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Short title: Fall application & planting date

Optimizing Weed Management in Chickpea Through Planting Date and Fall-Applied Residual Herbicides

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Abstract

Chickpea provides significant diversification benefits for semi-arid cropping systems. However, their slow emergence and open canopy growth habit make them poor competitors 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, Huntley, MT, and the MSU Post Agronomy Farm, Bozeman, MT, to evaluate broadleaf weed management by integrating planting date and fall-applied soil-active herbicides in 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 - 20 plants m^{-2} compared to 50 - 70 plants m^{-2} in untreated check. Pyridate applied POST (700 g ai ha^{-1}) was required in the above-mentioned 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. There was no impact of planting date on weed density and grain yield in plots with 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.

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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Introduction

Crop diversification is essential for sustainable agriculture, yet semi-arid cropping systems in the US 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 US Great Plains contributes $172.2 million in revenue from 148,000 hectares, of which Montana's share was $72 million from 70,000 hectares in 2023 (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 its 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 of 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 them a head start against the early flushes of weeds (Kwabiah 2004). While timely planting is crucial,

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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 (PRE) face activation challenges in semi-arid climates due to limited precipitation. Also, widely used herbicides like carfentrazone + sulfentrazone can inadvertently damage chickpea planted at shallow depths and in high soil pH conditions. Residual PRE 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 using fall application 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 underutilized, 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 multilocation trials across Montana to assess PRE 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 across Montana: the MSU- Southern Agricultural Research Center (SARC), Huntley, MT (45.924°N, 108.245°W) and the MSU Post Agronomy Farm (PAF), Bozeman, MT (45.404° N, 111.0929° W). Average monthly air temperatures and precipitation data was collected from the local weather station at each experimental site is presented in Table 1&2 (WRCC 2024). The soil type, organic matter, and soil pH at both sites are shown in Table 3 (WSS 2023). Kochia and redroot pigweed were the

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dominant weed species at SARC. Wild mustard (*Sinapis arvensi*s L.) and common mallow were the dominant weed species at PAF. The herbicide treatment list was designed as half treatments as PRE alone and the other half were PRE fb POST. This was done to evaluate the residual activity of PRE alone and to determine if POST herbicide treatment is 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 sub-plots were herbicide treatments. Fall applications of residual herbicides at the recommended label rates were conducted in the last week of October each year before ground freeze (Table 4). The applications were timed with precipitation for maximum activation and an average rainfall of 0.3-0.6 cm was received within a week of herbicide application each year facilitating 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. POST herbicide included Pyridate (Tough 5 EC) at 700 g ae ha^{-1} was applied when plants were 5 to 10 cm tall. All herbicide treatments were applied using a CO_2-pressurized backpack sprayer equipped with extended-range flat fan nozzles (XR8003 Teejet® nozzles) 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 one-meter row lengths in each plot 14 days after crop emergence (DAE). Concurrently, crop phytotoxicity symptoms, including yellowing, necrosis, and burning, were visually evaluated. Weed density was counted twice from 0.5 m × 0.5 m area within each plot, initially at 28 DAE when weeds were 5–10 cm tall and subsequently at 28 days after POST application (28 DAT) each year at both locations. Weed biomass at 28 DAT was measured at chickpea flowering from two 0.5 × 0.5 m quadrats per plot each year. The biomass samples were weighed after being oven-dried at 60 C for 24 hours. 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 was subjected to a linear mixed model using the IME4 function from the IMER 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 as 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 non-significant, data were combined for the sites. Estimated marginal means were calculated for each herbicide treatment and planting date combination, and comparisons were conducted using Fisher's protected Least Significant Difference (LSD) test with a significance level of $\alpha < 0.05$. The estimated marginal means (emmeans) package was utilized for the estimation of marginal means and post-hoc comparisons.

Results and Discussion

Effect of Planting Date and Herbicides on Weed Density and Biomass

The herbicides and planting date treatments reduced weed density and biomass compared to untreated check ($P < 0.001$) (Table 5). The year ($P < 0.001$) and site ($P < 0.001$) had significant interaction in the model; thus, the data was 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, herbicides and planting dates did not reduce wild mustard density or biomass ($P = 0.32$), whereas, in 2023, differences were observed by the interaction of planting date and herbicides for reducing common mallow density and biomass ($P < 0.001$, data not shown).

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Southern Agricultural Research Center (SARC)

Redroot Pigweed:

In 2022, early planting significantly had a lower pigweed density of 32 plants m^{-2} compared to late planting with 39 plants m^{-2} in untreated control plots (Table 6). Similarly, pyroxasulfone standalone treatment provided suppression of redroot pigweed up to 22 plants m^{-2} in early planting, which was better than redroot pigweed suppression (29 plants m^{-2}) in late planting (Table 6). Dimethenamid + pendimethalin and carfentrazone + sulfentrazone provided consistent residual activity, with a density count of up to 5 - 13 plants m^{-2} to similar levels in both early and late planting dates, 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 reduced and redroot pigweed density was 30 plants m^{-2} with 89 kg ha^{-1} biomass in the early planting treatment, which was better than the late planting plots with redroot pigweed count of 38 plants m^{-2} with 118 kg ha^{-1} biomass observed in the (Table 6). Pyridate applied POST to pyroxasulfone helped in reducing redroot pigweed count up to 15 plants m^{-2} with 60 kg ha^{-1} biomass in early planting plots, compared to late planting plots with redroot pigweed density up to 22 plants m^{-2} with 69 kg ha^{-1} biomass (Table 6). The addition of POST was necessary as the efficacy of pyroxasulfone was reduced later in the season. Dimethenamid + pendimethalin and carfentrazone + sulfentrazone provided consistent suppression for redroot pigweed with a count of 8 to 16 plants m^{-2} with 38 to 52 kg ha^{-1} biomass throughout the season in treated plots. The addition of pyridate as POST to these treatments reduced the weed density even further for redroot pigweed up to 3 to 8 plants m^{-2} with 18 to 34 kg ha^{-1} biomass, which was similar in early and late planting (Table 6). The addition of POST in these treatments was only needed to control weeds that escaped PRE to ensure no weed seed bank replenishment.

Kochia:

In 2023 at SARC, herbicide treatment, and planting date reduced kochia density and biomass compared to untreated check ($P < 0.001$, data not shown). Untreated check with early planting provided better weed suppression for kochia up to 48 plants m^{-2} than untreated check with late planting which had a higher density of kochia up to 62 plants m^{-2} (Table 7). During early chickpea growth (28 DAE), pyroxasulfone standalone treatment provided good residual activity in suppressing kochia density with 24 plants m^{-2} in the early planted and 29 plants m^{-2} in the late

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planted treatments (Table 7). The combination of dimethenamid + pendimethalin and carfentrazone + sulfentrazone provided increased residual activity due to multiple mode of actions, reducing kochia up to 6 to 16 plants m^{-2} with no difference between early and late planting conditions (Table 7). Later in the season (28 DAT), the residual activity of pyroxasulfone was reduced, suppressing kochia up to 30 plants m^{-2} with 108 kg ha^{-1} biomass in the early planting treatment, and up to 38 plants m^{-2} with 124 kg ha^{-1} biomass observed in the late planting plots (Table 7). Pyridate applied POST to pyroxasulfone helped in achieving a kochia count of 20 plants m^{-2} with 51 kg ha^{-1} biomass in early planting plots, and up to 29 plants m^{-2} with 76 kg ha^{-1} biomass suppression in late planting plots (Table 7). The addition of POST was necessary as the efficacy of pyroxasulfone was reduced later in the season. Dimethenamid + pendimethalin and carfentrazone + sulfentrazone provided consistent suppression for kochia up to 5 to 15 plants m^{-2} with 29 to 46 kg ha^{-1} biomass throughout the season. The addition of POST to these treatments reduced the weed density even further for kochia up to 4 to 12 plants m^{-2} with 17 to 31 kg ha^{-1} biomass which was similar in early and late planting (Table 7). The addition of POST in these treatments was only needed to control weeds that escaped PRE to ensure no weed seed bank replenishment.

Post Agronomy Farm (PAF)

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

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competitiveness. The addition of POST to pyroxasulfone helped in reducing common mallow density up to 14 plants m^{-2} and 36 kg ha^{-1} biomass in early planting plots, and up to 20 plants m^{-2} and 44 kg ha^{-1} biomass in late planting plots (Table 8). The application of POST was needed to manage the late emerging weeds as the efficacy of pyroxasulfone was reduced later in the season. Dimethenamid + pendimethalin and carfentrazone + sulfentrazone provided consistent suppression for common mallow up to 10 - 17 plants m^{-2} and 27 - 41 kg ha^{-1} biomass throughout the season. The addition of POST to these treatments reduced the weed density even further for common mallow up to 3 to 9 plants m^{-2} and 19 to 24 kg ha^{-1} biomass, which was similar in early and late planting plots (Table 8). The addition of POST in these treatments was only needed to control weeds that escaped PRE to ensure no weed seed bank replenishment.

This study's finding underscores the importance of multi-tactic approach when developing site-specific weed management plans, as the most effective combination may vary depending on the target weed species, location, and year. As this research results showed that both the herbicide choice and planting time were complimentary treatments for effective weed management in chickpea. The fall applied herbicides are activated from winter precipitation and will provide more reliable weed control than spring applied herbicides with sporadic spring rainfall in semi-arid regions. Weed suppression during the chickpea seeding stage allow them to establish which is essential for crop competitiveness and yield. Moreover, these herbicides help manage weeds before they can set seed that can contribute to a gradual depletion of soil seedbanks (Jha and Kumar 2017). Early planting helped provide additional weed suppression in plots with the treatment of pyroxasulfone and the untreated check. Carfentrazone + sulfentrazone and dimethenamid + pendimethalin provided a good residual activity for suppressing weed density as they helped delay weed emergence early in the season, minimizing the impact of weeds during chickpea stand establishment and allowing the extension of the planting interval for chickpea. Previous research suggested a similar efficacy of pyroxasulfone for suppressing kochia in soybeans (Kezar et al. 2024). POST herbicides were still needed for plots with pyroxasulfone for better weed management but only required in plots of carfentrazone + sulfentrazone and dimethenamid + pendimethalin to eliminate weeds that escaped PRE or emerged later in the season. This dual approach of combining PRE and POST herbicides is essential for reducing the potential for future weed infestations.

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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 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) were observed on chickpea. The grain yield data was 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 for both SARC (52 to 212 kg ha^{-1}) and PAF (34 to 176 kg ha^{-1}) was too low due to hail events occurring 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 across planting dates in the untreated check plots (408 to 456 kg ha^{-1}), whereas herbicide-treated plots had different yields (Table 9). Specifically, chickpea in standalone pyroxasulfone had higher grain yield of 618 (23.4) kg ha^{-1} for early planting compared to 551 (28.9) kg ha^{-1} for late planting plots (Table 9). This variation in grain yield was probably due to the additional weed suppression provided by the early planting. The addition of POST to pyroxasulfone increased the yield even further (598 - 624 kg ha^{-1}) (Table 9). Dimethenamid + pendimethalin and carfentrazone + sulfentrazone resulted in increased yield (670 to 754 kg ha^{-1}), and the addition of POST in these treatments further increased the yield (760 to 831 kg ha^{-1}). We did not observe differences in yield for any herbicide treatments between early and late planting plots (Table 9), except pyroxasulfone as the weeds were successfully suppressed early in the season, causing no impact on chickpea establishment and yield.

In 2023, the interaction between fall applied herbicides and planting date increased grain yield compared to untreated check at PAF. Specifically, there was no difference in grain yield with early and late planting dates in the untreated check (189 to 215 kg ha^{-1}), whereas there were differences in treated plots. The application of pyroxasulfone resulted in a higher yield with early planting up to 329 kg ha^{-1} and up to 288 kg ha^{-1} in late planting plots (Table 9). The addition of POST to pyroxasulfone increased the yield even further up to 347 to 376 kg ha^{-1}, by controlling escaped weeds and protecting crop yield (Table 9). Pyridate applied POST increased the yields and protected the crop against weeds compared to standalone treatments. Dimethenamid +

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pendimethalin and carfentrazone + sulfentrazone resulted in increased yield (410 to 489 kg ha^{-1}) due to consistent residual activity better than pyroxasulfone, and the addition of POST increased the yield further (472 to 551 kg ha^{-1}) which was similar in early and late planting conditions (Table 9). This can be attributed to the multiple Mode of action combined to target more than one site of action for better weed control and extend their half-lives in the soil.

Weed management in chickpea is crucial during the crop establishment for promoting crop competitiveness (Frenda et al. 2013). This necessity was effectively addressed by 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 of 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 in the treatment of pyroxasulfone, whereas no such yield increase was seen with dimethenamid + pendimethalin and carfentrazone + sulfentrazone with different planting dates. The addition of POST application of pyridate increased the yield of plots with pyroxasulfone, whereas it did not provide any increase in the yield of plots of dimethenamid + pendimethalin and carfentrazone + sulfentrazone. 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 by higher yields with lower input costs, enhancing overall farm sustainability.

Practical Implications

This study offers valuable insights for weed management in semi-arid cropping systems, particularly for growers, considering replacing fallow with chickpea cultivation. By integrating early planting with fall-applied herbicides grower can delay weed emergence leading to robust chickpea stand establishment and enhanced competitiveness. The use of a POST herbicide application, such as pyridate, further eliminated escaped weeds and prevented the addition of new seeds to the weed seed bank. This integrated approach, combining both PRE and POST herbicides, minimizes weed competition, safeguarding chickpea and reducing 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 approach provides asymmetric competition in favor of the crop. Practically, 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 utilizing herbicides compatible with chickpea, growers can improve 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, reducing 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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Competing Interests

The author(s) declare no competing interests.

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Table 1. Average monthly air temperature (C) and total precipitation (mm) from October to September during 2022 and 2023 growing season and long-term averages at Southern Agricultural Research Center, MT.

Month	Average monthly temperature			Total monthly precipitation		
	1998-2023	2021-22	2022-23	1998-2023	2021-22	2022-23
	--------------------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

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Table 2. Average monthly air temperature (C) and total precipitation (mm) from October to September during 2022 and 2023 growing season and long-term averages at Post Agronomy Farm, MT.

Month	Average monthly temperature			Total monthly precipitation		
	1998-2023	2021-22	2022-23	1998-2023	2021-22	2022-23
	------------------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

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

Agronomic practices	Southern Agricultural Research Center		Post Agronomy Farm	
	2021-22	2022-23	2021-22	2022-23
Fall herbicide application	Oct 27, 2022	Oct 21, 2023	Oct 30, 2022	Oct 26. 2022
Early planting	May 6, 2022	Apr 27, 2023	Apr 20, 2022	May 1. 2023
Late planting	May 20, 2022	May 16, 2023	May 5, 2022	May 20, 2023
POST herbicide application	Jun 26, 2022	Jun 12, 2023	Jun 27, 2022	Jun 6. 2023
Chickpea harvesting	Aug 10, 2022	Sep 14, 2023	Sep 13. 2022	Sep 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]Abbreviations: POST, Postemergence.

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Table 4. List of herbicides, trade names, rates used and manufacturer details used in the study.[a]

Herbicide(s)	Trade name	Rate	Manufacturer	Address
		g ai ha^{-1}		
Carfentrazone + sulfentrazone	Spartan Charge	238	FMC	Philadelphia, PA
Dimethamid + pendimethalin	Outlook + Prowl H2O	950 + 2130	BASF	Triangle Park, NC
Pyroxasulfone	Zidua SC	126	BASF	Triangle Park, NC
Pyridate	Tough 5EC	700	Belchim	Wilmington, DE

[a]All treatments contained crop oil concentrate (Kalo, Inc., Overland Park, KS) at 1% vol/vol.

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

		Weed density				Weed biomass			
		28 DAE		28 DAT		28 DAT		Grain yield	
Source of variation	Df	F	P-value	F	P-value	F	P-value	F	P-value
Whole Plot									
Planting date (PD)	1	2.4	NS	7.4	**	8.3	**	7.6	**
PD X Year	1	1.1	NS	1.9	NS	1.2	NS	1.6	NS
PD X Site	1	5.2	*	6.8	**	7.3	**	6.7	**
PD X Site X Year	1	8.9	**	7.1	**	8.8	**	4.5	***
Error	5								
Split Plot									
Herbicides treatment (HT)	5	11.6	***	13.8	***	8.9	**	10.2	**
HT X PD	5	8.8	**	5.9	**	8.3	**	6.4	**
HT X Year	5	1.7	NS	0.9	NS	1.2	NS	1.3	NS
HT X Site	5	8.3	**	7.3	**	8.1	**	6.1	**
HT X PD X Site	5	12.4	***	14.8	***	11.3	***	8.9	**
HT X PD X Year	5	3.9	*	4.3	*	3.7	*	4.5	*
HT X PD X Site X 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 POST application; NS, Non-significant, P > 0.1; *, P < 0.05; **, P<0.01; ***, P <0.05.

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

Herbicide	Planting date	Redroot pigweed density 28 DAE		Redroot pigweed density 28 DAT		Redroot pigweed biomass 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] Means within a column with same letters are not significantly different based on Fisher's protected LSD test (α = 0.05).

[b] Abbreviations fb, followed by; DAE, days after emergence; DAT, days after POST application.

[c] Pyridate was applied in the spring when weeds were 5 to 10 cm tall.

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Table 7. Effect of herbicides and planting date on kochia density and biomass at Southern Agricultural Research Center, MT.[1,2]

Herbicide	Planting date	Kochia density 28 DAE		Kochia density 28 DAT		Kochia biomass 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] Means within a column with same letters are not significantly different based on Fisher's protected LSD test (α = 0.05).

[b] Abbreviations fb, followed by; DAE, days after emergence; DAT, days after POST application.

[c] Pyridate was applied in the spring when weeds were 5 to 10 cm tall.

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Table 8. Effect of herbicides and planting date on common mallow density and biomass at Post Agronomy Farm, MT.[1,2]

Herbicide	Planting date	Common mallow density 28 DAE		Common mallow density 28 DAT		Common mallow biomass 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] Means within a column with same letters are not significantly different based on Fisher's protected LSD test (α = 0.05).

[b] Abbreviations fb, followed by; DAE, days after emergence; DAT, days after POST application.

[c] Pyridate was applied in the spring when weeds were 5 to 10 cm tall.

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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		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] Means within a column with same letters are not significantly different based on Fisher's protected LSD test (α = 0.05).

[b] Abbreviations fb, followed by; DAE, SARC, Southern Agricultural Research Center; PAF, Post Agronomy Farm.

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