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Postemergence herbicides for weed control in pearl millet hybrids

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Abstract

Greenhouse and field experiments were conducted in Kansas to test various postemergence herbicides for crop safety and weed control in pearl millet. Five pearl millet hybrids were used in greenhouse experiments and three hybrids (Hyb1, Hyb-2k, Hyb-3k) were used in field experiments at two sites. All herbicides were found to be safe (1% to 5% injury) for use on all pearl millet hybrids in both greenhouse and field experiments at 28 d after application (DAA), except imazamox and nicosulfuron, which were noted to cause 22% to 35% injury. At Site 1 at 42 DAA, 2,4-D, dicamba, bromoxynil + pyrasulfotole, 2,4-D + bromoxynil + fluroxypyr, and dicamba + 2,4-D effectively controlled Palmer amaranth by 88% to 91%, and density was reduced to 2 to 4 plants m^{-2} compared with 18 plants m^{-2} in nontreated control plots. The least control (60% to 65%) and greatest density (8 plants m^{-2}) of Palmer amaranth was observed after applications of imazamox and nicosulfuron. In contrast, green foxtail was effectively controlled by 91% to 92%, and density was reduced to just 2 plants m^{-2} when imazamox and nicosulfuron were applied, whereas 13 plants m^{-2} were recorded in a nontreated control plot at 42 DAA. No weed emergence was observed at Site 2 regardless of treatment, including nontreated plots. High grain yields were recorded (Hyb1, 3,866 to 4,619 kg ha^{-1}; Hyb-2k, 2,222 to 3,699 kg ha^{-1}; and Hyb-3k, 822 to 1,315 kg ha^{-1}) at both sites after applications of 2,4-D + bromoxynil + fluroxypyr. These results highlight that the postemergence herbicides tested in this study, except imazamox and nicosulfuron, can be safely used for weed control in fields of pearl millet.

Introduction

Pearl millet is a dryland cereal crop grown worldwide for food and feed because it has high nutritional value (Perumal et al. 2024). It is one of the most climate-resilient cereals and can tolerate high temperature stress during its reproductive stage (Prasad et al. 2017). For instance, pearl millet can flower in high temperatures (>42 C) without affecting yield quantity and quality (Daduwal et al. 2024). Furthermore, pearl millet has a C_4 photosynthetic pathway with Kranz anatomy that enables it to fix carbon dioxide and use water efficiently (Howarth et al. 1996; Walsh et al. 2024). In addition, pearl millet can grow and thrive well in soils with high salinity or low water-holding capacity (Prasad et al. 2020). Pearl millet is recognized for its nutritional value and it has the potential to help overcome global malnutrition (Rai et al. 2012; Satyavathi et al. 2021). Pearl millet is an important source of energy (361 kcal per 100 g) with a low glycemic index (55), and high fiber content (1.2 g per 100 g) compared to other major cereals (Nibhoria et al. 2024). Forage pearl millet has a high amount of crude protein (12% to 14%) and low fiber (2.8% to 17.6%) compared to corn (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench). Pearl millet hybrids with brown midrib genes are low in lignin, which improves forage digestibility (Bhattarai et al. 2019; Uppal et al. 2015).

Globally, pearl millet is the sixth most important cereal crop after rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), corn, barley (*Hordeum vulgare* L.), and sorghum (Satyavathi et al. 2021). It is a staple food for more than 90 million people in arid and semiarid regions in Africa and Asia (Satyavathi et al. 2024). Global pearl millet production in 2024 was 31×10^8 kg, 43% (13×10^8 kg) of which was grown in India (USDA-FAS 2024). In the United States, pearl millet is grown primarily for silage preparation and hay production over 0.6 million ha (Myers 2002). It also serves as a major component of poultry feed, and as a livestock feed due to the absence of prussic acid (Yadav et al. 2024). Pearl millet can potentially be grown as an alternative crop for grain, forage, and as a cover crop (replacing fallow periods) in the dryland Central Great Plains (CGP) of the United States in the existing cropping system (Kumar et al. 2024; Serba et al. 2020). However, improved agronomic practices for pearl millet production are warranted for widespread adoption of this alternative crop in this region.

Among various biotic stresses, weeds are major constraints to the successful production of pearl millet (Kumar et al. 2024). Weeds compete for nutrients, water, sunlight, and space, which results in lower grain yields and higher production costs (Kaur et al. 2018). Due to its slow initial growth, pearl millet is a poor competitor with weeds in its early growing stages (Balyan et al. 1993). The critical period of weed control for pearl millet ranges from 15 to 30 d after planting; therefore, early-season weed control is crucial to preventing grain yield loss (Kumar et al. 2024). Depending upon growing conditions, season-long weed interference can reduce pearl millet grain yields by 5% to 94% (Balyan et al. 1993; Chaudhary et al. 2018; Das and Yaduraju 1995; Sharma and Jain 2003).

Producers primarily rely on herbicides to control weeds in the no-till drylands of the CGP. However, limited preemergence and postemergence herbicide options are currently labeled for use in pearl millet production. Previous studies have reported the effectiveness of postemergence-applied atrazine, imazethapyr, tembotrione, and 2,4-D for weed control in pearl millet. For instance, effective control of broadleaf weeds has been reported with an early postemergence application of atrazine at 100 to 400 g ha^{-1} or 2,4-D at 500 to 700 g ha^{-1} (Dowler and Wright 1995; Girase et al. 2017; Samota et al. 2022). Similarly, Chaudhary et al. (2018) reported significant reductions in weed density and total weed dry weights with a single postemergence application of tembotrione at 80 to 100 g ha^{-1}. In contrast, Singh et al. (2015) reported significant phytotoxic injury and grain yield loss in pearl millet when 40 g ha^{-1} of imazethapyr was applied postemergence. Nonetheless, limited information exists on the crop safety and effectiveness of various postemergence herbicides for broad-spectrum weed control in pearl millet in the CGP. In addition, the widespread evolution of herbicide-resistant weeds is a serious challenge in the CGP region and warrants the need to expand effective chemical-based weed control programs for pearl millet (Heap 2025; Kumar et al. 2024). To fill these knowledge gaps, greenhouse and field studies were initiated to investigate the effectiveness of various postemergence herbicides (labeled for use on sorghum) for crop safety and broad-spectrum weed control when applied to advanced pearl millet hybrids. The postemergence herbicides tested in this study are not yet approved for use on pearl millet. We hypothesized that pearl millet exhibits a natural tolerance to postemergence herbicides labeled for use on sorghum, given that both cereal crop species share common biological and agronomic traits, including tolerance to abiotic stresses such as heat, drought, and salinity. Thus the main objectives for this research were to 1) investigate the safety of newly developed pearl millet hybrids when exposed to postemergence herbicides, 2) determine the effectiveness of postemergence herbicides to control weeds that grow with pearl millet, and 3) determine the impact of phytotoxicity and weed control on pearl millet grain yields.

Materials and Methods

Greenhouse Study

Advanced pearl millet parental lines initially developed at Kansas State University's Agricultural Research Center in Hays (KSU-ARCH) (Ramalingam et al. 2024; Serba et al. 2017) were used to develop pearl millet hybrids in summer 2022. Five pearl millet hybrids (Hyb1, ARCH-37A/ARCH-49R; Hyb2, ARCH-27A/ARCH-65R; Hyb3, ARCH-41A/ARCH-70R; Hyb4, ARCH-30A/ARCH-62R; and Hyb5, ARCH-32A/ARCH-21R) were used in this study. Greenhouse studies were conducted in summer and repeated in fall 2023 at KSU-ARCH. Seeds of each selected pearl millet hybrid were separately planted in 10- by 10-cm^2 plastic pots filled with a commercial potting mixture (Miracle-Gro Moisture Control Potting Mix; Miracle-Gro Lawn Products, Marysville, OH). Experiments were conducted in a randomized complete block (blocked by herbicides) design with 12 replications (1 pot = 1 plant = 1 replication). The greenhouse temperature was maintained at 32/29 ± 5 C day/night with a 15/9-h photoperiod, and plants were watered daily. A total of eight postemergence herbicides, including acetochlor + atrazine, atrazine, bromoxynil, bromoxynil + pyrasulfotole, 2,4-D, 2,4-D + bromoxynil + fluroxypyr, dicamba, and dicamba + 2,4-D, were tested on all five hybrids at the seedling stage (3- to 4-leaf stage; 10 to 12 cm tall). Information on the postemergence herbicides tested, their rates, trade names, and manufacturers is summarized in Table 1. A nontreated check treatment was also included for comparisons. A cabinet spray chamber equipped with an even flat-fan nozzle tip (AIXR110015; TeeJet Technologies, Glendale Heights, IL) calibrated to deliver 141 L ha^{-1} of the spray solution at 240 kPa was used. After postemergence herbicides were applied, the plants were returned to the greenhouse and watered after 24 h.

Field Experiments

Field experiments were conducted at two different sites in summer 2024 at KSU-ARCH. The soil type at both sites (Site 1, 38.86202°N, 99.33488°W; Site 2, 38.85144°N, 99.34108°W) was a Roxbury silt loam (fine-silty, mixed, superactive, mesic Cumulic Haplustolls), pH values of 6.9 and 7.1, and organic matter content of 1.5% and 1.7% at Sites 1 and 2, respectively. Site 1 had been farmed in a conventionally tilled sorghum-fallow rotation for >5 yr, whereas Site 2 had been farmed with a no-till dryland wheat-sorghum-fallow rotation for >10 yr. Two pearl millet hybrids, Hyb1 and Hyb-2k, developed by the millet breeding program at KSU-ARCH, along with one commercial hybrid (Hyb-3k, a Tifleaf hybrid, Albert Lea Seed, Albert Lea, MN), were used for field studies in both sites. A total of 10 postemergence herbicides applied at labeled field-use rates for sorghum were evaluated (Table 1). A nontreated weedy check was included for comparison purposes. A burndown treatment of glyphosate (1,260 g ha^{-1}, Roundup PowerMAX 3; Bayer CropScience, St. Louis, MO) was used to terminate all weeds that were present at Site 2 before planting the pearl millet. A fine seedbed was prepared using two cultivations (10 cm deep) at Site 1, whereas Site 2 was not tilled before pearl millet was planted. At both field sites, each hybrid was planted at a density of 172,149 seeds ha^{-1} in rows spaced 76 cm apart on June 16, 2024. The postemergence herbicides were applied 21 d after planting (when millet plants were at the 4- to 5-leaf stage, or 12 to 15 cm tall) using a CO_2-pressurized backpack sprayer equipped with two flat-fan 110015XR TeeJet nozzles (50 cm boom length) calibrated to deliver a spray solution at the rate of 141 L ha^{-1} at a consistent pressure of 276 kPa. A supplemental irrigation of 2.5 cm was applied using a sprinkler irrigation system on June 17, 2024, at Site 1, but no supplemental irrigation was applied at Site 2. Experiments were conducted in a split-plot (hybrids as main plots and postemergence herbicides as subplots), randomized complete block design with three replications. Each two-row plot, 1.5 m wide and 3 m long, constituted an experimental plot. All standard agronomic practices for pearl millet production, including time of planting, seeding rate, nutrients, and other management practices, were followed as recommended by agronomists at Kansas State University (Perumal et al. 2024). Data on

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Table 1. Postemergence herbicides, their rates, and adjuvants tested on pearl millet hybrids.

Trade name	Common name	Rate	Adjuvant[a]	Manufacturer[b]
		g ae or ai ha^{-1}		
2,4-D Amine	2,4-D	532	–	Alligare, LLC
Clarity®	Dicamba	280	–	BASF Ag Solutions, USA
Atrazine 4L	Atrazine	2,240	–	Loveland Products, Inc.
Huskie®	Bromoxynil + pyrasulfotole	300 + 40	NIS	Bayer CropScience
Moxy® 2E	Bromoxynil	420	NIS	WinField United
Kochiavore®	2,4-D + bromoxynil + fluroxypyr	351+ 351+140	–	WinField United
Weedmaster	Dicamba + 2,4-D	140 + 402	–	Nufarm Americas, Inc.
Degree Xtra®	Acetochlor + atrazine	1,513 + 751	–	Bayer CropScience
Beyond®	Imazamox	52	COC	BASF Ag Solutions
Zest™ WDG	Nicosulfuron	70	COC	Corteva Agriscience, USA

[a]Adjuvants included crop oil concentrate (COC) at 5 ml L–1, or nonionic surfactant (NIS) at 2.5 ml L–1.
[b]Manufacturer locations: Alligare, LLC, Opelika, AL; BASF Ag Solutions, USA, Research Triangle Park, NC; Bayer CropScience, St. Louis, MO; Corteva Agriscience, USA, Indianapolis, IN; Loveland Products, Inc., Greenville, MS; Syngenta Crop Protection, LLC, Greensboro, NC; UPL NA Inc., Cary, NC; WinField United, Arden Hills, MN.

mean monthly air temperature, total monthly precipitation during the field experiments, and 30-yr average were also recorded from the K-State Mesonet weather station (https://mesonet.k-state.edu/) and summarized in Table 2.

Data Collection

In greenhouse experiments, estimates of percent visible injury were recorded at 7, 14, and 28 DAA of postemergence herbicides on a scale of 0% to 100% (where 0% = no injury and 100% = complete death). Injury symptoms included stunting, chlorosis, and necrosis of treated plants for each hybrid. At 28 DAA, the aboveground shoot biomass of treated plants was collected by cutting plants from the soil surface and drying them at 65 C for 5 d to determine the shoot dry biomass reduction (% of nontreated). In field studies at both sites, visible injury on a similar scale of 0% to 100% was recorded at 14 and 28 DAA. Similarly, visible control ratings using the same scale of 0% to 100% for Palmer amaranth and green foxtail were recorded at 28 and 42 DAA at Site 1, whereas no weed emergence during the crop growing period was observed at Site 2. The density of individual weed species was also recorded at 42 DAA using a 1-m^2 quadrat from the center of each plot at Site 1. At maturity, pearl millet plants were manually harvested using two 1-m rows from each plot to estimate the grain yield at both sites. Harvested pearl millet plants were dried in an oven at 65 C for 7 d, and grain heads were threshed using a millet thresher (BT-14 Single Plant Belt Thresher; ALMACO, Nevada, IA) and weighed to estimate the grain yield (in kilograms per hectare; kg ha^{-1}) of each pearl millet hybrid under each tested postemergence herbicide.

Statistical Analysis

Treatment-by-experimental run interaction was nonsignificant for greenhouse experiments (P = 0.463); therefore, data (visible crop injury and shoot dry biomass reduction) were pooled across experimental runs. For field experiments, data were analyzed and presented separately for each site to account for differences in environmental conditions and agronomic practices (Site 1 had been conventionally tilled and received sprinkler irrigation, whereas Site 2 had not been tilled and was a dryland environment). Data were tested for homogeneity of variance and normality of the residuals using the UNIVARIATE procedure with SAS software (v.9.3; SAS Institute, Inc., Cary, NC), and all data met these assumptions. The fixed effects in the ANOVA for greenhouse and field experiments included postemergence herbicides, pearl millet hybrids, and their interactions. The random effects in the ANOVA included replication and all interactions involving replication for both greenhouse and field experiments. Data on visible weed control from nontreated plots were excluded from the analyses. The treatment means were separated using Fisher's protected LSD test (P < 0.05).

Table 2. Average monthly air temperature, cumulative precipitation during the 2024 growing season and 30-yr averages at the Kansas State University Agricultural Research Center near Hays.[a]

Months	2024	30-yr average	2024	30-yr average
	C		mm	
May	18	17	45	83
June	26	23	111	72
July	25	26	76	100
August	23	25	107	77
September	17	20	22	52
October	17	13	6	40

[a]Data were obtained from the K-State Mesonet weather station (https://mesonet.k-state.edu/)

Results and Discussion

Greenhouse Study

Percent Visible Injury. A nonsignificant interaction between pearl millet hybrids and postemergence herbicides was observed (P = 0.821) for percent visible injury; however, the main effect of postemergence herbicides was significant (P < 0.0001). Averaged across all five hybrids, the greatest injury (17%) was observed at 14 DAA after acetochlor + atrazine had been applied, followed by 15% injury when bromoxynil was applied alone, and then bromoxynil + pyrasulfotole, and dicamba + 2,4-D (Table 3). Millet exhibited relatively lower injury (12% to 13%) at 14 DAA when other herbicides, including atrazine, 2,4-D, dicamba, and 2,4-D + bromoxynil + fluroxypyr were applied. In contrast, only 1% to 3% injury was observed at 28 DAA after the majority of postemergence herbicides had been tested. Acetochlor + atrazine resulted in an average of 5% injury to all five pearl millet hybrids when evaluated at 28 DAA (Table 3). Pearl millet tolerance to atrazine was previously evaluated at Kansas State University during 1978 and 1979, and only slight injury was reported then (Ndahi et al. 1981). Robinson (1973) reported no visible injury to proso millet (*Panicum miliaceum*) when atrazine was applied.

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Table 3. Effect of postemergence herbicides on visible injury and shoot dry biomass reduction (as a percent of nontreated plots) assessed at 28 d after application, averaged among five pearl millet hybrids in greenhouse experiments.[a,b]

Herbicide	Rate	Crop injury		Shoot dry biomass reduction
		14 DAA	28 DAA	28 DAA
	g ae or ai ha^{-1}	———%———		% of nontreated
2,4-D	532	12 d	2 c	4 c
Dicamba	280	12 d	2 c	3 c
Atrazine	2,240	13 c	2 c	4 c
Bromoxynil + pyrasulfotole	300 + 40	15 b	3 b	7 b
Bromoxynil	420	15 b	3 b	6 b
2,4-D + bromoxynil + fluroxypyr	351+ 351+140	13 c	1 d	2 c
Dicamba + 2,4-D	140 + 402	15 b	3 b	6 b
Acetochlor + atrazine	1,513 + 751	17 a	5 a	9 a

[a]Abbreviation: DAA, days after application.
[b]Means followed by the same letters within each column indicate no statistical difference according to Fisher's protected LSD test (P < 0.0001).

In contrast, Lyon and Baltensperger (1993) reported visible injury to proso millet with higher rates (three times the field-use rate) of postemergence application of bromoxynil and dicamba, which declined over time and were not evident before harvest.

Shoot Dry Biomass Reduction. Consistent with visible injury, a reduction in shoot dry biomass (% of nontreated of pearl millet) was the only the main effect to demonstrate significance (P < 0.0001). Averaged across all hybrids, compared with the nontreated weedy check, the shoot dry biomass was lower after applications of all postemergence herbicides. For instance, the greatest reduction (9%) in shoot dry biomass occurred when acetochlor + atrazine was applied (Table 3). Furthermore, shoot dry biomass was reduced by 6% to 7% with applications of bromoxynil, bromoxynil + pyrasulfotole, and dicamba + 2,4-D (Table 3). In contrast, applications of atrazine, 2,4-D, dicamba, and 2,4-D + bromoxynil + fluroxypyr resulted in the least shoot dry biomass reduction (2% to 4%) when evaluated at 28 DAA (Table 3).

Field Experiments

Total monthly precipitation during the experimental period in 2024 growing season ranged from 6 to 111 mm, and the mean monthly air temperature during the experimental period ranged from 17 to 26 C (Table 2). These weather conditions represent a typical growing season compared with 30-yr average weather data in the semiarid region of western Kansas (Table 2).

Pearl Millet Injury

Field Site 1. The main effect of postemergence herbicides was significant (P < 0.0001) for pearl millet injury. Averaged across three pearl millet hybrids, atrazine, acetochlor + atrazine, 2,4-D, 2,4-D + bromoxynil + fluroxypyr, bromoxynil, bromoxynil + pyrasulfotole, dicamba, and dicamba + 2,4-D applied postemergence resulted in 1% to 3% visible injury at 28 DAA (Table 4). Ndahi et al. (1981) reported pearl millet tolerance to atrazine with slight visible injury. When imazamox and nicosulfuron were applied, visible injury was 22% to 27% among the hybrids at 28 DAA (Table 4). These results are consistent with those reported by Tugoo et al. (2025), who recorded variable injury (5% to 70%) among 56 different pearl millet parental lines when imazamox and nicosulfuron were applied postemergence in a greenhouse study. In fact, all pearl millet hybrids tested in the current study were originally developed by using some of the male and female parental inbred lines previously evaluated by Tugoo et al. (2025).

Field Site 2. Averaged across pearl millet hybrids, when evaluated at 28 DAA, visible injury was 1% to 4% when atrazine, acetochlor + atrazine, 2,4-D, 2,4-D + bromoxynil + fluroxypyr, bromoxynil, bromoxynil + pyrasulfotole, dicamba, and dicamba + 2,4-D were applied postemergence. Furthermore, visible injury was 29% to 35% at 28 DAA when imazamox and nicosulfuron were applied (Table 5).

Palmer Amaranth Control and Density

Field Site 1. The main effect of postemergence herbicides was significant (P < 0.0001) for Palmer amaranth control at 28 and 42 DAA and density at 42 DAA. Averaged among three pearl millet hybrids, postemergence applications of 2,4-D, dicamba, dicamba + 2,4-D, bromoxynil + pyrasulfotole, and 2,4-D + bromoxynil + fluroxypyr provided effective control (91% to 96%) of Palmer amaranth at 28 DAA (Table 4). These results are consistent with those reported by Jhala et al. (2014) that 94% to 98% of Palmer amaranth was controlled with 2,4-D and dicamba in a greenhouse study in Nebraska. Grabouski (1971) reported effective control of redroot pigweed (*Amaranthus retroflexus* L.) with 2,4-D, bromoxynil, and dicamba in proso millet fields. Similarly, Aulakh et al. (2021) reported 88% to 92% control of glyphosate-resistant (GR) Palmer amaranth when 2,4-D and dicamba were applied postemergence in a greenhouse study in Connecticut. In contrast, Kumar et al. (2021a) previously reported slightly lower control of Palmer amaranth with postemergence-applied dicamba (79% control), 2,4-D (83% control), dicamba + 2,4-D (86% control), and 2,4-D + bromoxynil + fluroxypyr (72% control) in wheat stubble. In that study, postemergence herbicides were applied to Palmer amaranth plants that were taller (at the inflorescence initiation stage) in wheat stubble (Kumar et al. 2021a). In the current study, control averaged 82% to 85% at 28 DAA with postemergence applications of atrazine, bromoxynil, and acetochlor + atrazine (Table 4). These results are contrary to those reported by Chahal et al. (2017), that control of GR Palmer amaranth was lower with postemergence-applied atrazine (23% control) and bromoxynil (9% control) in a greenhouse study. In that study, the GR Palmer amaranth population that was tested was also suspected of being resistant to herbicides that inhibit the photosystem II process (Chahal et al. 2017), whereas the herbicide resistance status of the Palmer amaranth population in the current study was not known. Among all postemergence herbicides tested,

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Table 4. Percent visible crop injury, Palmer amaranth and green foxtail control, and density after application of postemergence herbicides averaged among three pearl millet hybrids at experimental Site 1.[a,b]

Herbicide	Rate	Crop injury	Palmer amaranth control 28 DAA	Palmer amaranth control 42 DAA	Palmer amaranth density 42 DAA	Green foxtail control 28 DAA	Green foxtail control 42 DAA	Green foxtail density 42 DAA
	g ae or ai ha^{-1}	——%——			plants m^{-2}	——%——		plants m^{-2}
2,4-D	532	3 c	91 A	88 a	3 c	15 e	12 e	10 a
Dicamba	280	2 c	92 A	90 a	2 c	18 de	15 de	10 a
Atrazine	2,240	2 c	82 B	77 b	6 b	70 c	63 c	6 b
Bromoxynil + pyrasulfotole	300 + 40	2 c	94 A	89 a	4 c	85 b	79 b	5 b
Bromoxynil	420	2 c	83 B	78 b	6 b	82 b	77 b	5 b
2,4-D + bromoxynil + fluroxypyr	351+ 351+ 140	1 c	96 A	91 a	2 c	84 b	78 b	5 b
Dicamba + 2,4-D	140 + 402	2 c	95 A	91 a	3 c	23 d	18 d	10 a
Acetochlor + atrazine	1,513 + 751	3 c	85 B	78 b	5 bc	75 c	68 c	6 b
Imazamox	52	22 b	75 C	65 c	8 b	94 a	92 a	2 c
Nicosulfuron	70	27 a	70 C	60 c	8 b	92 a	91 a	2 c
Nontreated	–	–	–	–	18 a	–	–	13 a

[a]Abbreviation: DAA, days after application.
[b]Means followed by the same letters within each column indicate no statistical difference according to Fisher's protected LSD test ($P < 0.0001$).

Table 5. Percent visible crop injury at 14 and 28 d after application of postemergence herbicides averaged among three pearl millet hybrids at field Site 2.[a,b]

Herbicide	Rate	14 DAA	28 DAA
	g ae or ai ha^{-1}	——%——	
2,4-D	532	5 cd	2 cd
Dicamba	280	4 d	2 cd
Atrazine	2,240	5 cd	3 cd
Bromoxynil + pyrasulfotole	300 + 40	4 d	2 cd
Bromoxynil	420	4 d	2 cd
2,4-D + bromoxynil + fluroxypyr	351+ 351+140	5 cd	2 cd
Dicamba + 2,4-D	140 + 402	4 d	1 d
Acetochlor + atrazine	1,513 + 751	8 c	4 c
Imazamox	52	35 b	29 b
Nicosulfuron	70	40 a	35a

[a]Abbreviation: DAA, days after application.
[b]Means followed by the same letters within each column indicate no statistical difference according to Fisher's protected LSD test ($P < 0.001$).

the least control of Palmer amaranth was observed with applications of imazamox and nicosulfuron, ranging from 70% to 75% at 28 DAA (Table 4). These results are consistent with those reported by Chahal et al. (2017) that lower control (23%) of GR Palmer amaranth was obtained when imazamox was applied postemergence in a greenhouse study. At 42 DAA, Palmer amaranth control declined slightly with the majority of the herbicides; however, the trend remained similar to what was observed at 28 DAA. For instance, 2,4-D, dicamba, dicamba + 2,4-D, bromoxynil + pyrasulfotole, and 2,4-D + bromoxynil + fluroxypyr provided excellent control (88% to 91%) of Palmer amaranth at 42 DAA. Control with atrazine, bromoxynil, and acetochlor + atrazine averaged 78% at 42 DAA, whereas control declined to 60% to 65% with applications of nicosulfuron and imazamox (Table 4). Lower control of Palmer amaranth with imazamox and nicosulfuron was probably due to the widespread presence of resistance to herbicides that inhibit acetolactate synthase among Palmer amaranth populations in the CGP region (Heap 2025).

Consistent with percent visible control, when evaluated at 42 DAA, Palmer amaranth density was also lower with all postemergence herbicides. For instance, at 42 DAA, 2 to 5 plants m^{-2} of Palmer amaranth were observed with applications of 2,4-D, dicamba, bromoxynil + pyrasulfotole, 2,4-D + bromoxynil + fluroxypyr, dicamba + 2,4-D, and acetochlor + atrazine, whereas 18 plants m^{-2} were counted in nontreated plots (Table 4). Furthermore, when atrazine, bromoxynil, imazamox, and nicosulfuron were applied, Palmer amaranth density was also reduced (to 6 to 8 plants m^{-2}) compared with nontreated plots, where 18 plants m^{-2} were counted at 42 DAA (Table 4).

Green Foxtail Control and Density

Field Site 1. Postemergence herbicides had a significant effect ($P < 0.0001$) on green foxtail control at 28 and 42 DAA and density at 42 DAA. Averaged among three pearl millet hybrids, imazamox and nicosulfuron provided the greatest control (91% to 94%) of green foxtail at 28 and 42 DAA (Table 4). Kumar et al. (2021b) reported 77% to 83% control of green foxtail with applications of imazamox and nicosulfuron in a fallow study. In the current study, bromoxynil alone, bromoxynil + pyrasulfotole, and 2,4-D + bromoxynil + fluroxypyr provided an average of 84% control at 28 DAA, which dropped to 78% on average at 42 DAA (Table 4). When atrazine alone or acetochlor + atrazine was applied, 70% to 75% control was observed at 28 DAA, and 63% to 68% control at 42 DAA. As expected, when observed at 28 and 42 DAA, the least control (10% to 15%) of green foxtail occurred when 2,4-D or dicamba were applied (Table 4). Grabouski (1971) reported that a postemergence application of dicamba was ineffective for green foxtail control. In contrast, in that same study, about 80% to 90% control of green foxtail was observed when 2,4-D and bromoxynil were applied (Grabouski 1971). Robinson (1973) reported effective control of foxtails with atrazine without causing injury to proso millet.

Table 6. Grain yield from three pearl millet hybrids as influenced by postemergence herbicides at both experimental sites.[a,b]

		Grain yield					
		Site 1			Site 2		
Herbicide	Rate	Hyb1	Hyb-2k	Hyb-3k	Hyb1	Hyb-2k	Hyb-3k
	g ae or ai ha^{-1}	kg ha^{-1}			kg ha^{-1}		
2,4-D	532	3,903 bA	3,094 bA	1,158 abB	2,371 cA	1,395 cB	604 bC
Dicamba	280	4,236 abA	3,008 bB	1,078 bC	2,130 cA	2,186 aA	451 cB
Atrazine	2,240	3,662 bcA	3,145 bB	1,129 abC	2,495 cA	1,502 bcB	417 cC
Bromoxynil + pyrasulfotole	300 + 40	3,903 bA	3,374 abB	1,475 aB	2,500 cA	2,189 aA	744 aB
Bromoxynil	420	3,483 cA	3,173 bA	1,131 abB	3,096 bA	1,798 bB	373 cC
2,4-D + bromoxynil + fluroxypyr	351+ 351+140	4,619 aA	3,699 aB	1,315 aC	3,866 aA	2,222 aB	822 aC
Dicamba + 2,4-D	140 + 402	4,044 bA	3,559 aB	1,295 aB	3,303 bA	1,853 bB	676 abC
Acetochlor + atrazine	1,513 + 751	3,584 bcA	3,241 abA	1,057 bB	2,267 cA	1,761 bB	640 abC
Imazamox	52	1,486 dA	970 cAB	560 cB	1,202 dA	928 dA	382 cB
Nicosulfuron	70	1,040 dA	1,289 cA	435 cB	728 eA	542 eA	142 dB
Nontreated	–	3,359 cA	3,139 bA	1,079 bB	1,833 cdA	1,265 cdB	357 cC

[a]Abbreviations: Hyb1, Hyb-2k, and Hyb-3k are the pearl millet hybrids that were tested.
[b]Means followed by the same lowercase letters within each hybrid indicate no statistical difference according to Fisher's protected LSD test ($P < 0.0001$), whereas means followed by the same uppercase letters within each herbicide treatment indicate no statistical difference ($P < 0.0001$).

When assessed at 42 DAA, green foxtail density was 2 plants m^{-2} after postemergence applications of imazamox and nicosulfuron compared 13 plants m^{-2} in the nonweedy plots. Similarly, compared with nontreated plots where 13 plants m^{-2} were counted, just 4 to 5 plants m^{-2} were counted after atrazine, bromoxynil, bromoxynil + pyrasulfotole, 2,4-D + bromoxynil + fluroxypyr, and acetochlor + atrazine were applied (Table 4). At 42 DAA the least reduction in green foxtail density (10 plants m^{-2} on average) was observed when 2,4-D, dicamba, or dicamba + 2,4-D were applied (Table 4).

Field Site 2. Weed emergence was not observed at Site 2, thus no data on weed control efficacy were collected at this location. The lack of any weed emergence during the experimental period at Site 2 was probably due to effective weed control achieved when postemergence burndown herbicides were applied in early spring and prior to pearl millet planting (M. Tugoo, personal observations). The primary focus was instead directed toward evaluating the phytotoxicity response of pearl millet hybrids to postemergence herbicides and assessing the yield performance of pearl millet hybrids under no-till, dryland conditions.

Pearl Millet Grain Yield

Field Site 1. Among the three pearl millet hybrids tested, Hyb1 outperformed the other two hybrids and produced the highest grain yield regardless of the herbicide that was tested on it. Hyb1 grain yield ranged from 3,584 to 4,044 kg ha^{-1} with postemergence-applied 2,4-D, atrazine, bromoxynil + pyrasulfotole, dicamba + 2,4-D, and acetochlor + atrazine. The highest grain yields (4,236 to 4619 kg ha^{-1}) occurred after postemergence applications of dicamba alone or 2,4-D + bromoxynil + fluroxypyr (Table 6). Hyb1 grain yield was 3,483 kg ha^{-1} after bromoxynil alone was applied, which is not much different from that of the nontreated weedy check (3,359 kg ha^{-1}). The least grain yield (1,040 to 1,486 kg ha^{-1}) from Hyb1 was observed after applications of imazamox and nicosulfuron (Table 6).

For Hyb-2k, most of the nontreated plots and those that received postemergence herbicides produced grain yields of 3,008 to 3,699 kg ha^{-1}. Outliers included plots that were treated with imazamox, for which yield was 970 kg ha^{-1}, and nicosulfuron, for which yield was 1,289 kg ha^{-1} (Table 5). Greater visible crop injury and relatively less weed control resulted in lower Hyb-2k grain yield when imazamox and nicosulfuron were applied. The highest grain yield of Hyb-2k (3,699 kg ha^{-1}) was observed when 2,4-D + bromoxynil + fluroxypyr were applied, which is not much different from yields after applications of bromoxynil + pyrasulfotole (3,374 kg ha^{-1}) and dicamba + 2,4-D (3,559 kg ha^{-1}). A similar grain yield trend was observed with Hyb-3k; however, the overall yield of that hybrid was lower than that of Hyb1 and Hyb-2k. The grain yield from all Hyb-3k plots (including nontreated) ranged between 1,078 and 1,475 kg ha^{-1}, except plots that received applications of imazamox (560 kg ha^{-1}) and nicosulfuron (435 kg ha^{-1}) (Table 6).

Field Site 2. Overall, the grain yields from all three hybrids at Site 2 were lower than those recorded at Site 1 (Table 6). The grain yields of Hyb1 and Hyb-2k from the nontreated weedy check plots were 1,833 and 1,265 kg ha^{-1}, respectively. The greatest yield (3,866 kg ha^{-1}) from Hyb1 was observed after postemergence applications of 2,4-D + bromoxynil + fluroxypyr, followed by dicamba + 2,4-D (3,303 kg ha^{-1}) and bromoxynil alone (3,096 kg ha^{-1}) (Table 6). Furthermore, the Hyb1 grain yield after applications of 2,4-D, dicamba, atrazine, bromoxynil + pyrasulfotole, and acetochlor + atrazine ranged from 2,130 to 2,500 kg ha^{-1}. The lowest Hyb1 grain yield was observed after imazamox (1,202 kg ha^{-1}) and nicosulfuron (728 kg ha^{-1}) had been applied, which is similar to yield recorded at Site 1 (Table 6).

The grain yield from Hyb-2k ranged from 1,395 to 1,728 kg ha^{-1} after postemergence applications of 2,4-D, atrazine, bromoxynil, dicamba + 2,4-D, and acetochlor + atrazine. The highest grain yield (2,199 kg ha^{-1}) occurred with applications of dicamba, bromoxynil + pyrasulfotole, and 2,4-D + bromoxynil + fluroxypyr. The least grain yield (542 to 928 kg ha^{-1}) from Hyb-2k occurred after imazamox and nicosulfuron were applied (Table 6), which is similar to what occurred with other hybrids.

Similar to results recorded at Site 1, the overall grain yield from Hyb-3k was lower with all tested postemergence herbicides. The highest Hyb-3k grain yields (640 to 822 kg ha^{-1}) were recorded after applications of bromoxynil + pyrasulfotole, 2,4-D + bromoxynil + fluroxypyr, and dicamba + 2,4-D (Table 6). Hyb-3k grain yield from all other herbicide-treated plots (and

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nontreated plots) ranged from 142 to 604 kg ha^{-1}, with the least grain yield occurring after imazamox and nicosulfuron were applied (Table 6).

Practical Implications

Results from greenhouse and field studies demonstrated that the postemergence herbicides we tested, except imazamox and nicosulfuron, were safe to use on pearl millet hybrids, with visible injury estimates of 22% to 35% among all three hybrids at two field sites. Imazamox and nicosulfuron provided excellent (90% to 92%) control of giant foxtail. Furthermore, 2,4-D + bromoxynil + fluroxypyr, bromoxynil + pyrasulfotole, and 2,4-D, dicamba, and dicamba + 2,4-D provided effective (>90%) control of Palmer amaranth. We stress that the postemergence herbicides assessed in this study are not yet approved for use on pearl millet. However, the information gained through this research may provide support the approval and registration process. Future research on pearl millet hybrids at a variety of locations with diverse environmental and soil conditions will be crucial for advancing this process. Future investigations are needed to evaluate the combinations of preemergence and postemergence herbicides (two-pass strategies) to ensure crop safety and effective season-long weed control in pearl millet. Studies should also explore how combining both chemical and nonchemical methods can advance weed control efforts in pearl millet.

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