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Postemergence-directed applications of pendimethalin for control of early-season weeds in chile pepper

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Research Article

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Abstract

In New Mexico chile pepper production, pendimethalin is traditionally applied shortly after crop thinning, which is 9 to 10 wk after crop seeding. Pendimethalin applications before crop thinning may be a method for controlling early-season weeds in chile pepper; however, chile pepper tolerance to early-season applications of pendimethalin is poorly understood. We conducted a greenhouse study to evaluate young chile pepper responses to pendimethalin. We also conducted a field study to determine weed and chile pepper responses to early-season, postemergence-directed pendimethalin in combination with herbicides registered for preemergence applications. The greenhouse study included three treatments administered when chile pepper was at the four-leaf stage: (i) pendimethalin applied to foliage and soil, (ii) pendimethalin applied to soil only, and (iii) a nontreated control. The field study included four treatments: (i) preemergence applications of napropamide followed by postemergence-directed pendimethalin at 5 wk after crop seeding, (ii) preemergence applications of clomazone followed by postemergence-directed pendimethalin at 5 wk after crop seeding, (iii) postemergence-directed pendimethalin without preemergence herbicides, and (iv) nontreated, weed-free control. We conducted the field study at two sites that differed in soil texture. Pendimethalin application rates were maximum labeled rates for the specific soil. Results from the greenhouse study indicated that pendimethalin applied to foliage and soil stunted two of five cultivars, whereas pendimethalin applied to soil did not affect chile pepper height, fresh weight, dry weight, or root area. Results from the field study indicated that postemergence-directed pendimethalin did not affect chile pepper height or fruit yield, or cause visible symptoms of herbicide injury. Postemergence-directed pendimethalin reduced the densities of weeds, including junglerice. The results of this study indicate that postemergence-directed applications of pendimethalin at 5 wk after crop seeding do not cause crop injury or yield loss in chile pepper, while providing some weed control benefits.

Introduction

Chile pepper (*Capsicum* spp.) is an important crop in New Mexico and has long been part of the history and culture of the state (Bosland 2015; Hawkes et al. 2008). Among the five domesticated species in the genus *Capsicum*, *Capsicum annuum* includes chile peppers grown for vegetables and spices (Bosland and Votava 2012). In New Mexico, *C. annuum* is grown for green fruits and red fruits. Each fruit color type (green, red) is sold in fresh markets and processed forms. The value of all chile pepper production in New Mexico in 2022 was US$46.2 million, with chile pepper for processing worth US$41.8 million and chile pepper for fresh markets worth US$4.4 million (USDA-NASS 2023). Of the 3,966 ha of chile pepper harvested in the United States in 2022, 84% (3,318 ha) were in New Mexico (USDA-NASS, 2023).

Chile pepper is not competitive with weeds. The critical period for weed control in transplanted chile pepper is up to 126 d (Amador-Ramirez 2002) and is likely longer in direct-seeded chile pepper (Tursun et al. 2012). These weed control periods for chile pepper are longer than other crops including lettuce (28 d after crop emergence; Fennimore et al. 2014) and cucumber (24 to 36 d after crop emergence; Friesen 1978). Weeds in chile pepper reduce crop yield (Schroeder 1993), interfere with harvest (Schroeder 1993; Schutte 2017), potentially harbor organisms that cause crop disease (Sanogo et al. 2013), and can produce seeds and propagules that cause weed infestations in subsequent crops (Schutte 2017). Hand hoeing is commonly used to control weeds in chile pepper in New Mexico. However, hand hoeing is expensive and substantially decreases profitability of chile pepper production operations (Hawkes et al. 2008). Reliance on hand hoeing is caused, in part, by the limited options for chemical weed control in chile pepper.

Options to reduce hand hoeing in chile pepper include herbicides that can be applied after crop emergence and provide several weeks of weed control following a single application. For chile pepper in New Mexico, such herbicides include flumioxazin, halosulfuron-methyl, imazosulfuron, pendimethalin, *S*-metolachlor, and trifluralin. Among these herbicides, pendimethalin possibly provides chile pepper growers greater convenience and opportunities for sustained weed control. Pendimethalin provides preemergence control of many annual grass and certain annual broadleaf weeds, which is unlike halosulfuron-methyl and imazosulfuron that are effective on certain broadleaf weeds and *Cyperus* species (Shaner 2014). Unlike trifluralin, pendimethalin does not require mechanical incorporation (Shaner 2014); moreover, unlike flumioxazin and *S*-metolachlor, pendimethalin does not feature a registration that requires chile pepper growers in New Mexico to release the manufacturer from liability for crop damage.

In direct-seeded chile pepper in New Mexico, pendimethalin is conventionally applied to bases of chile pepper plants (postemergence-directed) shortly after crop thinning, which is typically 9 to 10 wk after chile pepper seeding. These applications are in accordance with label regulations that specify pendimethalin cannot be applied over-the-top or contact foliage of chile pepper plants (Anonymous 2022). Growers may be able to apply pendimethalin before crop thinning; however, little is known about the risk of chile pepper injury from pendimethalin applied before 9 to 10 wk after crop seeding. If postemergence-directed applications of pendimethalin prior to crop thinning do not cause significant crop injury and crop yield loss, postemergence-directed pendimethalin may facilitate reductions in hand hoeing during the early phases of the chile pepper growing season.

Dinitroaniline herbicides like pendimethalin are absorbed by roots and coleoptiles of emerging seedlings (Appleby and Valverde 1989) and inhibit growth of susceptible plant species by arresting division of root cells in emerging seedlings (Cobb and Reade 2010). Pendimethalin solutions that contact crop foliage can cause stunting, leaf deformities, and chlorosis (Figueroa et al. 2016; Miller et al. 2003), although some crops are minimally injured by pendimethalin on their foliage (Grichar et al. 2005; Lewthwaite and Triggs 2000; Meyers et al. 2020). The development of pendimethalin strategies for chile pepper may need to account for individual crop cultivars. This is known from previous studies that indicated cultivars of solanaceous crops differed in degrees of injury from identical herbicide applications (Hutchinson et al. 2005; Linder et al. 2016; Mohsemi-Moghadam and Doohan 2017). Risk of injury from pendimethalin is also influenced by soil type. Soil with lower clay content features reduced capacity for herbicide sorption compared to soil with higher clay content (Pritchard and Stobbe 1980). Consequently, to avoid potential injury from pendimethalin, pendimethalin product labels specify lower application rates for coarse-textured soil (Anonymous 2022).

The overall objective of this research was to assess possibilities for crop injury, crop yield loss, and weed control from postemergence-directed applications of pendimethalin administered several weeks before crop thinning in chile pepper. To address this objective, we first determined young chile pepper plant responses to excessive rate applications of pendimethalin under greenhouse conditions. Results from the greenhouse study informed a field study, because it indicated symptoms of injury from pendimethalin applied after chile pepper emergence. We then conducted a field study to determine the effects of early-season, postemergence-directed pendimethalin on chile pepper plant height, chile pepper fruit yield, and weed densities. Each study included five chile pepper cultivars that are commonly grown in New Mexico. Our studies were not designed and executed to compare cultivars for tolerance to early-season, postemergence-directed applications of pendimethalin. Rather, we included multiple cultivars so that our conclusions potentially apply to a wider range of conditions compared to conclusions from a study with only one chile pepper cultivar.

Materials and Methods

Greenhouse Study

The greenhouse study was conducted to evaluate chile pepper responses to pendimethalin applied under conditions likely to cause injury. To do this, pendimethalin was applied at twice the labeled rate for the soil used in the study. In addition, pendimethalin treatments included applications to chile pepper foliage. Such applications are prohibited by label (Anonymous 2022).

The greenhouse study was conducted on the main campus of New Mexico State University (NMSU) in Las Cruces, New Mexico. The greenhouse was set to maintain an air temperature between 24 and 30 C. The study included two experimental runs, with experimental run 1 occurring from August 13, 2020 to October 9, 2020 and experimental run 2 occurring from October 1, 2020 to November 26, 2020. Each experimental run was a randomized complete block with four replications. Experimental units were 0.5-L square pots (8.9 cm by 8.9 cm by 8.9 cm) containing two chile pepper plants that were grown from seed buried 2 cm in soil within pots. Chile pepper plants were grown for 4 wk before herbicide treatments. At the time of herbicide application, chile pepper plants were in the four-leaf stage.

The experimental substrate included soil (Glendale clay loam; fine-silty, mixed, superactive, calcareous, thermic Typic Torrifluvents) (USDA-NRCS 2023) obtained from the NMSU Leyendecker Plant Science Research Center (32.20° N, 106.74° W; herein "Leyendecker"). Prior to use, soil was sieved to remove debris that did not pass through a 4-mm screen. Sand (Quikrete® All-Purpose Sand; The Quikrete Companies LLC, Atlanta, GA) was then added to create a substrate of sand and soil (1:0.67 vol/vol). The addition of sand ensured a coarse-textured substrate that would aid in root system recovery during data collection. After sand addition, the substrate textural class was loamy sand (82% sand, 10 % silt, and 8% clay) with 0.4% organic matter.

Treatments were factorial combinations of five chile pepper cultivars and three pendimethalin treatments. Chile pepper cultivars in this study included 'Barker Hot', 'Big Jim', 'Lumbre', 'NM 6-4', and 'Sandia'. These cultivars are commonly grown on commercial farms in New Mexico. Pendimethalin treatments consisted of (i) pendimethalin applied to chile pepper foliage and soil, (ii) pendimethalin applied to soil only, and (iii) a nontreated control. Herbicide solution was applied using a moving-nozzle spray chamber (DeVries Manufacturing, Hollendale, MN) equipped with an even-flat nozzle tip (8002EVS; TeeJet Technologies, Wheaton, IL). While spraying, chile pepper plants in the "soil only" treatment were covered with conical tubes that were 11.5 cm long and 2.5 cm diam (1 tube per pot). Pendimethalin (Prowl® H_2O, 0.45 kg ai L^{-1}; BASF Corp., Research Triangle Park, NC) was applied at 1.60 kg ha^{-1}. Immediately after application, pendimethalin was incorporated by applying 200 ml of water per pot over 10 min to the soil surface. Thereafter, pots were watered every 2 d by adding 20 ml water to the soil surface in each pot. These irrigation procedures did not cause water to exit through the holes in the bottoms of pots.

At 28 d after treatment (DAT), chile pepper plants were evaluated for visible symptoms of herbicide injury including leaf chlorosis, leaf necrosis, and leaf malformation. These possible symptoms of herbicide injury were reported on a percentage scale, with 0% indicating no difference from nontreated control and 100% indicating complete desiccation of leaves. Also at 28 DAT, chile pepper plant heights were determined, and whole plants were extracted from soil by hand. Root systems were washed by hand in buckets of water. After roots had been washed, plant surfaces were blotted dry with paper towels and plant fresh weights determined. Plants were then clipped to separate roots from shoots. Root systems were positioned on a flat surface so that root branches did not overlap. The surface areas of flattened root systems were determined with a leaf area meter (LI-3100C; LICOR Biosciences, Lincoln, NE). Chile pepper roots and shoots were then oven-dried at 60 C for 72 h.

Field Study

A field study was conducted in 2021 at Leyendecker and the NMSU Agricultural Science Center at Los Lunas, New Mexico (34.77 °N, 106.76° W; herein "Los Lunas"). The Leyendecker study site featured fine-textured soil (23% sand, 40% silt, 37% clay; 1.9% organic matter) classified as Belen clay loam [clayey over loamy, montmorillonitic (calcareous), thermic VerticTorrifluvent] (USDA-NRCS 2023). The Los Lunas study site featured coarse-textured soil (81% sand, 15% silt, 4% clay; 1.1% organic matter) classified as Gila loam soil [coarse-loamy, mixed, superactive, calcareous, thermic Typic Torrifluvents] (USDA-NRCS 2023).

Fields were prepared following practices that are common for chile pepper production in New Mexico. Specifically, fields were tilled, laser leveled, and listed to make raised beds spaced 1 m apart at Leyendecker, 0.75 m apart at Los Lunas. Dissimilarity between sites in bed spacing reflected regional differences in conventional practice for producing chile pepper in New Mexico. The width of a raised bed was 0.8 m. At Leyendecker, chile pepper was seeded into raised beds at 5.04 kg ha^{-1} to a depth of 2 cm using a mechanical planter (MaxEmerge Plus; John Deere, Moline, IL) on April 19, 2021. At Los Lunas, chile pepper was seeded into raised beds at 5.04 kg ha^{-1} to a 2-cm depth using a mechanical planter (Cole Planet Jr.; Cole Planter Company, Albany, GA) on April 22, 2021. After seeding, fields were watered as needed with flood-furrow irrigation.

At each study site, five chile pepper cultivars ('Barker Hot', 'Big Jim', 'Lumbre', 'NM 6-4', and 'Sandia') were grown in contiguous field sections (one cultivar per section). Each cultivar section was 8 m wide, 27 m long. Within each cultivar section, treatments were arranged in a randomized complete block design with four replications. An experimental unit (herein "plot") was a 6-m length section of crop row. Adjacent plots were separated by single crop rows that did not receive herbicide and hand hoed as needed.

Treatments were as follows: (i) preemergence applications of napropamide followed by postemergence-directed applications of pendimethalin at 5 wk after crop seeding, (ii) preemergence applications of clomazone followed by postemergence-directed applications of pendimethalin at 5 wk after crop seeding, (iii) postemergence-directed applications of pendimethalin at 5 wk after crop seeding, and (iv) nontreated control. Herbicide application rates were maximum labeled rates for the soil texture at the study site. At Leyendecker (fine-textured soil), herbicide application rates consisted of: napropamide, 2.24 kg ha^{-1}; clomazone, 1.12 kg ha^{-1}; pendimethalin, 1.60 kg ha^{-1}. At Los Lunas (coarse-textured soil), herbicide application rates consisted of: napropamide, 1.12 kg ha^{-1}; clomazone, 0.56 kg ha^{-1}; pendimethalin, 0.80 kg ha^{-1}. Herbicide trade names and product concentrations were as follows: clomazone, Command 3ME®, 0.36 kg ai L^{-1} (FMC Corp., Philadelphia, PA); napropamide, Devrinol® 2-XT, 0.24 kg ai L^{-1} (United Phosphorus Inc., King of Prussia, PA); and pendimethalin, Prowl® H_2O, 0.45 kg ai L^{-1} (BASF Corp., Research Triangle Park, NC).

Herbicides were applied using a CO_2-powered backpack sprayer calibrated to deliver 148 L ha^{-1} and equipped with a hooded (BellSpray Inc., Opelousas, LA), flat-fan nozzle (TeeJet 8002EVS, TeeJet Technologies, Wheaton, IL). The spray nozzle height was 15 cm from the soil surface. The spray nozzle was centrally placed over raised beds for preemergence applications. For postemergence-directed applications, the spray nozzle was positioned so that the outer surface of the covering hood touched chile pepper leaf tips. This nozzle position placed herbicide solution on both upper surfaces and sides of raised beds. Postemergence-directed applications were administered to each side of the crop row within a plot. At the time of postemergence-directed applications, chile pepper plants had four to five true leaves. Plots lacked emerged weeds at the time of herbicide application. Fields were furrow irrigated within 6 h of herbicide application. Irrigation water did not cover the upper surfaces of raised beds.

At 4 wk after crop seeding (1 wk before applying postemergence-directed pendimethalin) and 8 wk after chile pepper seeding (3 wk after applying postemergence-directed pendimethalin), weeds were counted using permanent quadrats (1 m by 0.25 m) positioned near the center of each plot. Weeds were identified to species and removed after counting. After determining weed densities, and periodically throughout the chile pepper growing season, weeds were removed by hand hoeing. This hoeing regime maintained near weed-free conditions throughout the growing season.

At 2, 4, and 8 wk after postemergence-directed applications of pendimethalin, chile pepper plants were evaluated for visible symptoms of herbicide injury including leaf chlorosis, leaf necrosis, and leaf malformation. Crop injury was reported on a percentage scale, with 0% indicating no difference from nontreated control and 100% indicating complete desiccation of chile pepper leaves. At 2 and 4 wk after postemergence-directed pendimethalin, chile pepper plant height was determined by measuring the distance from the soil surface to uppermost leaf using 10 plants for each plot. Marketable green chile pepper fruits were harvested by hand from central 4-m sections of each plot. At Leyendecker, fruits were harvested from August 17, 2021 through August 23, 2021. At Los Lunas, fruits were harvested August 31, 2021 through September 7, 2021. Harvested fruits were weighed in the field to determine crop yield fresh weight.

Data Analysis

For the greenhouse study, preliminary analyses indicated that response variables were not affected by experimental run or interactions between treatments and runs ($P > 0.05$). Therefore, data for the two experimental runs were combined. Pendimethalin treatment effects on heights, fresh weights, dry weights, and root areas of chile pepper plants were separately assessed with response

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indices (Williamson and Richardson 1988). The response index (*RI*) was determined as:

$$\text{If } T \geq C, \text{then } RI = 1 - C/T; \text{If } T < C, \text{then } RI = T/C - 1 \quad [1]$$

where *T* is the response variable for the pendimethalin treatment, and *C* is the response variable in the nontreated control. *RI* values range from + 1 to –1. Positive values indicate stimulation by the pendimethalin treatment, and negative values indicate inhibition by the herbicide treatment. *RI* values, means, and 95% confidence intervals were calculated using Microsoft Excel (Office 2019; Microsoft, Redmond, WA). *RI* means with 95% confidence intervals not overlapping zero indicated statistically significant effects of pendimethalin treatment.

For the field study, statistical analyses were performed using R version 4.1.0 (R Core Team, 2021). Treatment effects on weed densities were assessed with generalized linear models with negative binomial distributions produced with the R package *mass*. In these models, herbicide treatment and replication were predictor variables. Weed density data for these models were means across cultivars at a specific site. The R package *emmeans* was used for pairwise comparisons of estimated marginal means with Tukey-adjusted P values. Estimated marginal means back-transformed from the log scale are reported in results. Herbicide treatment effects on chile pepper plant height and fruit yield were evaluated for each combination of cultivar and site separately. To do this, height and yield data for combinations of cultivar and site were subjected to ANOVA, followed by Tukey's HSD test, using the *agricolae* package in R.

Results and Discussion

Greenhouse Study

Pendimethalin applied to foliage and soil, and pendimethalin applied to soil only, did not cause visible injury on chile pepper plants other than stunting (data not shown). Pendimethalin applied to foliage and soil stunted 'Big Jim' and 'Sandia', reduced the fresh and dry weight of 'Big Jim', but increased the dry weight of 'Barker Hot' (Figure 1A). Chile pepper root area was not affected by pendimethalin applications to foliage and soil. Pendimethalin applied to the soil only did not affect dry weight, fresh weight, height, and root area of chile pepper plants (Figure 1B).

For cultivars including 'Barker Hot', 'Lumbre', and 'NM 6-4', fresh weight and dry weight responses to pendimethalin applied to foliage and soil were consistent with a previous study that determined postemergence over-the-top applications of pendimethalin at 1.62 kg ha^{-1} did not reduce aboveground biomass of bell pepper (*Capsicum annuum* L.) under greenhouse conditions (Figueroa et al. 2016). Differences among chile pepper cultivars to pendimethalin applied to foliage and soil was consistent with a previous study that showed degrees of yield loss and injury from post-transplant applications of pendimethalin varied among varieties of cabbage (*Brassica oleracea* L.) (Miller et al. 2003). Corn (*Zea mays* L.) cultivars exhibit differential tolerance to preemergence applications of trifluralin, which is in the same chemical family as pendimethalin (dinitroaniline chemical family) (Uludag et al. 2006). Chile pepper cultivars differed in tolerance to postemergence-directed applications of flumioxazin at 107 g ha^{-1} on coarse-textured soil (Schutte et al. 2019).

Reduced growth of specific chile pepper cultivars following applications of pendimethalin to foliage and soil indicates the importance of adherence to label guidelines for rate and spray coverage. Excessive rates, such as the rate in this study, can promote pendimethalin leaching to crop root zones and crop injury (Bandyopadhyay and Choudhury 2009). Pendimethalin that contacts foliage can cause leaf deformities (Miller et al. 2003), although it is important to note that pendimethalin-induced leaf deformities were detected with a herbicide formulation that likely differed from the formulation in this study. The pendimethalin product in this study was an aqueous capsule suspension and first registered by the U.S. Environmental Protection Agency in 2003–– 5 yr after the completion of the study that demonstrated deformities from pendimethalin on foliage (Miller et al. 2003). Nonetheless, because of the risk of crop injury, pendimethalin applications that contact chile pepper foliage or stems are prohibited (Anonymous 2022). These label guidelines were supported by our greenhouse study that indicated excessive rate applications of pendimethalin that contact chile pepper foliage reduced growth of specific cultivars.

Field Study

The five most abundant weed species at Leyendecker at 4 wk after crop seeding were Palmer amaranth (*Amaranthus palmeri* S. Watson), Wright groundcherry [*Physalis acutifolia* (Miers) Sandw], oakleaf datura (*Datura quercifolia* Kunth), junglerice, and prostrate spurge (*Euphorbia prostrata* Ait.). At 8 wk after crop seeding, abundant weed species included Palmer amaranth, Wright groundcherry, junglerice, prostrate spurge, and spurred anoda [*Anoda cristata* (L.) Schltdl.]. The five most abundant weed species at 4 and 8 wk after crop seeding were 99.0% of weeds counted at Leyendecker. At Los Lunas, the five most abundant weed species were Palmer amaranth, kochia [*Bassia scoparia* (L.) A.J. Scott], Russian thistle (*Salsola tragus* L.), stinkgrass [*Eragrostis cilianensis* (All.) Vignolo ex Janch.], and puncturevine (*Tribulus terrestris* L.). These five species were 99.6% of weeds at Los Lunas at 4 and 8 wk after crop seeding.

Weather conditions across growing seasons were similar between sites (Table 1). Air temperatures increased from April through June, generally decreased from July through September. Early phases of growing seasons featured low amounts of precipitation compared to later phases of growing seasons. Leyendecker received 37.9 mm of precipitation from April through June, 132.5 mm in July and August. Los Lunas received 26.2 mm of precipitation from April through June, 107.4 mm from July through September.

At Leyendecker at 4 wk after crop seeding, preemergence applications of clomazone reduced densities of oakleaf datura compared to the nontreated control (Table 2). Preemergence applications of both clomazone and napropamide reduced densities of Palmer amaranth, junglerice, and ground spurge. Preemergence applications of clomazone and napropamide also reduced densities of Wright groundcherry; however, Wright groundcherry densities were high (>73 plants m^{-2}) in all treatments at 4 wk after crop seeding. All weeds were removed after counting at 4 wk after crop seeding, and thus, weed densities at 8 wk after crop seeding were caused by newly emerged seedlings. At 8 wk after crop seeding at Leyendecker, plots treated with postemergence-directed pendimethalin had fewer weeds than nontreated control plots. This was primarily because post-emergence-directed applications of pendimethalin caused 58% to 73% reductions in junglerice compared to nontreated control plots, and 24% to 31% reductions in Wright groundcherry. However,

Table 1. Monthly weather data for the study period at the New Mexico State University (NMSU) Leyendecker Plant Science Research Center near Las Cruces, New Mexico and the NMSU Agricultural Science Center at Los Lunas, New Mexico.[a]

Location	Weather parameter	April	May	June	July	August	September
Leyendecker	Average air temperature (C)[b]	17.8	21.5	26.3	25.3	25.1	–[c]
	Minimum air temperature (C)	8.2	10.0	17.3	18.6	18.7	–
	Maximum air temperature (C)	25.4	31.2	34.6	32.9	32.5	–
	Rainfall (mm)	2.3	0.0	35.6	75.9	56.6	–
Los Lunas	Average air temperature (C)	14.2	19.5	25.0	24.9	23.4	21.2
	Minimum air temperature (C)	3.8	8.9	15.5	17.8	16.0	12.8
	Maximum air temperature (C)	23.6	29.0	34.2	33.4	33.1	30.8
	Rainfall (mm)	7.9	0.3	18.0	58.9	28.4	20.1

[a]Weather data obtained from the ZiaMet Weather Station Network (https://weather.nmsu.edu/ziamet/). Weather stations were located 275 m from the Leyendecker study site, 390 m from the Los Lunas study site. The study occurred in 2021.
[b]Air temperature data are monthly means. Rainfall data are monthly totals.
[c]September weather data are not reported for Leyendecker because the study at this site concluded before September 1.

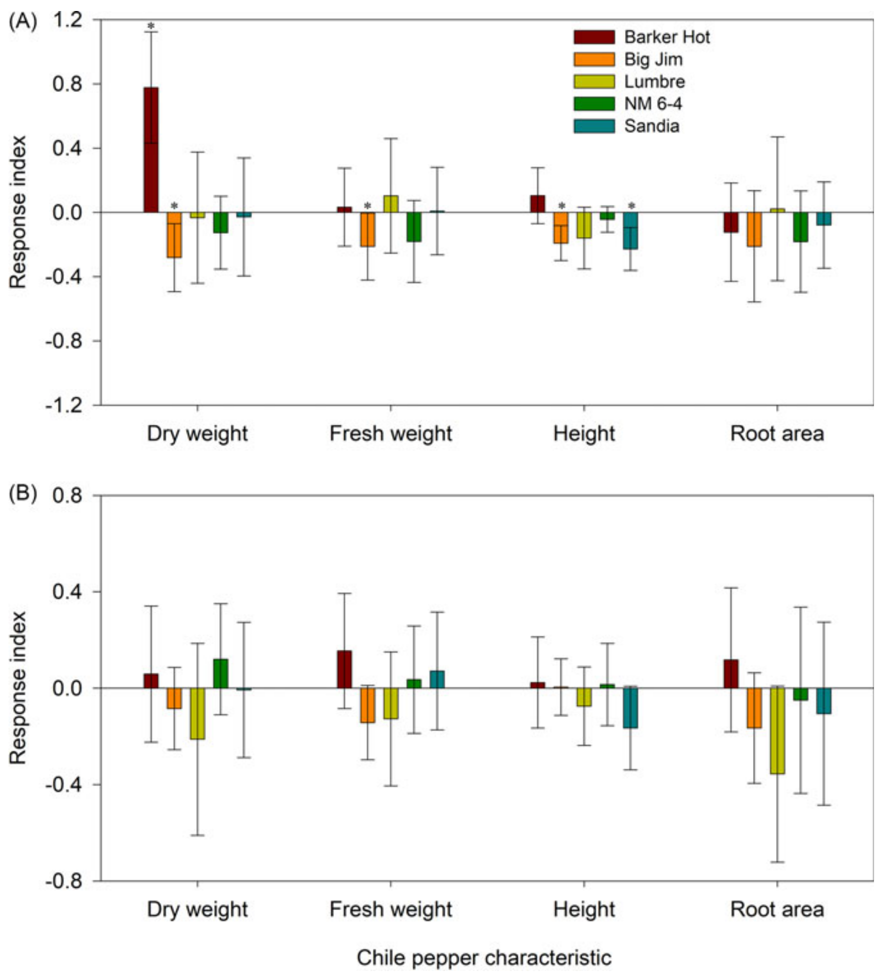

Figure 1. Chile pepper responses to pendimethalin applied to foliage and soil (A) and pendimethalin applied to soil only (B). Positive values for Response Index (*RI*) indicate stimulation by the pendimethalin treatment, whereas negative values for *RI* indicate inhibition by the pendimethalin treatment. The study was conducted under greenhouse conditions and included the following five cultivars: 'Barker Hot', 'Big Jim', 'Lumbre', 'NM 6-4', and 'Sandia'. Bars are means of eight replications with 95% confidence intervals. Asterisks above bars indicate combinations of characteristics and cultivars for which 95% confidence intervals do not overlap zero.

similar to 4 wk after crop seeding, Wright groundcherry densities were generally high (>31 plants m^{-2}) for all treatments at 8 wk after crop seeding at Leyendecker.

At Los Lunas at 4 wk after crop seeding, the preemergence application of clomazone reduced densities of puncturevine compared to the nontreated control (Table 3). At 8 wk after crop seeding, densities of Palmer amaranth, stinkgrass, kochia, and Russian thistle were not statistically different among treatments. However, overall weed densities at 8 wk after chile pepper seeding were numerically lower in plots treated with postemergence-directed applications of pendimethalin compared to the nontreated control.

Results from this study indicate that postemergence-directed applications of pendimethalin at 5 wk after crop seeding controlled some broadleaf and grass weeds in chile pepper.

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Table 2. Densities of the five most abundant weed species, and total weed densities, in chile pepper grown at the New Mexico State University Leyendecker Plant Science Research Center near Las Cruces, New Mexico. Treatments included preemergence (PRE) applications of napropamide or clomazone followed by (fb) postemergence-directed (POST-directed) applications of pendimethalin at 5 wk after crop seeding. Values are estimated marginal means from negative binomial models back-transformed from the log scale. Marginal means within a column followed by the same letter are not different according to pairwise comparisons with Tukey-adjusted P values ($P < 0.05$).

	4 wk after crop seeding						8 wk after crop seeding					
Treatment	AMAPA[a]	DATFE	ECHCO	EPHPT	PHYSA	Total[b]	AMAPA	ANVCR	ECHCO	EPHPT	PHYSA	Total
	Plants m^{-2}											
PRE clomazone fb POST-directed pendimethalin	18.2 a	2.7 a	5.2 a	0.3 a	73.7 a	104.0 a	2.0 a	0.4 a	3.5 a	2.3 a	32.6 a	41.4 a
PRE napropamide fb POST-directed pendimethalin	13.4 a	9.7 b	7.2 a	0.5 a	81.8 b	118.8 b	3.8 a	0.6 a	3.1 a	2.2 a	31.8 a	42.2 a
POST-directed pendimethalin	–[c]	–	–	–	–	–	1.6 a	0.8 a	4.8 a	2.5 a	35.2 a	45.3 a
Nontreated control	34.9 b	7.3 b	36.5 b	6.4 b	90.9 c	186.2 c	4.0 a	0.6 a	11.5 b	2.3 a	46.4 b	65.5 b

[a]Abbreviations: AMAPA, Palmer amaranth, *Amaranthus palmeri* S. Watson; ANVCR, spurred anoda, *Anoda cristata* (L.) Schltdl; DATFE, oakleaf datura, *Datura quercifolia* Kunth; ECHCO, junglerice, *Echinochloa colona* (L.) Link; EPHPT, prostrate spurge, *Euphorbia prostrata* Ait.; PHYSA, Wright groundcherry, *Physalis acutifolia* (Miers) Sandw.
[b]Sum of all weed species, including weed species not in the table. Species in table accounted for 99.0% of weeds at study site.
[c]No data presented for 4 wk after crop seeding because POST-directed pendimethalin was not applied until 5 wk after crop seeding.

Table 3. Densities of abundant weed species, and total weed densities, in chile pepper grown at the New Mexico State University Agricultural Science Center at Los Lunas, New Mexico. Treatments included preemergence (PRE) applications of napropamide or clomazone followed by (fb) postemergence-directed (POST-directed) applications of pendimethalin at 5 wk after crop seeding. Values are estimated marginal means from negative binomial models back-transformed from the log scale. Marginal means within a column followed by the same letter are not different according to pairwise comparisons with Tukey-adjusted P values ($P < 0.05$).

	4 wk after crop seeding						8 wk after crop seeding				
Treatment	AMAPA[a]	ERAME	KCHSC	SASKT	TRBTE	Total[b]	AMAPA	ERAME	KCHSC	SASKT	Total
	Plants m^{-2}										
PRE clomazone fb POST-directed pendimethalin	7.7 a	4.2 a	0.2 a	2.0 a	4.5 a	24.8 a	1.0 a	0.3 a	1.4 a	0.2 a	2.9 a
PRE napropamide fb POST-directed pendimethalin	7.3 a	5.4 a	1.6 a	2.2 a	11.2 c	33.8 b	2.2 a	0.6 a	0.8 a	0.3 a	3.9 a
POST-directed pendimethalin	–[c]	–	–	–	–	–	1.6 a	0.5 a	1.6 a	0.0 a	3.7 a
Nontreated control	7.7 a	7.6 a	1.2 a	2.3 a	8.6 b	32.7 b	3.5 a	1.1 a	1.4 a	0.0 a	6.0 a

[a]Abbreviations: AMAPA, Palmer amaranth, *Amaranthus palmeri* S. Watson; ERAME, stinkgrass, *Eragrostis cilianensis* (All.) Vignolo ex Janch.; KCHSC, kochia, *Bassia scoparia* (L.) A. J. Scott; SASKT, Russian thistle, *Salsola tragus* L.; TRBTE, puncturevine (*Tribulus terrestris* L.).
[b]Sum of all weed species, including weed species not in the table. Species in table accounted for 99.6% of weeds at study site.
[c]No data presented for 4 wk after crop seeding because POST-directed pendimethalin was not applied until 5 wk after crop seeding.

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Table 4. F-values from analyses of variance for herbicide treatment effects on chile pepper height at 2 wk and 4 wk after postemergence-directed applications of pendimethalin. At the time of postemergence-directed applications, chile pepper plants had four to five true leaves.[a]

Site[b]	Cultivar	Height 2 wk after postemergence-directed pendimethalin			Height 4 wk after postemergence-directed pendimethalin		
		$F_{3,9}$	P	cm[c]	$F_{3,9}$	P	cm
Leyendecker	'Barker Hot'	1.158	0.378	11.0	1.663	0.243	28.3
	'Big Jim'	0.635	0.611	8.6	0.793	0.528	23.2
	'Lumbre'	2.892	0.095	9.1	0.232	0.872	22.2
	'NM 6-4'	3.311	0.071	9.6	1.297	0.334	24.8
	'Sandia'	0.745	0.552	10.5	0.523	0.676	25.6
Los Lunas	'Barker Hot'	0.977	0.445	12.3	0.961	0.452	29.7
	'Big Jim'	0.059	0.980	10.9	0.667	0.593	20.6
	'Lumbre'	2.215	0.156	13.7	1.005	0.434	22.2
	'NM 6-4'	1.056	0.414	12.6	2.992	0.088	21.7
	'Sandia'	1.531	0.272	11.7	0.595	0.634	29.1

[a]Herbicide treatments were: (i) preemergence applications of napropamide followed by postemergence-directed applications of pendimethalin at 5 wk after crop seeding, (ii) Preemergence applications of clomazone followed by postemergence-directed applications of pendimethalin at 5 wk after crop seeding, (iii) postemergence-directed applications of pendimethalin at 5 wk after crop seeding, and (iv) nontreated control. Herbicide application rates were maximum labeled rates for the soil texture at the study site.
[b]Chile pepper was grown at the New Mexico State University (NMSU) Leyendecker Plant Science Research Center near Las Cruces, New Mexico and the NMSU Agricultural Science Center at Los Lunas, New Mexico.
[c]Heights are means of four replications. As there were no effects for herbicide treatment, herbicide treatment plots were considered subsamples for cultivars.

Postemergence-directed applications of pendimethalin reduced, but did not control, Wright groundcherry. This was consistent with previous studies that determined Wright groundcherry was not controlled by pendimethalin and other dinitroaniline herbicides (Umeda and Fredman 1996). Wright groundcherry plants in chile pepper can be terminated with hooded, row-middle applications of carfentrazone (Anonymous 2016) or glyphosate (Anonymous 2020). However, controlling Wright groundcherry with carfentrazone or glyphosate alone will likely be difficult, as these herbicides lack residual activity and this species exhibits prolonged periods of seedling emergence. Management of Wright groundcherry in chile pepper might be best achieved with combinations of chemical, mechanical, and cultural tactics, including tactics that diminish soil seedbanks (Schutte et al. 2021).

For all cultivars at both sites, herbicide treatment did not affect chile plant height at 2 and 4 wk after postemergence-directed applications of pendimethalin (Table 4). At 2, 4, and 8 wk after postemergence-directed applications of pendimethalin, all cultivars at both sites lacked visible symptoms of herbicide injury including chlorosis, necrosis, or malformation of vegetative growth (data not shown). Fruit yield for all cultivars at both sites was not affected by herbicide treatment (Table 5). Overall mean fruit yield at Leyendecker was 16,516 kg ha^{-1} and 12,586 kg ha^{-1} at Los Lunas.

Table 5. F-values from analyses of variance for herbicide treatment effects on chile pepper fruit yield. Fruit yields are fresh weights of green fruits.[a]

Site[b]	Cultivar	Fruit yield		
		$F_{3,9}$	P	kg ha^{-1} [c]
Leyendecker	'Barker Hot'	2.580	0.118	11,933
	'Big Jim'	1.467	0.287	20,317
	'Lumbre'	0.105	0.955	19,475
	'NM 6-4'	1.048	0.418	16,144
	'Sandia'	0.415	0.746	14,713
Los Lunas	'Barker Hot'	1.644	0.247	10,246
	'Big Jim'	0.759	0.545	15,845
	'Lumbre'	0.836	0.507	13,751
	'NM 6-4'	3.317	0.071	11,051
	'Sandia'	1.901	0.199	12,038

[a]Herbicide treatments were: (i) preemergence applications of napropamide followed by postemergence-directed applications of pendimethalin at 5 wk after crop seeding, (ii) Preemergence applications of clomazone followed by postemergence-directed applications of pendimethalin at 5 wk after crop seeding, (iii) postemergence-directed applications of pendimethalin at 5 wk after crop seeding, and (iv) nontreated control. Herbicide application rates were maximum labeled rates for the soil texture at the study site.
[b]Chile pepper was grown at the New Mexico State University (NMSU) Leyendecker Plant Science Research Center near Las Cruces, New Mexico and the NMSU Agricultural Science Center at Los Lunas, New Mexico.
[c]Fruit yields are means of four replications. As there were no effects for herbicide treatment, herbicide treatment plots were considered subsamples for cultivars.

The absence of herbicide injury symptoms in this study differed from Buzanini and Boyd (2023), who reported injury on bell pepper following postemergence-directed applications of pendimethalin. Specifically, pendimethalin (0.53 kg ha^{-1}) applications directed to bases of bell pepper at 2 wk after transplant in plasticulture on sandy soil caused 19% crop injury, with 0% injury representing no visible injury and 100% injury indicating complete plant desiccation (Buzanini and Boyd 2023). Differences in crop injury between Buzanini and Boyd (2023) and this study may reflect variability between bell pepper and chile pepper in tolerance to postemergence-directed pendimethalin. In addition, differences in crop injury between Buzanini and Boyd (2023) and this study could have been partly caused by differences in precipitation between the two study sites. In Buzanini and Boyd (2023), 340.8 mm of precipitation fell across the growing season. In this study, only 133.6 and 170.4 mm of precipitation fell during the growing seasons. Relatively high amounts of precipitation following pendimethalin application may have promoted downward movement of the herbicide through soil, absorption by bell pepper roots, and visible signs of crop injury in the previous study (Buzanini and Boyd 2023). In this study, relatively low amounts of precipitation, and the absence of irrigation water on surfaces of raised beds, may have prevented pendimethalin movement through soil. Further research on the effects of precipitation after postemergence-directed applications of pendimethalin is needed to clarify conditions that promote or prevent visible symptoms of injury from this herbicide in pepper crops.

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Practical Implications. Postemergence-directed applications of pendimethalin prior to crop thinning are currently registered for chile pepper in New Mexico. Thus, the pendimethalin application reported in this study can be immediately implemented by the growers. The current conventional timing for pendimethalin applications in chile pepper is shortly after crop thinning (9 to 10 wk after crop seeding). Post-directed applications of pendimethalin at 5 wk after crop seeding can used to reduce densities of early-season weeds in chile pepper. Because weed density is a determinant of time required for hand hoeing (Melander and Rasmussen 2001; Schutte 2017), post-directed applications of pendimethalin at 5 wk after crop seeding potentially reduce hand hoeing expenses for chile pepper production.

Postemergence-directed applications of pendimethalin prior to crop thinning may necessitate an herbicide other than pendimethalin applied at, or shortly after, crop thinning. This is because the total amount of pendimethalin applied to a chile pepper field in a growing season crop cannot exceed 1.62 kg ha^{-1} (Anonymous 2022). To replace the postemergence-directed application of pendimethalin conventionally applied at crop thinning, chile pepper growers in New Mexico can consider postemergence-directed applications of *S*-metolachlor or row middle applications of flumioxazin (Schutte et al. 2019). As a part of a comprehensive management program that includes mechanical and cultural strategies for controlling weeds in chile pepper, postemergence-directed applications of pendimethalin at 5 wk after crop seeding may help chile pepper growers to control early-season weeds and possibly reduce expenses for hand hoeing.

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