

## Research Article

# Rice Cultivar Response to Florpyrauxifen-Benzyl When Applied with Imazethapyr and a Cytochrome P450 Inhibitor

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Understanding cultivar responses to a new herbicide is crucial to determining appropriate herbicide use and management practices. Florpyrauxifen-benzyl is a new rice herbicide developed to control troublesome weeds in rice production. Little research has been conducted to characterize rice cultivar responses to florpyrauxifen-benzyl, and thus, a field experiment was conducted at the Pine Tree Research Station (PTRS) in 2017 and 2018 and at the Rice Research and Extension Center (RREC) in 2018 to determine rice cultivar tolerance to florpyrauxifen-benzyl as influenced by herbicide rate, the addition of imazethapyr, and rice growth stage. Another experiment was conducted in 2018 at PTRS and RREC to assess crop response when florpyrauxifen-benzyl at different rates is applied with and without malathion, a known cytochrome P450 inhibitor. Three cultivars were evaluated in both experiments: a long-grain variety “CL111,” a medium-grain variety “CL272,” and a long-grain hybrid “CLXL745.” Injury in the first experiment was higher when florpyrauxifen-benzyl was applied at 60 g ae ha<sup>-1</sup> than at the labeled rate of 30 g ha<sup>-1</sup>, with the most injury being 10% when averaged over growth stage at the time of application. Generally, applications made at the 3-leaf growth stage resulted in the most injury; however, this injury was at most 14%. Additionally, there was no reduction in grain yield for any cultivar, indicating florpyrauxifen-benzyl can be used safely in conjunction with imazethapyr in imidazolinone-resistant rice. In the second experiment, there was no more than 10% injury and no reduction in grain yield, with the addition of malathion not causing an increase in rice injury. Results from these experiments indicate florpyrauxifen-benzyl can be mixed with imazethapyr and the addition of malathion will not lead to increased risk for injury to rice.

## 1. Introduction

Crop tolerance to a herbicide, in most instances, is due to the ability of the plant to metabolize and detoxify the toxin to a nonphytotoxic compound, with the most common detoxifying pathways being P450 monooxygenase and glutathione S-transferase (GST) enzymes [1]. In certain instances, P450-inhibiting insecticides such as malathion can cause a herbicide to be more injurious to the crop, due to a reduced ability to metabolize the herbicide [2]. Understanding the ability of a crop to metabolize a new herbicide is crucial in determining if the herbicide will be a good fit for use in production.

Malathion is an organophosphate insecticide used in many crops and is recommended in rice for control of rice stink bug (*Oebalus pugnax*) [3]. It is a cytochrome P450 inhibitor and, when applied as a mixture with other pesticides, or in close succession of an herbicide application, could cause the herbicide to injure the crop [4]. For example, malathion should not be applied within 14 days of propanil, a photosystem II-inhibiting herbicide. A study from [5] found that propanil applied with malathion resulted in 50% injury to rice and a significant reduction in rough rice yield.

There are several examples of rice cultivars exhibiting differential tolerances to herbicides. One example is greater tolerance of rice varieties “Mars” and “Tebonnet” to a

triclopyr application, a synthetic auxin herbicide (WSSA Group 4) than “Lemont.” This was especially evident when triclopyr was applied at a higher rate to 2- to 3-leaf rice [6]. Another study showed differential tolerance of Clearfield® rice cultivars, which are imidazolinone-resistant. A long-grain rice variety “CL161” experienced less injury following an application of imazamox, another acetolactate synthase-inhibiting herbicide in the imidazolinone family (WSSA Group 2), than the two hybrids “CLXL745” and “CLXL729.” In this study by Bond and Walker [7], the variety had no reduction in yield compared to the hybrids, which saw a 9 to 21% reduction in yield. From that same study, it is evident that the growth stage or timing of the herbicide application can affect the level of injury. Relative yield was not affected by an application of imazamox when the herbicide was applied at panicle initiation; however, the relative yield was reduced when the herbicide was applied 14 days after panicle initiation and boot [7].

In another study, Bond et al. [8] also found that a 12.5% drift rate of acetolactate synthase (ALS)-inhibiting herbicides on non-imidazolinone-resistant rice resulted in as much as 35% injury 7 days after application when applied early postemergence (EPOST) on 2- to 3-leaf rice compared to 0% when application was made at panicle differentiation as a late-postemergence (LPOST) application. However, relative yield was more affected by applications made at LPOST than at EPOST. From these studies, it is apparent that rice injury following a herbicide application can be influenced by cultivar, growth stage, and herbicide rate. Also, injury may or may not ultimately affect yield.

Imidazolinone-resistant rice cultivars were introduced to allow imazethapyr and imazamox to be used for red rice (*Oryza sativa* L.) control beginning in 2002 [9, 10]. Imidazolinone herbicides are used to control numerous weeds in rice but are most valuable for red rice control [10]. A survey of rice consultants in Arkansas and Mississippi indicated that barnyardgrass (*Echinochloa crus-galli* L. Beauv.), sprangletop species (*Leptochloa* spp.), and red rice were among the most troublesome weeds in rice production in this region [11]. Of these, red rice and barnyardgrass are the most difficult to control and, when not controlled can cause as much as 82% and 65% yield loss at 40 and 50 plants m<sup>-2</sup>, respectively [12]. Further complicating this issue, 45% of Arkansas rice is planted to an imidazolinone-resistant cultivar and will receive an application of an imidazolinone herbicide at least once during the growing season [13]. As expected with the widespread use of any herbicide, several weed species have evolved resistance to ALS-inhibiting herbicides. Norsworthy et al. [11] indicated that four out of the top five most problematic weeds in rice production had at least some resistance to ALS-inhibiting herbicides, which is concerning as resistance to this site of action appears to have increased from a previous survey and is now a more pressing issue in rice production [14, 15]. Increased occurrence of resistance coupled with weeds having multiple resistance highlights the need for herbicide stewardship and additional effective sites of action [15, 16].

To combat the evolution of herbicide resistance, florypyrauxifen-benzyl was commercialized in US rice in 2018 by

Corteva™ Agriscience as the active ingredient in Loyant™ herbicide. Florypyrauxifen-benzyl is a synthetic auxin herbicide (WSSA Group 4) with a broad spectrum of activity. Florypyrauxifen-benzyl has a unique site of action compared to other auxin herbicides in that it prefers the AFB5 IAA coreceptor rather than the TIR1 coreceptor [17, 18]. This difference in binding site affinity allows florypyrauxifen-benzyl to control quinclorac-resistant barnyardgrass, indicating resistance to quinclorac does not confer resistance to florypyrauxifen-benzyl [19]. Florypyrauxifen-benzyl also provides high levels of control of other troublesome weeds in rice production including sedges and various broadleaf weeds, such as Palmer amaranth (*Amaranthus palmeri* S. Wats.) and hemp sesbania (*Sesbania herbacea* (Mill.) McVaugh) [20]. The use rate of the florypyrauxifen-benzyl is 30 g ae ha<sup>-1</sup>, with a season maximum of 60 g ae ha<sup>-1</sup> and a minimum of 14 days between sequential applications [21]. Florypyrauxifen-benzyl has limited residual activity and therefore should be applied in conjunction with a residual herbicide to mitigate the evolution of resistance [16, 20].

While florypyrauxifen-benzyl can be an effective herbicide option in rice, the label indicates there could be an increased risk for injury to medium-grain varieties and long-grain hybrids in the form of height reductions and malformed leaves [21]. However, although the novelty of florypyrauxifen-benzyl limited data exists on differential cultivar tolerances thus, further experimentation is needed to determine cultivar responses to this herbicide.

The objectives of these experiments were to further quantify cultivar tolerance to florypyrauxifen-benzyl when applied with a cytochrome P450-inhibiting insecticide and when mixed with imazethapyr.

## 2. Materials and Methods

**2.1. Florypyrauxifen-Benzyl plus Imazethapyr.** Field experiments were initiated in 2017 and 2018 at the Pine Tree Research Station (PTRS) near Colt, AR, on a Calloway silt loam (fine-silty, mixed, active, thermic Aquic Fraglossudalf) with 1.3% organic matter, 10.6% sand, 68.6% silt, 20.8% clay, and a pH of 7.5 and in 2018 at the Rice Research and Extension Center (RREC) in Stuttgart, AR, on a DeWitt silt loam (fine, smectic, thermic Typic Albaqualf) with 1.8% organic matter, 8.4% sand, 71.4% silt, 20.2% clay, and a pH of 6.0.

The experiment was conducted with a randomized complete block, two-factor factorial design with four replications. The first factor was the rate of florypyrauxifen-benzyl, and the second factor was the crop stage. Three rice cultivars were planted in separate trials on May 17, 2017, at PTRS and April 19, 2018, at both locations using a 10-row drill with 18 cm row spacing. A long-grain variety “CL111” and a medium-grain variety “CL272” were planted at 72 seeds m<sup>-1</sup> row and a long-grain hybrid “CLXL745” was planted at 26 seeds m<sup>-1</sup> row. Though there are several varieties of medium-grain and long-grain rice and several long-grain hybrid cultivars, only one of each was selected for trial size management. Long-grain variety CL111, medium-grain variety CL272, and long-grain hybrid CLXL745 were

selected for these studies due to their acreage in 2016. Plots were 5.2 m long. A nontreated control was included for each cultivar. Imazethapyr at 106.5 g ai ha<sup>-1</sup> and imazosulfuron at 341 g ae ha<sup>-1</sup> were applied immediately following planting. A second application of imazethapyr at 106.5 g ha<sup>-1</sup> was applied alone and with florpyrauxifen-benzyl at 30 or 60 g ha<sup>-1</sup> when rice reached the 1-leaf, 3-leaf, or 5-leaf growth stage. Methylated seed oil was added to florpyrauxifen-benzyl treatments at 0.6 L ha<sup>-1</sup>. Nonionic surfactant was added to imazethapyr-only treatment at 0.25% v/v. The 1-leaf applications were made on May 11 and 14, 3-leaf applications were made on May 16 and 17, and 5-leaf applications were made on May 28 and 30 at RREC and PTRS in 2018, respectively. Applications were made on May 30, June 6, and June 14 in 2017. Herbicide applications were made using a CO<sub>2</sub>-pressurized backpack and handheld boom sprayer at 140 L ha<sup>-1</sup> with 110015 AIXR nozzles (TeeJet Technologies, Springfield, IL 62703). The test sites at RREC were flooded on May 31, 2018, and at PTRS, the flood was established on June 21, 2017, and June 2, 2018. These trials were maintained weed-free using labeled herbicides and hand-weeding as necessary. The weed-free herbicide program consisted of propanil at 3,360 g ai ha<sup>-1</sup> (SuperWham!®, Rice Co. LLC, 5100 Poplar Ave., 24<sup>th</sup> floor, Memphis, TN 38137), halo-sulfuron-methyl at 35 g ai ha<sup>-1</sup> (Permit® Gowan Company, P.O. Box 5569, Yuma, AZ 85366), fenoxaprop at 122 g ai ha<sup>-1</sup> (Ricestar® HT, Bayer CropScience LP, 800 N Lindbergh Blvd., St. Louis, MO 63167), quinclorac at 420 g ae ha<sup>-1</sup> (Facet® L, BASF Corporation, 36 Davis Dr., Research Triangle Park, NC 27709), and cyhalofop at 313 g ai ha<sup>-1</sup> (Clincher® SF, Corteva Agriscience, 9660 Zionsville Rd, Indianapolis, IN 46268). Trials were managed according to the University of Arkansas System Division of Agriculture recommendations by preplant and pre-flood applications of nitrogen in the form of urea totaling 130 kg N ha<sup>-1</sup>. Additionally, an early-postemergence application of potassium chloride was made at PTRS, and pre-plant potassium chloride and phosphorous were applied at RREC.

**2.2. Florpyrauxifen-Benzyl plus Malathion.** Additional field experiments were conducted in 2018 at RREC and PTRS using the same cultivars to determine the impact of malathion on rice tolerance when applied in close proximity to florpyrauxifen-benzyl. The same three previously mentioned cultivars were seeded on April 19, 2018, at both locations.

This experiment was established as a randomized complete block with a two-factor factorial arrangement of treatments and four replications. The first factor consisted of florpyrauxifen-benzyl applied at 0, 30, or 60 g ha<sup>-1</sup>. Methylated seed oil was added to florpyrauxifen-benzyl treatments at 0.6 L ha<sup>-1</sup>. The second factor was the addition of malathion at 0 or 700 g ai ha<sup>-1</sup>. Treatments were applied pre-flood when rice was at the 5-leaf growth stage which was May 28 and 30 at RREC and PTRS, respectively. Rice at RREC was flooded on May 31, 2018, and at PTRS on June 2, 2018. These trials were kept weed-free and managed according to the University of Arkansas System Division of

Agriculture recommendations. The weed-free herbicide program was similar to the previous experiment, with the addition of clomazone at 336 g ai ha<sup>-1</sup> (Command® 3ME, FMC Corporation, 2929 Walnut St., Philadelphia, PA 19104) at planting. Florpyrauxifen-benzyl plus malathion is not a labeled mixture [21].

**2.3. Assessments.** In the imazethapyr experiment, visible injury was recorded 2 and 4 weeks after each POST application. Heights and number of tillers for three plants were recorded in each plot 2 weeks after the last herbicide application and reported relative to the nontreated control. In the malathion experiment, visible injury was recorded 2 and 4 weeks after application. Injury for both experiments was determined as reduced tillering, reduced canopy formation, and onion-like leaf appearance and estimated on a 0 to 100 scale, where 0 is no injury and 100 is plant death. The nontreated for each cultivar was used for comparison and did not have any injury. In both experiments, days to 50% heading were recorded and reported relative to the nontreated for each cultivar. Additionally, rice grain was harvested from the center of each plot using a small-plot combine, and rough rice yields were then calculated and adjusted to 12% moisture.

**2.4. Statistical Analyses.** Locations were analyzed separately due to differences in environment and soil characteristics (Figures 1(a) and 1(b) and 2). Additionally, the purpose of this experiment was to report responses, long-grain varieties, medium-grain varieties, and long-grain hybrids rather than make comparisons among cultivars, and thus, cultivars were analyzed separately. In the imazethapyr experiment, florpyrauxifen-benzyl rate and growth stage at the time of application were considered fixed effects. Site years for the PTRS location were combined due to similarities in soil texture and crop response. Replication was considered a random effect for RREC, and replication nested within site year was considered a random effect for PTRS, since there were two years of data for that location. In the malathion experiment, florpyrauxifen-benzyl rate and malathion rate were considered fixed effects and replication was considered a random effect. All data were analyzed using PROC GLIMMIX in SAS v 9.4. A beta distribution was assumed for injury data, and a gamma distribution was assumed for yield, number of tillers, and plant heights [22]. An analysis of variance was conducted, and means were separated using Fisher's protected least significant difference ( $p = 0.05$ ). Due to the large number of zeros, formal analysis was not performed on heading data for both experiments and on injury 4 weeks after application for the malathion experiment, and thus, means and standard error are reported.

### 3. Results and Discussion

**3.1. Response to Florpyrauxifen-Benzyl and Imazethapyr.** For the long-grain variety CL111, there was an interaction between florpyrauxifen-benzyl rate and growth stage at PTRS, but at RREC there was only a main effect of

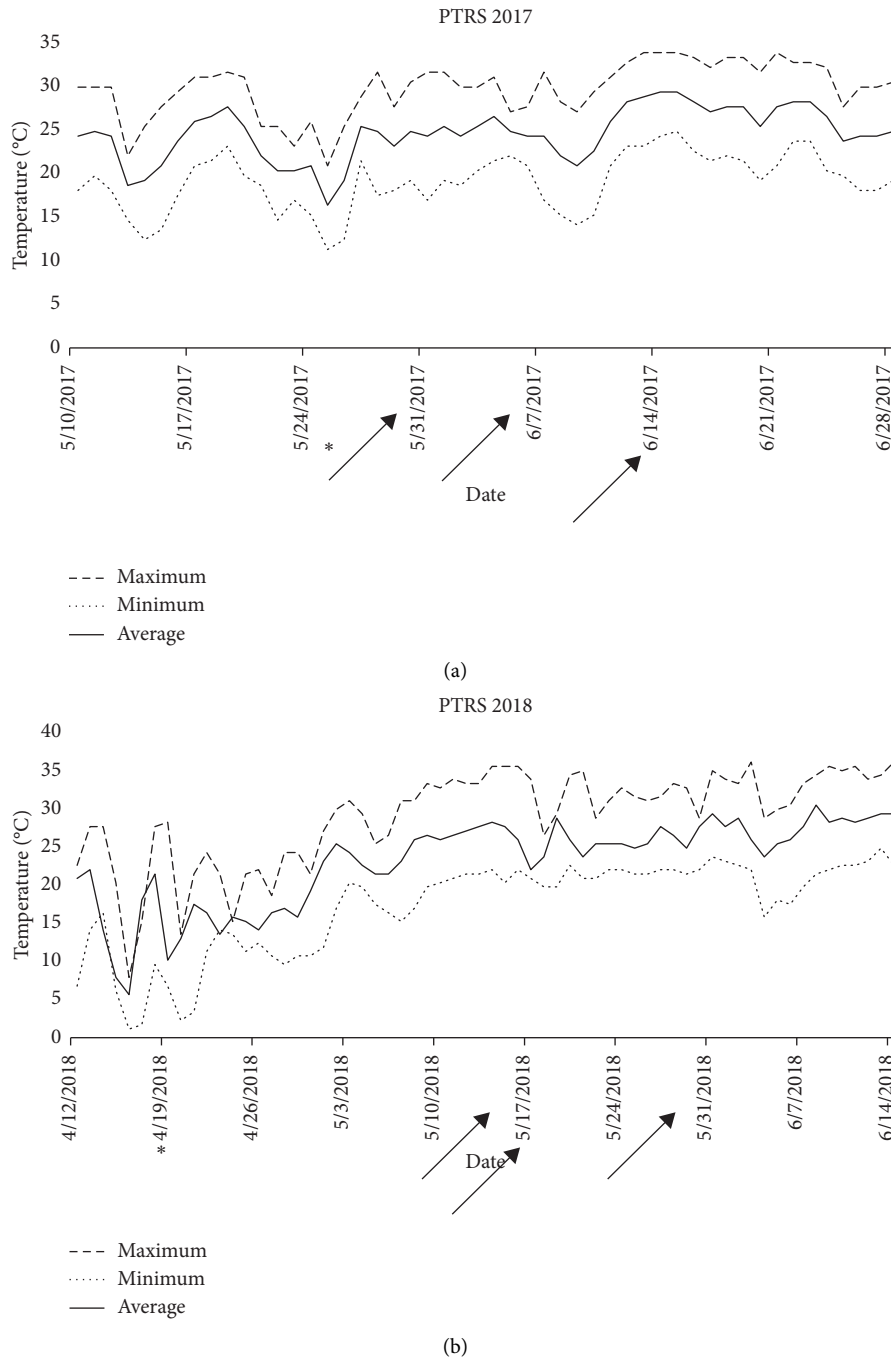


FIGURE 1: Daily minimum, maximum, and average temperatures at the Pine Tree Research Station near Colt, AR, in (a) 2017 and (b) 2018 (a, b) for dates ranging from 7 days before planting to 14 days after the last application for the floryprauxifen-benzyl and imazethapyr experiment. Rice cultivars CL111, CL272, and CLXL745 were planted on April 19, 2018, and on May 27, 2017. The 1-leaf (1f) applications were made on May 30 and 14, 3-lf applications were made on June 6 and May 17, and 5-lf applications were made on June 14 and May 30 in 2017 and 2018, respectively. Planting date is indicated by (\*) and application dates are indicated by an arrow.

floryprauxifen-benzyl rate on injury 2 weeks after the second application (WAA) (Table 1). No more than 3% injury was observed at any location 2 WAA. At 4 WAA, only growth stage was significant at both locations. Applications made at the 3-leaf growth stage averaged over rate caused 3 and 4% injury at PTRS and RREC, respectively (Table 1).

Additionally, there was no significant reduction in height or tillers for any treatment (Table 2). A 0.6- to 2.1-day delay in heading was found for CL111 relative to the nontreated at PTRS and 0- to 3.8-day delay in heading was found at RREC (Table 3). Grain yields ranged from 6,890 to 7,730 kg ha<sup>-1</sup> at PTRS and 7,410 to 8,550 kg ha<sup>-1</sup> at RREC. Though there

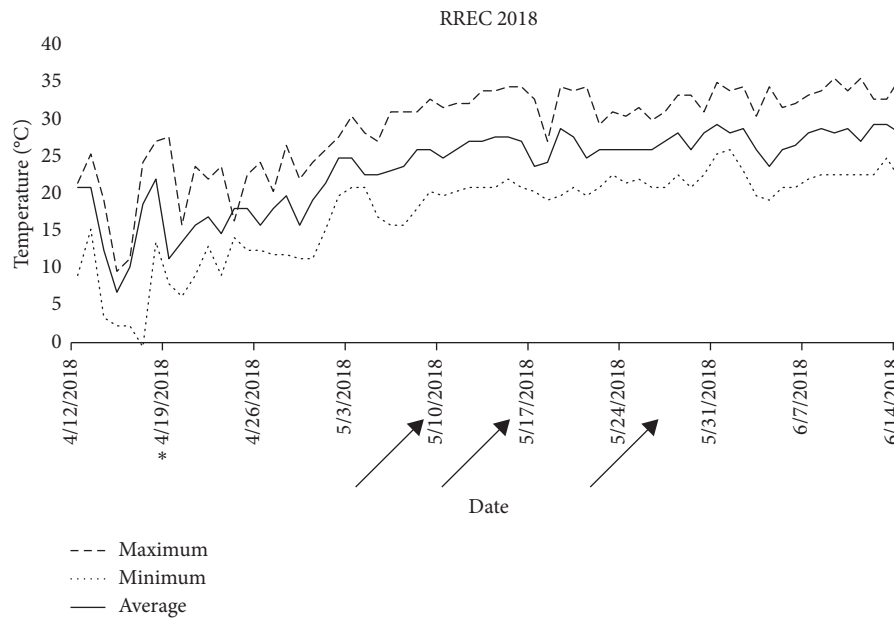


FIGURE 2: Daily minimum, maximum, and average temperatures at the Rice Research and Extension Center (RREC) in Stuttgart, AR, in 2018 for dates ranging from 7 days before planting to 14 days after the last application for the floryprauxifen-benzyl and imazethapyr experiment. Rice cultivars CL111, CL272, and CLXL745 were planted on April 19, 2018. The 1-leaf (1f) application was made on May 11, the 3-1f application was made on May 16, and the 5-1f application was made on May 28. Planting date is indicated by (\*) and application dates are indicated by an arrow.

appears to be a wide range of grain yield responses, there were no differences among treatments, likely due to variability across replication within the trial area.

For the medium-grain variety CL272, there was no interaction between floryprauxifen-benzyl rate and growth stage at the time of POST application at 2 WAA; however, the main effects were significant at both locations (Table 4). Generally, floryprauxifen-benzyl at 60 g ae ha<sup>-1</sup> caused more injury, when averaged over growth stage, and applications made at the 5-leaf growth stage resulted in more injury, when averaged over floryprauxifen-benzyl rate. However, the highest injury observed 2 WAA was only 9%. Again, at 4 WAA, there was no significant interaction, only the main effects of growth stage at PTRS and floryprauxifen-benzyl rate and growth stage at RREC. There were no reductions in the number of tillers or plant heights (Table 2). A 0.1- to 2.1-day delay in heading was found at PTRS and a 0- to 1-day delay in heading was found for RREC. Grain yields ranged from 7,210 to 8,470 kg ha<sup>-1</sup> at PTRS and 6,120 to 8,080 kg ha<sup>-1</sup> at RREC, and there were no significant differences in yields among treatments at either location (Table 5).

For long-grain hybrid CLXL745 at 2 WAA, floryprauxifen-benzyl applied at the higher rate with imazethapyr resulted in 8 and 10% injury at PTRS and RREC, respectively, when averaged over growth stage at the time of application (Table 6). At 4 WAA, the higher rate of floryprauxifen-benzyl still exhibited more injury than the lower rate or imazethapyr-only treatments with 8 and 5% injury. There was no reduction in the number of tillers or heights for any treatment relative to the corresponding nontreated (Table 2). Days delayed in heading ranged from

0.6 to 2.4 at PTRS and 0 to 0.8 at RREC. Yields ranged from 8,540 to 9,510 kg ha<sup>-1</sup> at PTRS and 8610 to 11000 kg ha<sup>-1</sup>, with no significant differences, again likely due to variability within the field (Table 7).

Based on the findings from this experiment, crop injury increases when floryprauxifen-benzyl is applied in conjunction with imazethapyr. However, the increase in injury could be intensified by stressing rice plants early in development by using two ALS-inhibiting herbicides preemergence, leading to a reduction in the rate of floryprauxifen-benzyl metabolism in rice. Further research is needed to determine crop injury response when plants are not stressed by herbicides early in the season.

Injury was slightly higher at RREC than PTRS and is likely a function of site differences. Floryprauxifen-benzyl applied at a higher rate resulted in more injury, which is consistent with previous research that found triclopyr, another auxin herbicide, caused more injury to rice when applied at a higher rate [6]. However, the maximum application rate for floryprauxifen-benzyl is the lower rate of 30 g ae ha<sup>-1</sup>, so injury from a higher rate is likely to be an issue only where there is an overlap during application. Generally, applications made at the 5-leaf growth stage exhibited higher levels of injury 2 WAA and could be due to proximity to flooding and anaerobic environment; however, by 4 WAA most of this injury was nonexistent. These results appear to be contradictory to the results from experiments conducted by Wright et al. [23], where 1-leaf rice was more injured than 5-leaf rice. However, that experiment was conducted in a controlled environment, whereas the injury observed in this experiment was the result of a field experiment conducted in an uncontrolled environment.

TABLE 1: Rice injury for CL111 as influenced by floryprauxifen-benzyl rate applied with imazethapyr at various rice growth stages<sup>a,b,c</sup>.

Factor	Injury 2 WAA				Injury 4 WAA			
	PTRS		RREC		PTRS		RREC	
	% of nontreated							
Rate	0	1	<1	b	1	<1	<1	
	30	1	2	a	1	<1	<1	
	60	2	3	a	1	1	1	
Stage	1-leaf	2	2		<1	b	<1	b
	3-leaf	2	1		3	a	4	a
	5-leaf	1	1		<1	b	<1	b
Rate × stage	0 × 1-leaf	1	bc	<1	<1	<1	<1	
	30 × 1-leaf	3	ab	2	2	<1	<1	
	60 × 1-leaf	2	abc	4	<1	2	2	
	0 × 3-leaf	1	bc	<1	3	3	3	
	30 × 3-leaf	2	abc	1	2	6	6	
	60 × 3-leaf	3	a	3	3	3	3	
	0 × 5-leaf	2	abc	<1	1	<1	<1	
	30 × 5-leaf	<1	c	2	<1	<1	<1	
	60 × 5-leaf	2	abc	2	1	<1	<1	
	<i>p</i> value							
Rate	0.1064		0.0224*		0.7921		0.4447	
Stage	0.7724		0.7290		0.0003*		<0.0001*	
Rate × stage	0.0252*		0.9455		0.3990		0.0631	

<sup>a</sup>Factors: floryprauxifen-benzyl rate and growth stage at the time of the second application. All rates of floryprauxifen-benzyl reported in g ae ha<sup>-1</sup> were applied with imazethapyr at 106.5 g a ha<sup>-1</sup>. Floryprauxifen-benzyl rates of 0 g ae ha<sup>-1</sup> were imazethapyr-only treatments. <sup>b</sup>Abbreviations: WAA: weeks after application; PTRS: Pine Tree Research Station near Colt, AR; RREC: Rice Research and Extension Center near Stuttgart, AR. <sup>c</sup>Means are separated using Fisher's protected LSD (*p* = 0.05). Means followed by the same letter within a column and factor are not different.

TABLE 2: Number of tillers and plant height for CL111, CL272, and CLXL745 to various rates of floryprauxifen-benzyl and imazethapyr at different growth stages<sup>a,b,c</sup>.

Rate	Stage	CL111				CL272				CLXL745			
		PTRS		RREC		PTRS		RREC		PTRS		RREC	
		Tillers	Height	Tiller	Height	Tiller	Height	Tiller	Height	Tiller	Height	Tiller	Height
g ae ha <sup>-1</sup>		#	cm	#	cm	#	cm	#	cm	#	cm	#	cm
Nontreated		4.1	35.5	4.3	47.5	4.6	37.0	5.0	46.0	5.9	32.5	8.3	47.0
0	1-leaf	4.1	35.0	3.9	48.0	4.7	38.0	4.4	53.5	3.9	31.5	6.8	47.0
30	1-leaf	4.6	33.5	4.1	48.0	3.5	36.0	3.4	48.0	4.6	33.5	6.5	48.0
60	1-leaf	3.9	30.0	4.8	48.0	4.1	35.0	3.2	48.0	4.7	32.5	7.4	45.5
0	3-leaf	4.3	35.0	4.6	51.5	4.4	36.0	4.2	51.0	4.3	34.5	6.9	45.5
30	3-leaf	3.9	33.5	3.6	46.0	3.3	33.0	4.2	52.0	5.4	32.0	6.7	47.5
60	3-leaf	3.3	34.0	3.4	50.0	4.2	35.0	4.2	46.0	3.7	33.0	6.6	44.0
0	5-leaf	3.8	34.0	3.6	51.5	4.1	36.5	5.2	49.5	5.6	31.5	7.6	50.5
30	5-leaf	3.3	34.0	3.7	49.0	4.3	34.5	5.1	47.0	4.3	31.5	7.9	46.5
60	5-leaf	3.3	33.0	4.6	50.5	4.8	34.5	4.3	51.0	5.3	28.5	6.8	48.0
		<i>p</i> value											
		0.7729	0.4884	0.3463	0.1394	0.6228	0.1311	0.4872	0.4651	0.1259	0.1629	0.6822	0.4068

<sup>a</sup>All rates of floryprauxifen-benzyl were mixed with imazethapyr at 106.5 g ai ha<sup>-1</sup>. Floryprauxifen-benzyl rates of 0 g ae ha<sup>-1</sup> were imazethapyr-only treatments. <sup>b</sup>Crop growth stage at second application following the first application made preemergence. <sup>c</sup>Abbreviations: PTRS: Pine Tree Research Station near Colt, AR; RREC: Rice Research and Extension Center near Stuttgart, AR.

Additionally, results from Wright et al. [23] indicate warmer temperatures can increase visual injury. In this experiment, daily high temperatures at the time of and following the 5-leaf application were above or near 30°C, which could explain the injury observed. Low levels of injury combined with no reduction in yield suggest that injury had no lasting

impact on rice development, which is likely a function of applications being made during the vegetative growth stage. Further research should be conducted to determine the impacts of floryprauxifen-benzyl applied in early reproductive stages. Under the conditions of this study, results from this experiment indicate that floryprauxifen-benzyl

TABLE 3: Heading and grain yield response of CL111 at the Pine Tree Research Station (PTRS) and Rice Research and Extension Center (RREC)<sup>a,b,c</sup>.

Florpyrauxifen-benzyl rate G ae ha <sup>-1</sup>	Stage	PTRS				RREC			
		Delay in heading		Grain yield		Delay in heading		Grain yield	
		Days		kg ha <sup>-1</sup>		Days		kg ha <sup>-1</sup>	
Nontreated		—	—	6,890	(767)	—	—	7,410	(338)
0	1-leaf	0.6	(0.4)	7,730	(861)	1.8	(1.2)	8,430	(384)
30	1-leaf	1.5	(1.0)	7,560	(841)	1.3	(0.3)	8,110	(370)
60	1-leaf	1.3	(0.7)	7,550	(840)	2.3	(1.3)	8,540	(389)
0	3-leaf	0.8	(0.5)	7,130	(794)	1.0	(0.4)	8,260	(377)
30	3-leaf	1.3	(0.7)	7,600	(846)	3.8	(0.8)	7,860	(358)
60	3-leaf	0.9	(0.4)	7,540	(839)	1.5	(0.9)	8,500	(388)
0	5-leaf	1.3	(0.5)	7,490	(834)	0	(0)	8,550	(390)
30	5-leaf	0.9	(0.5)	7,490	(834)	0.3	(0.3)	8,050	(367)
60	5-leaf	2.1	(0.9)	7,190	(800)	0.3	(0.3)	8,180	(434)
<i>p</i> value		0.6382				0.3997			

<sup>a</sup>All rates of florpyrauxifen-benzyl were applied with imazethapyr at 106.5 g ai ha<sup>-1</sup>. Florpyrauxifen-benzyl rates of 0 g ae ha<sup>-1</sup> were imazethapyr-only treatments. <sup>b</sup>Crop growth stage at second application. <sup>c</sup>Mean followed by standard error in parentheses.

TABLE 4: Rice injury for CL272 as influenced by florpyrauxifen-benzyl rate applied with imazethapyr at various rice growth stages<sup>a,b,c</sup>.

Factor	Injury 2 WAA					Injury 4 WAA			
	PTRS		RREC			PTRS		RREC	
	% of nontreated								
Rate	0	1	b	2	b	1	1	1	b
	30	2	b	3	b	2	3	3	b
	60	6	a	6	a	3	6	6	a
Stage	1-leaf	2	b	1	b	3	a	1	b
	3-leaf	2	b	2	b	3	a	14	a
	5-leaf	4	a	9	a	<1	b	1	b
Rate × stage	0 × 1-leaf	<1		<1		1		<1	
	30 × 1-leaf	2		1		4		1	
	60 × 1-leaf	6		5		5		2	
	0 × 3-leaf	<1		1		2		10	
	30 × 3-leaf	2		4		2		13	
	60 × 3-leaf	5		4		7		21	
	0 × 5-leaf	4		8		<1		<1	
	30 × 5-leaf	3		7		1		1	
	60 × 5-leaf	7		13		<1		5	
	<i>p</i> value								
Rate	<0.0001*		0.0080*			0.0998		0.0143*	
Stage	0.0086*		0.0001*			0.0078*		<0.0001*	
Rate × stage	0.2274		0.2002			0.2232		0.6779	

<sup>a</sup>Factors: florpyrauxifen-benzyl rate and growth stage at the time of the second application. All rates of florpyrauxifen-benzyl reported in g ae ha<sup>-1</sup> were applied with imazethapyr at 106.5 g ai ha<sup>-1</sup>. Florpyrauxifen-benzyl rates of 0 g ae ha<sup>-1</sup> were imazethapyr-only treatments. <sup>b</sup>Abbreviations: WAA: weeks after application; PTRS: Pine Tree Research Station near Colt, AR; RREC: Rice Research and Extension Center near Stuttgart, AR. <sup>c</sup>Means are separated using Fisher's protected LSD ( $p = 0.05$ ). Means followed by the same letter within a column and factor are not different.

applied with imazethapyr does not cause a reduction in grain yield, indicating it is a good fit for use in imidazolinone-resistant rice production.

**3.2. Response to Florpyrauxifen-Benzyl and Malathion.** Injury for the long-grain variety CL111 at 2 and 4 WAA at PTRS was very low (2%) (Table 8). Additionally, only florpyrauxifen-benzyl at 60 g ae ha<sup>-1</sup> applied with malathion at 700 g ai ha<sup>-1</sup>, respectively, resulted in a 1.7-day delay in

heading while all other treatments caused no delay in heading. There was no significant difference in yield for any treatment, and yields ranged from 8,350 to 9,430 kg ha<sup>-1</sup>. At RREC, the most injury seen was 3% at 2 WAA, and no injury was present at 4 WAA. There was a 0.3-day delay in heading for all treatments, and yields ranged from 7,880 to 9,020 kg ha<sup>-1</sup> with no differences among treatments.

For the medium-grain variety CL272, florpyrauxifen-benzyl at 60 g ae ha<sup>-1</sup> plus malathion at 700 g ai ha<sup>-1</sup> resulted in 11 and 15% injury at PTRS and RREC, respectively, 2

TABLE 5: Heading and grain yield response of CL272 at the Pine Tree Research Station (PTRS) and Rice Research and Extension Center (RREC)<sup>a,b,c</sup>.

Florpyrauxifen-benzyl rate g ae ha <sup>-1</sup>	Stage	PTRS				RREC			
		Delay in heading		Grain yield		Delay in heading		Grain yield	
		Days		kg ha <sup>-1</sup>		Days		kg ha <sup>-1</sup>	
Nontreated		—	—	7,210	(403)	—	—	6,870	(515)
0	1-leaf	0.1	(0.1)	8,020	(420)	0	(0)	6,900	(520)
30	1-leaf	0.5	(0.5)	8,120	(426)	0.3	(0.3)	8,030	(605)
60	1-leaf	0.8	(0.4)	8,060	(422)	1.0	(1.0)	6,120	(461)
0	3-leaf	0.9	(0.4)	7,350	(385)	0.8	(0.8)	7,830	(590)
30	3-leaf	0.4	(0.3)	8,470	(444)	0.3	(0.3)	7,740	(583)
60	3-leaf	1.3	(0.6)	7,220	(378)	0.3	(0.3)	7,790	(587)
0	5-leaf	1.3	(0.5)	7,700	(404)	0.5	(0.5)	6,850	(596)
30	5-leaf	1.8	(0.8)	7,790	(408)	0	(0)	8,080	(609)
60	5-leaf	2.1	(0.8)	7,860	(412)	0.3	(0.3)	7,050	(530)
<i>p</i> value				0.3490				0.2623	

<sup>a</sup>All rates of florpyrauxifen-benzyl were applied with imazethapyr at 106.5 g ai ha<sup>-1</sup>. Florpyrauxifen-benzyl rates of 0 g ae ha<sup>-1</sup> were imazethapyr-only treatments. <sup>b</sup>Crop growth stage at second application. <sup>c</sup>Mean followed by standard error in parentheses.

TABLE 6: Rice injury for CLXL745 as influenced by florpyrauxifen-benzyl rate applied with imazethapyr at various rice growth stages<sup>a,b,c</sup>.

Factor	Injury 2 WAA					Injury 4 WAA			
	PTRS		RREC			PTRS		RREC	
	% of nontreated								
Rate	0	1	b	2	b	1	1	b	
	30	2	b	3	b	2	3	b	
	60	6	a	6	a	3	6	a	
Stage	1-leaf	2	b	1	b	3	a	1	b
	3-leaf	2	b	2	b	3	a	14	a
	5-leaf	4	a	9	a	<1	b	1	b
Rate × stage	0 × 1-leaf	<1		<1		1		<1	
	30 × 1-leaf	2		1		4		1	
	60 × 1-leaf	6		5		5		2	
	0 × 3-leaf	<1		1		2		10	
	30 × 3-leaf	2		4		2		13	
	60 × 3-leaf	5		4		7		21	
	0 × 5-leaf	4		8		<1		<1	
	30 × 5-leaf	3		7		1		1	
	60 × 5-leaf	7		13		<1		5	
			<i>p</i> value						
Rate		<0.0001*		0.0080*		0.0998		0.0143*	
Stage		0.0086*		0.0001*		0.0078*		<0.0001*	
Rate × stage		0.2274		0.2002		0.2232		0.6779	

<sup>a</sup>Factors: florpyrauxifen-benzyl rate and growth stage at the time of the second application. All rates of florpyrauxifen-benzyl reported in g ae ha<sup>-1</sup> were applied with imazethapyr at 106.5 g a ha<sup>-1</sup>. Florpyrauxifen-benzyl rates of 0 g ae ha<sup>-1</sup> were imazethapyr-only treatments.

WAA, which was higher than florpyrauxifen-benzyl alone (8 and 7%) (Table 9). However, this injury was transient and rice plants were mostly recovered by 4 WAA. While the addition of malathion to the higher rate of florpyrauxifen-benzyl caused more injury than florpyrauxifen-benzyl alone, and this difference was numerically small. There was a 0.3- to 1.3-day delay in heading at PTRS but no delay in heading at RREC. Additionally, grain yields ranged from 7,880 to 9,590 kg ha<sup>-1</sup> at PTRS and 6,360 to 7,890 kg ha<sup>-1</sup> at RREC, and there were no differences among treatments.

For the long-grain hybrid CLXL745, more injury was observed at PTRS than RREC 2 WAA, with the most injury

being 12 and 3%, respectively (Table 10). However, by 4 WAA, there was at most 3% injury at PTRS and no injury at RREC. Injury data show florpyrauxifen-benzyl applied at the higher rate caused more injury and do not suggest the addition of malathion caused an increase in injury. Additionally, there was a 0- to 0.5-day delay in heading at both PTRS and RREC. Grain yields at both locations ranged from 10,140 to 11,600 kg ha<sup>-1</sup> and 10,240 to 12,050 kg ha<sup>-1</sup> at PTRS and RREC, respectively, with no significant differences.

There was injury associated with an application of florpyrauxifen-benzyl, with generally more injury caused by



TABLE 7: Heading and grain yield response of CLXL745 at the Pine Tree Research Station (PTRS) and Rice Research and Extension Center (RREC)<sup>a,b,c</sup>.

Florpyrauxifen-benzyl rate g ae ha <sup>-1</sup>	Stage	PTRS				RREC			
		Delay in heading		Grain yield		Delay in heading		Grain yield	
		Days		kg ha <sup>-1</sup>		Days		kg ha <sup>-1</sup>	
Nontreated		—	—	8,540	(1,049)	—	—	9,910	(638)
0	1-leaf	0.6	(0.3)	9,440	(1,159)	0.3	(0.3)	9,600	(618)
30	1-leaf	1.3	(0.9)	8,970	(1,101)	0.5	(0.3)	10,680	(794)
60	1-leaf	2.3	(0.9)	9,440	(1,159)	0.3	(0.3)	10,760	(692)
0	3-leaf	1.6	(0.7)	8,700	(1,068)	0	(0)	11,000	(708)
30	3-leaf	1.7	(0.8)	9,510	(1,167)	0.8	(0.5)	10,400	(671)
60	3-leaf	2.4	(0.9)	8,770	(1,077)	0.5	(0.5)	8,610	(554)
0	5-leaf	2.4	(0.8)	9,400	(1,154)	0	(0)	10,100	(650)
30	5-leaf	1.4	(0.5)	9,270	(1,137)	0.3	(0.3)	10,250	(659)
60	5-leaf	1.6	(0.5)	8,800	(1,080)	0.5	(0.5)	9,640	(621)
<i>p</i> value				0.2338				0.3201	

<sup>a</sup>All rates of florpyrauxifen-benzyl were applied with imazethapyr at 106.5 g ai ha<sup>-1</sup>. Florpyrauxifen-benzyl rates of 0 g ae ha<sup>-1</sup> were imazethapyr-only treatments. <sup>b</sup>Crop growth stage at second application. <sup>c</sup>Mean followed by standard error in parentheses.

TABLE 8: Injury 2 and 4 weeks after application (WAA), heading delay, and grain yield response of CL111 to different rates of florpyrauxifen-benzyl and malathion applied pre-flood<sup>a,b</sup>.

Rate g ai ha <sup>-1</sup>	PTRS				RREC							
	Injury		Delay in heading		Grain yield		Injury		Delay in heading		Grain yield	
	2 WAA	4 WAA	Days		kg ha <sup>-1</sup>		2 WAA	4 WAA	Days		kg ha <sup>-1</sup>	
Nontreated	—	—	—	—	9,430	—	—	—	—	—	8,600	
30 + 0	<1	0	(0)	0.0	(0.0)	9,010	<1	0	(0)	0.3	(0.3)	9,020
60 + 0	2	0	(0)	0.0	(0.0)	9,250	2	0	(0)	0.3	(0.3)	8,760
30 + 700	<1	0	(0)	0.0	(0.0)	9,290	1	0	(0)	0.3	(0.3)	8,170
60 + 700	2	2	(1.7)	1.7	(1.2)	8,350	3	0	(0)	0.3	(0.3)	7,880
<i>p</i> value	0.2925				0.6245	0.0645						0.2078

<sup>a</sup>Rate of florpyrauxifen-benzyl + malathion. Florpyrauxifen-benzyl rate is reported in g ae ha<sup>-1</sup>. <sup>b</sup>Mean followed by standard error in parentheses.

TABLE 9: Injury 2 and 4 weeks after application (WAA), heading delay, and grain yield response of CL272 to different rates of florpyrauxifen-benzyl and malathion applied pre-flood<sup>a,b,c</sup>.

Rate g ai ha <sup>-1</sup>	PTRS				RREC									
	Injury		Delay in heading		Grain yield		Injury		Delay in heading		Grain yield			
	2 WAA	4 WAA	Days		kg ha <sup>-1</sup>		2 WAA	4 WAA	Days		kg ha <sup>-1</sup>			
Nontreated	—	—	—	—	9,590	—	—	—	—	—	7,610			
30 + 0	2	c	0	(0)	0.3	(0.3)	8,710	4	c	<1	(0.3)	0.0	(0.0)	7,320
60 + 0	8	ab	0	(0)	1.0	(0.4)	7,880	7	bc	0	(0)	0.0	(0.0)	6,730
30 + 700	5	b	0	(0)	1.0	(0.6)	8,380	9	b	<1	(0.8)	0.0	(0.0)	6,360
60 + 700	11	a	<1	(0.8)	1.3	0.5	8,810	15	a	2	(1.2)	0.0	(0.0)	7,890
<i>p</i> value	0.0084				0.4231	0.0042								0.1947

<sup>a</sup>Rate of florpyrauxifen-benzyl + malathion. Florpyrauxifen-benzyl rate is reported in g ae ha<sup>-1</sup>. <sup>b</sup>Mean followed by standard error in parentheses. <sup>c</sup>Means are separated using Fisher's protected LSD ( $p = 0.05$ ). Means in a column containing the same letter are not significantly different.

the higher rate. However, this injury was transient and was nearly undetectable by 4 WAA. Additionally, no treatment for any cultivar resulted in more than a 2-day delay in heading or reduction in grain yield. One explanation for the absence of injury or reduction in grain yield could be due to florpyrauxifen-benzyl metabolism in rice not being through the P450 pathway or the P450 enzymes inhibited by malathion are not responsible for metabolism in rice. The

lack of high injury and yield loss could also be because florpyrauxifen-benzyl was not applied at a high enough rate to cause substantial injury. From other experiments, it is known that growth stage can influence crop response to a herbicide, especially on yield when herbicide applications are made during reproductive stages [6, 8, 24]. Additionally, these herbicide applications were made 1 and 4 days before flooding at RREC and PTRS, respectively, when rice was at

TABLE 10: Injury at 2 and 4 weeks after application (WAA), heading delay, and grain yield response of CLXL745 to different rates of florpyrauxifen-benzyl and malathion applied pre-flood<sup>a,b,c</sup>.

Rate	PTRS				RREC			
	Injury		Delay in heading	Grain yield	Injury		Delay in heading	Grain yield
2 WAA	4 WAA	2 WAA			4 WAA			
g ai ha <sup>-1</sup>	%		Days	kg ha <sup>-1</sup>	%		Days	kg ha <sup>-1</sup>
Nontreated	—		—	11,600	—		—	11,600
30 + 0	4	b 2 (1.2)	0.3 (0.3)	10,140	2	0 (0)	0.3 (0.3)	11,230
60 + 0	9	a 3 (1.0)	0.5 (0.3)	10,790	2	0 (0)	0.5 (0.3)	10,240
30 + 700	4	b 2 (0.9)	0 (0)	10,900	2	0 (0)	0 (0)	11,940
60 + 700	12	a 1 (1.0)	0.5 (0.3)	10,950	3	0 (0)	0.3 (0.3)	12,050
p value	0.0015			0.3634	0.7870			0.4468

<sup>a</sup>Rate of florpyrauxifen-benzyl + malathion. Florpyrauxifen-benzyl rate is reported in g ae ha<sup>-1</sup>. <sup>b</sup>Mean followed by standard error in parenthesis. <sup>c</sup>Means are separated using Fisher's protected LSD ( $p = 0.05$ ). Means in a column containing the same letter are not significantly different.

the tillering vegetative growth stage and thus had ample time to recover with no effects on yield. Based on the findings reported here, florpyrauxifen-benzyl can be safely applied with malathion; however, this is not currently a labeled application. Further research is needed to determine to what extent the environment impacts risk for injury when florpyrauxifen-benzyl is applied with malathion.

#### 4. Conclusions

These experiments indicate that there is an increased risk for injury when florpyrauxifen-benzyl is applied with an ALS-inhibiting herbicide. However, this injury was transient and did not result in any lasting effects or yield loss. This shows florpyrauxifen-benzyl can be utilized in imidazolinone-tolerant rice. Additionally, florpyrauxifen-benzyl applied with malathion does not increase rice risk for injury, indicating florpyrauxifen-benzyl is likely not metabolized through the P450 pathway.

#### Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

#### Disclosure

This article is part of a thesis entitled "Florpyrauxifen-benzyl Use in Arkansas Rice (*Oryza sativa* L.)" by Hannah E. Wright for fulfillment of a degree from the University of Arkansas.

#### Conflicts of Interest

The authors declare that no conflicts of interest are reported regarding the publication of this article.

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