followed by.
[b]Means within a column with same letters are not significantly different based on Fisher's protected LSD test ($\alpha = 0.05$).
[c]Pyridate was applied in the spring when weeds were 5 to 10 cm tall.

and 44 kg ha^{-1} biomass in plots planted late (Table 8). The application of a postemergence herbicide was needed to manage the late-emerging weeds because the efficacy of pyroxasulfone wears off later in the season. Dimethenamid + pendimethalin and carfentrazone + sulfentrazone provided consistent suppression of common mallow by up to 10 to 17 plants m^{-2} and 27 to 41 kg ha^{-1} biomass throughout the season. The addition of a postemergence herbicide to these treatments resulted in an even further reduction in common mallow density of up to 3 to 9 plants m^{-2} and 19 to 24 kg ha^{-1} biomass, which was similar in plots that were planted both early and late (Table 8). The addition of a postemergence herbicide to these treatments was needed to control weeds that escaped a preemergence application to ensure the weed seedbank was not replenished.

Findings from this study underscore the importance of taking a multi-tactic approach when developing site-specific weed management plans, because the most effective combination may vary depending on the target weed species, location, and year. Results from this research showed that both the herbicide choice and planting time were complimentary treatments for effective weed management in chickpea. The fall-applied herbicides are activated by winter precipitation and will provide more reliable weed control than spring-applied herbicides when rainfall in semiarid regions may be sporadic. Weed suppression during the chickpea seeding stage allows the crop to establish, which is essential for crop competitiveness and yield. Moreover, fall-applied herbicides help suppress weeds before they can set seed, which can contribute to a gradual depletion of soil seedbanks (Jha and Kumar 2017). Early planting provided additional weed suppression both in untreated check plots and plots that were treated with pyroxasulfone. Carfentrazone + sulfentrazone and dimethenamid + pendimethalin provided residual activity in suppressing weed density by helping delay weed emergence early in the season, thereby promoting chickpea stand establishment and allowing the extension of the chickpea planting interval. Previous research reported a similar efficacy of pyroxasulfone in suppressing kochia in a soybean crop (Kezar et al. 2024). Postemergence herbicides were still needed to achieve better weed management in plots treated with pyroxasulfone, but only to eliminate weeds that escaped preemergence herbicides or that emerged later in the season. This dual approach of combining preemergence and postemergence herbicides is essential for reducing the potential for future weed infestations.

Effect of Planting Date and Herbicides on Crop Establishment and Grain Yield

Across all treatment combinations, chickpea seedling counts of 40 plants m^{-2} at 14 DAE were similar during both years and at both sites, indicating a good stand establishment, and no crop loss attributed to the herbicides or planting date ($P < 0.001$; data not shown). Additionally, no visual signs of herbicide injury (e.g., yellowing, necrosis, or burning) to chickpea were observed. The grain yield data were analyzed separately for each year and site due to an interaction ($P < 0.001$) in the model. During 2022, herbicides and planting dates did not affect the crop yield at SARC ($P = 0.614$) or PAF ($P = 0.384$). The average grain yield in 2022 at both SARC (52 to 212 kg ha^{-1}) and PAF (34 to 176 kg ha^{-1}) was too low due to a hailstorm that occurred at crop harvesting time. However, in 2023, the interaction effects of herbicides and planting date affected grain yield at both SARC ($P < 0.001$) and PAF ($P < 0.001$).

At SARC in 2023, there was no difference in grain yield for any planting date in the untreated check plots (408 to 456 kg ha^{-1}), whereas herbicide-treated plots produced different yields (Table 9). Specifically, chickpea that received a stand-alone application of pyroxasulfone produced a higher grain yield of 618 (±23.4) kg ha^{-1} when the crop was planted early compared with 551 (±28.9) kg ha^{-1} from plots that were planted late (Table 9). This variation in grain yield was probably due to the additional weed suppression provided by the early planting. The addition of postemergence a herbicide to a preemergence application of pyroxasulfone increased the yield even further (598 to 624 kg ha^{-1}) (Table 9). An application of dimethenamid + pendimethalin and carfentrazone + sulfentrazone resulted in a higher yield (670 to 754 kg ha^{-1}), and the addition of postemergence herbicide to these treatments further increased

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Table 9. Effect of herbicides and planting date on chickpea yield at both experimental locations in 2023.[a,b]

Herbicide treatment	Planting date	Chickpea yield SARC		Chickpea yield PAF	
		kg ha^{-1}			
Untreated check	Early	456 (±24.8)	a	215 (±24.1)	a
	Late	408 (±39.7)	a	189 (±29.4)	a
Pyroxasulfone	Early	618 (±23.4)	c	329 (±23.7)	c
	Late	551 (±28.9)	b	288 (±29.1)	b
Pyroxasulfone fb pyridate	Early	624 (±33.1)	c	376 (±18.7)	cd
	Late	598 (±24.7)	bc	347 (±44.5)	cd
Dimethamid + pendimethalin	Early	725 (±19.8)	d	467 (±23.8)	de
	Late	670 (±21.7)	cd	410 (±39.9)	d
Dimethamid + pendimethalin fb pyridate	Early	810 (±42.5)	de	524 (±22.4)	e
	Late	760 (±13.1)	d	472 (±33.2)	de
Carfentrazone + sulfentrazone	Early	754 (±24.5)	d	466 (±31.5)	de
	Late	704 (±39.4)	cd	450 (±24.6)	d
Carfentrazone + sulfentrazone fb pyridate	Early	831 (±20.9)	e	551 (±32.4)	e
	Late	794 (±24.5)	de	484 (±29.6)	de
P-value		<0.001		<0.001	

[a]Abbreviations: DAE days after emergence; fb, followed by; SARC, Southern Agricultural Research Center; PAF, Post Agronomy Farm.
[b]Means within a column with same letters are not significantly different based on Fisher's protected LSD test (α = 0.05).

the yield (760 to 831 kg ha^{-1}). We did not observe differences in yield from any herbicide treatment between plots planted early or late (Table 9), except the stand-alone pyroxasulfone treatment because the weeds were successfully suppressed early in the season, causing no impact on chickpea establishment and yield.

In 2023 at the PAF location, the interaction between fall-applied herbicides and planting date resulted in a grain yield increase compared with yield from the untreated check. Specifically, there was no difference in grain yield between early and late planting dates from the untreated checks (189 to 215 kg ha^{-1}), whereas there were differences in yield from the treated plots. The early planting up yielded up to 329 kg ha^{-1} of grain and up to 288 kg ha^{-1} from late-planted plots after an application of pyroxasulfone (Table 9). The addition of a postemergence herbicide to pyroxasulfone resulted in an even further increase in yield of up to 347 to 376 kg ha^{-1}, by controlling escaped weeds and protecting crop yield (Table 9). Pyridate applied postemergence resulted in increased yields, and the crop was protected against weeds compared to stand-alone treatments. Yield was increased (410 to 489 kg ha^{-1}) when dimethenamid + pendimethalin and carfentrazone + sulfentrazone were applied due to the consistent residual activity they provided over pyroxasulfone, and the addition of post-emergence herbicide increased the yield even further (472 to 551 kg ha^{-1}). These results were similar from both early and late plantings (Table 9), and can be attributed to the multiple modes of action that combine to target more than one site of action for better weed control and extend their half-lives in the soil.

Weed management in chickpea production is crucial during the crop establishment period for promoting crop competitiveness (Frenda et al. 2013). Weed management was effectively addressed via the fall application of residual herbicides, which delayed weed emergence at the start of the season. This increase in yield can be attributed to reduced competition for soil and water resources during the early growth phase. The treatments with dimethenamid + pendimethalin and carfentrazone + sulfentrazone provided good residual activity throughout the season and were associated with an increase in crop yield. Early planting provided additional weed suppression, showing an increase in yield after treatment with pyroxasulfone, whereas no such yield increase was observed with applications of dimethenamid + pendimethalin and carfentrazone + sulfentrazone regardless of planting date. The addition of a postemergence application of pyridate increased the yield from plots that had been treated with pyroxasulfone, whereas it did not provide any increase in the yield from plots where dimethenamid + pendimethalin and carfentrazone + sulfentrazone were applied. The economic benefits of increased yields and reduced herbicide usage can improve the overall farm profitability of chickpea growers (Lyon and Wilson 2005). With robust early-season weed control through fall-applied herbicides and early planting, growers can benefit from higher yields with lower input costs, thereby enhancing overall farm sustainability.

Practical Implications

This study offers valuable insights for growers who manage weeds in semiarid cropping systems, particularly by replacing fallow with chickpea cultivation. By integrating early planting of a chickpea crop with fall-applied herbicides, growers can delay weed emergence, which will lead to robust chickpea stand establishment and enhanced competitiveness. The use of a postemergence herbicide such as pyridate further eliminated escaped weeds and prevented the adding of new seeds to the weed seedbank. This integrated approach, of combining both preemergence and postemergence herbicides, minimizes weed competition and safeguards chickpea production and reduces yield losses (Kumar and Jha 2015).

Early planting and fall-applied herbicides suppress weed emergence during the critical early growth stage of chickpea when the crop is most vulnerable to weeds. This practice provides asymmetric competition in favor of the crop. On a practical level, growers can adopt these methods as part of a comprehensive weed management strategy, in line with previous research (Beiermann et al. 2022; Kezar et al. 2024), to optimize yield potential (Jha and Kumar 2017). By diversifying weed control tactics and using herbicides that are compatible with chickpea, growers can improve their overall weed management effectiveness while maintaining crop yield (Jha and Kumar 2017). This integrated approach also helps manage weed communities that have developed under continuous chemical management, which will reduce the risk of herbicide resistance (Riemens et al. 2022).

However, excessive reliance on herbicides poses significant risks, including reduced efficacy, increased production costs, and the potential for herbicide resistance, ultimately affecting crop yields (Owen 2016). To mitigate these risks, growers must incorporate a variety of weed management tactics—cultural, chemical, mechanical, and biological—such as crop rotation, cover cropping, and optimized planting methods (Riemens et al. 2022). This integrated approach should be tailored to local weed pressures, available resources, and weather conditions (Tidemann et al. 2023). By diversifying weed management strategies, growers can reduce reliance on a single method, conserve herbicide efficacy, and ensure long-term crop sustainability.

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