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Response of Commercial Rice Cultivars to Postemergence Applications of Saflufenacil

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Research was conducted in 2012 and 2013 to evaluate the response of the rice cultivars 'Cheniere', 'CL151′, 'Caffey', 'CL261′, and 'CLXL745′ response to POST applications of saflufenacil. Treatments included a nontreated control, saflufenacil at 50 g ai ha^{-1}, and carfentrazone at 35 g ai ha^{-1} applied mid-POST (MPOST) to rice in the three- to four-leaf stage. Pooled across cultivars, injury was greatest at 3 and 7 d after treatment (DAT), 21 and 17%, respectively. Rice injury was only 5% at 14 DAT and 1% at 28 DAT. Hybrid long-grain cultivar CLXL745 was injured more than inbred long-grain cultivars CL151 and Cheniere. Cheniere was more tolerant than inbred medium-grain cultivars CL261 and Caffey. All cultivars exhibited tolerance to saflufenacil as evidenced by similar normalized difference vegetative index (NDVI), maturity, mature plant height, and rice yield (rough, whole, and total milled rice).
Nomenclature: Carfentrazone; saflufenacil; rice, *Oryza sativa* L.
Key words: Differential susceptibility, herbicide tolerance, hybrid rice, normalized difference vegetative index.

Se realizó un investigación en 2012 y 2013 para evaluar la respuesta de los cultivares de arroz 'Cheniere', 'CL151′, 'Caffey', 'CL261′, and 'CLXL745′ a aplicaciones POST de saflufenacil. Los tratamientos incluyeron un testigo no-tratado, saflufenacil a 50 g ai ha^{-1}, y carfentrazone a 35 g ai ha^{-1} aplicados en POST intermedio (MPOST) a arroz en los estadios de tres a cuatro hojas. Promediando los cultivares, el daño fue mayor a 3 y 7 d después del tratamiento (DAT), 21 y 17%, respectivamente. El daño en el arroz fue solamente 5% a 14 DAT y 1% a 28 DAT. El cultivar híbrido de grano largo CLXL745 sufrió más daño que los cultivares autofecundados de grano largo CL151 y Cheniere. Cheniere fue más tolerante que el cultivar autofecundado de grano mediano CL261 y Caffey. Todos los cultivares presentaron tolerancia a saflufenacil como se evidenció al obtener valores similares del índice de diferencia de vegetación normalizada (NDVI), madurez, altura de planta madura, y rendimiento del arroz (en granza, entero, y total pulido).

Rice production in Mississippi began in 1948 with one producer planting approximately 120 ha (Miller and Street 2008). Approximately 2,000 ha were planted in Mississippi the following year (Anonymous 2014a). Since that time, Mississippi has grown to the fourth largest rice-producing state behind Arkansas, Louisiana, and California (Anonymous 2014a; Miller and Street 2008). Rice production in Mississippi is primarily concentrated along the Mississippi and Yazoo river basins, which encompass the northwestern part of the state (Miller and Street 2008). Rice hectarage in Mississippi peaked in 1981 with about 136,000 ha harvested (Anonymous 2014a). Since that time, hectarage has stabilized at approximately 100,000 ha (Miller and Street 2008).

Effective weed control is vital for successful rice production (Riar and Norsworthy 2011). Weeds are the most detrimental pest of rice production in Mississippi (Buehring and Bond 2008). When the last survey was conducted in 2006, producers in Mississippi applied 1.1 million kg of herbicides, in comparison to 117,000 kg of insecticides, fungicides, and desiccants combined (Anonymous 2014a). Rice producers in Mississippi spend $7.5 to $15 million annually on weed control (Buehring and Bond 2008).

Successful weed management in agronomic fields requires chemical and cultural control methods. Common herbicides for rice include acifluorfen,

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bensulfuron, bentazon, bispyribac, carfentrazone, halosulfuron, imazethapyr, propanil, and triclopyr (Zhang et al. 2006). These herbicides are effective; however, because many producers rely heavily on only a few of these herbicides, herbicide resistance is becoming problematic in rice fields (Hoagland et al. 2004).

Saflufenacil is a protoporphyrinogen IX oxidase (PPO)–inhibiting herbicide marketed by BASF (Grossman et al. 2010). Saflufenacil is similar to other PPO-inhibiting herbicides because it catalyzes the conversion of protoporphyrinogen IX to protoporphyrin IX in tetrapyrrole biosynthesis (Grossman et al. 2011). Treated plants undergo lipid peroxidation that results in a rapid loss of membrane integrity and function, particularly in the plasmalemma, tonoplast, and chloroplast envelope (Grossman et al. 2010). This process also elicits synthesis of the growth-regulating phytohormone ethylene. These processes cause the necrotic leaf spotting that is characteristic of PPO-inhibiting herbicides (Grossman et al. 2011).

Saflufenacil is mobile in the plant, whether absorbed through foliage or roots, and is moved throughout the plant via xylem shortly after application (Grossman et al. 2011). Saflufenacil efficacy is improved by the addition of adjuvants (Eubank et al. 2013; Knezevic et al. 2009). The addition of nonionic surfactant, crop oil concentrate, or methylated seed oil improved weed control over saflufenacil alone (Knezevic et al. 2009).

As weed management has become more challenging, producers and basic manufacturers have begun evaluating new herbicides and herbicide modes of action to help combat those problems. Saflufenacil was initially developed to be used as a preplant burndown and residual PRE herbicide for broadleaf weed control (Grossman et al. 2010). Saflufenacil currently has a label for use in fallow and postharvest chickpea (*Cicer arietinum* L.), corn (*Zea mays* L.; field, pop, silage), cotton (*Gossypium hirsutum* L.), field pea [*Pisum sativum* L. ssp. *sativum* var. *arvense* (L.) Poir.], small grains and grain sorghum [*Sorghum bicolor* (L.) Moench ssp. *bicolor*], soybean [*Glycine max* (L.) Merr], and most recently for POST applications in rice (Anonymous 2013b, 2014b). Saflufenacil is commonly used for burndown in cotton, corn, and soybean because of its effective control of many broadleaf species, including glyphosate-resistant (GR) horseweed [*Conyza canadensis* (L.) Cronq.] and GR Palmer amaranth (*Amaranthus palmeri* S. Wats) (Anonymous 2013b; Eubank et al. 2013; Waggoner et al. 2011).

Saflufenacil is labeled for broadleaf weed control in grain crops and has potential to be used in rice (Camargo et al. 2012). Saflufenacil applied alone and in mixtures with other rice herbicides controls broadleaf weed species in rice (Meier et al. 2010). Hemp sesbania [*Sesbania herbacea* (P. Mill.) McVaugh] and Palmer amaranth are among the most common and troublesome weeds of rice in Mississippi (Webster 2012). Although clomazone and imazethapyr are among the most commonly used herbicides for grass control in rice, these herbicides provide inadequate control of broadleaf weeds, leaving a niche for a broadleaf herbicide in current rice weed-control programs (Camargo et al. 2010). Saflufenacil could be a useful tool in rice production because it controls Palmer amaranth (Anonymous 2013b; Camargo et al. 2012; Geier et al. 2009).

Camargo et al. (2012) reported that saflufenacil POST caused rice injury, but that injury did not reduce yield. Rice cultivar and growth stage can affect rice tolerance to herbicide applications (Lanclos et al. 2003; Zhang and Webster 2002). Previous research has indicated that long-grain cultivars exhibit greater tolerance than medium-grain or hybrid cultivars (Bond and Walker 2011, 2012; Bond et al. 2007; Scherder et al. 2004; Willingham et al. 2008; Zhang and Webster 2002; Zhang et al. 2004). The long-grain cultivar 'Cocodrie' was more tolerant to bispyribac-sodium compared with the medium-grain cultivar 'Bengal', and shoot and root growth were inhibited more in 'Bengal' when bispyribac-sodium was applied to one- to two-leaf rice compared with two- to three-leaf rice (Zhang et al. 2005). Willingham et al. (2008) reported that long-grain hybrid cultivar 'XP712′ was more sensitive to penoxsulam than inbred long- or medium-grain cultivars 7 DAT.

The prevalence of Palmer amaranth, combined with the limited number of herbicides available to control this species has created a need for broadleaf herbicides in rice (MSU-ES 2014; Norsworthy et al. 2010; Webster 2012). Rice cultivar can influence tolerance to herbicide applications (Bond et al. 2007; Lanclos et al. 2003; Zhang et al. 2005). Saflufenacil received labeling for POST applications to rice in 2014 (Anonymous 2014b), but no research has been published on cultivar tolerance to this herbicide. Therefore, research was conducted to evaluate the response of five commercial rice cultivars to POST applications of saflufenacil and compare this response to that following carfentrazone.

Materials and Methods

A study to compare the response of commercial rice cultivars to POST applications of saflufenacil and carfentrazone was conducted once in 2012 (33.40°N, 90.94°W) and twice in 2013 (33.43°N, 90.90°W; 33.41°N, 90.93°W) at the Mississippi State University Delta Research and Extension Center in Stoneville, MS. Soil each site–year was a Sharkey clay (very fine, smectitic, thermic Chromic Eqiaquerts) with a pH ranging from 6.8 to 8.2, and an organic matter content of approximately 2.0%. The experimental sites were in a 1 : 1 rotation with soybean. Field preparation each site–year consisted of fall disking and field cultivation, followed by an application of clomazone (Command herbicide, FMC Corporation, 1735 Market St., Philadelphia, PA 19103) at 840 g ai ha^{-1} in November for control of GR Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot] (Bond et al. 2014). Emerged vegetation was controlled before planting using glyphosate (Roundup Weathermax herbicide, Monsanto Company, 800 N. Lindbergh Blvd., St. Louis, MO 63167) at 840 g ae ha^{-1}. Plots were maintained weed-free by an application of clomazone at 560 g ha^{-1} at planting followed by halosulfuron (Permit herbicide, Gowan Company L.L.C., 370 Main St. Yuma, AZ 85364) at 12 g ai ha^{-1} applied at the one- to two-leaf rice stage. Nitrogen fertilizer at 168 kg ha^{-1} as urea was applied immediately before flood establishment. Standard agronomic and pest management practices were used during the growing season (Buehring 2008).

Two inbred, long-grain cultivars, 'Cheniere' (registration number [Reg. No.] CV-120-120, PI 634719) and 'CL151' (Blanche et al. 2011; Reg. No. CV-133PI 654463), two inbred, medium-grain cultivars 'Caffey' (Blanche et al. 2012; Reg. No. CV-138, PI 665059) and 'CL261' (CV-143, PI658539), and one long-grain hybrid cultivar, 'CLXL745', were planted on May 9, 2012, April 9, 2013, and April 30, 2013. All inbred cultivars were seeded at 95 kg ha^{-1} or 400 to 450 seed m^{-2}. Because of heterosis, a seeding a rate of 28 kg ha^{-1} or 125 seed m^{-2} was used for CLXL745 as recommended by the manufacturer (Anonymous 2014c). Rice was drill-seeded to a depth of 2 cm using a small-plot grain drill (Great Plains 1520, Great Plains Mfg, Inc., 1525 East North St. Salina, KS 67401) equipped with double-disk openers and press wheels spaced 20 cm apart. Individual plots consisted of eight 4.6-m-long rows. Plots were flooded to an approximate depth of 6 to 10 cm when rice reached the one- to two-tiller stage.

Treatments were arranged as a two-factor factorial within a randomized complete-block design with four replications. The first factor was cultivar and consisted of the five commercial rice cultivars previously described. The second factor was herbicide and consisted of a control (no herbicide treatment), saflufenacil (Sharpen herbicide, BASF Crop Protection, 26 Davis Dr., Research Triangle Park, NC, 27709) at 50 g ha^{-1}, and carfentrazone (Aim herbicide, FMC Corporation, 1735 Market Street, Philadelphia, PA, 19103) at 35 g ha^{-1}. The saflufenacil rate was chosen because it represented twice the labeled rate for POST applications in rice (Anonymous 2014b). Although labeling allows a range of application rates for carfentrazone (Anonymous 2013a), 35 g ha^{-1} was chosen because it represents twice the rate typically used by producers in Mississippi. Treatments were applied when rice reached the three- to four-leaf stage. Saflufenacil and carfentrazone treatments included crop oil concentrate (Agri-Dex 99% crop oil concentrate, Helena Chemical Co., 5100 Poplar Ave., Memphis, TN, 38137) at 1% (v/v) and were applied with a CO_2-pressurized backpack sprayer equipped with extended-range, flat-fan spray nozzles (XR11002 TeeJet nozzles, Spraying Systems Co., P.O. Box 7900, Wheaton, IL, 60189) set to deliver 140 L ha^{-1} at 172 kPa.

Rice injury was visually estimated at 3, 7, 14, and 28 DAT on a scale of 0 (no rice injury) to 100% (complete plant death). The number of days to 50% heading was determined as an indication of rice maturity by calculating the time from seedling emergence until 50% of rice plants in an individual plot had visible panicles. NDVI was assessed as an indication of plant health using a hand-held crop sensor (GreenSeeker crop sensing system, Trimble

Table 1. Significance of the main effects of cultivar and herbicide treatment and interaction among the main effects for normalized difference vegetative index (NDVI), number of days to 50% heading, mature rice height, and rice yield (rough, total, and whole milled) in an experiment evaluating the rice cultivar response to saflufenacil at Stoneville, MS, in 2012 and 2013.

Effect	NDVI	Days to 50% heading	Mature height	Rough rice yield	Total milled rice yield	Whole milled rice yield
	P value					
Cultivar	0.0750	0.0693	0.2502	0.5587	0.5115	0.6723
Herbicide	0.9738	0.3898	0.9538	0.9911	0.4294	0.4086
Cultivar × herbicide	0.9787	0.6129	0.7184	0.6784	0.5556	0.7905

Navigation Limited, 935 Stewart Drive, Sunnyvale, CA 94085) at 4 wk after flood establishment. Average mature plant height was determined before harvest by calculating the mean height of 10 plants in each plot measured from the soil surface to the tip of the extended panicle. Rice was harvested with a small-plot combine (Wintersteiger Delta, Wintersteiger, Inc., 4705 W. Amelia Earhart Dr., Salt Lake City, UT 84116) at a moisture content of approximately 20% on October 23, 2012, August 29, 2013, and September 6, 2013. Final rough rice grain yields were adjusted to 12% moisture content. Whole and total milled rice yields were estimated from 100-g samples of cleaned rough rice using the procedure outlined by Adair et al. (1972). Rough rice was mechanically hulled, milled in a McGill No. 2 miller for 30 s and size-separated with a No. 12 4.76-mm screen. Whole and total milled rice yields were calculated as a mass fraction of the original 100-g sample of rough rice.

Because of inherent differences among the five cultivars, data for number of days to 50% heading, NDVI, mature plant height, and rice yield (rough, whole, and total milled rice) were converted to a percentage of the control for the respective cultivar in each replication. Percentage of control data was calculated by dividing the data from the treated plot by that in the control plot of the same cultivar in the same replication and multiplying by 100.

All data were subjected to the Mixed Procedure (Statistical software Release 9.3, SAS Institute, SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513-2414). Type III statistics were used to test all possible fixed effects or interactions among the fixed effects. Random effects were site–years and replications nested within site–years (Blouin et al. 2011). Considering site–year an environmental or random effect permits inferences about treatments to be made over a range of environments (Blouin et al. 2011; Carmer et al. 1989). Evaluation interval was considered a repeated-measures variable for rice-injury data, which allows for comparisons across intervals and the changes in rice injury over time (Blouin et al. 2004). The square roots of visual injury data were arcsine transformed. The transformation improved homogeneity of variance based on visual inspection of the plotted residuals. Transformed data were used to determine mean separation; however, for ease of interpretation, actual means are presented with separation based on the arcsine square root–transformed data. Data from control plots were excluded from analysis of rice injury. Nontransformed data were used for rice NDVI, number of days to 50% heading, mature rice height, and yield (rough, total or whole milled). Fixed effects for these parameters were cultivar and herbicide. Least-square means were calculated, and mean separation ($P \leq 0.05$) was produced using PDMIX800 in SAS software, which is a macro for converting mean-separation output letter groupings (Saxton 1998).

Results and Discussion

The main effects of cultivar and herbicide treatment and the interaction of those factors were not significant for NDVI, days to 50% heading, mature rice height, or yield (rough, total milled, and whole milled) (Table 1). No differences in injury following saflufenacil or carfentrazone were observed on individual cultivars; however, cultivars responded differently. Pooled across herbicide treatments and rating intervals, injury was greater on CLXL745 at 13%, compared with CL151 or Cheniere at 10% and 9%, respectively (Table 2). Cheniere was injured less than Caffey or CL261 (Table 2). Injury at 3 and 7 DAT was similar, regardless of cultivar or herbicide treatment, declining to 5 and 1% at 14 and 28 DAT, respectively (Table 3).

Table 2. Response of five commercial rice cultivars to PPO-inhibiting herbicides at Stoneville, MS, in 2012 and 2013.[a]

Rice type	Cultivar	Injury[b]
		%
Long-grain hybrid	CLXL745	13 a
Inbred medium grain	Caffey	12 ab
	CL261	11 ab
Inbred long grain	CL151	10 bc
	Cheniere	9 c

[a] Data pooled over two PPO-inhibiting herbicides (saflufenacil at 50 g ai ha^{-1} and carfentrazone at 35 g ai ha^{-1}), four evaluation interval (3, 7, 14, and 28 d after treatment), and three experiments.

[b] Nontransformed data are presented with statistical interpretation on the basis of arcsine square root–transformed data. Means followed by the same letter are not significantly different at $P \leq 0.05$.

Table 3. Injury of commercial rice cultivars at four evaluation intervals following application of two PPO-inhibiting herbicides at Stoneville, MS, in 2012 and 2013.[a]

Rating interval	Injury[c]
DAT[b]	%
3	21 a
7	17 a
14	5 b
28	1 c

[a] Data pooled over five commercial rice cultivars (CL151, Cheniere, CL261, Caffey, and CLXL745), two PPO-inhibiting herbicides (saflufenacil at 50 g ai ha^{-1} and carfentrazone at 35 g ai ha^{-1}), and three experiments.

[b] Abbreviations: DAT, days after treatment.

[c] Nontransformed data presented with statistical interpretation on the basis of arcsine square root–transformed data. Means followed by the same letter are not significantly different at $P \leq 0.05$.

Previous research has shown different results for rice cultivar tolerance to herbicides. Bond et al. (2007) reported no differences in response among rice cultivars following applications of penoxsulam at twice the labeled rate. Long-grain rice cultivars exhibited similar tolerance to bispyribac-sodium, but differential tolerance was observed among medium-grain cultivars (Zhang et al. 2005). Medium-grain 'Mars' was more susceptible to fenoxaprop than was long-grain cultivars 'Tebonnet' and 'Lamont' (Griffin and Baker 1990). Lanclos et al. (2003) reported that glufosinate applications to glufosinate-resistant cultivars delayed heading from 7 to 15 and only 3 to 5 d for medium- and long-grain cultivars, respectively. An experimental cultivar 'RU961096′ was less tolerant to clomazone than other cultivars (Scherder et al. 2004). Inbred, long-grain cultivars 'CL161′ and Cocodrie were more tolerant to postflood applications of quinclorac than was long-grain hybrid 'XL723′ (Bond and Walker 2012).

Although differences in injury were observed among the cultivars evaluated in the current research, injury following saflufenacil was similar to that with carfentrazone, which is currently labeled for POST applications to rice (Anonymous 2013a). Inbred long-grain cultivars CL151 and Cheniere were more tolerant to both herbicides than was long-grain hybrid CLXL745 based on visual estimates of injury. Herbicide tolerance of medium-grain cultivars CL261 and Caffey was similar to that of long-grain cultivar CL151; however, long-grain cultivar Cheniere was injured less than medium-grain Caffey was (Table 2). Although rice injury was evident, saflufenacil at 50 g ha^{-1} did not negatively affect the agronomic performance of the five commercial rice cultivars in this study.

As previously reported for other rice herbicides, hybrid and inbred, medium-grain cultivars were injured more than inbred, long-grain cultivars were. However, for all cultivars evaluated, injury observed following saflufenacil did not negatively affect NDVI, days to 50% heading, mature rice height, or yield (rough, whole, or total milled). This research demonstrates that saflufenacil is safe for POST applications to rice cultivars grown in the southern United States.

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