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Effectiveness of preemergence- and postemergence-applied oxyfluorfen in rice compared to current standards

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Research Article

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Abstract

Control of barnyardgrass is becoming increasingly difficult as plants evolve resistance to herbicides. ROXY oxyfluorfen-resistant rice (ROXY® Rice Production System) has been developed to provide an alternative mode of action for controlling barnyardgrass and other weeds. In 2021 and 2022, field trials were conducted at the Pine Tree Research Station near Colt, AR; the Northeast Research and Extension Center in Keiser, AR; and the University of Arkansas Pine Bluff Small Farm Research Center near Lonoke, AR, to determine the level of weed control and crop tolerance following oxyfluorfen applied preemergence (PRE) or postemergence (POST) relative to herbicides currently labeled for use in rice crops. When applied post-plant PRE on silt loam soil, oxyfluorfen alone at 1,120 and 1,680 g ai ha^{-1} resulted in barnyardgrass control comparable to that of clomazone applied alone at 336 g ha^{-1}. Still, injury to rice was often greater than with clomazone, ranging from 20% to 45%. On clay soil, oxyfluorfen applied at 1,680 g ha^{-1} resulted in barnyardgrass control that was comparable to that of clomazone alone in both site-years at 3 wk after emergence but caused up to 18% injury to rice. When oxyfluorfen was applied at 560 to 1,680 g ha^{-1} at the 2-leaf rice growth stage, barnyardgrass control was ≥85% in three of four site-years 1 wk after treatment. However, injury to rice ranged from 38% to 73% for the rates evaluated. Propanil caused the greatest injury by a herbicide currently labeled for use in rice at 34%. Oxyfluorfen should be used as a post-plant PRE herbicide rather than a POST herbicide due to the injury that occurred after a POST application. The data indicate that if used as a PRE herbicide, oxyfluorfen should be applied at 560 g ha^{-1} to reduce the injury that occurred on silt loam and clay soils.

Introduction

Grass weed species can be difficult to control in rice fields without causing injury to the crop. In rice, barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] and weedy rice (*Oryza sativa* L.) are difficult to control due to herbicide resistance and, for weedy rice, its genetic similarity to cultivated rice (Butts et al. 2022). Efforts to reduce weed emergence such as the use of preemergence (PRE) herbicides, are important resistant management practices, which increases the effectiveness of postemergence (POST) herbicides and minimizes the risk for the evolution of resistance (Norsworthy et al. 2012). Common PRE herbicides used in Arkansas rice production for grass weed control include pendimethalin, thiobencarb, and clomazone (Barber et al. 2022).

Herbicides applied PRE can help control grass weed species in a rice field early in the growing season. Still, complete control is seldom achieved, indicating escaped weeds will be present and must be controlled using POST herbicides (Norsworthy et al. 2013). There are multiple options for producers to use for POST control of barnyardgrass; however, in areas where multiple herbicide-resistant barnyardgrass is present, there are limited control options (Barber et al. 2022).

Clomazone is classified as a Group 13 herbicide by the Herbicide Resistance Action Committee (HRAC) and the Weed Science Society of America (WSSA) and is commonly applied PRE in rice fields. In Arkansas rice production, clomazone is used on more than 80% of rice hectares (Miller et al. 2015). Clomazone controls many annual broadleaf and grass weed species found in rice fields, but it does not control weedy rice due to its similarities with cultivated rice (Zimdahl 2018). While populations of clomazone-resistant barnyardgrass exist in

Table 1. List of dates for agronomic practices at the Pine Tree Research Station near Colt, AR, the Northeast Research and Extension Center in Keiser, AR, and the University of Arkansas Pine Bluff Small Farm Research Center near Lonoke, AR, for the trials evaluating oxyfluorfen in comparison to current pre- and postemergence herbicides in rice during 2021 and 2022.[a]

Location	Trial	Year	Rice planting	Rice emergence	POST application	Flooding
PTRS	PRE	2021	May 13	May 21	–	June 16
PTRS	PRE	2022	May 12	May 19	–	June 20
NEREC	PRE	2021	April 22	May 5	–	June 20
NEREC	PRE	2022	May 10	May 16	–	June 16
UAPB	PRE	2021	May 24	May 29	–	July 5
UAPB	PRE	2022	May 11	May 17	–	June 20
PTRS	POST	2021	May 13	May 21	2-leaf rice	June 16
PTRS	POST	2022	May 12	May 19	2-leaf rice	June 20
NEREC	POST	2021	May 20	May 24	4-leaf rice	June 30
NEREC	POST	2022	May 10	May 16	4-leaf rice	June 16

[a]Abbreviations: NEREC, Northeast Research and Extension Center in Keiser, AR; POST, postemergence; PRE, preemergence; PTRS, Pine Tree Research Station near Colt, AR; UAPB, University of Arkansas Pine Bluff Small Farm Research Center near Lonoke, AR.

the mid-southern United States, resistance is not widespread; therefore, the herbicide still provides an effective control option in most fields (Heap 2023; Miller et al. 2015).

Control of weedy rice is currently only available in some areas with imazethapyr, imazamox, or quizalofop-P-ethyl, all of which require a herbicide-resistant rice cultivar. The Clearfield® (BASF, Florham Park, NJ) and FullPage® (RiceTec, Alvin, TX) technologies allow rice producers to use herbicides in the imidazolinone family. The Clearfield technology was released in 2002 to control problematic barnyardgrass and weedy rice found in rice fields (Sudianto et al. 2013). Both imazethapyr and imazamox are categorized by HRAC and WSSA as Group 2 herbicides that inhibit acetolactate synthase (ALS). Barnyardgrass and weedy rice have evolved resistance to ALS-inhibiting herbicides in the mid-southern U.S. rice-growing region, making control difficult (Heap 2023; Miller et al. 2015). Barnyardgrass has also evolved resistance to herbicides in Groups 1, 4, 5, 13, and 29 (Heap 2023), indicating that new modes of action will be needed to effectively control barnyardgrass.

Rice cultivars that are resistant to the herbicide quizalofop-P-ethyl were first released in 2017, allowing producers to control barnyardgrass and weedy rice that had developed resistance to ALS-inhibiting herbicides. Quizalofop-P-ethyl is a Group 1 herbicide that inhibits acetyl CoA carboxylase (ACCase), which will selectively remove barnyardgrass, weedy rice, and other grasses in rice, but the rice crop requires a resistance trait. In 2022, a population of weedy rice was confirmed to be resistant to quizalofop-P-ethyl and imidazolinone herbicides in Arkansas, meaning no effective herbicide options are available to control weedy rice in fields of cultivated rice (JKN, personal communication). Confirming quizalofop-P-ethyl weedy rice in Arkansas further enhances the need for alternative herbicides in rice production.

The evolution of herbicide resistance in barnyardgrass exemplifies the need for additional modes of action in mid-southern U.S. rice production. Currently, Group 14 herbicides, which inhibit protoporphyrinogen oxidase (PPO), are used in rice production to control broadleaf weeds but not grasses (Barber et al. 2022). The use of oxyfluorfen, a PPO-inhibiting herbicide, may give producers a control option for barnyardgrass and weedy rice that has evolved resistance to commonly used herbicides in rice (Lee et al. 1991; McKenzie et al. 2021). Currently, oxyfluorfen is not registered for use on rice and can be applied only to rice that has the trait conferring resistance to oxyfluorfen (McKenzie et al. 2021).

The aim of this research was to determine the effectiveness of oxyfluorfen applied post-plant PRE and POST on barnyardgrass and weedy rice and to compare its effect on commonly used herbicides. Trials were conducted on silt loam and clay soils, and tolerance of the oxyfluorfen-resistant rice to oxyfluorfen relative to other herbicides was evaluated.

Materials and Methods

Common Methodology

Field trials were conducted during the 2021 and 2022 growing seasons at the Pine Tree Research Station (PTRS) near Colt, AR; the Northeast Research and Extension Center (NEREC) in Keiser, AR; and the University of Arkansas Pine Bluff Small Farm Research Center (UAPB) near Lonoke, AR. Trials conducted at PTRS were evaluated on a Calhoun silt loam soil (fine-silty, mixed, thermic Typic Glossaqualfs) (USDA-NRCS 2022) consisting of 12% sand, 70% silt, 18% clay, and 1.02% organic matter, pH 7.7. Trials at UAPB were conducted on an Immanuel silt loam soil (fine-silty, mixed, thermic Oxyaquic Glossaqualfs) (USDA-NRCS 2022) consisting of 14% sand, 72% silt, 14% clay, and 1.25% organic matter, pH 5.6. Trials at NEREC were conducted on a Sharkey silty clay (very-fine, smectitic, thermic Chromic Epiaquerts) (USDA-NRCS 2022) with 41% sand, 1% silt, 58% clay, and 2.8% organic matter, pH 5.5. Soil content from all three locations was determined by the Arkansas Agricultural Diagnostic Laboratory, in Fayetteville, AR. In all trials, an early maturing, long-grain rice cultivar known to be resistant to oxyfluorfen was planted at a rate of 72 seeds per meter row. At PTRS and NEREC, the trials were planted with a nine-row, small-plot drill at a 1.3-cm depth with 19 cm between rows. The plots at PTRS and NEREC were 1.7 m wide and 5 m long. At UAPB, a seven-row, small-plot drill at a 1.3-cm depth and 19 cm between rows was used to establish 1.3-m-wide and 8-m-long plots. Each location's planting, emergence, and flooding dates are listed below (Table 1). At all locations, soil fertility and water were managed by soil test reports and published information (Henry et al. 2021; Roberts et al. 2021).

All trials were designed as a randomized complete block with a single factor. The PRE applications were applied to the soil on the day of planting, and all POST applications occurred at the 2-leaf stage of rice. All herbicide sprays at PTRS and NEREC were applied with a four-nozzle, CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} with TeeJet AIXR 110015 nozzles (Spraying Systems Co., Glendale Heights, IL) at a speed of 4.8 kph. Plots at the

Table 2. Herbicides and herbicide rates used in the preemergence application timing trials to compare oxyfluorfen against commercial standards in 2021 and 2022 on silt loam and clay soil.

Herbicide	Silt loam soil	Clay soil
	g ai ha^{-1}	
Clomazone	336	785
Quinclorac	420	566
Clomazone + quinclorac	336 + 420	785 + 566
Clomazone + oxyfluorfen	336 + 673	785 + 673
Quinclorac + oxyfluorfen	420 + 1,120	566 + 1,120
Oxyfluorfen	560	560
Oxyfluorfen	1,120	1,120
Oxyfluorfen	1,680	1,680

UAPB location were sprayed using a tractor-mounted, multiboom sprayer calibrated to deliver 94 L ha^{-1} with TeeJet AIXR 110015 nozzles at 4.8 kph. Barnyardgrass seed production per square meter was estimated approximately 2 wk before rice harvest by collecting 20 panicles from the trial area and counting the number of panicles in a randomly selected 1-m^2 quadrat in each plot. The average seed number per panicle was determined after threshing the panicles. The average seed production per panicle was then multiplied by panicles per square meter. Rough rice was harvested from all trials in 2021 at the PTRS location and 2022 at UAPB; however, the absence of a season-long weed control program resulted in severe rice lodging and the inability to collect yield data at the PTRS and NEREC sites in 2022, and UAPB site in 2021. All rough rice yield data were adjusted to 12% moisture and reported in kilograms per hectare (kg ha^{-1}).

Preemergence Herbicides

Trials to evaluate PRE herbicides were conducted at the NEREC, PTRS, and UAPB sites. The trials contained nine treatments, including a nontreated control for comparison (Table 2). Treatments included oxyfluorfen (ALB2023; Albaugh LLC, Ankeny, IA) at three rates ranging from 560 to 1,680 g ha^{-1}, while clomazone (Command 3ME; FMC Corporation, Philadelphia, PA), and quinclorac (Quinstar; Albaugh LLC) treatments were used as PRE standards (Table 2). Additionally, varying rates of oxyfluorfen and clomazone or quinclorac were evaluated. Visible weed control and injury ratings were taken at 3 wk and 6 to 7 wk after rice emergence (WAE) and were based on a scale of 0% to 100% compared with the nontreated control. Visible weed control ratings of 0% were equal to no control, while 100% represented complete control compared with nontreated plots (Frans and Talbert 1977). In addition, oxyfluorfen-resistant rice shoot densities were taken in two 1-m sections of the row at 2 WAE in 2021 and 2022 at the PTRS site and in 2022 at the UAPB site.

Postemergence Herbicides

Field trials were conducted at the PTRS and NEREC locations. Each experiment had eight treatments replicated four times each site-year. Treatments consisted of florpyrauxifen-benzyl (Loyant; Corteva Agriscience, Indianapolis, IN) applied at 15 g ha^{-1}; fenoxaprop (Ricestar HT; Bayer CropScience, St. Louis, MO) applied at 122 g ha^{-1}; propanil (Stam; RICECO LLC, Memphis, TN) applied at 4,480 g ha^{-1}; bispyribac-sodium (Regiment®; Valent U.S.A, Walnut Creek, CA) applied at 71 g ha^{-1}; and oxyfluorfen (ALB2024; Albaugh LLC) applied at 560, 1,120, and 1,680 g ha^{-1}. Additionally, a nontreated control was included for comparison purposes. In all site-years, methylated seed oil (MES-100; Drexel Chemical Company, Memphis, TN) was included with florpyrauxifen-benzyl and oxyfluorfen at a rate of 1% v/v. Dyne-A-Pak (Helena Agri-Enterprises, Collierville, TN), was mixed with bispyribac-sodium at a rate of 2.5% v/v. Visible weed control and oxyfluorfen-resistant rice injury were rated at 1, 2, and 4 to 5 wk after treatment (WAT) using the scale described previously. Due to severe lodging, rough rice yields were collected only in 2021 at the PTRS and NEREC sites.

Data Analysis

All data were analyzed using JMP Pro software (version 17.0) or SAS software (version 9.4; SAS Institute Inc, Cary, NC). Data distributions were analyzed as continuous within the Fit Model function with JMP Pro, while the Akaike information criterion was used to determine the best fit for all data. In addition, all data were subjected to ANOVA, and Tukey's honestly significant difference test was used to separate means with value of $\alpha = 0.05$ to minimize the Type I errors.

All injury and weed control data were beta distributed and analyzed using the GLIMMIX procedure with SAS software (Gbur et al. 2012). In addition, oxyfluorfen-resistant rice shoot densities, rough rice yields, and weed seed production were normally distributed and analyzed using the Fit Model with JMP Pro software. All analyses were separated by site-year due to differences in planting dates, which led to significant year-by-treatment interactions.

Results and Discussion

Preemergence Herbicides

Barnyardgrass

Barnyardgrass control following the PRE application of oxyfluorfen was mainly a result of reduced weed emergence based on visible ratings. Oxyfluorfen applied alone at 1,120 and 1,680 g ha^{-1} provided barnyardgrass control that was comparable to all treatments containing clomazone or quinclorac in two of four site-years on a silt loam soil 3 WAE (Table 3). In previous research (Price et al. 2008) oxyfluorfen applied at 1,120 g ha^{-1} provided residual barnyardgrass control when rated at 3 wk after application. Our research indicates that oxyfluorfen can provide barnyardgrass control, an alternative weed control option in rice production. Using a Group 14 herbicide for barnyardgrass control would reduce selection pressure on herbicides in Groups 1 and 2.

By 6 to 7 WAE, there was no difference in barnyardgrass control among treatments containing oxyfluorfen alone in three of four site-years on a silt loam soil (Table 3). Barnyardgrass control at this final rating exceeded 80% in three site-years at the highest rate of oxyfluorfen, whereas no more than 53% control was obtained in the other year. Oxyfluorfen applied PRE to a silt loam soil at the two highest rates provided comparable barnyardgrass control to that of clomazone and quinclorac, both s used for comparison, at 6 to 7 WAE. Based on this research, if using oxyfluorfen alone, the 1,120 or 1,680 g ha^{-1} rate should be used to provide barnyardgrass control comparable to that of clomazone alone. If oxyfluorfen can provide results similar to those of clomazone, then the herbicide could provide rice producers with an alternative herbicide for controlling barnyardgrass. Using an alternative herbicide to control barnyardgrass would give producers an option for combating herbicide-resistant barnyardgrass on silt loam soil.

Table 3. Barnyardgrass control and seed production following a preemergence application on silt loam soil in 2021 and 2022 at the Pine Tree Research Station near Colt, AR, and the University of Arkansas Pine Bluff Small Farm Research Center near Lonoke, AR.[a,b]

		Barnyardgrass control								Barnyardgrass seed production		
		3 WAE				6-7 WAE						
		PTRS		UAPB		PTRS		UAPB		PTRS		UAPB
Herbicide	Rate	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2022
	g ai ha^{-1}	——%							——	——Thousands m^{-2}——		
Nontreated	n/a									28	50 A	23
Clom	336	93 AB	98 A	32	89 B	99 A	50	17	73	1	4 B	10
Quin	420	94 AB	98 A	58	99 A	99 A	71	29	76	3	7 B	21
Clom + quin	336 + 420	91 ABC	99 A	37	95 AB	99 A	84	21	85	2	7 B	13
Clom + oxy	336 + 673	87 BC	99 A	38	94 AB	99 A	74	19	83	0	0 B	11
Quin + oxy	420 + 1,120	95 A	99 A	69	96 AB	89 A	88	52	88	4	0 B	11
Oxy	560	81 C	90 B	35	87 B	61 B	63	19	78	11	13 B	18
Oxy	1,120	91 ABC	98 A	37	91 B	98 A	83	20	79	6	3 B	13
Oxy	1,680	91 ABC	98 A	68	92 B	98 A	88	53	81	4	5 B	12
							P-value					
		0.0009	<0.0001	0.4794	0.0009	<0.0001	0.3066	0.2005	0.6564	0.0512	<0.0001	0.5343

[a]Abbreviations: Clom, clomazone; Oxy, oxyfluorfen; PTRS, Pine Tree Research Station near Colt, AR; Quin, quinclorac; UAPB, University of Arkansas Pine Bluff Small Farm Research Center near Lonoke, AR; WAE, weeks after rice emergence.
[b]Means within a column followed by the same letter are not different according to Tukey's honestly significant difference test (α = 0.05); the absence of letters indicates no treatment differences.

Table 4. Barnyardgrass control and seed production following a preemergence application on clay soil in 2021 and 2022 at the Northeast Research and Extension Center in Keiser, AR.[a,b]

		Barnyardgrass control				Barnyardgrass seed production	
		3 WAE		6–7 WAE			
Herbicide	Rate	2021	2022	2021	2022	2021	2022
	g ai ha^{-1}	——%			——	—Thousands of m^{-2}—	
Nontreated	n/a					22 A	38 A
Clom	785	94 AB	88 A	69 A	72 AB	6 B	9 BC
Quin	566	81 C	88 A	55 AB	73 AB	16 AB	7 C
Clom + quin	785 + 566	93 AB	88 A	78 A	78 A	8 B	7 C
Clom + oxy	785 + 673	97 AB	86 A	84 A	71 AB	3 B	13 BC
Quin + oxy	566 + 1,120	96 A	86 A	78 A	70 AB	13 AB	9 BC
Oxy	560	86 BC	45 B	19 B	10 C	22 A	23 ABC
Oxy	1,120	93 AB	50 B	64 A	16 C	11 AB	24 ABC
Oxy	1,680	97 A	74 AB	85 A	26 BC	10 B	24 AB
				P-value			
		0.0001	0.0003	0.0020	0.0005	<0.0001	<0.0001

[a]Abbreviations: Clom, clomazone; Oxy, oxyfluorfen; Quin, quinclorac; WAE, weeks after rice emergence.
[b]Means within a column followed by the same letter are not different according to Tukey's honestly significant difference test (α = 0.05); the absence of letters indicates no treatment differences.

In 2021 on clay soil, all rates of oxyfluorfen applied alone provided barnyardgrass control that was similar to that of clomazone alone and mixtures containing oxyfluorfen at 3 WAE (Table 4). In one site-year, at 6 to 7 WAE, barnyardgrass control with oxyfluorfen applied at 1,120 and 1,680 g ha^{-1} was comparable to that provided by clomazone and quinclorac alone and in combinations. In the additional site-year, clomazone provided greater barnyardgrass control than the 560 and 1,120 g ha^{-1} rates of oxyfluorfen. However, oxyfluorfen applied alone at 1,680 g ha^{-1} provided barnyardgrass control that was similar to that of clomazone alone and mixtures of clomazone or quinclorac plus oxyfluorfen. Therefore, the studies conducted on clay soil suggests that oxyfluorfen alone should be applied at 1,680 g ha^{-1} to control barnyardgrass; however, similar to silt loam soil, the best recommendation would be to use oxyfluorfen in combination with other herbicides. Using multiple modes of action for weed control is a best management practice recommended to prevent herbicide resistance (Norsworthy et al. 2012). On clay soil, oxyfluorfen applied at 1,680 g ha^{-1} might be an alternative herbicide for controlling barnyardgrass that is resistant to herbicides currently labeled for use in rice production.

Barnyardgrass seed production was comparable across all treatments on silt loam soil in all site-years (Table 3). Clomazone is currently used on >90% of rice hectares in Arkansas and Mississippi (Norsworthy et al. 2013), but in some areas barnyardgrass has become resistant to clomazone; therefore, new herbicides will be needed to provide PRE control (Heap 2023). Oxyfluorfen did not decrease the amount of barnyardgrass seed returned to the soil seedbank compared to herbicides currently labeled for use on rice fields, indicating that oxyfluorfen would be neither better nor worse for long-term barnyardgrass control compared to current herbicides, particularly when it is used against barnyardgrass populations that are susceptible to clomazone and quinclorac.

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Table 5. Oxyfluorfen-resistant shoot densities and rough rice yields following a preemergence application on silt loam soil in 2021 and 2022 at the Pine Tree Research Station near Colt, AR, and the University of Arkansas Pine Bluff Small Farm Research Center near Lonoke, AR in 2022.[a,b]

		Oxyfluorfen-resistant rice shoot density			Oxyfluorfen-resistant rice yield	
		PTRS		UAPB	PTRS	UAPB
Herbicide	Rate	2021	2022	2022	2021	2022
	g ai ha^{-1}	Shoots m row^{-1}			kg ha^{-1}	
Nontreated	n/a	23 AB	44	55	2,170 B	0 C
Clom	336	22 AB	46	24	4,590 A	3,130 AB
Quin	420	30 AB	45	50	3,680 AB	3,530 AB
Clom + quin	336 + 420	29 AB	47	31	5,050 A	4,290 A
Clom + oxy	336 + 673	16 B	49	37	4,440 A	4,240 A
Quin + oxy	420 + 1,120	20 AB	37	37	5,500 A	4,690 A
Oxy	560	24 AB	40	42	4,090 AB	1,510 BC
Oxy	1,120	23 AB	38	30	4,090 AB	3,080 AB
Oxy	1,680	30 A	35	29	4,290 AB	2,620 ABC
		P-value				
		0.0292	0.1058	0.2259	0.0031	0.0001

[a]Abbreviations: Clom, clomazone; PTRS, Pine Tree Research Station, near Colt, AR; Quin, quinclorac; UAPB, University of Arkansas Pine Bluff Small Farm Research Center near Lonoke, AR; WAE, weeks after rice emergence.
[b]Means within a column followed by the same letter are not different according to Tukey's honestly significant difference test (α = 0.05); the absence of letters indicates no treatment differences.

Table 6. Oxyfluorfen-resistant rice injury following a preemergence application on silt loam soil in 2021 and 2022 at the Pine Tree Research Station near Colt, AR, and the University of Arkansas Pine Bluff Small Farm Research Center near Lonoke, AR.[a,b]

		Injury							
		3 WAE				6–7 WAE			
		PTRS		UAPB		PTRS		UAPB	
Herbicide	Rate	2021	2022	2021	2022	2021	2022	2021	2022
	g ai ha^{-1}	%							
Clom	336	7 BC	14 C	0	0	15 AB	2	0	0
Quin	420	7 ABC	2 D	0	0	14 AB	1	0	0
Clom + quin	336 + 420	6 C	16 C	0	0	6 B	3	0	0
Clom + oxy	336 + 673	44 ABC	16 C	0	0	34 A	3	0	0
Quin + oxy	420 + 1,120	13 ABC	3 AB	0	0	19 AB	10	0	0
Oxy	560	6 C	14 C	0	0	8 AB	1	0	0
Oxy	1,120	45 A	20 BC	0	0	35 A	3	0	0
Oxy	1,680	45 AB	36 A	0	0	30 AB	5	0	0
		P-value							
		0.0024	<0.0001	1.000	1.000	0.0127	0.0563	1.000	1.000

[a]Abbreviations: Clom, clomazone; PTRS, Pine Tree Research Station near Colt, AR; Oxy, oxyfluorfen; Quin, quinclorac; UAPB, University of Arkansas Pine Bluff Small Farm Research Center near Lonoke, AR; WAE, weeks after rice emergence
[b]Means within a column followed by the same letter are not different according to Tukey's honestly significant difference test (α = 0.05); the absence of letters indicates no treatment differences.

In 2021, oxyfluorfen applied at 1,120 and 1,680 g ha^{-1} led to barnyardgrass seed production that was comparable to that of clomazone and quinclorac alone and in combinations (Table 4). Barnyardgrass seed production with oxyfluorfen applied alone at 560 g ha^{-1} was comparable to that when a combination of quinclorac and oxyfluorfen was applied. However, in 2022, all rates of oxyfluorfen led to barnyardgrass seed production that was comparable to that of clomazone alone and clomazone or quinclorac plus oxyfluorfen. Generally, barnyardgrass plants produce a variable amount of seed, likely due to the environment in which the plant grows (Bagavathiannan et al. 2012). However, in both site-years, the amount of barnyardgrass seed produced followed a trend similar to visible barnyardgrass control observed.

Based on this research, oxyfluorfen applied at 1,120 and 1,680 g ha^{-1} could provide an alternative PRE herbicide to control barnyardgrass on silt loam soil with results that are comparable to those of the standard herbicides quinclorac and clomazone in most instances. Using oxyfluorfen introduces a new mode of action for barnyardgrass control in rice production. No barnyardgrass has been confirmed to be resistant to Group 14 herbicides, indicating that oxyfluorfen could be used in all rice-growing areas in the mid-southern United States (Heap 2023). Using oxyfluorfen in addition to herbicides that are already being used would help to combat herbicide-resistant weeds (Norsworthy et al. 2012).

Injury

Injury to oxyfluorfen-resistant rice following a PRE application of oxyfluorfen was in the form of reduced shoot density and decreased plant vigor; however, in two of three site-years, there was no difference in the number of oxyfluorfen-resistant rice shoots (Table 5). On a silt loam soil, oxyfluorfen applied alone at 560, 1,120, and 1,680 g ha^{-1} resulted in injury to oxyfluorfen-resistant rice that ranged from 6% to 45% 3 WAE in both years at the PTRS site (Table 6). At the UAPB site, no injury was observed to

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Table 7. Oxyfluorfen-resistant rice injury following a preemergence application on clay soil in 2021 and 2022 at the Northeast Research and Extension Center near Keiser, AR.[a,b]

		Injury					
		3 WAE			6–7 WAE		
Herbicide	Rate	2021		2022	2021		2022
	g ai ha^{-1}	——————%——————					
Clom	785	2	BC	9	8	BC	3
Quin	566	0	C	5	2	C	2
Clom + quin	785 + 566	0	C	11	10	BC	3
Clom + oxy	785 + 673	8	AB	4	20	AB	2
Quin + oxy	566 + 1,120	2	BC	5	13	B	2
Oxy	560	1	BC	12	11	B	2
Oxy	1,120	2	BC	17	12	B	2
Oxy	1,680	18	A	10	29	A	2
		P-value					
		<0.0001		0.1086	<0.0001		0.9704

[a]Abbreviations: Clom, clomazone; Oxy, oxyfluorfen; quin, quinclorac; WAE, weeks after rice emergence.
[b]Means within a column followed by the same letter are not different according to Tukey's honestly significant difference test (α = 0.05); the absence of letters indicates no treatment differences.

oxyfluorfen-resistant rice at 3 WAE, possibly due to lower soil moisture levels than at other sites. As soil moisture levels increase, the potential for injury with oxyfluorfen also increases (C. Arnold, unpublished data). By 6 to 7 WAE, injury to oxyfluorfen-resistant rice was ≤10% in three of four site-years. This research indicates that applying oxyfluorfen to oxyfluorfen-resistant rice can cause severe injury, but in some instances the plants can recover.

Oxyfluorfen applied PRE at 560 and 1,120 g ha^{-1} to clay soil resulted in injury to oxyfluorfen-resistant rice that was comparable to that of clomazone and quinclorac alone and mixtures containing oxyfluorfen at 3 WAE (Table 7). In both years at 3 WAE, all injury was ≤18%. In both years, no treatment resulted in fewer oxyfluorfen-resistant rice shoots on clay soil. By 6 to 7 WAE, the 1,680 g ha^{-1} rate of oxyfluorfen resulted in greater injury than all treatments except for clomazone plus oxyfluorfen. In general, the use of oxyfluorfen PRE on clay soil will result in less activity than when applied on a silt loam soil due to the herbicide being adsorbed to the clay particles and not being available for uptake by the plant (Ross and Lembi 1985; Senseman 2007). The potential for injury to oxyfluorfen-resistant rice after applying oxyfluorfen should be considered when choosing a rate that provides barnyardgrass control. Rough rice yields were comparable in all treated plots except for oxyfluorfen applied alone at 1,680 g ha^{-1} in 2021 and clomazone plus quinclorac applied in 2022. The rough rice yields observed at the NEREC location were likely influenced by the barnyardgrass and injury observed.

Postemergence Herbicides

Weed Control

In both years, at 1 wk after treatment (WAT) on a silt loam soil, barnyardgrass control was comparable among all rates of oxyfluorfen and fenoxaprop (Table 8). However, barnyardgrass control was greatest on clay soil with oxyfluorfen at 1,120 g ha^{-1} in 2021, when control ranged from 11% to 64%. In 2022 on clay soil, barnyardgrass control ranged from 81% to 96% among all treatments at 1 WAE. The difference in barnyardgrass control on the clay soil could be a function of barnyardgrass density, in that an average of 89 and 336 barnyardgrass plants per square meter were counted in 2021 and 2022, respectively. The density of barnyardgrass plants could have influenced the amount of herbicide that was absorbed by each plant, thereby not providing effective control in 2022 (Winkle et al. 1981).

When applied to 2-leaf barnyardgrass, all herbicide treatments, except for florpyrauxifen-benzyl, provided barnyardgrass control that was comparable to that of all oxyfluorfen rates at 2 WAT in two of four site-years (Table 8). Barnyardgrass control would likely be diminished if oxyfluorfen was applied to larger plants. These findings suggest that oxyfluorfen could be an alternative herbicide for POST control of barnyardgrass, albeit with varying levels of control. At 4 to 5 WAT, all rates of oxyfluorfen provided barnyardgrass control that was comparable to that of bispyribac-sodium but not to other herbicide treatments in one of four site-years. The data collected at 4 to 5 WAT further suggest that oxyfluorfen provides varying levels of barnyardgrass control. Inconsistent control levels may indicate that barnyardgrass-tolerant populations exist, and herbicide mixtures with oxyfluorfen will be needed.

There were no differences in barnyardgrass seed production following a herbicide treatment in all four site-years (Table 9). There may not have been an effect on barnyardgrass seed production because the trial received only one herbicide application, which is abnormal for rice production in Arkansas. Typically, rice producers apply three herbicide treatments in a growing season (Norsworthy et al. 2013). It is also worth mentioning that the amount of barnyardgrass seed produced in each plot varied in all site-years following the treatments.

Injury

Injury to oxyfluorfen-resistant rice was ≤24% at 1 WAT with herbicides labeled for use on rice in three of four site-years (Table 10). In all site-years, injury from an application of oxyfluorfen at the 2-leaf rice growth stage ranged from 48% to 73% at the PTRS location, whereas injury at the NEREC location ranged from 38% to 59% at 1 WAT. Oxyfluorfen that was on the soil surface could provide residual activity after application, and that could have influenced the different injury levels that we observed at the PTRS and NEREC locations due to the different soil textures at each site (Ross and Lembi 1985; Senseman 2007). By 4 to 5 WAT, the 1,120 g ha^{-1} rate of oxyfluorfen resulted in injury to oxyfluorfen-resistant rice that was similar to that when 560 and 1,680 g ha^{-1} rates were applied, and to that of florpyrauxifen-benzyl in two of the four site-years. Based on the findings of this research, oxyfluorfen-resistant rice can outgrow the injury caused by oxyfluorfen; however, this was not consistently observed.

Rough rice yields were determined at only two of four site-years due to severe lodging in the trial. Even though injury to oxyfluorfen-resistant rice was observed at 4 to 5 WAT, there was no difference in rough rice yields in both site-years (Table 9). There was likely no difference in rough rice yields because there was no difference in the amount of barnyardgrass seed produced before harvest, which is a result of the number of plants that are competing with the rice. However, a single herbicide application to rice is uncommon in Arkansas; therefore, differences may be observed when oxyfluorfen is used in a traditional rice weed control program (Norsworthy et al. 2013).

Practical Implications

Oxyfluorfen has shown the ability to control barnyardgrass at a level that is comparable with some standard PRE and POST herbicides currently labeled for use on rice fields on silt loam and

Table 8. Barnyardgrass control following a herbicide application at the 2-leaf rice growth stage at the Pine Tree Research Station near Colt, AR, and the Northeast Research and Extension Center in Keiser, AR.[a,b]

		Barnyardgrass control											
		1 WAT				2 WAT				4–5 WAT			
		PTRS		NEREC		PTRS		NEREC		PTRS		NEREC	
Herbicide	Rate	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
	g ai ha^{-1}	%											
FPB	15	41 C	36 D	90	11 D	52 C	46 D	94	6 B	86	58 D	93	28 AB
Fenox	122	86 A	82 AB	92	28 C	97 A	96 AB	98	77 A	92	78 BC	95	66 A
Prop	4,485	76 BC	59 CD	94	42 B	92 AB	70 CD	93	59 A	89	64 CD	92	5 BC
Bispyr	71	66 BC	67 BC	81	48 B	76 BC	77 C	96	55 A	89	83 AB	94	9 BC
Oxy	560	97 A	85 AB	95	51 B	96 AB	83 BC	90	61 A	94	90 AB	89	5 BC
Oxy	1,120	97 A	87 A	96	64 A	96 AB	97 AB	95	71 A	96	93 A	96	3 C
Oxy	1,680	97 A	93 A	95	53 B	97 AB	99 A	98	50 A	94	93 A	94	2 C
		P-value											
		<0.0001	<0.0001	0.0597	<0.0001	0.0006	<0.0001	0.1075	<0.0001	0.2964	<0.0001	0.4076	<0.0001

[a]Abbreviations: Bispyr, bispyribac-sodium; Fenox, fenoxaprop; FPB, florpyrauxifen-benzyl; NEREC, Northeast Research and Extension Center near Keiser, AR; Oxy, oxyfluorfen; Prop, propanil; PTRS, Pine Tree Research Station near Colt, AR; WAE, weeks after emergence.
[b]Means within a column followed by the same letter are not different according to Tukey's honestly significant difference test ($\alpha = 0.05$); the absence of letters indicates no treatment differences.

Table 9. Barnyardgrass seed production and rough rice yields following a herbicide application at the 2-leaf rice growth stage at the Pine Tree Research Station near Colt, AR, and the Northeast Research and Extension Center in Keiser, AR.[a,b]

		Barnyardgrass seed production				Oxyfluorfen-resistant rice yield	
		PTRS		NEREC		PTRS	NEREC
Herbicide	Rate	2021	2022	2021	2022	2021	2021
	g ai ha^{-1}	Thousands m^{-2}				kg ha^{-1}	
Nontreated	n/a	28 A	20	47	117	40,90	3,230 B
FPB	15	3 B	10	23	150	5,400	7,360 A
Fenox	122	2 B	4	25	114	5,900	7,870 A
Prop	4,485	11 B	10	18	112	6,210	6,810 A
Bispyr	71	11 B	16	28	135	5,300	7,720 A
Oxy	560	1 B	13	50	138	4,980	6,960 A
Oxy	1,120	0 B	6	48	130	4,670	6,910 A
Oxy	1,680	1 B	10	30	140	5,720	7,420 A
		P-value					
		<0.0001	0.6386	0.8416	0.8449	0.2227	0.0001

[a]Abbreviations: Bispyr, bispyribac-sodium; Fenox, fenoxaprop; FPB, florpyrauxifen-benzyl; NEREC, Northeast Research and Extension Center near Keiser, AR; Oxy, oxyfluorfen; Prop, propanil; PTRS, Pine Tree Research Station near Colt, AR;WAE, weeks after emergence.
[b]Means within a column followed by the same letter are not different according to Tukey's honestly significant difference test ($\alpha = 0.05$); the absence of letters indicates no treatment differences.

Table 10. Oxyfluorfen-resistant rice injury following a herbicide application at the 2-leaf rice growth stage at the Pine Tree Research Station near Colt, AR, and the Northeast Research and Extension Center in Keiser, AR.[a,b]

		Injury											
		1 WAT				2 WAT				4–5 WAT			
		PTRS		NEREC		PTRS		NEREC		PTRS		NEREC	
Herbicide	Rate	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
	g ai ha^{-1}	%											
FPB	15	0 C	0 C	13 D	1 D	1 D	0 D	2 D	4 B	14 BC	5 BC	13	1
Fenox	122	1 BC	0 C	19 CD	9 C	3 CD	0 D	5 BCD	10 B	7 C	2 C	19	1
Prop	4,485	0 C	0 C	34 BC	24 BC	1 BC	0 D	18 ABC	17 AB	4 C	2 C	17	0
BS	71	4 B	0 C	11 D	11 C	1 D	0 D	4 CD	6 B	12 BC	2 C	14	1
Oxy	560	66 A	48 B	45 AB	38 AB	45 AB	33 C	23 AB	40 A	36 AB	3 BC	17	0
Oxy	1,120	68 A	64 A	51 AB	51 A	51 AB	46 B	22 AB	44 A	38 AB	17 AB	21	0
Oxy	1,680	69 A	73 A	59 A	48 A	61 A	63 A	27 A	37 A	52 A	26 A	18	0
		P-value											
		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0004	<0.0001	<0.0001	0.0006	0.2891	0.9920

[a]Abbreviations: BS, bispyribac-sodium; Fenox, fenoxaprop; FPB, florpyrauxifen-benzyl; NEREC, Northeast Research and Extension Center near Keiser, AR; Oxy, oxyfluorfen; Prop, propanil; PTRS, Pine Tree Research Station near Colt, AR;WAE, weeks after emergence.
[b]Means within a column followed by the same letter are not different according to Tukey's honestly significant difference test ($\alpha = 0.05$); the absence of letters indicates no treatment differences.

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clay soil. Using oxyfluorfen alone or in mixtures for barnyardgrass control in rice production would mean using a mode of action that has not previously been used for barnyardgrass control. The glaring issue with using oxyfluorfen in rice production is the injury we observed following application of the herbicide. When used as a PRE herbicide, oxyfluorfen applied at 560 g ha^{-1} appeared to be the optimum rate because ≤14% injury was observed in all site-years at 3 WAE, whereas all rates of oxyfluorfen caused ≤18% injury in all site-years on clay soil. If oxyfluorfen were to be applied to rice as a PRE herbicide, producers should likely use the 560 g ha^{-1} rate on silt loam soil and the 560 or 1,120 g ha^{-1} rates on a clay soil to achieve barnyardgrass control. Applied at those rates, injury to rice should not last throughout the growing season. When applied to both soil textures, oxyfluorfen could be mixed with clomazone or quinclorac, following the best management practices for weed control.

When oxyfluorfen was applied at various rates as a POST herbicide, no difference in barnyardgrass control was observed in three of the four site-years. However, at 1 WAT the same rates of oxyfluorfen caused injury to oxyfluorfen-resistant rice that would not be acceptable in a commercial setting. In one site-year, the rice outgrew the injury, but in the other three site-years, the injury was still present at 4 to 5 WAT. Oxyfluorfen did not reduce the rough rice yields collected in any site-year, which may result from the cultivar, which is neither high yielding nor adapted to mid-southern U.S. rice production. Therefore, oxyfluorfen likely should not be used as a POST herbicide because it has the potential to cause severe injury to cultivated rice.

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