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Evaluation of Saflufenacil in Drill-Seeded Rice (*Oryza sativa*)

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Palmer amaranth is the most common and troublesome broadleaf weed species of rice in Mississippi because of the effects of early-season interference and infestations on rice levees, and herbicides for residual or POST control of Palmer amaranth in rice are limited. Three studies were conducted in 2012 and 2013 to evaluate application rates and timings of saflufenacil in rice and to determine the influence of adjuvants when mixed with saflufenacil applied POST. In a PRE study, no injury occurred after saflufenacil PRE, and no control was observed from carfentrazone. Hemp sesbania and Palmer amaranth control increased with increasing saflufenacil rate when applied PRE. Hemp sesbania control with saflufenacil at any rate PRE was $\leq$ 25% at 35 d after treatment (DAT). Palmer amaranth and ivyleaf morningglory control with saflufenacil at 75 g ai ha^{-1} PRE was $\geq$ 94% 35 DAT. In a POST study, rice injury was influenced by application timing and rate of saflufenacil; however, efficacy was not. Rice injury with saflufenacil at 25 g ha^{-1} and carfentrazone early POST (EPOST) and late POST was similar 7 DAT. Saflufenacil at 50 and 75 g ha^{-1} EPOST were the most injurious 7 DAT. Control of hemp sesbania and ivyleaf morningglory was similar for all rates of saflufenacil and carfentrazone; however, Palmer amaranth control with saflufenacil at any rate was greater than that of carfentrazone 14 and 28 DAT. In an adjuvant study, rice injury was influenced by adjuvant and saflufenacil rate. Saflufenacil applied alone or in mixture with crop oil concentrate (COC) was least injurious, and saflufenacil at 50 g ha^{-1} was more injurious than saflufenacil at 25 g ha^{-1}. Saflufenacil applied in combination with any adjuvant provided better control of hemp sesbania and Palmer amaranth than saflufenacil alone. On the basis of this research, saflufenacil should be applied PRE at 50 or 75 g ha^{-1}, depending on weed spectrum, and POST applications should be made at 25 g ha^{-1} in combination with COC after the two-leaf rice growth stage.

Nomenclature: Carfentrazone; saflufenacil; hemp sesbania, *Sesbania herbacea* (P. Mill.) McVaugh SEBEX; ivyleaf morningglory, *Ipomoea hederacea* (L.) Jacq. IPOHE; Palmer amaranth, *Amaranthus palmeri* S. Wats AMAPA; rice, *Oryza sativa* L.

Key words: Adjuvant, application rate, application timing, surface applications.

Amaranthus palmeri es la especie de malezas de hoja ancha más común y problemática en arroz en Mississippi debido a sus efectos en la interferencia temprano durante la temporada de crecimiento y sus infestaciones en los diques en los campos de arroz, además hay pocos herbicidas para el control residual y POST de esta maleza en arroz. En 2012 y 2013, se realizaron tres estudios para evaluar la dosis y momentos de aplicación de saflufenacil en arroz y así determinar la influencia de adyuvantes cuando estos se mezclaron con saflufenacil y fueron aplicados POST. En un estudio PRE, no hubo daño después de aplicaciones PRE de saflufenacil, y no se observó control alguno con aplicaciones de carfentrazone. El control de *Sesbania herbacea* y *A. palmeri* aumentó con el incremento en las dosis de saflufenacil cuando se aplicó PRE. A cualquier dosis, el control de *S. herbacea* con saflufenacil PRE fue $\leq$25% a 35 d después del tratamiento (DAT). El control de *A. palmeri* e *Ipomoea hederacea* con saflufenacil a 75 g ai ha^{-1} PRE fue $\geq$94% 35 DAT. En un estudio POST, el daño en el arroz fue influenciado por el momento y dosis de aplicación de saflufenacil, sin embargo, la eficacia no lo fue. El daño en el arroz con saflufenacil a 25 g ha^{-1} y carfentrazone en POST temprana (EPOST) y POST tardía fue similar a 7 DAT. Saflufenacil a 50 y 75 g ha^{-1} EPOST fueron los tratamientos más dañinos 7 DAT. El control de *S. herbacea* e *I. hederacea* fue similar para todas las dosis de saflufenacil y carfentrazone. Sin embargo, el control de *A. palmeri* con saflufenacil a cualquiera de las dosis fue mayor que el control con carfentrazone 14 y 28 DAT. En un estudio con adyuvantes, el daño al arroz fue influenciado por el adyuvante y la dosis de saflufenacil. Saflufenacil aplicado solo o en mezcla con aceite concentrado de cultivo (COC) causó menos daño, y saflufenacil a 50 g ha^{-1} causó más daño que saflufenacil a 25 g ha^{-1}. Saflufenacil aplicado en combinación con cualquier adyuvante brindó mejor control de *S. herbacea* y *A. palmeri* que saflufenacil solo. Con base en esta investigación, saflufenacil debería ser aplicado PRE a 50 ó 75 g ha^{-1}, dependiendo del espectro de malezas, y las aplicaciones POST deberían hacerse a 25 g ha^{-1} en combinación con COC y después del estado de crecimiento de dos hojas del arroz.

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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 harvested ha (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 with 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).

The three most common weeds in Mississippi rice fields are barnyardgrass [*Echinochloa crus-galli* (L.) Beauv], Palmer amaranth, and hemp sesbania (Webster 2012). Weeds compete with the crop for nutrients, sunlight, water, and space and can increase the incidence of disease in certain scenarios (Buehring 2008; Everman et al. 2008). Successful weed management in agronomic fields requires chemical and cultural weed control methods. Common herbicides for rice include acifluorfen, bensulfuron, bentazon, bispyribac, carfentrazone, halosulfuron, imazethapyr, propanil, and triclopyr (Zhang et.al. 2006). These herbicides are effective; however, herbicide resistance is becoming problematic in rice fields because many producers rely heavily on only a few of these (Hoagland et al. 2004).

Saflufenacil is a new protoporphyrinogen IX oxidase (PPO)-inhibiting herbicide marketed by BASF (Grossman et al. 2010). It is similar to other PPO-inhibiting herbicides in that 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 treated plants whether absorbed through foliage or roots and, in susceptible species, is moved throughout the entire plant through xylem less than 24 h after contact.

As weed management has become more challenging, researchers have reported a need for new herbicide management programs in many of the major agronomic crops to sustainably combat these problems (Riar et al. 2013). Saflufenacil was initially developed to be used as a preplant burndown and residual PRE herbicide for broadleaf weed control (Grossman et al. 2010). Saflufenacil is labeled for use in chickpea (*Circer arietinum* L.), corn (*Zea mays* L.) (field, pop, silage), cotton (*Gossypium hirsutum* L.), fallow and postharvest, field pea [*Pisum sativum* L. ssp. *sativum* var. *arvense* (L.) Poir.], small grains, grain sorghum (*Sorghum bicolor* ssp. *bicolor*), soybean [*Glycine max* (L.) Merr], and most recently for POST applications in rice (Anonymous 2013b, 2014b). Saflufenacil is commonly utilized for burn-down in cotton, corn, and soybean because of its effective control of many broadleaf species, including glyphosate-resistant (GR) horseweed [*Conyza canadensis* (L.) Cronq.] and Palmer amaranth (Anonymous 2013b; Eubank et al. 2013; Waggoner et al. 2011).

Herbicide timing is a critical component of weed control (Parker et al. 2006). Timely herbicide applications improve weed control and increase crop yield. Crop stage, weed stage, and emergence timing of weeds can influence herbicide application timing (Norsworthy et al. 2007). Significant crop yield and quality loss due to weed interference can occur when herbicides are not applied in a timely manner (Loux et al. 2011). Generally, a mixture of PRE and POST herbicides provide the best weed control and highest crop yields (Gower et al. 2002). Relying on POST herbicides with no residual activity can fail because they allow weeds to germinate and compete with the crop after the application (Loux et al. 2011). Weeds are generally easier to control when they are small and have not reached reproductive stages. Research on the effects of weed interference on development and yield of crops, including rice, is extensive (Askew et al. 2000; Carlson et al. 2012; Everman et al. 2008; Page et al 2012; Parker et al 2006; Smith 1988). Most species have a specific window where they should be controlled to avoid yield loss in the crop (Gower et al. 2002).

Adjuvants can influence weed control and crop injury with POST herbicides (Eubank et al. 2013; Javaid and Tanveer 2013). Adjuvants affect the biological activity of herbicides by altering spray solution surface tension, pH, viscosity, droplet size, and distribution (Green and Cahill 2003). The adjuvant influence on herbicide efficacy is dependent on the herbicide applied (Green and Cahill 2003; Javaid and Tanveer 2013; Knezevic et al. 2009). Saflufenacil efficacy is improved by the addition of adjuvants (Eubank et al. 2013; Knezevic et al. 2009). The addition of nonionic surfactant (NIS), COC, or methylated seed oil (MSO) improved weed control over saflufenacil alone (Knezevic et al. 2009). Eubank et al. (2013) also reported that the addition of MSO or COC improved control of horseweed over that of saflufenacil applied with no adjuvant.

Saflufenacil is labeled for broadleaf weed control in grain crops (Anonymous 2013b), and Camargo et al. (2012) proposed that it has potential to be used in rice. The second most troublesome weed of rice in Mississippi is Palmer amaranth (Webster 2012). This weed has become common in corn, cotton, and soybean (Bond and Oliver 2006; Klingaman and Oliver 1994; Ward et al. 2013) but has recently begun to become problematic in rice (Webster 2012). Saflufenacil applied alone and in mixtures with other rice herbicides controls broadleaf weeds in rice (Meier et al. 2010). Although clomazone and imazethapyr are among the most commonly used herbicides for grass control in rice, these herbicides provide only limited control of broadleaf weeds, leaving a niche for a broadleaf herbicide in current rice weed control programs (Camargo et al. 2010). Saflufenacil shows potential to become a useful tool in rice production because it controls Palmer amaranth (Anonymous 2013b; Camargo et al. 2012; Geier et al. 2009), the most troublesome broadleaf weed species in Mississippi (Webster 2012, 2013). Camarago et al. (2012) reported that saflufenacil injured rice but the observed injury did not reduce yield. Therefore, research was conducted to determine the optimum application rate, timing, and adjuvant for saflufenacil applications in rice with respect to weed control efficacy and crop injury.

Materials and Methods

PRE Evaluation. A study to evaluate rice response and weed control with different rates of saflufenacil PRE was conducted once in 2012 (33.44°N, 90.91°W) and twice in 2013 (33.45°N, 90.90°W and 33.40°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 of 8.1 to 8.3 and an organic matter content of 2.1%. The experimental site was in a rice–fallow rotation where rice was seeded every other year. During the fallow year, weeds were allowed to grow and produce seed to maintain the soil seed bank for the following year. Additionally, hemp sesbania, Palmer amaranth, and ivyleaf morningglory were surface-seeded before rice planting to ensure uniform infestations.

The long-grain rice cultivar ‘CL151’ was drill-seeded at 75 kg ha^{-1} (312 seed m^{-2}) on May, 10, 2012, and May 29, 2013. Rice was seeded to a depth of 2 cm with 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 rows measuring 4.6 m in length. In all site years, plots were surface-irrigated within 5 d of planting and then again as needed, and a 10-cm flood was established at the one- to two-tiller rice growth stage. Flooding is common in rice production because the floodwater provides a good environment for rice growth, supplements weed control, and stabilizes ammonium nitrogen (Buehring 2008). Nitrogen fertilizer was applied as urea at approximately 165 kg ha^{-1} immediately before flood establishment. Standard agronomic practices were used during the growing season (Buehring 2008). Monocot weeds were controlled with clomazone (Command, herbicide, FMC Corporation, 1735 Market St., Philadelphia, PA 19103) at 560 g ai ha^{-1} applied after planting but before crop or weed emergence. After the final visual evaluation, acifluorfen (Ultra Blazer herbicide, United Phosphorus, Inc., 630 Freedom Business Center, Suite 402, King of Prussia, PA 19406) at 28 g ai ha^{-1} mixed with 1% (v/v) COC (Agri-Dex, a 99% crop-oil concentrate, Helena Chemical Co., 5100 Poplar Ave., Memphis, TN 38137) was applied as a broadcast treatment to all plots for control of hemp sesbania to facilitate mechanical harvest. Plots were drained approximately 2 wk before harvest maturity.

The experimental design was a randomized complete block design with four replications. Treatments were applied PRE before rice emerged but after planting. Treatments consisted of saflufenacil (Sharpen herbicide, BASF Crop Protection, 26 Davis Dr., Research Triangle Park, NC 27709) at 25, 50, and 75 g ha^{-1} mixed with MSO (Soysurf MSO, 99% methylated seed oil, Jimmy Sanders, Inc., 518 N Sharpe Ave., Cleveland, MS 38732) at 1% (v/v). A nontreated check and carfentrazone at 35 g ha^{-1} mixed with 1% (v/v) COC were included for comparison with saflufenacil treatments. Treatments 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 and control of hemp sesbania, ivyleaf morningglory, and Palmer amaranth were visually estimated on a scale of 0 to 100%, where 0 represented no injury or control and 100 represented complete plant death at 20, 28, and 35 d after application (DAT). 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. 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 September 28, 2012, and October 3, 2013. Final rough rice grain yields were adjusted to 12% moisture content.

Carfentrazone provided no control of broadleaf weeds and caused no rice injury when applied PRE; therefore, data from plots treated with carfentrazone were excluded from analyses of weed control and rice injury. The square roots of visual injury and control estimates were arcsine transformed. The transformation did not improve homogeneity of variance on the basis of visual inspection of plotted residuals; therefore, nontransformed data were used in analyses. Data from the nontreated control were deleted before analysis of visual control estimates to stabilize variance. Rough rice yield data were analyzed in comparison with the nontreated control. Yield of the nontreated control was averaged for each site year and then subtracted from the yield of each plot in that site year to provide a number for relative yield. Nontransformed data were subjected to the mixed procedure (statistical software release 9.3, SAS Institute Inc., 100 SAS Campus Dr., Cary, NC 27513-2414) with year and replication (nested within year) as random effect parameters (Blouin et al. 2011). Type III statistics were used to test the fixed effect of herbicide. Least-square means were calculated and mean separation ($P \leq 0.05$) was produced using PDMIX800 in SAS, which is a macro for converting mean separation output to letter groupings (Saxton 1998).

POST Evaluation. A study to evaluate rice response and weed control with different rates of saflufenacil applied at two POST application timings was conducted in 2012 (33.44°N, 90.91°W) and 2013 (33.45°N, 90.90°W) at the Mississippi State University Delta Research and Extension Center in Stoneville, MS. Soil and plot information, maintenance, and agronomic practices were similar to those described in the PRE evaluation.

Treatments were arranged as a two-factor factorial within a randomized complete block design with four replications. The first factor was application timing and consisted of an EPOST application to two- to three-leaf rice and a late-POST (LPOST) application to four-leaf to one-tiller rice. The second factor was herbicide and consisted of saflufenacil at 25, 50, and 75 g ha^{-1} mixed with MSO at 1% (v/v) and carfentrazone 35 g ha^{-1} mixed with COC at 1% (v/v). When this research was initiated, there was no information on the adjuvant that would be recommended for POST applications of saflufenacil to rice, so MSO was chosen because it was recommended for burn-down applications (Anonymous 2013b). Application equipment was as previously described in the PRE evaluation.

Table 1. Hemp sesbania, ivyleaf morningglory, and Palmer amaranth control with saflufenacil applied PRE at Stoneville, MS in 2012 and 2013.[a, b]

Treatments		Hemp sesbania			Ivyleaf morningglory			Palmer amaranth		
		20 DAT	28 DAT	35 DAT	20 DAT	28 DAT	35 DAT	20 DAT	28 DAT	35 DAT
	g ai ha^{-1}	%								
Saflufenacil	25	60 bc	44 c	8 b	91 b	92 b	87 b	88 b	91 b	79 c
Saflufenacil	50	66 b	52 b	13 b	93 a	95 a	93 a	94 a	95 a	88 b
Saflufenacil	75	74 a	59 a	25 a	94 a	95 a	95 a	95 a	95 a	94 a

[a] Data are pooled over three experiments. Means within a column followed by the same letter are not significantly different at $P \leq 0.05$.
[b] Abbreviation: DAT, days after treatment.

Rice injury and control of hemp sesbania, ivyleaf morningglory, and Palmer amaranth were visually estimated on the scale of 0 to 100% described previously. Treatments were evaluated at 7, 14, and 28 DAT. Hemp sesbania populations were 43 plants m^{-2} in 2012 and 33 and 43 plants m^{-2} EPOST and LPOST, respectively, in 2013. Hemp sesbania plants were 3 and 25 cm in height at the respective timings, both site years. Ivyleaf morningglory populations were 5 plants m^{-2} at each application both site years, and were 3 and 10 cm in height at the respective timings in both site years. Palmer amaranth populations were 65 and 85 plants m^{-2} in 2012 and 22 and 11 plants m^{-2} EPOST and LPOST, respectively, in 2013. Palmer amaranth plants were 3 and 10 cm in 2012 and were 2 and 6 cm in height at the respective timings in 2013. Rice maturity and yield determinations as well as data analyses were as previously described in the PRE evaluation. However, in contrast to the PRE evaluation, data from plots treated with carfentrazone were included in analyses of weed control and rice injury.

Adjuvant Evaluation. A study to evaluate weed control and rice injury with POST applications of saflufenacil in combination with different adjuvants was conducted in 2012 (33.44°N, 90.91°W) and 2013 (33.45°N, 90.90°W) at the Mississippi State University Delta Research and Extension Center in Stoneville, MS. Soil and plot information, maintenance, and agronomic practices were similar to those described in the PRE evaluation.

Treatments were arranged as a two-factor factorial within a randomized complete block with four replications. The first factor was saflufenacil rate and included saflufenacil at 25 and 50 g ha^{-1}. The second factor was adjuvant and included no adjuvant, NIS (Induce, a 90% NIS, Helena Chemical Co., 5100 Poplar Ave., Memphis, TN 38137) at 0.25% (v/v), COC at 1% (v/v), MSO at 1% (v/v), and a proprietary blend of MSO/organosilicon/urea ammonium nitrate (MSO/OSL/UAN) (Dyne-A-Pak, proprietary blend of polyalkyleneoxide-modified polydimethylsiloxane, nonionic emulsifiers, methylated vegetable oils, and nitrogen fertilizer solution, Helena Chemical Co., Suite 300, 225 Schilling Blvd., Collierville, TN 38017) at 1% (v/v). All treatments were applied mid-POST to three- to four-leaf rice. Treatments were applied as previously described in the PRE evaluation.

Rice injury and control of hemp sesbania, ivyleaf morningglory, and Palmer amaranth were visually estimated on the scale of 0 to 100% previously described. Treatments were evaluated at 7, 14, and 28 DAT. Hemp sesbania populations were 50 and 43 plants m^{-2} in 2012 and 2013, respectively. Hemp sesbania plants were 6 and 10 cm in height in 2012 and 2013, respectively. Ivyleaf morningglory populations were 5 plants m^{-2}, and 6 cm each site year. Palmer amaranth populations were 60 and 10 plants m^{-2} in 2012 and 2013, respectively. Palmer amaranth plants were 3 and 6 cm in 2012 and 2013 respectively. Rice maturity and yield determinations as well as data analyses were as previously described in the PRE evaluation.

Results and Discussion

PRE Evaluation. No injury was observed after any of the treatments imposed in this study, and no effect on days to 50% heading or rough rice yield was detected (data not presented). Hemp sesbania control 20 DAT was 60, 66, and 74% for

Table 2. Significance of the main effects of application timing and herbicide treatment and interaction among the main effects for rice injury and control of hemp sesbania, ivyleaf morningglory, and Palmer amaranth control 7, 14, and 28 d after treatment (DAT), days to 50% heading, and rice yield in POST evaluation of saflufenacil at Stoneville, MS in 2012 and 2013.

Effects	Rice injury			Hemp sesbania			Ivyleaf morningglory			Palmer amaranth			Days to 50% heading	Rice yield
	7[a]	14	28	7	14	28	7	14	28	7	14	28		
	P-value													
Application timing	0.076	0.282	0.323	0.492	0.347	0.360	0.423	0.323	0.845	0.459	0.470	0.468	0.896	0.448
Herbicide treatment	0.039	0.054	0.402	0.827	0.219	0.009	0.500	0.402	0.500	0.249	0.015	0.003	0.476	0.694
Application timing × herbicide treatment	0.017	0.001	0.402	0.764	0.367	0.190	0.500	0.402	0.381	0.301	0.370	0.882	0.220	0.884

[a] Column headings 7, 14, and 28 designate evaluation intervals of 7, 14, and 28 d after herbicide treatment.

saflufenacil at 25, 50, and 70 g ha^{-1}, respectively (Table 1). Control declined to 8, 13, and 25% for the same treatments by 35 DAT. Although saflufenacil at 75 g ha^{-1} controlled more hemp sesbania than when applied at the 25 or 50 g ha^{-1} rates at each evaluation, hemp sesbania control with saflufenacil PRE was poor. Uncontrolled populations of hemp sesbania can cause reductions in rice yield (Smith 1968). Hemp sesbania can reach heights of 3 m (Lorenzi and Jeffery 1987). The stature of this plant provides a competitive advantage over the crop and allows it to intercept light, and reduce the competitive ability of the crop (Norsworthy and Oliver 2002; Smith 1988). The level of hemp sesbania control with saflufenacil PRE was not adequate to protect rice yield throughout the growing season.

Ivyleaf morningglory control was $\geq$ 93% and similar after saflufenacil at 50 and 75 g ha^{-1} at all evaluations (Table 1). Although saflufenacil at 25 g ha^{-1} controlled of ivyleaf morningglory $\geq$ 87% at all evaluations, control was less than the two higher rates. Palmer amaranth control 20 and 28 DAT was $\geq$ 94% and similar with saflufenacil at 50 and 75 g ha^{-1}. By 35 DAT, the level of Palmer amaranth control increased with saflufenacil rate. However, only the highest rate controlled Palmer amaranth > 90%.

POST Evaluation. A treatment-by-timing interaction was detected for rice injury 7 and 14 DAT (Tables 2 and 3). Rice injury 7 DAT was greatest after saflufenacil at 50 and 75 g ha^{-1} (24 and 26%, respectively) EPOST (Table 3). Saflufenacil at 25 g ha^{-1} EPOST or LPOST caused rice injury similar to that of carfentrazone. No differences in rice injury 14 DAT were observed among the three rates of saflufenacil. However, saflufenacil at 75 g ha^{-1} resulted in greater injury 14 DAT than carfentrazone EPOST. Rice injury after LPOST was similar and $\leq$ 1% for treatments 14 DAT. Injury was $\leq$ 1% for all treatments 28 DAT (data not presented).

The main effects of application timing and herbicide and their interaction were not significant at any evaluation for hemp sesbania or ivyleaf morningglory control (Table 2). All treatments controlled hemp sesbania and ivyleaf morningglory $\geq$ 93 and 98%, respectively, 28 DAT (data not presented). A main effect of herbicide was observed for Palmer amaranth control 14 and 28 DAT (Table 4). Palmer amaranth control with all rates of

Table 3. Rice injury 7 and 14 d after treatment (DAT) with POST applications (EPOST, early POST; LPOST, late POST) of protoporphyrinogen IX oxidase (PPO)-inhibiting herbicides applied at two POST timings at Stoneville, MS in 2012 and 2013.[a]

Application timing	Herbicide	Rate	Injury[b] 7 DAT	Injury[b] 14 DAT
		g ai ha^{-1}	%	
EPOST	Carfentrazone	35	7 bc	6 b
	Saflufenacil	25	14 b	10 ab
	Saflufenacil	50	24 a	16 ab
	Saflufenacil	75	26 a	19 a
LPOST	Carfentrazone	35	3 c	0 c
	Saflufenacil	25	6 bc	0 c
	Saflufenacil	50	8 bc	1 c
	Saflufenacil	75	8 bc	1 c

[a] Data pooled over two experiments.

[b] Means within a column separated by the same letter are not significantly different at $P \leq 0.05$.

Table 4. Palmer amaranth control 14 and 28 d after treatment (DAT) with POST applications of protoporphyrinogen IX oxidase-inhibiting herbicides at Stoneville, MS in 2012 and 2013.[a]

		Palmer amaranth[b]	
Treatment	Rate	14 DAT[c]	28 DAT
	$g\ ai\ ha^{-1}$	%	
Carfentrazone	35	80 b	88 b
Saflufenacil	25	95 a	97 a
Saflufenacil	50	96 a	97 a
Saflufenacil	75	97 a	98 a

[a] Data pooled over two application timings (early POST, to one- to two-leaf rice, and late POST, to four-leaf to one-tiller rice) and two experiments.

[b] Means within a column followed by the same letter are not significantly different at $P \leq 0.05$.

Table 6. Rice injury 7 d after application of two rates of saflufenacil applied in mixtures with different adjuvants at Stoneville, MS in 2012 and 2013.[a]

	Injury
Adjuvant[b, c]	%
No adjuvant	6 d
COC	9 cd
MSO	17 ab
MSO/OSL/UAN	19 a
NIS	12 bc
Saflufenacil rate	
$25\ g\ ai\ ha^{-1}$	11 b
$50\ g\ ai\ ha^{-1}$	15 a

[a] Means for each adjuvant treatment and saflufenacil rate followed by the same letter are not significantly different at $P \leq 0.05$.

[b] Data for each adjuvant treatment are pooled across the two POST application rates of saflufenacil. Data for each saflufenacil rate are pooled across adjuvants. All data pooled across two experiments.

[c] Abbreviations: COC, crop oil concentrate; MSO, methylated seed oil; MSO/OSL/UAN, proprietary blend of methylated seed oil/organosilicate/urea ammonium nitrate; NIS, nonionic surfactant.

saflufenacil was similar and greater than that with carfentrazone at each evaluation. The number of days to 50% heading and rice yield were not affected by the treatments imposed in this study (Table 2).

Adjuvant Evaluation. The main effects of saflufenacil rate and adjuvant and all interactions containing these variables were not significant for rice injury 14 or 28 DAT, ivyleaf morningglory control at all evaluations, Palmer amaranth control 7 or 28 DAT, and the number of days to 50% heading (Table 5). For ivyleaf morningglory control, all treatments provided ≥ 95% control 28 DAT. The main effects of adjuvant and saflufenacil rate were significant for rice injury 7 DAT, but no interaction between these variables was detected.

Pooled across saflufenacil rate, rice injury 7 DAT was greater with mixtures containing MSO/OSL/UAN than those with NIS, COC, or no adjuvant (Table 6). Rice injury with mixtures containing MSO was similar to those with MSO/OSL/UAN or NIS 7 DAT. Saflufenacil treatments including no adjuvant or COC caused similar rice injury 7 DAT. Pooled across adjuvant treatments, saflufenacil applied at $50\ g\ ha^{-1}$ injured rice more than when applied at $25\ g\ ha^{-1}$.

The main effect of adjuvant was significant at all evaluations for hemp sesbania control and at 7 and 14 DAT for Palmer amaranth control (Table 5). Pooled across saflufenacil rates, the addition of any adjuvant to saflufenacil improved control of hemp sesbania over that of saflufenacil applied alone at all

Table 5. Significance of the main effects of saflufenacil rate and adjuvant and the interaction between the main effects for rice injury and ivyleaf morningglory, Palmer amaranth, and hemp sesbania control 7, 14, and 28 d after application (DAT), days to 50% heading, and rice yield in adjuvant evaluation.[a]

	Injury			Ivyleaf morningglory			Palmer amaranth			Hemp sesbania			Days	
Effects	7	14	28	7	14	28	7	14	28	7	14	28	to 50% heading	Rice Yield
	P-value													
Adjuvant	0.012	0.125	0.416	0.413	0.072	0.500	0.251	0.021	0.499	0.054	0.025	0.001	0.207	0.006
Saflufenacil rate	0.001	0.088	0.322	0.262	0.158	0.500	0.881	0.967	0.435	0.456	0.389	0.303	0.748	0.464
Adjuvant × saflufenacil rate	0.956	0.825	0.416	0.140	0.467	0.500	0.304	0.671	0.458	0.359	0.236	0.280	0.175	0.006

[a] Column headings 7, 14, and 28 designate evaluation intervals of 7, 14, and 28 d after herbicide treatment.

Table 7. Hemp sesbania and Palmer amaranth control with saflufenacil applied in mixtures with different adjuvants at Stoneville, MS in 2012 and 2013.[a, b]

Adjuvant	Hemp sesbania			Palmer amaranth	
	7 DAT	14 DAT	28 DAT	7 DAT	14 DAT
	———————————	———————	%	———————	———————
No adjuvant	71 b	63 b	44 b	92 b	86 b
COC	94 a	92 a	91 a	97 a	96 a
MSO	98 a	97 a	95 a	98 a	97 a
MSO/OSL/UAN	98 a	97 a	95 a	98 a	98 a
NIS	97 a	97 a	94 a	97 a	97 a

[a] Data are pooled across two rates of saflufenacil (25 and 50 g ai ha^{-1}) and two experiments. Means within a column followed by the same letter are not significantly different at $P \leq 0.05$.

[b] Abbreviations: DAT, days after treatment; COC, crop oil concentrate; MSO, methylated seed oil; MSO/OSL/UAN, proprietary blend of methylated seed oil/organosilicate/urea ammonium nitrate; NIS, nonionic surfactant.

Table 8. Net rough rice yield above the nontreated check after two rates of saflufenacil applied in mixtures with different adjuvants at Stoneville, MS in 2012 and 2013.[a]

Adjuvant[b]	Yield: Saflufenacil at 25 g ai ha^{-1}	Yield: Saflufenacil at 50 g ai ha^{-1}
	—————kg ha^{-1}	—————
No adjuvant	3,566 e	2,248 f
COC	4,833 a–d	5,153 a–d
MSO	5,356 abc	4,505 d
MSO/OSL/UAN	5,475 a	5,006 a–d
NIS	4,941 a–d	5,417 ab

[a] Data are pooled across two experiments. Means followed by the same letter are not significantly different at $P \leq 0.05$.

[b] Abbreviations: COC, crop oil concentrate; MSO, methylated seed oil; MSO/OSL/UAN, proprietary blend of methylated seed oil/organosilicate/urea ammonium nitrate; NIS, nonionic surfactant.

evaluations (Table 7). Hemp sesbania control 28 DAT was $\geq$ 91% for treatments that included adjuvants, but was only 44% for those with no adjuvant. Similar to hemp sesbania, Palmer amaranth control was improved with the addition of any adjuvant compared with treatments that did not include an adjuvant. However, differences in Palmer amaranth control with and without the addition of an adjuvant were not as drastic as observed with hemp sesbania. Palmer amaranth control with no adjuvant was 86% and increased to $\geq$ 96% 14 DAT for treatments that included an adjuvant.

An interaction of saflufenacil rate and adjuvant was detected for rough rice yield (Table 5). Rough rice yields were lowest after treatments that did not include an adjuvant, regardless of saflufenacil rate (Table 8). Rough rice yields after saflufenacil at both rates in combination with COC, MSO/OSL/UAN, or NIS, or saflufenacil at 25 g ha^{-1} with MSO, were greater than those after saflufenacil at 50 g ha^{-1} in combination with MSO. Yield after saflufenacil at 50 g ha^{-1} was similar to that of saflufenacil at either rate with COC, saflufenacil at 25 g ha^{-1} with NIS, and saflufenacil at 50 g ha^{-1} with MSO/OSL/UAN.

Few herbicides currently recommended for PRE application in Mississippi rice are effective against broadleaf weed species, and none of these controls Palmer amaranth (MSU-ES 2014a). Glyphosate- and acetolactate synthase (ALS)-resistant Palmer amaranth is prevalent in the Mississippi Delta region (Nandula et al. 2012). Although glyphosate is not used in rice, it is a foundation for herbicide weed control programs in crops that are rotated with rice (MSU-ES 2014a). The prevalence of GR/ALS-resistant Palmer amaranth in Mississippi has caused an overall increase in Palmer amaranth escapes and the amount of Palmer amaranth seed in the soil seed bank (MSU-ES 2014a; Nandula et al. 2012). The lack of a residual herbicide in rice for control of broadleaf weed species, especially Palmer amaranth, has negatively affected Mississippi rice production in recent years. Saflufenacil PRE controlled Palmer amaranth and other broadleaf weed species and caused no rice injury or negative impacts on rice maturity or yield. Saflufenacil at 50 g ha^{-1} provided 95% control of Palmer amaranth and ivyleaf morningglory 28 DAT, but at 35 DAT control of Palmer amaranth decreased to 88% while ivyleaf morningglory control was still 95%. Although hemp sesbania control with saflufenacil PRE was commercially unacceptable, control of Palmer amaranth and ivyleaf morningglory, which are both common and troublesome weeds of rice in Mississippi (Buehring and Bond 2008, Webster 2012), was $\geq$ 94% with saflufenacil at 75 g ha^{-1}.

Herbicides for POST control of hemp sesbania and ivyleaf morningglory in rice are currently available (MSU-ES 2014a). However, options for POST control of Palmer amaranth are very limited.

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Norsworthy et al. (2010) reported that triclopyr, 2,4-D, acifluorfen, carfentrazone, penoxsulam, halosulfuron, bentazon, and bispyribac applied alone or in combination with propanil or quinclorac did not control Palmer amaranth. The rapid spread of Palmer amaranth in Mississippi has created a need for a POST broadleaf herbicide to control this weed. Saflufenacil provides POST control of Palmer amaranth ($\geq$ 95%) greater than that of carfentrazone, which is commonly used for broadleaf weed control in rice. The addition of this herbicide would be beneficial to producers in Mississippi.

Palmer amaranth was recently moved to the most troublesome broadleaf weed of rice in Mississippi (Webster 2012). Early-season interference from Palmer amaranth can cause yield reductions in rice (Meyer et al. 2014). Control of *Amaranthus* spp. with PPO-inhibiting herbicides has been widely documented in other crops (Bond et al. 2006; Kichler et al. 2011; Meyers et al. 2013; Riar et al. 2012; Whitaker et al. 2010). However, PPO-inhibiting herbicides such as carfentrazone and acifluorfen that are traditionally used in rice do not control this weed to commercially acceptable levels (Grichar 2007; Norsworthy et al. 2008, 2010). Saflufenacil PRE and POST controlled Palmer amaranth. No rice injury was observed from PRE applications of saflufenacil. Injury was detected after POST applications; however, injury from saflufenacil at 25 g ha^{-1}, the currently labeled rate for POST applications in rice, was similar to that with carfentrazone at 35 g ha^{-1} (Anonymous 2013a). Control of Palmer amaranth was similar with all rates of saflufenacil and greater than that of carfentrazone applied POST. Rice injury and weed control were also influenced by saflufenacil rate and adjuvant combination. Rice injury was lowest after saflufenacil with no adjuvant and saflufenacil mixed with COC. Hemp sesbania and Palmer amaranth control was similar when any adjuvant was mixed with saflufenacil and was greater than that of saflufenacil applied alone.

In conclusion, saflufenacil controlled Palmer amaranth PRE and POST while causing injury no greater than that of currently labeled herbicides. Saflufenacil should be applied PRE at 50 to 75 g ha^{-1} depending on the timing of the next herbicide application and the weed spectrum present in the area. Weed control with POST applications was not influenced by saflufenacil rate or adjuvant; however, rice injury was influenced by saflufenacil rate, application timing, and adjuvant. Saflufenacil should be applied POST at 25 g ha^{-1} in combination with COC after rice reaches the two-leaf stage to maintain weed control and minimize injury, which coincides with the supplemental label granted recently received for saflufenacil in rice (Anonymous 2014b).

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