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Green foxtail (*Setaria viridis*) and puncturevine (*Tribulus terrestris*) control in imazamox-, quizalofop-, and nicosulfuron-resistant grain sorghum in semiarid Central Great Plains

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Abstract

Recent commercialization of herbicide-resistant (HR) grain sorghum [*Sorghum bicolor* (L.) Moench] hybrids, including iGrowth, DoubleTeam, and Inzen enables the use of imazamox, quizalofop, and nicosulfuron, respectively, for annual grass weed control. However, effective season-long strategies for broad-spectrum weed control remain lacking. Field studies were conducted in 2021 at Kansas State University Agricultural Research Center near Hays, KS, to evaluate preemergence (PRE) and postemergence (POST) herbicide programs for weed control in these HR sorghum systems. In imazamox-resistant sorghum, imazamox (79 g ha^{-1}) applied PRE alone or with *S*-metolachlor, PRE *S*-metolachlor followed by (*fb*) POST imazamox, or POST imazamox alone achieved 84%–96% control of green foxtail (*Setaria viridis*) and puncturevine (*Tribulus terrestris*) and reduced total weed biomass by 92%–99%. In quizalofop-resistant sorghum, PRE atrazine alone or with *S*-metolachlor *fb* POST quizalofop, alone or tank-mixed with dicamba, provided 90%–97% green foxtail control. PRE atrazine *fb* POST quizalofop alone or mixed with 2,4-D or dicamba controlled puncturevine by 86%–97%. In nicosulfuron-resistant sorghum, PRE atrazine alone or with *S*-metolachlor *fb* POST nicosulfuron controlled green foxtail by 88%–93%. PRE atrazine *fb* POST nicosulfuron plus 2,4-D or dicamba achieved 84%–95% puncturevine control. Overall, effective PRE and POST programs provided consistent, season-long control of green foxtail and puncturevine across all three HR sorghum systems.

Abbreviations: POST, postemergence; PRE, preemergence; WAPOST, weeks after POST; WAPRE, weeks after PRE.

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Plain Language Summary

New herbicide-resistant grain sorghum systems, including iGrowth, DoubleTeam, and Inzen, allow farmers to use specific grass herbicides without damaging the crop. In 2021, field studies at Kansas State University Agricultural Research Center near Hays, KS, tested different herbicide programs for green foxtail and puncturevine control. Results showed that applying herbicides before weeds emerged, after emergence, or using both timings provided season-long control. The imazamox-tolerant system achieved up to 96% weed control and greatly reduced total weed growth. In the quizalofop- and nicosulfuron-resistant systems, combining early and follow-up applications controlled 84%–97% of target weeds. Overall, using both preemergence and postemergence treatments provided reliable, season-long weed control across all three sorghum systems.

1 | INTRODUCTION

Grain sorghum [*Sorghum bicolor* (L.) Moench] is the world's fifth most important cereal crop, with a global production of about 58 million metric tons (MMT) in 2023, and the United States ranked first by producing >8 MMT (USDA-NASS, 2024). It is a drought-tolerant crop that is well suited to no-tillage dryland production systems in the south and central Great Plains (Chadalavada et al., 2021; Hadebe et al., 2017). Sorghum is primarily grown for livestock feed and for industrial uses such as bioethanol production in the United States; however, its use as a food source is also increasing. Despite its high potential as a climate-resilient crop, grain sorghum production has declined globally in recent years, primarily due to its agronomic challenges, such as limited weed management options (USDA-NASS, 2024). Similar to other crops, weeds compete with sorghum for essential resources such as nutrients, water, and sunlight and reduce grain yield as well as grain quality (Lancaster et al., 2019). For instance, season-long weed interference resulted in grain yield loss of 37%, 38%, 30%, 56%, 61%, and 60%, respectively, in Arkansas, Kansas, Missouri, Nebraska, South Dakota, and Texas (Dille et al., 2020). It was further estimated that the US farmers could lose about 5.7 MMT of grain sorghum each year, resulting in an estimated annual economic loss of approximately $953 million without effective weed management (Dille et al., 2020).

The most troublesome grass weeds in grain sorghum production across the Great Plains include johnsongrass [*Sorghum halepense* (L.) Pers.], green foxtail [*Setaria viridis* (L.) P. Beauv.], shattercane [*Sorghum bicolor* (L.)], large crabgrass (*Digitaria sanguinalis* (L.) Scop.), and barnyard grass [*Echinochloa crus-galli* (L.) P. Beauv.] (Kumar et al., 2023). Among broadleaf weeds, Palmer amaranth (*Amaranthus palmeri* S. Watson), kochia [*Bassia scoparia* (L.) A. J. Scott], and puncturevine (*Tribulus terrestris* L.) are the most troublesome (Dhanda et al., 2025). Weed management in grain sorghum is challenging due to the limited availability of herbicide options and the lack of effective postemergence (POST) herbicides for controlling grass weeds (Peerzada et al., 2017; Werle et al., 2016). Most grain sorghum farmers rely on preemergence (PRE) herbicides to manage annual grass weeds (Hennigh et al., 2010; Werle et al., 2017).

More recently, the availability of three herbicide-resistant (HR) technologies, including iGrowth, DoubleTeam, and Inzen, has provided flexibility to farmers by allowing over-the-top herbicide applications for control of annual grass weeds (Bajwa et al., 2015; Givens et al., 2009). The iGrowth sorghum allows PRE and POST applications of imazamox (IMIFLEX herbicide; UPL Company), whereas Inzen sorghum allows only POST applications of nicosulfuron (Zest WDG herbicide; Corteva Agriscience). The DoubleTeam sorghum hybrid is resistant to quizalofop-p-ethyl (FirstAct herbicide, Adama Agricultural Solutions) (Kumar et al., 2023). All three HR grain sorghum technologies (iGrowth, Inzen, and Double Team) can potentially improve the grass and weed control options (Hennigh et al., 2010).

However, knowledge gaps exist on effective herbicide strategies for season-long and broad-spectrum weed control in these HR grain sorghum technologies. Information on various PRE and POST herbicides, applied alone or in combinations, along with their rates, that can provide effective broad-spectrum weed control in HR grain sorghum hybrids is lacking. Tank-mix compatibility of imazamox, nicosulfuron, and quizalofop with auxinic herbicides (2,4-D and/or dicamba) for weed control is also somewhat unknown in these HR grain sorghum systems. Therefore, there is a need to evaluate different herbicide combinations to achieve season-long broad-spectrum weed control in these HR sorghum hybrids. The main objective of this study was to evaluate weed control with various PRE and POST herbicides alone or in combi-

nations in iGrowth, DoubleTeam, and Inzen grain sorghum hybrids.

2 | MATERIALS AND METHODS

Three different field studies were conducted during the 2021 growing season at Kansas State University Agricultural Research Center (KSU-ARC) near Hays, KS (38.86177° N, 99.33396° W) to evaluate various PRE and POST herbicide strategies for weed control in the iGrowth, DoubleTeam, and Inzen grain sorghum hybrids. All studies were conducted in a randomized complete block design with four replications. The soil type at the study site was silt clay loam (24% sand, 48% silt, 28% clay), with a pH of 7.6 and organic matter of 2.1%. The study site was under a no-till dryland system for over 10 years with a 3-year rotation of winter wheat (*Triticum aestivum* L.) followed by (*fb*) grain sorghum *fb* fallow period. Prior to initiating the study, the experimental site was sprayed with glyphosate (Roundup PowerMax, Bayer CropScience) at 1260 g ha^{-1} with 2% w/v ammonium sulfate to kill winter annual weeds, including henbit (*Lamium amplexicaule* var. *aleppicum*), blue mustard (*Chorispora tenella*), tansy mustard (*Descurainia pinnata* (Walt.) Britt.), and downy brome (*Bromus tectorum*). The experimental site had a uniform infestation of green foxtail and puncturevine. All three HR sorghum hybrids were planted separately on June 7, 2021, at a seeding rate of 114,855 seeds ha^{-1} in 76-cm spaced rows, with a plot size of 3.0 m × 9.1 m and a seeding depth of 2.5 cm. In all three studies, PRE herbicides were immediately applied after sorghum planting, whereas POST herbicides were tested at 21 days after sorghum planting, when weeds were 8–10 cm tall. Herbicide programs and their respective rates are summarized in Table 1. PRE alone, PRE *fb* POST, and POST alone herbicide programs (Table 2) were evaluated on imazamox-resistant grain sorghum hybrid (ADVXG39016). Similarly, PRE alone and PRE *fb* POST herbicide programs (Table 3) were investigated on quizalofop-resistant grain sorghum hybrid (SP45A45DT). PRE *fb* POST herbicide combinations (Table 4) were tested on nicosulfuron-resistant grain sorghum hybrid (XSA5527). All herbicide applications were made using a CO_2-operated backpack sprayer equipped with a handheld four-nozzle boom (Turbo TeeJet XR 110015 nozzles with 51-cm spacing; Spraying Systems Co.). The sprayer was calibrated to deliver a spray solution at a rate of 140 L ha^{-1}, maintaining a consistent pressure of 276 kPa.

2.1 | Data collection

Data on percent control of green foxtail and puncturevine were visually assessed 3 weeks after PRE (WAPRE), 5 WAPRE, 7 WAPRE, and 11 WAPRE on a scale of 0%–100% (where 0% = *no control* and 100% = *complete control*). At 11 WAPRE, both green foxtail and puncturevine plants were manually harvested at the soil level using a 1 m^2 quadrat from the center of each plot. The harvested samples from each plot were oven-dried at 65°C for 5 days to determine aboveground shoot dry biomass. Weed shoot dry biomass from herbicide-treated plots was expressed as a percent shoot dry biomass reduction relative to the nontreated plots using Equation (1):

$$Y\,(\%) = \left[\frac{A - B}{A}\right] \times 100 \quad (1)$$

where Y represents shoot dry biomass reduction (%), A is the average shoot dry biomass from nontreated plots, and B is the shoot dry biomass from the herbicide-treated plot. Yield data were not collected because the hybrids evaluated in this study were experimental or pre-commercial lines not approved for yield assessment. Weather data, including daily minimum and maximum air temperature (°C) and precipitation (mm), were collected from a weather station located at KSU-ARC (https://mesonet.k-state.edu/).

Core Ideas

- Imazamox premergence (PRE) alone or with *S*-metolachlor, *S*-metolachlor PRE followed by (*fb*) imazamox postemergence (POST), or imazamox POST alone provided 84%–96% control of green foxtail and puncturevine in iGrowth sorghum.
- PRE *S*-metolachlor + atrazine *fb* POST quizalofop provided 86%–96% green foxtail control, whereas atrazine *fb* quizalofop + dicamba/2,4-D achieved 92%–97% control of puncturevine in DoubleTeam sorghum.
- PRE atrazine + *S*-metolachlor *fb* POST nicosulfuron provided 90%–93% control of green foxtail, whereas tank-mixing nicosulfuron with 2,4-D or dicamba improved late puncturevine control (89%–95%) in Inzen sorghum.

2.2 | Statistical analysis

Data from all three studies were separately analyzed. Data were subjected to analysis of variance (ANOVA) for each evaluation timing using the PROC MIXED procedure in SAS 9.3. Data were checked for ANOVA assumptions (normality of residuals and homogeneity of variance) using PROC UNIVARIATE in SAS (SAS Institute), and all data met

TABLE 1 List of various herbicides tested for weed control in imazamox-, quizalofop-, and nicosulfuron-resistant grain sorghum at Kansas State University, Agricultural Research Center near Hays, KS.

Herbicide	Rate (g ha^{-1})	Trade name	Manufacturer
S-metolachlor	1424	Moccasin II Plus	UPL NA Inc.
Imazamox[a]	53, 79	Imiflex	UPL NA Inc.
Atrazine	1121	Atrazine	Loveland Products, Inc.
Quizalofop	73	FirstAct	Makhteshim Agan of NA, Inc.
S-metolachlor + atrazine	1177 + 1520	Bicep II Magnum	Syngenta Crop Protection, LLC
2,4-D	532	2,4-D Amine	Alligare, LLC
Dicamba	280	Clarity	BASF Ag Products
Nicosulfuron	35	Zest WDG	Corteva Agriscience, USA

[a]Crop oil concentrate (COC) at 1% v/v was included.

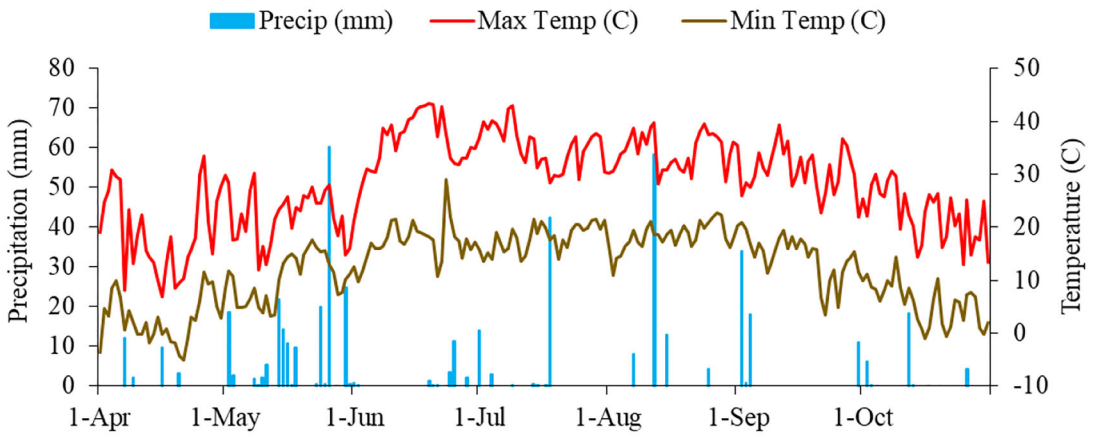


FIGURE 1 Daily minimum and maximum air temperature (˚C) and precipitation (mm) during the 2021 sorghum growing season at Kansas State University Agricultural Research Center near Hays, KS.

those assumptions. Herbicide treatments were considered as fixed effects, whereas replications were considered as random effects. Data on weed control (%) from nontreated plots were not included in the analysis. Treatment means were separated using a Fisher's protected least significant difference test ($p < 0.05$).

3 | RESULTS AND DISCUSSION

The total amount of rainfall during the sorghum growing season (June to October) was 256 mm (Figure 1). The minimum and maximum air temperatures during the growing season ranged from 4˚C to 40˚C (Figure 1). Green foxtail was the dominant weed species as compared to puncturevine, with a total density ranging from 34 to 45 m^{-2} across all nontreated plots at the time of POST application. In contrast, the density of puncturevine ranged from 10 to 15 plants m^{-2} across all nontreated plots.

3.1 | Study 1: Imazamox-resistant grain sorghum

3.1.1 | Green foxtail control

Among all tested herbicide programs, a PRE application of imazamox (79 g ha^{-1}) alone or in combination with *S*-metolachlor provided excellent control (90%–95%) of green foxtail throughout the growing season (Table 2). Similarly, control with *S*-metolachlor applied PRE followed by (*fb*) imazamox applied POST or a single POST application of imazamox did not differ from PRE alone treatments and ranged from 85% to 96% throughout the growing season (Table 2). These results are consistent with Thompson et al. (2019), who reported effective grass weed control with atrazine and acetamide herbicides. Singh and Jhala (2025) also reported 96%–98% and 78%–89% control of corn volunteers 28 days after treatment with imazamox (53 and 79 g ai ha^{-1}) applied early-postemergence (EPOST) and

TABLE 2 Effect of various preemergence (PRE) and postemergence (POST) herbicide programs on percent visual control of green foxtail, puncturevine and total weed biomass reduction (% of nontreated) in imazamox-resistant grain sorghum during 2021 growing season at Kansas State University Agricultural Research Center near Hays, KS.

Herbicides	Rate (g ha^{-1})	Timing	3 WAPRE		5 WAPRE/2 WAPOST		7 WAPRE/4 WAPOST		11 WAPRE/8 WAPOST		Total weed biomass reduction (%)
			Green foxtail	Puncture vine	Green foxtail	Puncture vine	Green foxtail	Puncture vine	Green foxtail	Puncture vine	
			% visual control								
S-metolachlor	1424	PRE	71b	76c	68c	76c	54b	74c	30d	70c	17c
S-metolachlor + Atrazine	1177 + 1520	PRE	74b	84b	63c	81bc	58b	80ab	56c	79b	60b
Imazamox	53	PRE	89a	85b	86b	84ab	84a	84ab	83b	81b	93a
Imazamox	79	PRE	95a	91a	91a	88a	90a	85ab	90a	84ab	97a
Imazamox + *S*-metolachlor	79 + 1424	PRE	95a	94a	92a	92a	90a	92a	90a	91a	96a
S-metolachlor *fb* Imazamox	1424 *fb* 53	PRE *fb* POST	76b	73c	85b	89a	89a	91a	91a	88ab	92a
Imazamox	53	POST	–	–	86b	90a	94a	94a	96a	96a	99a

Note: Means followed by the same letter within a column are not different according to Fisher's protected LSD at $p < 0.05$.
Abbreviations: WAPOST, weeks after postemergence; WAPRE, weeks after preemergence.

late-postemergence (LPOST) in iGrowth sorghum in a 2-year study in Nebraska. Furthermore, a single PRE application of imazamox at 53 g ha^{-1} provided 83%–89% control of green foxtail throughout the growing season. In contrast, green foxtail control with a single PRE application of *S*-metolachlor or *S*-metolachlor + atrazine ranged from 71% to 74% at 3 WAPRE, which was further reduced to 30%–56% at 11 WAPRE (Table 2). Although not tested on green foxtails, Rodriguez et al. (2023) have also reported 68%–71% control of fall panicum (*Panicum dichotomiflorum* Michx.) at 8 WAPRE application of *S*-metolachlor or *S*-metolachlor + atrazine in sweet corn grown on organic soil in the Everglades Agricultural Area in southern Florida. Drouin et al. (2021) reported quick degradation of atrazine and *S*-metolachlor by both direct and indirect processes, with half-lives of less than 5 and 7 days, respectively, reducing their effectiveness in providing season-long control.

3.1.2 | Puncturevine control

Compared to green foxtail, PRE alone applications of imazamox at 79 g ha^{-1} or imazamox + *S*-metolachlor, PRE-applied *S*-metolachlor *fb* POST application of imazamox, and single POST application of imazamox provided excellent control of puncturevine (84%–96%) at 5, 7, and 11 WAPRE (Table 2). In contrast, control with PRE-applied imazamox alone at 53 g ha^{-1} or *S*-metolachlor + atrazine was moderate and ranged from 79% to 85% throughout the growing season (Table 2). The least puncturevine control (70%–76%) was observed with a single PRE application of *S*-metolachlor throughout the growing season (Table 2).

3.1.3 | Total weed dry biomass reduction

Consistent with percent visual control of green foxtail and puncturevine, PRE-applied imazamox or imazamox + *S*-metolachlor, PRE-applied *S*-metolachlor *fb* POST application of imazamox, and single POST application of imazamox resulted in 92%–99% reduction in shoot dry biomass compared to the nontreated control (Table 2). In contrast, PRE-applied *S*-metolachlor or *S*-metolachlor + atrazine resulted in 17%–60% reduction in shoot dry biomass compared to the nontreated control (Table 2).

3.2 | Study 2: Quizalofop-resistant grain sorghum

3.2.1 | Green foxtail control

Among all herbicide programs tested, a PRE application of *S*-metolachlor + atrazine *fb* a POST application of quizalofop provided excellent control (86%–96%) of green foxtail throughout the growing season. Atrazine applied PRE alone provided only 66% control of green foxtail at 3 WAPRE. However, a subsequent POST application of quizalofop increased green foxtail control to 91% at 5 WAPRE/2 weeks after POST (WAPOST) and 94% at 7 WAPRE/5 WAPOST, before declining to 76% at 11 WAPRE/8 WAPOST (Table 3). Sim-

TABLE 3 Effect of various preemergence (PRE) and postemergence (POST) herbicide programs on percent visual control of green foxtail, puncturevine, and total weed dry weight reduction (% of nontreated) in quizalofop-resistant grain sorghum during 2021 growing season at Kansas State University Agricultural Research Center near Hays, KS.

			3 WAPRE		5 WAPRE/2 WAPOST		7 WAPRE/4 WAPOST		11 WAPRE/8 WAPOST		Total weed biomass reduction (%)
Herbicides	Rate (g ha^{-1})	Timing	Green foxtail	Puncture vine	Green foxtail	Puncture vine	Green foxtail	Puncture vine	Green foxtail	Puncture vine	
			% visual control								
Atrazine *fb* quizalofop	1121 *fb* 73	PRE *fb* POST	66b	81a	91a	81ab	94a	60b	76b	55b	75a
S-metolachlor + atrazine *fb* quizalofop	1177 + 1520 *fb* 73	PRE *fb* POST	86a	84a	93a	71b	95a	64b	96a	54b	77a
Atrazine *fb* 2,4-D + quizalofop	1121 *fb* 532 + 73	PRE *fb* POST	66b	80a	66b	86ab	55b	90a	37c	92a	33b
Atrazine *fb* dicamba + quizalofop	1121 *fb* 280 + 73	PRE *fb* POST	68b	79a	90a	91a	94a	95a	97a	97a	73a

Note: Means followed by the same letter within a column are not different according to Fisher's protected LSD at $p < 0.05$.
Abbreviations: WAPOST, weeks after postemergence; WAPRE, weeks after preemergence.

ilarly, green foxtail control with PRE-applied atrazine was only 68% at 3 WAPRE and a subsequent POST application of dicamba + quizalofop resulted in 90%–97% control of green foxtail at later evaluation timings (Table 3). Singh and Jhala (2025) reported 98% and 99% control of volunteer corn with quizalofop applied EPOST and LPOST (58 and 73 g ha^{-1}) in DoubleTeam sorghum in a 2-year study in Nebraska. The least control (37%–66%) of green foxtail was observed with atrazine applied PRE *fb* a POST application of 2,4-D + quizalofop throughout the growing season (Table 3). This reduction in green foxtail control could be due to antagonism of tank mixing 2,4-D with quizalofop (Leise et al., 2025). This antagonistic interaction could be due to reduced uptake or translocation, or enhanced metabolism of quizalofop through upregulation of cytochrome P450s (Han et al., 2013; Olson & Nalewaja, 1982). Lancaster et al. (2019) have also reported that tank-mixing 2,4-D with quizalofop can antagonize significant reductions in control of grass weed species as compared to quizalofop alone. Similarly, Singh et al. (2023) also reported that mixing 2,4-D choline can reduce quizalofop efficacy on glufosinate/glyphosate-resistant corn volunteers up to 2 weeks when applied at the V3 or V6 growth stage of Enlist corn.

3.2.2 | Puncturevine control

Among all herbicide programs, a sequential program of atrazine applied PRE *fb* a POST application of quizalofop tank mixed with 2,4-D or dicamba provided up to 80% control of puncturevine at 3 WAPRE, which further improved from 92% to 97% at 11 WAPRE/8 WAPOST (Table 3). In contrast, atrazine applied PRE alone or in combination with *S*-metolachlor *fb* quizalofop applied POST provided 81%–84% control of puncturevine at 3 WAPRE, which declined at later evaluation timings and ranged from 54% to 55% at 11 WAPRE/8 WAPOST (Table 3).

3.2.3 | Total weed dry biomass reduction

PRE-applied atrazine alone or in combination with *S*-metolachlor *fb* a POST application of quizalofop alone or in tank mixture with dicamba reduced total weed dry biomass by 73%–77% as compared to nontreated (Table 3). In contrast, the least reduction in total weed dry biomass (33%) was observed with PRE-applied atrazine *fb* a POST application of quizalofop tank-mixed with 2,4-D (Table 3).

3.3 | Study 3: Nicosulfuron-resistant grain sorghum

3.3.1 | Green foxtail control

Among all herbicide programs tested, PRE-applied atrazine alone or in combination with *S*-metolachlor *fb* POST application of nicosulfuron provided excellent control (90%–93%) of green foxtail at 11 WAPRE/8 WAPOST (Table 4). Furthermore, PRE-applied atrazine alone had 73% control of green foxtail at 3 WAPRE, whereas a subsequent POST application of 2,4-D tank-mixed with nicosulfuron improved

TABLE 4 Effect of various preemergence (PRE) and postemergence (POST) herbicide programs on percent visual control of green foxtail, puncturevine and total weed dry weight reduction (% of nontreated) in nicosulfuron-resistant grain sorghum during 2021 growing season at Kansas State University Agricultural Research Center near Hays, KS.

Herbicides	Rate (g ha^{-1})	Timing	3WAPRE		5 WAPRE/2 WAPOST		7 WAPRE/4 WAPOST		11 WAPRE/8 WAPOST		Total weed biomass reduction (%)
			Green foxtail	Puncture vine	Green foxtail	Puncture vine	Green foxtail	Puncture vine	Green foxtail	Puncture vine	
			% visual control								
Atrazine *fb* nicosulfuron	1121 *fb* 35	PRE *fb* POST	69b	83a	88ab	90a	89ab	90a	93a	79b	31b
S-metolachlor + atrazine *fb* nicosulfuron	1177 +1520 *fb* 35	PRE *fb* POST	84a	88a	89a	89a	90a	89a	90a	77b	35b
Atrazine *fb* 2,4-D + nicosulfuron	1121 *fb* 532 + 35	PRE *fb* POST	73ab	85a	83c	95a	86ab	95a	56b	89a	65a
Atrazine *fb* dicamba + nicosulfuron	1121 *fb* 280 + 35	PRE *fb* POST	71b	84a	85bc	95a	82b	95a	48b	95a	70a

Note: Means followed by the same letter within a column are not different according to Fisher's protected LSD at $p < 0.05$.
Abbreviations: WAPOST, weeks after postemergence; WAPRE, weeks after preemergence.

green foxtail control to 83% at 5 WAPRE/2 WAPOST and 86% at 7 WAPRE/5 WAPOST. Control then declined to 56% at 11 WAPRE/8 WAPOST (Table 4). Similarly, atrazine applied PRE provided only 71% control of green foxtail at 3 WAPRE; however, a subsequent POST application of dicamba + nicosulfuron improved control to 85% at 5 WAPRE/2 WAPOST. Green foxtail control decreased to 82% at 7 WAPRE/4 WAPOST and 48% at 11 WAPRE/8 WAPOST (Table 4).

3.3.2 | Puncturevine control

All tested PRE *fb* POST programs provided 83%–95% control of puncturevine from 3 WAPRE through 7 WAPRE/4 WAPOST (Table 4). Control declined to 77%–79% with PRE-applied atrazine alone or in combination with *S*-metolachlor *fb* a POST application of nicosulfuron at 11 WAPRE/8 WAPOST (Table 4). Among all tested programs, PRE-applied atrazine *fb* a POST application of nicosulfuron tank-mixed with 2,4-D or dicamba provided 89%–95% control of puncturevine at 11 WAPRE/8 WAPOST (Table 4).

3.3.3 | Total weed dry biomass reduction

PRE-applied atrazine *fb* POST application of nicosulfuron tank-mixed with 2,4-D or dicamba resulted in the highest total weed dry weight reduction, ranging from 65% to 70% compared to nontreated (Table 4). In contrast, PRE-applied atrazine alone or in combination with *S*-metolachlor *fb* a POST application of nicosulfuron resulted in the least total weed dry biomass reduction (31%–35% of nontreated) (Table 3).

4 | CONCLUSION AND PRACTICAL IMPLICATIONS

Results from this single-site-year study showed that for imazamox-resistant grain sorghum, PRE application of imazamox (79 g ha^{-1}) alone or in combination with *S*-metolachlor, PRE-applied *S*-metolachlor *fb* a POST application of imazamox, or a single POST application of imazamox resulted in 85%–95% green foxtail control and 84%–96% puncturevine control throughout the growing season. In quizalofop-resistant sorghum, PRE-applied atrazine *fb* a POST application of quizalofop tank-mixed with dicamba resulted in excellent control (up to 97%) of green foxtail and puncturevine throughout the growing season. For nicosulfuron-resistant sorghum, PRE-applied atrazine alone or in combination with *S*-metolachlor *fb* a POST application of nicosulfuron provided 88%–93% control of green foxtail, whereas PRE-applied atrazine *fb* a POST application of nicosulfuron tank-mixed with 2,4-D or dicamba provided an 84%–95% control of puncturevine throughout the growing season. Given the limited herbicide options for season-long weed control in grain sorghum, these results provide farmers with effective strategies to manage green foxtail and puncturevine in three HR grain sorghum hybrids. It is important to note that this study included infestations of only green foxtail and puncturevine. However, Palmer

amaranth is another major weed challenge in grain sorghum production. Herbicides such as atrazine (PRE) and dicamba or 2,4-D (POST) tested in this study could also provide effective control of other small-seeded broadleaf weeds, including Palmer amaranth. This research also emphasizes the importance of diversifying herbicide use to reduce the risk of resistance evolution, rather than relying on a single herbicide site of action. Future research should evaluate a broader range of herbicide tank-mix partners and application timings to better understand herbicide interactions and crop response in these HR grain sorghum hybrids. Integrating these effective PRE and POST herbicides into comprehensive management strategies that include diversified crop rotations, cover crops, and mechanical methods (electrocution, interrow mower, seed impact mill, etc.) will be crucial for sustainable and cost-effective weed management in these HR sorghum hybrids.

AUTHOR CONTRIBUTIONS

Midhat Z. Tugoo: Data curation; formal analysis; methodology; visualization; writing—original draft. **Sachin Dhanda**: Investigation; methodology; validation; visualization; writing—review and editing. **Rui Liu**: Investigation; methodology; validation; visualization; writing—review and editing. **Vipan Kumar**: Conceptualization; funding acquisition; methodology; project administration; resources; software; supervision; validation; visualization; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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