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Impact of florpyrauxifen-benzyl on hybrid rice seeded at different densities

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Research Article

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Abstract

Florpyrauxifen-benzyl is a postemergence rice herbicide that has reduced rice yield in some situations, and producers are concerned that the impact could be even greater with low rice seeding densities. Therefore, research was conducted in Stoneville, MS, from 2019 to 2021, to evaluate the effect of florpyrauxifen-benzyl on rice yield when a hybrid was seeded at reduced densities. Rice cultivar FullPage RT 7521 FP was seeded at 10, 17, 24, 30, and 37 kg ha^{-1}. At the 4-leaf to 1-tiller growth stage, florpyrauxifen-benzyl was applied at 0 or 58 g ai ha^{-1}. Rice injury following application of florpyrauxifen-benzyl was ≤8% across all seeding rates and evaluation intervals. Application of florpyrauxifen-benzyl reduced plant heights by 14% to all seeding rates but did not result in delayed rice maturity. When florpyrauxifen-benzyl was not applied to rice that was seeded at 10 and 17 kg ha^{-1} seeding rates, rice matured slower than when it was seeded at 24, 30, and 37 kg ha^{-1}. When florpyrauxifen-benzyl was applied, rough rice grain yields were reduced by at the 17 and 37 kg ha^{-1} seeding rates, but not at any other seeding rate. In conclusion, application of florpyrauxifen-benzyl at a 2× rate can cause a loss of yield resulting from variation in rice densities.

Introduction

Rice is one of the most important food crops, providing 19% of the caloric intake for the world's population (McKenzie et al. 2014). In 2022, Mississippi produced 34,008 ha of rice, with an average yield of 8,264 kg ha^{-1} (USDA-NASS 2022). Rice production in Mississippi is almost completely limited to counties within the Mississippi-Yazoo Delta area, which consists of a 19-county area that borders the Mississippi River to the west. Bolivar and Tunica counties rank first and second in terms of harvested rice area with 8,947 and 7,773 ha during 2022, respectively, accounting for an average yield of 8,533 kg ha^{-1} and 8,130 kg ha^{-1} from the two respective counties (USDA-NASS 2022).

Weeds are one of the most limiting factors in rice production (Buehring 2008) and compete with rice for nutrients, water, space, and sunlight (Smith et al. 1977). The three most troublesome weeds in mid-southern U.S. rice production are *Cyperus* spp., *Echinochloa* spp., sprangletop species, and red rice (*Oryza sativa*) biotypes (Van Wychen 2020). Barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] is a rice-mimicking weed that can cause substantial yield losses of up to 57% in severe cases (Dayan et al. 2012). One barnyardgrass plant per 40 cm^{-1} of row can reduce rice yield by up to 27% (Stauber 1991).

Herbicide-resistant weeds were not known to occur in U.S. rice fields prior to 1990 (Miller and Norsworthy 2018). Repeated use of herbicides with the same mode of action led to the selection and buildup of resistant plant populations (Carey et al. 1997; Retzinger and Mallory-Smith 1997). Propanil, a Group 7 herbicide (as categorized by the Herbicide Resistance Action Committee and Weed Science Society of America), has been used extensively by rice producers since its introduction in 1959 (Smith 1961). However, the continued use of propanil led to the development of propanil-resistant barnyardgrass, which was first verified in Poinsett County, Arkansas, in 1989 (Smith 1993). The resistance mechanism of barnyardgrass was documented to be elevated metabolism of propanil by the enzyme aryl acylamidase (Carey et al 1997). Following the discovery of propanil-resistant barnyardgrass, quinclorac, a Group 4 herbicide, was introduced in 1992 and became the standard for barnyardgrass control (Talbert and Burgos 2007). However, in 1999, a barnyardgrass biotype from Arkansas was found to have resistance to both quinclorac and propanil (Lovelace et al. 2000). Since the initial observation of herbicide resistance in barnyardgrass, additional resistance to the chemicals developed to replace propanil has been observed. The development of barnyardgrass resistance to propanil, quinclorac, and herbicides in Group 2, including imazamox and imazethapyr, has limited the herbicide options for controlling barnyardgrass (Carey et al. 1997; Lovelace et al. 2000, Norsworthy et al. 2013).

Florpyrauxifen-benzyl is a Group 4 postemergence herbicide belonging to the arylpicolinate family of synthetic auxins that was commercialized in 2018 by Corteva Agriscience (Indianapolis, IN). Florpyrauxifen-benzyl can control problematic weeds such as yellow nutsedge (*Cyperus esculentus* L.), hemp sesbania [*Sesbania exaltata* (Raf.) Cory], and barnyardgrass when applied at the labeled rate (Miller and Norsworthy 2018). Florpyrauxifen-benzyl has a site of action different from that of quinclorac, favoring the AFB5-IAA co-receptor instead of the TIR1 co-receptor, which allows florpyrauxifen-benzyl to have activity on quinclorac-resistant barnyardgrass (Lee et al. 2014; Miller and Norsworthy 2018; Walsh et al. 2006). In rice production, florpyrauxifen-benzyl provides an alternate mode of action, which controls barnyardgrass resistance to photosystem II, synthetic auxin, 1-deoxy-D-xylulose-5-phosphate synthase, and acetolactate synthase (Epp et al. 2016).

Previous research has shown the propensity of florpyrauxifen-benzyl to control barnyardgrass to be greater than 96% (Miller and Norsworthy 2018). However, rice sensitivity to florpyrauxifen-benzyl application has been documented (Beesinger et al. 2022; Sanders et al. 2020; Wright et al. 2020). Rice cultivar selection and many environmental factors can influence rice injury following florpyrauxifen-benzyl application, such as extremely dry or saturated conditions, above average temperatures, and cloudy conditions (Beesinger et al. 2022; Sanders et al. 2020). Beesinger et al. (2022) observed up to 36% injury following soil moisture conditions at 40% and 100%, indicating that both drought and saturated soils can increase injury symptoms. Wright et al. (2020) reported 34% injury 3 wk after florpyrauxifen-benzyl was applied 5 d apart to hybrid rice cultivar CLXL745, whereas injury to CL111 was <10% 3 wk after sequential applications. Sanders et al. (2020) observed 6% greater injury following florpyrauxifen-benzyl applications to cultivar PVL01 compared with cultivars CLXL745, PVL013, and PVL081. Injury following florpyrauxifen-benzyl application has been shown to be influenced by temperature, soil moisture conditions, and cultivar selection. Research has not focused on the impact florpyrauxifen-benzyl application can have on seeding rates of rice.

In the rice-producing areas of the mid-southern United States, proper seeding rate is critical for stand establishment and producing high yields (Bond et al. 2005; Gravois and Helms 1992; Miller et al. 1991). Environmental conditions and management factors such as seeding method, cultivar, and tillage can cause the optimum seeding rate for rice to fluctuate (Harrell and Blanche 2010). Rice has the capacity to overcome low plant populations by producing more reproductive tillers, which are culms that grow from the parent stem and produce panicles (Pinson et al. 2015). Gravois and Helms (1992) reported that rice seeding rates reduced by 66% produced yields comparable to those following greater seeding rates. When seeding rates are reduced, rice can compensate for the reductions and increase panicle density and filled grain per panicle (Counce 1987; Gravois and Helms 1992; Jones and Synder 1987; Ottis and Talbert 2005; Wells and Faw 1978; Yoshida and Parao 1972). Conversely, when rice seeding rates are increased, a decrease in panicles per plant is observed (Ottis and Talbert 2005). Counce et al. (1987) attributed the reduction in rice yield at excessive rice densities to be associated with population-dependent stressors such as water deficits, disease, and nutrient deficiencies.

Ottis and Talbert (2005) reported that increased seeding rates of rice resulted in poor emergence likely caused by intraspecific competition among neighboring plants. Alternatively, reduced seeding rates resulted in improved emergence from decreased intraspecific competition.

The advancement of breeding and genetic technologies has led to the development of more productive rice cultivars (Nalley et al. 2016). Introduction of hybrid rice began in 2000 in the mid-southern United States (Nalley et al. 2017). The overall number of hectares seeded to hybrid rice in the mid-southern United Staters increased from 15% to 40% between 2005 and 2013. Hybrid rice returned US$0.16 more profit for every dollar invested than inbred cultivars. Research into the productivity of hybrid rice has shown 15% to 20% higher yield potential compared with inbred cultivars under reduced and optimum growing conditions (Katsura et al. 2007; Yuan et al. 1994). Yuan et al. (1994) reported that inbred rice produced more panicles and spikelets per square meter than hybrid rice, but fewer spikelets per panicle and 1,000 grain weight. Filled grain number per panicle has been the main yield component in support of the variability of yield between inbred and hybrids (Bueno and Lafarge 2009).

The development of hybrid rice, along with the natural ability of rice to compensate for low densities, has led to a decrease in seeding rates. With florpyrauxifen-benzyl possessing the potential to reduce rice yield, producers are concerned that the negative impact could be even greater in field situations where reduced seeding densities are employed. Therefore, research was conducted to evaluate the effect of florpyrauxifen-benzyl on rice performance and yield when hybrid rice was seeded at reduced densities.

Materials and Methods

The research was conducted once in 2019 and twice in 2020 and 2021 at the Mississippi State University Delta Research Extension Center in Stoneville, Mississippi, to determine the how florpyrauxifen-benzyl would affect the growth and yield of hybrid rice seeded at different densities. Geographic coordinates and soil information from each site year are presented in Table 1. Rice was seeded using a Great Plains 1520 small-plot grain drill (Great Plains Manufacturing, Inc., Salina, KS). Plots were 1.5 by 4.5 m, containing eight rows of rice spaced 20 cm apart, and separated by a fallow perpendicular alley 1.5 m in width. In all studies, glyphosate (Roundup PowerMax 4.5 L, 1,120 g ae ha^{-1}; Bayer Crop Science, St. Louis, MO), paraquat (Gramoxone 2.0 SL, 560 g ai ha^{-1}; Syngenta Crop Protection, Greensboro, NC), and/or 2,4-D (2,4-D Amine 3.8 SL, 560 g ae ha^{-1}; Agri Star, Ankeny, IA) were applied in late March to early April each site-year to control emerged vegetation. Clomazone (Command 3 ME, 560 g ai ha^{-1}; FMC Corporation, Philadelphia, PA) plus saflufenacil (Sharpen 2.85 SC, 50 g ai ha^{-1}; BASF Crop Protection, Research Triangle Park, NC) were applied preemergence each site year for residual weed control. Imazethapyr (Newpath 2 L, 105 g ai ha^{-1}; BASF) plus quinclorac (Facet 1.5 L, 420 g ai ha^{-1}; BASF) plus a petroleum oil surfactant (Herbimax, 83% petroleum oil; Loveland Products, Greeley, CO) at 50 mL L^{-1} was applied at 2-leaf rice (early postemergence) to maintain experimental sites free of weeds.

The experimental design was a randomized, complete block with a two (florpyrauxifen-benzyl treatment) by five (seeding rate) factorial arrangement of treatments and four replications. Factor A was florpyrauxifen-benzyl rate and included florpyrauxifen-benzyl (Corteva Agriscience) applied at 0 or 58 g ai ha^{-1} plus methylated seed oil surfactant (MSO Concentrate, 70% methylated seed oil of soybean; Loveland Products) at 41.5 mL L^{-1} when rice reached the

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Table 1. Locations, soil series, and soil description for the experimental sites in Stoneville, MS.

Site-year	Coordinates	Soil series	Description
2019	33.440558°N, 90.931758°W	Commerce very fine sandy loam	Silty over clay, mixed, superactive, nonacid, thermic, Fluvaquentic Endoaquepts
2020	33.440672°N, 90.931492°W	Commerce very fine sandy loam	Silty over clay, mixed, superactive, nonacid, thermic, Fluvaquentic Endoaquepts
2021-A	33.440689°N, 90.931708°W	Commerce very fine sandy loam	Silty over clay, mixed, superactive, nonacid, thermic, Fluvaquentic Endoaquepts
2021-B	33.423781°N, 90.931794°W	Tunica clay	Clayey over loamy, smectitic over mixed, superactive, nonacid, thermic Vertic Epiaquepts

Table 2. Regression coefficients for rice plant height in research evaluating rice hybrid response to seeding rates and postemergence application of florpyrauxifen-benzyl from 2019 to 2021 at Stoneville, MS.

Parameter	Rate	Intercept	SE	Linear	SE	Quadratic	SE
	g ai ha^{-1}						
Rice plant height	0	62.2028	1.9271	0.8500	0.2039	−0.01587	0.0048
	58	56.4131	2.5219	0.8208	0.2668	−0.0211	0.0062

4-leaf to 1-tiller growth stage. Applications of florpyrauxifen-benzyl were made at twice (2×) the labeled rate to evaluate herbicide tolerance (Sanders et al. 2020; Wright et al. 2020). Factor B was the seeding rate and included hybrid rice RT 7521 FP (RiceTec Inc., Alvin, TX) seeded at 10, 17, 24, 30, or 37 kg ha^{-1}. The seeding rates were percentages (120%, 80%, 56.67%, and 33.3%) based on the recommended seeding rate of 30 kg ha^{-1} for RT 7521 FP (Harrell et al. 2021). Seeding rates in these experiments were chosen to cover a range of seeding rates from 25% higher than the maximum recommended seeding rate to 33% of the recommended seeding rate to simulate poor rice populations (Bond et al. 2005). Treatments were applied with a CO_2-pressurized backpack sprayer equipped with flat-fan AM11002 nozzles (Greenleaf Technologies, Covington, LA) set to deliver 140 L ha^{-1}.

Data collection included visible injury assessed on a scale of 0% to 100%, where 0% indicated no injury, and 100% indicated complete death at 7, 14, 21, and 28 d after application (DAA) (Frans and Talbert 1977). Rice plant height was recorded by measuring from the base of the plant to the tip of the uppermost leaf of five randomly selected plants on rows two and seven of each plot 14 DAA. Rice maturity was estimated as the number of days to 50% heading (when 50% of panicles in an individual plot had emerged from the leaf sheath) and recorded as days after emergence. Plots were mechanically harvested with a small-plot combine (Zürn Harvesting GmbH & Co. Schöntal-Westernhausen, Germany) to obtain rough rice yield. Rough rice yields were recorded and adjusted to 12% moisture for uniform statistical analysis.

Data were regressed against the seeding rate, allowing for both linear and quadratic terms with coefficients depending on the seeding rate, and nonsignificant model terms were removed sequentially until a satisfactory model was obtained (Golden et al. 2006). Data that did not exhibit a significant trend were subjected to ANOVA using the GLIMMIX procedure with SAS software (v.9.4; SAS Institute Inc., Cary, NC) with site-year and replication (nested within site-year) as random effects parameters (Blouin et al. 2011). Estimates of the least square means at a 5% significance level were used for mean separation.

Results and Discussion

No biological trends in seeding rate were detected for rice injury across evaluations or rice maturity (P = 0.0659 to 0.9166). Pooled across seeding rates, rice injury following florpyrauxifen-benzyl application was 4%, 7%, 6%, and 5% at 7, 14, 21, and 28 DAA, respectively (data not presented). Wright et al. (2020) reported that in a field study, the CL111 cultivar exhibited <10% injury 3 wk after florpyrauxifen-benzyl application. Additionally, injury observed in a corresponding growth chamber trial never exceeded 9%. Sanders et al. (2020) reported that injury to eight modern cultivars did not exceed 13% at 28 d after florpyrauxifen-benzyl had been applied. Differential tolerance of certain rice cultivars to florpyrauxifen-benzyl could be attributed to a lack of bioactivation, metabolic activity, or differences in receptor affinity at the site of action (Velásquez et al. 2021). Previous research has discussed the effects that environmental factors such as light, soil moisture, and temperature levels can have when florpyrauxifen-benzyl is applied to rice. Beesinger et al. (2022), for example, reported that when florpyrauxifen-benzyl was applied to rice, injury was 20% when the plants were subjected to high (24/35 C night/day) temperatures and low (700 μmol m^{-2} s^{-1}) light. Furthermore, when soil moisture concentrations were 40% and 100%, injury to rice from florpyrauxifen-benzyl was 35% and 36%, respectively. Saturated soil that is typically found in a rice field can exacerbate crop injury following florpyrauxifen-benzyl application.

Table 3. Influence of seeding rate on rice maturity when evaluating postemergence applications of florpyrauxifen-benzyl.[a,b]

Seeding rate	Rice maturity
kg ha^{-1}	DAE
10	75 a
17	75 a
24	74 b
30	74 b
37	73 b

[a]Abbreviation: DAE, days after emergence.
[b]Data were pooled over two florpyrauxifen-benzyl rates and four studies. Means within a column followed by the same letter are not different at α = 0.05.

In the current research, rice plant height was reduced following exposure to florpyrauxifen-benzyl. Quadratic regression analysis indicated that the intercept for rice plant height was 62.20 when no florpyrauxifen-benzyl was applied (P = 0.0475, R^2 = 0.9524). When florpyrauxifen-benzyl was applied at 58 g ai ha^{-1}, quadratic regression analysis indicated that the intercept for rice plant height was 56.41 (P = 0.0775, R^2 = 0.8735) (Table 2). Plant height was

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Table 4. Regression coefficients for rough rice yield in research evaluating rice hybrid response to seeding rates and postemergence applications of florpyrauxifen-benzyl.

Parameter	Rate	Intercept	SE	Linear	SE	Quadratic	SE	Cubic	SE
	g ai ha^{-1}								
Rough rice yield	0	−1527.6648	454.7881	2142.4931	78.4015	−110.6166	4.0400	1.7964	0.0638
	58	8812.1305	188.2147	147.7229	19.9177	−2.9122	0.4676	–	–

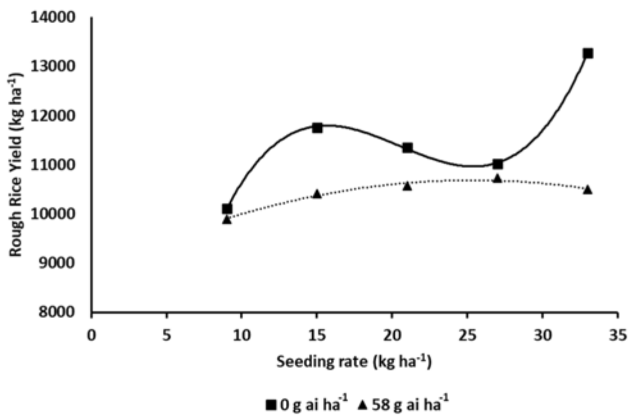

Figure 1. Rough rice grain yield for different Clearfield XL 7521 seeding rates following application of florpyrauxifen-benzyl from 2019 to 2021 at experimental sites in Stoneville, MS.

reduced by 14% across all seeding rates after florpyrauxifen-benzyl was applied. The greatest reduction in rice plant height between the two florpyrauxifen-benzyl treatments was 19% when rice was seeded at 37 kg ha^{-1}. Previous research has indicated that the height of certain rice cultivars can be reduced by up to 20% when florpyrauxifen-benzyl is used (Beesinger et al. 2022; Sanders et al. 2020; Wright et al. 2020).

The main effect of the seeding rate was significant for rice maturity ($P < 0.0001$) (Table 3). Hybrid rice seeded at 10 and 17 kg ha^{-1} matured more slowly than that seeded at 24, 30, and 37 kg ha^{-1} (Table 3). Aklilu (2020) reported that rice planted at lower seeding rates had less competition for resources, resulting in delayed maturity. When florpyrauxifen-benzyl was applied, rice maturity was not affected ($P = 0.0588$). No differences in rice maturity were detected among eight different rice cultivars when florpyrauxifen-benzyl was applied (Sanders et al. 2020).

Rough rice yield is reduced when florpyrauxifen-benzyl is used. Cubic and quadratic regression analysis indicated that the intercept for rough rice yield when no florpyrauxifen-benzyl was applied was −1527.6688 ($P = 0.0286$, $R^2 = 0.9995$), and 8812.13 when florpyrauxifen-benzyl was applied at 58 g ai ha^{-1} ($P = 0.0201$, $R^2 = 0.9798$) (Table 4; Figure 1). When RT 7521 FP was seeded at 17 and 37 kg ha^{-1}, rough rice yields were reduced 12% and 23%, respectively, when florpyrauxifen-benzyl was applied at 58 g ai ha^{-1} compared to the same seeding rates that received no florpyrauxifen-benzyl. Rough rice yield from the 10 kg ha^{-1} seeding rate was reduced by 27% compared with yield from the 37 kg ha^{-1} seeding rate. However, when florpyrauxifen-benzyl was applied, rough rice yield from the 10 kg ha^{-1} seeding rate was reduced by 5.9% compared with yield from the 37 kg ha^{-1} seeding rate. Sanders et al. (2020) reported that eight cultivars exhibited reduced rough rice yields when florpyrauxifen-benzyl was applied. Wright et al. (2020) reported that the CL111 cultivar did not exhibit a yield loss when florpyrauxifen-benzyl was applied, but yield from the CLXL245 cultivar was significantly reduced'. In contrast to the current research, Velásquez et al. (2021) reported that while rice injury from florpyrauxifen-benzyl increased with an increase in the herbicide rate, yield was not affected.

Practical Implications

This research demonstrates that florpyrauxifen-benzyl has the capacity to reduce rough rice yield of hybrid rice seeded at lower-than-recommended densities. Rice injury from florpyrauxifen-benzyl applied at a 2 × rate was ≤8% across all hybrid seeding rates. Sanders et al. (2020) reported ≤10% injury to commercial and experimental rice cultivars 14 d after florpyrauxifen-benzyl was applied at a 2× rate. The injury was 11% and 13% greater when florpyrauxifen-benzyl was applied to the inbred cultivars CL163 and PVLO24-B, respectively, compared with the Clearfield CL XL745 cultivar (Sanders et al. 2020). Rice cultivar differential tolerance to florpyrauxifen-benzyl has been attributed to varying crop metabolism rates among cultivars (Velásquez et al. 2021). In some cases, non-bioactivation of the florpyrauxifen-benzyl ester could be the cause of a lack of injury.

Similar to previous research, this study found that florpyrauxifen-benzyl applied to rice can reduce the height of the crop. Wright et al (2020) observed that injury from florpyrauxifen-benzyl may not always be visible. Rice maturity was significantly affected by the seeding rate, because the 10 kg ha^{-1} seeding rate matured 2 d slower than the 37 kg ha^{-1} seeding rate. Delaying rice maturity could potentially negatively impact rice producers in the mid-southern United States due to the tropical storm systems that are common during the harvest months of August and September. In the current study, florpyrauxifen-benzyl had no effect on rice maturity. Sanders et al. (2020) reported no delay in rice maturity when florpyrauxifen-benzyl was applied to multiple rice cultivars. Previous research has documented the ability of florpyrauxifen-benzyl to reduce rice yield (Beesinger et al. 2022; Sanders et al. 2020; Wright et al. 2020). The current research indicates that applying florpyrauxifen-benzyl at a 2× rate can result in a loss of yield due to variation in rice densities. Rice producers should consider the effects of applying florpyrauxifen-benzyl to lower-seeded or highly seeded rice plant populations. Growers should ensure that rice has been planted at the recommended seeding rate of 30 kg ha^{-1} for cultivar RT 7521 FP when applying florpyrauxifen-benzyl.

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Competing interests. The authors declare they have no competing interests.

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