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Nomenclature:
Barnyardgrass, *Echinochloa crus-galli* (L.) Beauv.; broadleaf signalgrass, *Urochloa platyphylla* (Nash) R.D. Webster; johnsongrass, *Sorghum halepense* (L.) Pers; Texas panicum, *Urochloa texana* (Buckl.) R. Webster; grain sorghum, *Sorghum bicolor* (L.) Moench

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Sensitivity of TamArk™ grain sorghum and monocot weed species to ACCase- and ALS-inhibiting herbicides

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Abstract

Only a limited number of herbicides are available to provide postemergence (POST) control of selective monocot weeds in grain sorghum crops. The herbicides currently labeled for use with grain sorghum have strict use restrictions, low efficacy on johnsongrass, or weed resistance issues. To introduce a new effective herbicide mode of action for monocot control, multiple companies and universities have been developing herbicide-resistant grain sorghum that would allow producers to use herbicides that inhibit either acetolactate synthase (ALS) or acetyl coenzyme A carboxylase (ACCase) for POST monocot control. An experiment was conducted in Fayetteville, AR, in 2020 and 2021, to determine the effectiveness of two ALS-inhibiting herbicides and nine ACCase-inhibiting herbicides on TamArk™ grain sorghum, conventional grain sorghum, and problematic monocot weed species. Grain sorghum and monocot weeds (johnsongrass, broadleaf signalgrass, barnyardgrass, and Texas panicum) were sprayed when TamArk grain sorghum reached the 2- to 3-leaf stage. TamArk grain sorghum was tolerant of all ACCase-inhibiting herbicides tested, exhibiting ≤10% injury at all evaluation timings, except clethodim and sethoxydim, and had no resistance to the ALS-inhibiting herbicides that were evaluated. Additionally, all ACCase inhibitors except diclofop and pinoxaden controlled all monocots tested by >91% at 28 d after application (DAA). Conversely, the two ALS inhibitors, imazamox and nicosulfuron, provided ≤81% control of broadleaf signalgrass 28 DAA but still controlled all other monocots by >95%. TamArk grain sorghum has low sensitivity to multiple ACCase-inhibiting herbicides and thus provides an effective POST option for monocot weed control. In addition, unwanted volunteer TamArk plants can be controlled with cledthodim, sethoxydim, nicosulfuron, or imazamox. Although the ALS-inhibiting herbicides imazamox and nicosulfuron were not useful on TamArk grain sorghum, they are effective options for monocot control on Igrowth™ and Inzen™ grain sorghum crops, respectively.

Introduction

The lack of selective postemergence (POST) herbicides that control late-season grass is a concern for many grain sorghum producers in the United States (Smith et al. 2010). Grain sorghum is a member of the Gramineae family, and POST herbicides that control grass weeds have a high risk of severely injuring the crop. Only three herbicides are available for POST grass control in conventional grain sorghum crops: atrazine (categorized as a Group 5 herbicide by the Weed Science Society of America [WSSA]), quinclorac (WSSA Group 4), and paraquat (WSSA Group 22). These herbicides present challenges. Paraquat, for example, requires that applications occur under hoods to mitigate significant crop injury, quinclorac resistance occurs in multiple annual types of grass, and atrazine provides only partial grass control as a POST application (Fromme et al. 2012; Heap 2022).

A significant development in grain sorghum research was the introduction of fluxofenim-based seed treatments that allow producers to use chloroacetamide herbicides such as *S*-metolachlor and dimethenamid-P preemergence to control both grass and small-seeded broadleaf weeds without injuring grain sorghum (Al-Khatib et al. 2004). However, relying on chloroacetamide herbicides for grass control presents some concerns when used on grain sorghum crops. Because grain sorghum is commonly grown in hot and dry conditions without irrigation, decreased efficacy of chloroacetamide herbicides can occur (Prasad et al. 2008). Chloroacetamide herbicides require adequate moisture for proper activation, which does not always occur in grain sorghum production (Brown et al. 1988; Regehr et al. 2008). When rainfall is less than 14 mm within the first 2 wk of application, a reduction in chloroacetamide efficacy has been observed on barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] (Jursik et al. 2013). Furthermore, chloroacetamide herbicides effectively control seedling johnsongrass [*Sorghum halepense* (L.) Pers] by more than 95% but they do not control johnsongrass plants that emerge from rhizomes (Scarabel et al. 2014). Because a johnsongrass plant can produce 5,000 or more rhizomes in a single growing season, other control options are necessary (McWhorter 1971).

Options for selective POST grass control in grain sorghum crops are needed. Four companies or universities have focused on developing herbicide-resistant grain sorghum to introduce new herbicides for POST grass control. Two would entail WSSA Group 1 acetyl CoA carboxylase (ACCase) inhibitors, and two would entail WSSA Group 2 acetolactate synthase (ALS) inhibitors.

Corteva (Indianapolis, IN) has developed Inzen™ grain sorghum, which is resistant to the ALS inhibitor nicosulfuron and is currently marketed under the tradename Accent® Q for use in corn (*Zea mays* L.) crops and labeled for use with grain sorghum as Zest™. Nicosulfuron is a sulfonylurea herbicide used to control problematic grasses in corn, especially johnsongrass (Camacho et al. 1991; Dobbels and Kapusta 1993). A collaboration between UPL (King of Prussia, PA) and Alta seeds (College Station, TX) led to the commercialization and release in 2021 of grain sorghum that is resistant to the ALS inhibitor imazamox, marketed as Igrowth™. Imazamox, an imidazolinone family herbicide, is commonly known by the tradenames Raptor® or Beyond® (BASF, Triangle Park, NC) and used for grass control in soybean [*Glycine max* (L.) Merr.] or Clearfield® production systems. While imazamox has been proven to control annual grasses such as barnyardgrass and goosegrass [*Eleusine indica* (L.) Gaertn] (Fish et al. 2016), little data are available regarding the control of perennial grasses such as johnsongrass.

S&W Seeds (Longmont, CO) collaborated with Adama (Raleigh, NC) to develop grain sorghum that is resistant to the ACCase inhibitor quizalofop, and marketed as Double Team™. Quizalofop is an aryloxyphenoxypropionate (AOPP) herbicide sold under many tradenames but was most recently integrated into rice production through the Provisia® system commercialized by BASF. Quizalofop has successfully controlled problematic annual and perennial grass weeds (Brewster and Spinney 1989; Sanders et al. 2020). The University of Arkansas System Division of Agriculture and Texas A&M University collaboratively developed grain sorghum known as TamArk™, which has a mutation in the *ACCase* gene (Norsworthy et al. 2020). Preliminary data show this mutation confers resistance to other ACCase inhibitors within the AOPP and phenylpyrazolin (PPN) families (Piveta et al. 2020).

Adding new herbicide-resistance technologies could significantly improve grass control in grain sorghum. Using effective modes of action not previously labeled for use with grain sorghum could allow producers to control problematic grasses better while helping mitigate resistance (Norsworthy et al. 2012). While herbicides that are to be labeled for use on grain sorghum have demonstrated grass control in crops such as rice (*Oryza sativa* L.), corn, and soybean, it is essential that we understand the control levels of grasses specific to grain sorghum under typical growing conditions. By understanding which herbicides are most effective on certain problematic grasses, producers can better decide which technologies they should use based on specific weed spectra in a specific location. Therefore, we conducted research to determine the effectiveness of two ALS- and nine ACCase-inhibiting herbicides on common grasses of grain sorghum, along with the sensitivity of conventional and TamArk grain sorghum to these herbicides.

Table 1. Herbicides and rates applied for monocot tolerance studies in 2020 and 2021.[a]

Common name	Trade name	WSSA group	Rate
			g ai ha^{-1}
Clethodim	Select Max	Group 1 ACCase inhibitor	135
Clodinafop	Discover NG	Group 1 ACCase inhibitor	70
Cyhalofop	Clincher	Group 1 ACCase inhibitor	312
Diclofop	Hoelon	Group 1 ACCase inhibitor	1,120
Fenoxaprop	Ricestar	Group 1 ACCase inhibitor	86
			120
Fluazifop	Fusilade DX	Group 1 ACCase inhibitor	210
			280
			420
Imazamox	Beyond	Group 2 ALS inhibitor	52
			78
Nicosulfuron	Accent Q	Group 2 ALS inhibitor	35
			51
Pinoxaden	Axial XL	Group 1 ACCase inhibitor	60
Quizalofop	Assure II	Group 1 ACCase inhibitor	46
			77
			92
Sethoxydim	Poast Plus	Group 1 ACCase inhibitor	210

[a]Abbreviations: ACCase, acetyl coenzyme A carboxylase; ALS, acetolactate synthase; WSSA, Weed Science Society of America.

Materials and Methods

Field experiments were conducted in 2020 and 2021 at the Milo J. Shult Arkansas Agricultural Research and Extension Center in Fayetteville, AR, on a Leaf silt loam (fine, mixed, active, thermic Typic Albaquults) with 19.6% sand, 57.8% silt, 22.6% clay, and pH 6.2. The experiments were a single-factor randomized complete block design with four replications. Ten ACCase and two ALS inhibitors were evaluated at various rates based on label suggestions for use on crops other than grain sorghum (Table 1). All herbicides were applied with crop oil concentrate at 1% v/v. A nontreated check was included for comparison purposes. The conventional grain sorghum hybrid DK553-67 and TamArk were planted at 18 seeds m^{-1} row. Initial plans were to include Inzen grain sorghum in this study, but it had to be removed due to research restrictions on the technology. Common grass weeds, including johnsongrass, broadleaf signalgrass [*Urochloa platyphylla* (Nash) R.D. Webster], barnyardgrass, and Texas panicum [*Urochloa texana* (Buckl.) R. Webster] included in the study were seeded in individual rows at approximately 40 seeds m^{-1}. All grass weeds were obtained from Azlin Seed Service (Leland, MS). All species, including grain sorghum, were planted into a conventionally tilled area using a Hege drill (Hege Company, Waldenburg, Germany) with individual seed boxes for each row with 38 cm between rows. The plot size was 2 m by 3 m, and herbicides were applied perpendicular to the direction planted. Weeds and crops were not grown past 28 d after application (DAA); hence, only preplant nitrogen was applied based on the Arkansas grain sorghum production handbook (Espinoza 2015). Broadleaf weeds were removed from all plots using a single application of 2,4-D at 950 g ae ha^{-1} when grain sorghum was 25 cm tall. No herbicides were sprayed to control natural grass populations to ensure the planted grasses were not injured or controlled before treatment applications. Treatments were applied when grain sorghum reached the 2- to 3-leaf stage (Table 2) using a CO_2-pressurized backpack sprayer, and a 6-nozzle boom with air induction extended range (AIXR) 110015 nozzles (TeeJet, Springfield, IL) spaced 50 cm apart at 4.8 kph delivering

Table 2. Average density and leaf stage of grain sorghum and grasses at the time of herbicide application.[a]

		2020		2021	
Common name	Scientific name	Density[b]	Size[c]	Density	Size
TamArk™ grain sorghum	*Sorghum bicolor* (L.) Moench	13	2–3	14	2–3
Conventional grain sorghum	*Sorghum bicolor* (L.) Moench	16	2–3	15	2–3
Johnsongrass	*Sorghum halepense* (L.) Pers	6	3–4	10	3–4
Barnyardgrass	*Echinochloa crus-galli* (L.) Beauv.	8	2–3	7	3–4
Broadleaf signalgrass	*Urochloa platyphylla* (Nash) R.D. Webster	20	4–6	15	4–5
Texas panicum	*Urochloa texana* (Buckl.) R. Webster	5	4–6	6	3–4

[a]Field experiments were conducted in Fayetteville, Arkansas, in 2020 and 2021.
[b]Density recorded as plants per meter of row.
[c]Size recorded as number of true leaves present.

140 L ha^{-1}. Boom height was 46 cm above the tallest plant in the plot to achieve proper coverage.

Both ACCase and ALS inhibitors typically elicit minimal symptoms in plants the first 7 d after treatment. Therefore, grain sorghum was evaluated for visible injury 14, 21, and 28 DAA. The injury was rated on a 0% to 100% scale, where 0% equals no visible injury, and 100% equals total crop mortality (Frans and Talbert 1986). Similarly, visible grass control was rated the same days on a scale of 0% to 100%, where 0% equals no control, and 100% equals no living tissue present (Frans and Talbert 1986). At 28 DAA, aboveground living tissue was collected by species or grain sorghum type. All living plants within 1 m of the row of each species in each plot were collected and air dried at 60 C for 2 wk, then removed and weighed individually. Data were used to calculate percent biomass reduction by species using the following equation:

$$\frac{Nontreated\,(g) - treated\,(g)}{nontreated\,(g)} \times 100 \qquad [1]$$

Data Analysis

All nontreated plots were rated 0% at all evaluation timings across all species; hence, they were excluded from the statistical analysis. The distribution function in JMP 16.1 Pro software (SAS Institute Inc., Cary, NC) was used to determine the correct distribution to analyze each variable based on corrected Akaike Information Criterion (AICc) and Bayesian Information Criterion (BIC) values. Visible control ratings of all grass species and conventional grain sorghum injury 14, 21, and 28 DAA were determined to follow a beta distribution. The visible sensitivity of TamArk grain sorghum to the herbicides followed a gamma distribution. Biomass reduction for each grass species and grain sorghum type followed a beta distribution. A single-factor statement was developed with the main effect of herbicide treatment for grain sorghum and all grass weeds at each evaluation timing and biomass reduction using the GLIMMIX procedure with SAS software (version 9.4; SAS Institute Inc., Cary, NC). Block and year were considered random effects in all statements. When herbicide treatment was significant, visible control and biomass reduction were subjected to mean separation using Tukey's HSD at $\alpha = 0.05$.

Results and Discussion

Conventional Grain Sorghum Sensitivity

High injury and biomass reduction levels occurred, ranging from 94% to 100% across all evaluation timings and herbicides other than pinoxaden and diclofop (Table 3). Pinoxaden and diclofop caused less injury than all other herbicide treatments at each respective evaluation timing. However, the injury was ≥67% by 28 DAA for both herbicides, which producers would deem to be unacceptable. Like the injury evaluations, all treatments resulted in >99% biomass reduction, other than pinoxaden and diclofop, which caused 81% and 83% reduction in biomass, respectively. None of the evaluated herbicides are labeled for conventional grain sorghum, and it is known that grain sorghum is susceptible to ACCase inhibitors (Lancaster et al. 2018); hence, high injury levels were expected.

TamArk Grain Sorghum Sensitivity

Differences in injury and biomass reduction of TamArk grain sorghum occurred among the herbicides tested at all evaluation timings (Table 4). Two ALS inhibitors, nicosulfuron and imazamox, completely controlled TamArk grain sorghum by 28 DAA, and biomass was reduced 100%. Since no known mutations to the ALS gene are present in TamArk grain sorghum, the high sensitivity to these herbicides was expected.

Among the ACCase inhibitors, the greatest injury resulted from the cyclohexanedione family, for which complete control was achieved with clethodim and sethoxydim by 21 DAA (Table 4). Conversely, the ACCase inhibitors from the AOPP and PPN families, specifically clodinafop, cyhalofop, diclofop, fenoxaprop, fluazifop, quizalofop, and pinoxaden, produced relatively low injury levels, with the highest being 10% caused by quizalofop at 92 g ha^{-1} at 28 DAA. Similarly, Piveta et al. (2020) observed high resistance to fluazifop, fenoxaprop, and quizalofop when conducting dose-response experiments on TamArk grain sorghum. Therefore, when labeled, herbicides from the AOPP and PPN families could be safely used for grass control in TamArk grain sorghum.

Johnsongrass Control

Like conventional grain sorghum, johnsongrass control by treatment varied 14 DAA, ranging from 80% to 100% across herbicide treatments, excluding the pinoxaden and diclofop treatments (Table 5). Diclofop at 1,120 g ha^{-1} and pinoxaden at 60 g ha^{-1} provided only 32% and 59% johnsongrass control 14 DAA. Johnsongrass control increased over time with pinoxaden, resulting in 92% control by 28 DAA; however, diclofop control 28 DAA was only 38%, a level that was unacceptable. Like the levels of johnsongrass control 28 DAA, all ACCase-inhibiting herbicide treatments, except diclofop and pinoxaden, produced ≥93% johnsongrass biomass reduction. While multiple herbicide treatments resulted in high levels of control, any treatment that did not provide 100% control may not be adequate since there is potential for seed or rhizome production from these surviving plants. Those herbicides that provided complete johnsongrass control and

Table 3. Percent visible injury and biomass reduction of DK553-67 grain sorghum by herbicide and rate, averaged over the years.[a,b,c]

Herbicide	Rate	Injury			Biomass reduction[d]
		14 DAA	21 DAA	28 DAA	28 DAA
	g ai ha^{-1}	%			
Clethodim	135	100 A[c]	100 A	100 A	100 A
Clodinafop	70	100 A	100 A	100 A	100 A
Cyhalofop	312	100 A	100 A	100 A	100 A
Diclofop	1,120	77 B	72 B	75 B	83 C
Fenoxaprop	86	96 A	98 A	100 A	100 A
Fenoxaprop	120	97 A	99 A	100 A	100 A
Fluazifop	210	98 A	97 A	99 A	99 B
Fluazifop	280	98 A	100 A	100 A	100 A
Fluazifop	420	100 A	100 A	100 A	100 A
Imazamox	52	100 A	100 A	100 A	100 A
Imazamox	78	100 A	100 A	100 A	100 A
Nicosulfuron	35	94 A	97 A	99 A	99 B
Nicosulfuron	51	100 A	100 A	100 A	100 A
Pinoxaden	60	19 C	51 C	67 C	81 C
Quizalofop	46	94 A	100 A	100 A	100 A
Quizalofop	77	100 A	100 A	100 A	100 A
Quizalofop	92	100 A	100 A	100 A	100 A
Sethoxydim	210	97 A	99 A	100 A	100 A
P-value		<0.0001	<0.0001	<0.0001	<0.0001

[a]Abbreviation: DAA, days after application.
[b]Field experiments were conducted in Fayetteville, Arkansas, in 2020 and 2021.
[c]Means within a column followed by the same letter are not significantly different based on Tukey's HSD ($\alpha = 0.05$).
[d]Percent reduction is relative to the nontreated plot within each replication.

Table 4. Percent visible injury and biomass reduction of TamArk™ grain sorghum by various herbicides and rates, averaged over the years.[a,b,c]

Herbicide	Rate	Injury			Biomass reduction[d]
		14 DAA	21 DAA	28 DAA	28 DAA
	g ai ha^{-1}	%			
Clethodim	135	95 A[c]	100 A	100 A	100 A
Clodinafop	70	5 D	5 E	5 C	6 B
Cyhalofop	312	7 D	7 DE	7 BC	6 B
Diclofop	1,120	6 D	5 E	5 C	0 B
Fenoxaprop	86	4 D	4 F	5 C	2 B
Fenoxaprop	120	5 D	6 DEF	6 BC	2 B
Fluazifop	210	4 D	5 EF	5 C	2 B
Fluazifop	280	5 D	5 EF	5 C	4 B
Fluazifop	420	5 D	7 DE	7 BC	5 B
Imazamox	52	55 C	92 C	100 A	100 A
Imazamox	78	56 C	92 C	100 A	100 A
Nicosulfuron	35	70 B	95 B	100 A	100 A
Nicosulfuron	51	90 A	100 A	100 A	100 A
Pinoxaden	60	8 D	6 DEF	6 BC	8 B
Quizalofop	46	4 D	4 F	6 BC	7 B
Quizalofop	77	4 D	6 DEF	7 BC	7 B
Quizalofop	92	7 D	8 D	10 B	10 B
Sethoxydim	210	73 B	100 A	100 A	100 A
P-value		<0.0001	<0.0001	<0.0001	<0.0001

[a]Abbreviation: DAA, days after application.
[b]Field experiments were conducted in Fayetteville, Arkansas, in 2020 and 2021.
[c]Means within a column followed by the same letter are not significantly different based on Tukey's HSD ($\alpha = 0.05$).
[d]Percent reduction is relative to the nontreated plot within each replication.

biomass reduction by 28 DAA included clethodim, sethoxydim, fenoxaprop, fluazifop, and quizalofop. Of these, only fluazifop, fenoxaprop, and quizalofop would be viable options for johnsongrass control in TamArk grain sorghum based on the low levels of injury caused by these herbicides (Table 4). Before 2022, no POST herbicide was available for johnsongrass control in grain sorghum; therefore, adding multiple ACCase-inhibiting herbicides such as those evaluated here would provide much-needed johnsongrass control options in grain sorghum production (Smith et al. 2010).

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Table 5. Percent visible control and biomass reduction of johnsongrass by various herbicides and rates, averaged over the years.[a,b,c]

Herbicide	Rate	Control			Biomass reduction[d]
		14 DAA	21 DAA	28 DAA	28 DAA
	g ai ha^{-1}	%			
Clethodim	135	100 A[c]	100 A	100 A	100 A
Clodinafop	70	95 A	96 B	98 AB	97 AB
Cyhalofop	312	92 A	96 B	97 AB	96 ABC
Diclofop	1,120	32 D	37 D	38 C	45 D
Fenoxaprop	86	96 A	100 A	100 A	100 A
Fenoxaprop	120	98 A	100 A	100 A	100 A
Fluazifop	210	80 B	92 BC	100 A	100 A
Fluazifop	280	92 A	100 A	100 A	100 A
Fluazifop	420	96 A	100 A	100 A	100 A
Imazamox	52	86 A	94 B	97 AB	85 C
Imazamox	78	93 A	97 B	98 AB	89 BC
Nicosulfuron	35	87 A	92 BC	95 AB	93 ABC
Nicosulfuron	51	91 A	96 B	97 AB	93 ABC
Pinoxaden	60	59 C	87 C	92 B	89 BC
Quizalofop	46	83 AB	97 A	97 AB	98 A
Quizalofop	77	87 A	100 A	100 A	100 A
Quizalofop	92	96 A	100 A	100 A	100 A
Sethoxydim	210	98 A	100 A	100 A	100 A
P-value		<0.0001	<0.0001	<0.0001	<0.0001

[a]Abbreviation: DAA, days after application.
[b]Field experiments were conducted in Fayetteville, Arkansas, in 2020 and 2021.
[c]Means within a column followed by the same letter are not significantly different based on Tukey's HSD ($\alpha = 0.05$).
[d]Percent reduction is relative to the nontreated plot within each replication.

Table 6. Percent visible control and biomass reduction of broadleaf signalgrass by various herbicides and rates, averaged over the years.[a,b,c]

Herbicide	Rate	Control			Biomass reduction[d]
		14 DAA	21 DAA	28 DAA	28 DAA
	g ai ha^{-1}	%			
Clethodim	135	95 AB[c]	100 A	100 A	100 A
Clodinafop	70	86 BC	95 AB	97 AB	98 A
Cyhalofop	312	86 BC	88 C	95 AB	92 AB
Diclofop	1,120	27 G	27 F	27 E	45 D
Fenoxaprop	86	94 AB	98 AB	96 AB	98 A
Fenoxaprop	120	99 A	100 A	100 A	100 A
Fluazifop	210	89 B	91 BC	92 B	93 A
Fluazifop	280	94 AB	95 AB	95 AB	94 A
Fluazifop	420	94 AB	95 AB	97 AB	95 A
Imazamox	52	56 E	72 E	68 D	65 DC
Imazamox	78	70 D	80 D	81 C	83 ABC
Nicosulfuron	35	36 F	71 E	68 D	62 CD
Nicosulfuron	51	40 F	72 E	70 D	68 BCD
Pinoxaden	60	90 AB	96 AB	95 AB	95 A
Quizalofop	46	92 ABC	95 AB	96 AB	93 A
Quizalofop	77	96 AB	97 AB	97 AB	95 A
Quizalofop	92	97 A	100 AB	100 A	100 A
Sethoxydim	210	98 A	98 AB	98 A	98 A
P-value		<0.0001	<0.0001	<0.0001	<0.0001

[a]Abbreviation: DAA, days after application.
[b]Field experiments were conducted in Fayetteville, Arkansas, in 2020 and 2021.
[c]Means within a column followed by the same letter are not significantly different based on Tukey's HSD ($\alpha = 0.05$).
[d]Percent reduction is relative to the nontreated plot within each replication.

Broadleaf Signalgrass Control

Control of broadleaf signalgrass varied among herbicide treatments 14 DAA, with the greatest control (≥90%) achieved with clethodim, sethoxydim, the two highest rates of fluazifop, both rates of fenoxaprop, pinoxaden, and all three rates of quizalofop; albeit none provided complete control (Table 6). By 21 DAA, clethodim, fenoxaprop (120 g ha^{-1}), and quizalofop (92 g ha^{-1}) provided 100% control of broadleaf signalgrass. At 28 DAA, a more apparent separation in treatments could be observed, specifically between the ALS and ACCase inhibitors. Both rates of imazamox and nicosulfuron at 28 DAA provided lower levels of broadleaf signalgrass control than all but one ACCase inhibitor treatment

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Table 7. Percent visible control and biomass reduction of barnyardgrass by various herbicides and rates, averaged over the years.[a,b,c]

Herbicide	Rate	Control			Biomass reduction[d]
		14 DAA	21 DAA	28 DAA	28 DAA
	g ai ha^{-1}	%			
Clethodim	135	100 A[c]	100 A	100 A	100 A
Clodinafop	70	100 A	100 A	100 A	100 A
Cyhalofop	312	100 A	100 A	100 A	100 A
Diclofop	1,120	91 B	91 B	91 B	92 B
Fenoxaprop	86	100 A	100 A	100 A	100 A
Fenoxaprop	120	100 A	100 A	100 A	100 A
Fluazifop	210	100 A	100 A	100 A	100 A
Fluazifop	280	100 A	100 A	100 A	100 A
Fluazifop	420	100 A	100 A	100 A	100 A
Imazamox	52	100 A	100 A	100 A	100 A
Imazamox	78	100 A	100 A	100 A	100 A
Nicosulfuron	35	100 A	100 A	100 A	100 A
Nicosulfuron	51	100 A	100 A	100 A	100 A
Pinoxaden	60	100 A	100 A	100 A	100 A
Quizalofop	46	100 A	100 A	100 A	100 A
Quizalofop	77	100 A	100 A	100 A	100 A
Quizalofop	92	100 A	100 A	100 A	100 A
Sethoxydim	210	100 A	100 A	100 A	100 A
P-value		<0.0001	<0.0001	<0.0001	<0.0001

[a]Abbreviation: DAA, days after application.
[b]Field experiments were conducted in Fayetteville, Arkansas, in 2020 and 2021.
[c]Means within a column followed by the same letter are not significantly different based on Tukey's HSD ($\alpha = 0.05$).
[d]Percent reduction is relative to the nontreated plot within each replication.

(diclofop). Like control levels, imazamox and nicosulfuron generally caused less broadleaf signalgrass biomass reduction than the ACCase-inhibiting herbicides, other than diclofop. Diclofop controlled broadleaf signalgrass by only 27% and reduced its biomass by 45%, which was not surprising considering it is listed as "suppressed" by the herbicide at the 3-leaf growth stage or smaller, according to the label (Anonymous 2003). Broadleaf signalgrass in this trial produced only 4 to 6 leaves in both years, which explains the low levels of control we observed (Table 2). Similarly, imazamox is reported to achieve suppression of only 2- to 5-leaf broadleaf signalgrass unless sequential applications are made (Anonymous 2019), and nicosulfuron is labeled for control of broadleaf signalgrass only when plants are no larger than 5 cm in height (Anonymous 2021). Because of the low levels of control achieved with the two ALS inhibitors or diclofop, these herbicides would not be recommended for broadleaf signalgrass control. Since TamArk grain sorghum is also sensitive to clethodim, fenoxaprop, quizalofop, or fluazifop would be recommended for broadleaf signalgrass control.

Barnyardgrass Control

All treatments resulted in 100% control of barnyardgrass across all application timings, except diclofop, which provided 91% control (Table 7). Similarly, all treatments except diclofop reduced biomass by 100%. Overall, the ACCase and ALS inhibitors controlled barnyardgrass, exceeding the effectiveness of traditional herbicides used for POST barnyardgrass control in grain sorghum (Grichar et al. 2005). Based on the diclofop label (Anonymous 2003), the herbicide is not recommended to control larger than 4-leaf barnyardgrass, which was present in plots (Table 2).

Texas Panicum Control

Complete control of Texas panicum was obtained at 14 DAA with all evaluated treatments, except diclofop (Table 8). By 28 DAA, Texas panicum control with diclofop improved, with all herbicide treatments providing complete control. The high levels of control were reflected in the complete absence of this species by 28 DAA for all herbicide treatments. Texas panicum is a common problematic weed of grain sorghum (Van Wychen 2020), and high levels of control are seldom achieved in the crop (Grichar et al. 2004). One of the most effective means of controlling Texas panicum in grain sorghum has been dimethenamid-p and atrazine, which generally provide <80% control (Grichar et al. 2004). Another herbicide evaluated for Texas panicum control in grain sorghum is quinclorac. Still, control is <40% (Kering et al. 2013), a level much lower than that achieved here with both ALS and ACCase inhibitors.

Practical Implications

With commercial tolerance to the AOPP and PPN herbicides within the ACCase-inhibitor group, TamArk grain sorghum can control the problematic grass weeds within grain sorghum using various POST herbicides based on label recommendations. Both fenoxaprop (120 g ai ha^{-1}) and quizalofop (96 g ai ha^{-1}) provided complete control of all grass weeds tested, making them ideal options for grass control in TamArk grain sorghum. Neither of these herbicides at the rates tested caused more than 10% injury or biomass reduction to TamArk grain sorghum.

While TamArk grain sorghum did not tolerate the ALS inhibitors we evaluated, these herbicides could be used in the labeled technology platform Inzen or Igrowth, for grass control. However, these herbicides were less effective than fenoxaprop or

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Table 8. Percent visible control and biomass reduction of Texas panicum by various herbicides and rates, averaged over the years.[a,b,c]

Herbicide	Rate	Control			Biomass reduction[d]
		14 DAA	21 DAA	28 DAA	28 DAA
	g ai ha^{-1}	%			
Clethodim	135	100 A	100 A	100	100
Clodinafop	70	100 A	100 A	100	100
Cyhalofop	312	100 A	100 A	100	100
Diclofop	1,120	94 B	96 B	100	100
Fenoxaprop	86	100 A	100 A	100	100
Fenoxaprop	120	100 A	100 A	100	100
Fluazifop	210	100 A	100 A	100	100
Fluazifop	280	100 A	100 A	100	100
Fluazifop	420	100 A	100 A	100	100
Imazamox	52	100 A	100 A	100	100
Imazamox	78	100 A	100 A	100	100
Nicosulfuron	35	100 A	100 A	100	100
Nicosulfuron	51	100 A	100 A	100	100
Pinoxaden	60	100 A	100 A	100	100
Quizalofop	46	100 A	100 A	100	100
Quizalofop	77	100 A	100 A	100	100
Quizalofop	92	100 A	100 A	100	100
Sethoxydim	210	100 A	100 A	100	100
P-value		<0.0001	<0.0001	–	–

[a]Abbreviation: DAA, days after application.
[b]Field experiments were conducted in Fayetteville, Arkansas, in 2020 and 2021.
[c]Means within a column followed by the same letter are not significantly different based on Tukey's HSD (α = 0.05).
[d]Percent reduction is relative to the nontreated plot within each replication.

quizalofop at controlling broadleaf signalgrass. Imazamox and nicosulfuron could be used to remove volunteer TamArk grain sorghum from fields planted with Inzen or Igrowth traits. The availability of ACCase and ALS inhibitors to grain sorghum offers producers sites of action that are also effective for johnsongrass control POST, an option that has not been previously available (Smith et al. 2010). One consideration with this research is climate and its effects on the efficacy of these herbicides. Grain sorghum is grown in many areas across the United States, which range from humid subtropical to arid climates. Although this research was conducted in a humid climate, when grain sorghum is planted in arid climates such as the Central Plains, a reduction in efficacy may occur.

ACCase and ALS inhibitors further offer a way to help mitigate herbicide resistance by adding two effective sites of action for grass control in grain sorghum (Norsworthy et al. 2012). By using either ACCase or ALS inhibitors in grass control efforts in grain sorghum crops, producers can reduce the pressure on quinclorac, which has been extensively used for grass control in both rice and grain sorghum crops in specific locations, leading to more quinclorac-resistant grass weed populations (Talbert and Burgos 2007; Heap 2022). It is also important to note that ALS- or ACCase-inhibitor–resistant populations of all the grasses evaluated in this study have been documented in the United States and other countries (Heap 2022). While these resistant grass populations are not widespread, it will be important not to overuse ACCase or ALS inhibitors for grass control in grain sorghum so as to mitigate future resistance. Therefore, these technologies should be used in a program approach that combines proper chemical, cultural, and mechanical weed control methods to reduce herbicide resistance risk.

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