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Evaluation of Saflufenacil Use in Southern U.S. Rice Production

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Evaluation of saflufenacil use in southern U.S. rice production

By

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Research was conducted in 2012 and 2013 to evaluate the use of saflufenacil in rice (*Oryza sativa* L.). Studies included a preemergence evaluation of different rates of saflufenacil in comparison to one rate of carfentrazone, a postemergence evaluation of saflufenacil at different rates and carfentrazone at one rate at different postemergence timings, an adjuvant evaluation to assess rice injury and weed control from different adjuvants when mixed with saflufenacil, a Clearfield program evaluation where saflufenacil was compared to other broadleaf herbicides in a Clearfield weed control program, and a cultivar tolerance evaluation where postemergence applications of saflufenacil were compared to carfentrazone on five different commercial rice cultivars.

DEDICATION

I would like to dedicate this work to my son, Clayton Montgomery, my sisters, Hope and Megan Montgomery, and my parents, Amy and Bob Montgomery. I will never be able to thank you enough for your support and encouragement through the good times and the tough situations. Without these people and many more, I would not be where I am today.

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CHAPTER I

INTRODUCTION

Rice (*Oryza sativa* L.) 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 north-western part of the state (Miller and Street 2008). Rice hectarage 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 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). 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).

The three most common weeds in Mississippi rice fields today are barnyardgrass [*Echinochloa crus-galli* (L.) Beauv], Palmer amaranth (*Amaranthus palmeri* S. Wats), and hemp sesbania [*Sesbania herbacea* (P. Mill.) McVaugh] (Webster 2012). Through competition for light, resources, nutrients, and spaces, these species can be detrimental to rice production (Buehring and Bond 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, because many producers rely heavily on only a few of these, herbicide resistance is becoming problematic in rice fields (Hoagland et al. 2004).

Barnyardgrass resistance to propanil was first documented in 1994 (Hoagland et al. 2004), and barnyardgrass populations have now evolved resistance to propanil, quinclorac, and imazethapyr (Heap 2013; Riar et al. 2012a). Barnyardgrass can reduce rice yield up to 70% (Ottis and Talbert 2007). While grass species are generally more competitive than broadleaf species, research indicates that high densities of broadleaf weeds in rice and other monocot crops can significantly reduce yield and grain quality (Bond and Walker 2009; Moore et al. 2004; Smith 1988). Early-season infestations of Palmer amaranth cause yield reductions (Meyer et al. 2014). Although herbicide-resistant crops have been a staple for weed control in many different crops, due to increasing herbicide resistance and poor management practices, acceptable weed control can still be difficult to maintain (Woodyard et al. 2009). This necessitates producers become more diverse with the herbicide chemistries utilized in their fields and also to be more precise with their application timing to maintain weed control.

Cultural practices such as disking, proper flood timing, and adequate flood depth are also critical in a rice weed control program (Buehring and Bond 2008). Areas that are flooded too deep or shallow in a field can create pockets for weeds to germinate, grow, and produce seed (Buehring and Bond 2008). Maintaining proper flood depth can supplement weed control, especially of non-aquatic weed species that may have been present in the field early in the season. Retention levees maintain water levels in a rice field but also provide an optimum area for non-aquatic weeds to grow, produce seed, and potentially become a problem during the next growing season (Buehring and Bond 2008). Rotating rice fields to soybean (*Glycine max* (L.) Merr.), corn (*Zea mays* L.), or cotton (*Gossypium hirsutum* L.) can allow producers to utilize a more diverse herbicide spectrum that controls many weeds that are more problematic in rice (Buehring and Bond 2008).

Herbicide timing is a component of weed control (Parker et al. 2006). Timely herbicide applications improve weed control and increase crop yield (Parker et al. 2006). 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 greatest crop yields (Gower et al. 2002). Weeds are generally easier to control with POST herbicides when they are small and have not reached reproductive stages. When residual herbicides are not included with timely POST herbicide applications, weeds can emerge after the herbicide application, compete with the crop, and ultimately reduce yields (Loux et al. 2011). 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).

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 (Grossman et al. 2010). 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 hours after contact (Grossman et al. 2011). Saflufenacil efficacy is improved by the addition of adjuvants (Knezevic et al. 2009). Nonionic surfactant (NIS), crop oil concentrate (COC), or methylated seed oil (MSO) mixed with saflufenacil 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 [*Conyza canadensis* (L.) Cronq.] over that of saflufenacil applied with no adjuvant.

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 (field, pop, silage), cotton (fallow and postharvest), field pea [*Pisum sativum* L. ssp. *sativum* var. *arvense* (L.) Poir.], small grains, grain sorghum (*Sorghum bicolor* ssp. *bicolor*), soybean, and most recently for PRE and POST applications in rice (Anonymous 2013, 2014b). Saflufenacil has been commonly utilized for burndown in cotton, corn, and soybean because of its effective control of many broadleaf species, including glyphosate-resistant (GR) horseweed and GR Palmer amaranth (Anonymous 2013; Eubank et al. 2013; Waggoner et al. 2011).

Saflufenacil is labeled for broadleaf weed control in grain crops (Anonymous 2013) and has potential to be used in rice (Camargo et al. 2012). Hemp sesbania and Palmer amaranth are among the most common and troublesome weeds of rice in Mississippi (Webster 2012). Broadleaf weeds can be controlled with applications of saflufenacil alone and in combination with other rice herbicides (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). Camargo et al. (2012) reported that saflufenacil caused rice injury but the observed injury did not reduce yield. Palmer amaranth is difficult to control with the herbicides that are currently available in rice (Norsworthy et al. 2010). Saflufenacil controls Palmer amaranth, and has potential to be a useful tool in rice production (Anonymous 2013; Camargo et al. 2012). Control of *Amaranthus* ssp. with PPO-inhibiting herbicides has been widely documented in other crops (Bond et al. 2006; Kichler et al. 2012; Meyers et al. 2013; Riar et al. 2012b; Whitaker et al. 2010); however, PPO-inhibiting herbicides that are traditionally used in rice do not adequately control these species (Grichar 2007; Norsworthy et al. 2010; Shoup et al. 2003).

Saflufenacil has potential to benefit rice producers. This research will be beneficial in production scenarios by advancing weed control and determining the level of rice injury that could be expected following in-season applications of saflufenacil. The overall objective of this research is to determine if saflufenacil can be a tool for weed control in rice production. Specific objectives of this research are to (1) evaluate application rates and timings of saflufenacil in rice, (2) compare the efficacy of saflufenacil applied in mixtures with different adjuvants, (3) compare the efficacy of saflufenacil to other broadleaf herbicides applied in mixtures with imazethapyr in a Clearfield® rice system, and (4) evaluate response of different commercial rice cultivars to in-season applications of saflufenacil. We determined the effect that different application rates and timings of saflufenacil have on rice yield and weed control, the best adjuvant to mix with saflufenacil, how saflufenacil compares with other broadleaf herbicides, and the effects of saflufenacil when applied to different commercial rice cultivars.

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CHAPTER II

EVALUATION OF SAFLUFENACIL IN DRILL-SEEDED RICE (*Oryza sativa* L.)

Abstract

Herbicides for residual or POST control of Palmer amaranth in rice, the most common and troublesome broadleaf weed species of rice in Mississippi, are limited. Three studies were conducted in 2012 and 2013 at the Mississippi State University Delta Research and Extension Center in Stoneville to evaluate application rates and timings of saflufenacil in rice, and also the influence of adjuvants when mixed with saflufenacil applied POST. In the first and second studies, saflufenacil was applied at 25, 50, and 75 g ai ha^{-1} and was compared with carfentrazone at 35 g ai ha^{-1}. These herbicide treatments were applied PRE in the first study and early-postermergence (EPOST) to two- to three-leaf rice and late-postemergence (LPOST) to four-leaf to one-tiller rice in the second study. In the third study, saflufenacil was applied at 25 and 50 g ai ha^{-1} alone and in combination with non-ionic surfactant (NIS) at 0.25% v/v, crop oil concentrate (COC) at 1% v/v, methylated seed oil (MSO) at 1% v/v, and a proprietary blend of methylated seed oil/organosilicon/urea-ammonium nitrate (MSO/OSL/UAN) at 1% v/v at the mid-postemergence (MPOST) timing to three- to four-leaf rice. No injury occurred following the PRE treatments, and no control was observed from PRE applications of carfentrazone. Hemp sesbania and Palmer amaranth control increased with increasing saflufenacil rate. Hemp sesbania control with saflufenacil at any rate $\leq$25% at 35 DAT.

Palmer amaranth and ivyleaf morningglory control with saflufenacil applied PRE at 75 g ha^{-1} was $\geq$ 94% 35 DAT. In the second study, rice injury was influenced by application timing and rate of saflufenacil; however efficacy was not. Rice injury from saflufenacil at 25 g ha^{-1} and carfentrazone were similar EPOST and LPOST 7 DAT. Saflufenacil at 50 and 75 g ha^{-1} were the most injurious applied EPOST at 7 DAT. Control of hemp sesbania and ivyleaf morningglory were 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 the third study, rice injury was influenced by adjuvant and saflufenacil rate. Saflufenacil applied alone or in mixture with COC were 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 applied alone. 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.

Introduction

Rice (*Oryza sativa* L.) 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 north-western part of the state (Miller and Street 2008). Rice hectarage 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).

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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 (Grossman et al. 2010). 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 (Grossman et al. 2011).

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 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 (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 (Parker et al. 2006). 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/or 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 NIS, COC, or 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

Preemergence Evaluation

A study to evaluate rice response and weed control with different rates of saflufenacil PRE was conducted once in 2012 (33.44ºN, 90.91ºW) and twice in 2013

(33.45ºN, 90.90ºW and 33.40ºN, 90.93ºW) at the Mississippi State University Delta Research and Extension Center in Stoneville, MS. The soil series for 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 [*Ipomoea hederacea* (L.) Jacq.] were surface-seeded prior to 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 prior to 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 prior to 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 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 for 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 based on visual inspection of plotted residuals; therefore, nontransformed data were used in analyses. Data from the nontreated control were deleted prior to analysis of visual control estimates to stabilize variance. Yield data were analyzed in comparison to 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 siteyear 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 Drive, 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).

Postemergence 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 (33.44ºN, 90.91ºW) and 2013 (33.45ºN, 90.90ºW) 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 Preemergence 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 early-postemergence (EPOST) applied to two- to three-leaf rice and late-postemergence (LPOST) applied 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 burndown applications (Anonymous 2013b). Application equipment was as previously described in the Preemergence Evaluation.

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 Preemergence evaluation. However, in contrast to the Preemergence evaluation, data from plots treated with carfentrazone was 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 (33.44ºN, 90.91ºW) and 2013 (33.45ºN, 90.90ºW) 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 Preemergence Evaluations.

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% non-ionic surfactant, 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 MSO/OSL/UAN (Dyne-A-Pak, proprietary blend of polyalkyleneoxide-modified polyimethyliloxane, nonionic emulsifiers, methylated vegetable oils, and nitrogen fertilizer solution, Helena Chemical Co., Suite 300, 225 Schilling Boulevard, Collierville, TN 38017) at 1% (v/v). All treatments were applied mid-postemergence (MPOST) to three- to four-leaf rice. Treatments were applied as previously described in the Preemergence 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 Preemergence Evaluation.

Results and Discussion

Preemergence Evaluation

No injury was observed following 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 saflufenacil at 25, 50, and 70 g ha^{-1}, respectively (Table 2.1). 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 interval, 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 puts it at 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 following saflufenacil at 50 and 75 g ha^{-1} at all evaluations (Table 2.1). Although saflufenacil at 25 g ha^{-1} controlled of ivyleaf morningglory ≥ 87% at all evaluations, control was less than the two higher rates. Palmer amaranth control 20 and 28 DAT was similar with saflufenacil at 50 and 75 g ha^{-1}. By 35 DAT, the level of Palmer amaranth control increased with saflufenacil rate.

Few herbicides currently recommended for PRE application in Mississippi rice are effective against broadleaf weed species, and none of these control Palmer amaranth (MSU-ES 2014). 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 2014). The prevalence of glyphosate/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 (Nandula et al. 2012; MSU-ES 2014). 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 (J. A. Bond, personal communication). 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 ≥ 94% with saflufenacil at 75 g ha^{-1}.

Postemergence Evaluation

A treatment by timing interaction was detected for rice injury 7 and 14 DAT (Tables 2.2 and 2.3). Rice injury 7 DAT was greatest following saflufenacil at 50 and 75 g ha^{-1} (24 and 26%, respectively) EPOST (Table 2.3). 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 than carfentrazone EPOST at 14 DAT. Rice injury following 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 2.2). 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 at 14 and 28 DAT (Table 2.4). Palmer amaranth control with all rates of 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 2.2).

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

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 2.5). For ivyleaf morningglory control, all treatments provided $\geq$ 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 2.7). 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 it was 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. Pooled across saflufenacil rates, the addition of any adjuvant to saflufenacil improved control of hemp sesbania over that of saflufenacil applied alone at all evaluations (Table 2.7). 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 2.5). Rough rice yields were lowest following treatments that did not include an adjuvant, regardless of saflufenacil rate (Table 2.8). Rough rice yields following saflufenacil at both rates in combination with COC, MSO/OSL/UAN, or NIS, or saflufenacil at 25 g ha with MSO, were greater than those following saflufenacil at 50 g ha^{-1} in combination with MSO. Yield following 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.

In conclusion, 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 following POST applications; however injury from saflufenacil at 25 g ha^{-1} was similar to that with carfentrazone at 35 g ha^{-1}, the currently labeled rate for POST applications in rice (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 efficacy were also influenced by saflufenacil rate and adjuvant combination. Rice injury was lowest following 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.

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 efficacy of 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).

Table 2.1 Hemp sesbania, ivyleaf morningglory, and Palmer amaranth control with saflufenacil applied PRE at Stoneville, MS in 2012 and 2013[a, b]

		Hemp sesbania control			Ivyleaf morningglory control			Palmer amaranth control		
Treatments		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 based on $p \leq 0.05$.
[b] Abbreviation: DAT, days after treatment.

Table 2.2 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 days after treatment (DAT), days to 50% heading, and rice yield in postemergence evaluation of saflufenacil in Stoneville, MS, in 2012 and 2013.

Effects	Rice Injury			Hemp sesbania			Ivyleaf morningglroy			Palmer amaranth			Days to 50% heading	Rice yield
	7	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 days after herbicide treatment.

Table 2.3 Rice injury 7 and 14 days after treatment (DAT) with postemergence applications of PPO-inhibiting herbicides applied at two POST timings at Stoneville, MS, in 2012 and 2013[a].

		Rate	Injury[a]	
Application timing	Herbicide	g ai ha^{-1}	7 DAT	14 DAT
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. Means within a column separated by the same letter are not significantly different at $p \leq 0.05$.

Table 2.4 Palmer amaranth control 14 and 28 days after treatment (DAT) with postemergence applications of PPO-inhibiting herbicides at Stoneville, MS, in 2012 and 2013.

Treatment[a]	g ai ha^{-1}	Palmer amaranth control[b]	
		14 DAT	28 DAT
		——%——	
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 postemergence, to one- to two-leaf rice, and late postemergence, to four- to five-leaf rice) and two experiments.
[b] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$.

Table 2.5 Significance of the main effects of saflufenacil rate (SR) 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 days after application (DAT), days to 50% heading and rice yield in Adjuvant Evaluationa.

Main Effects[a]	Injury			Ivyleaf morningglory			Palmer amaranth			Hemp sesbania			Days to 50% heading	Rice Yield
	7	14	28	7	14	28	7	14	28	7	14	28		
	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	<.001	0.207	0.006
SR	<.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*SR	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 days after herbicide treatment.

Table 2.6 Rice injury 7 days after application of two rates of saflufenacil applied in mixtures with different adjuvants at Stoneville, MS, in 2012 and 2013[a].

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

Table 2.7 Hemp sesbania and Palmer amaranth control with saflufenacil applied in mixtures with different adjuvants at Stoneville, MS in 2012 and 2013[a, b, c]

	Hemp sesbania control			Palmer amaranth control	
Adjuvant	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.
[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.
[c] Means within a column followed by the same letter are not significantly different based at $p \leq 0.05$.

Table 2.8 Net rough rice yield above the nontreated check following two rates of saflufenacil applied in mixtures with different adjuvants at Stoneville, MS, in 2012 and 2013.

	Yield[a]	
Adjuvant[b]	Saflufenacil at 25 g ai ha^{-1}	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.

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CHAPTER III

UTILIZATION OF SAFLUFENACIL IN A CLEARFIELD® RICE WEED CONTROL PROGRAM

Abstract

Herbicides for postemergence control of Palmer amaranth, the most common and troublesome broadleaf weed of rice in Mississippi, are limited. Research was conducted in 2012 and 2013 at the Mississippi State University Delta Research and Extension Center in Stoneville to compare the efficacy of saflufenacil to other broadleaf herbicides applied in mixtures with imazethapyr in a Clearfield® rice system. Saflufenacil (50 g ai ha^{-1}), carfentrazone (35 g ai ha^{-1}), a prepackaged mixture of halosulfuron plus thifensulfuron (35 plus 4 g ai ha^{-1}), and a prepackaged mixture of propanil plus thiobencarb (2,240 plus 2,240 g ai ha^{-1}) were applied in mixture with imazethapyr (70 g ai ha^{-1}) early-postemergence (EPOST), to one- to rice in the two-leaf stage, and late-postemergence (LPOST), to rice in the four-leaf to one-tiller stage. No differences in injury among the broadleaf herbicides or between application timings were detected at any evaluation. Imazethapyr combined with propanil plus thiobencarb or saflufenacil provided the greatest control of barnyardgrass 7 and 14 DAT. Hemp sesbania, ivyleaf morningglory, and Palmer amaranth control was greatest and similar for imazethapyr combined with carfentrazone, propanil plus thiobencarb, and saflufenacil; however, rough rice yield was greatest for imazethapyr combined with propanil plus thiobencarb or

saflufenacil. Propanil plus thiobencarb or saflufenacil can be used in a Clearfield® rice weed control program to achieve optimum weed control and highest rice yields. Propanil plus thiobencarb or saflufenacil can be used in a Clearfield® rice weed control program to achieve optimum weed control and highest rice yields.

Introduction

Rice (*Oryza sativa* L.) 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 north-western 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 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).

The three most common weeds in Mississippi rice fields today are barnyardgrass [*Echinochloa crus*-galli (L.) Beauv], Palmer amaranth (*Amaranthus palmeri* S. Wats), and hemp sesbania [*Sesbania herbacea* (P. Mill.) McVaugh] (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 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).

While grass species are generally more competitive than broadleaf species, research indicates that high densities of broadleaf weeds in rice and other grass crops can reduce yield and grain quality (Bond and Walker 2009; Moore et al. 2004; Smith 1988). Barnyardgrass can reduce rice yield 70% (Ottis and Talbert 2007). Barnyardgrass resistance to propanil was first documented in 1994 (Hoagland et al. 2004), and barnyardgrass populations have now evolved resistance to propanil, quinclorac, and imazethapyr (Heap 2014; Riar et al. 2012). Although herbicides have been a staple for weed control in many different crops, due to increasing herbicide resistance and poor management practices, acceptable weed control can still be difficult to maintain (Norsworthy et al. 2010; Woodyard et al. 2009). This necessitates producers become more diverse with the herbicide chemistry they utilize and also to be more precise with application timings to maintain weed control.

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). This causes the plant to 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 (Grossman et al. 2010). 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 through 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 (NIS), crop oil concentrate (COC), or methylated seed oil (MSO) improved weed control over saflufenacil alone (Knezevic et al. 2009).

Herbicide timing is a critical component of weed control (Parker et al. 2006). Timely herbicide applications improve weed control and increase crop yield (Parker et al. 2006). 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). Weeds are generally easier to control with POST herbicides when weeds are small and have not reached reproductive stages. When residual herbicides are not included with timely POST herbicide applications, it is possible for weeds to emerge after the herbicide application, compete with the crop, and ultimately reduce yields (Loux et al. 2011). 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 when they should be controlled to avoid yield loss in the crop (Gower et al. 2002).

As weed management has become more challenging, researchers have reported a need for new herbicides and modes of action 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 currently labeled for preplant 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 use in rice (Anonymous 2014b). Saflufenacil is commonly utilized 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 (Anonymous 2013; Eubank et al. 2013; Waggoner et al. 2011).

Imidazolinone-resistant or Clearfield® rice was developed in 1993 through chemically induced mutation and exhibits tolerance to the imidazolinone herbicides (Croughan 1994). The herbicide used primarily in Clearfield rice is imazethapyr

(Anonymous 2011). Imazethapyr is also labeled for use in soybean and peanut (*Arachis hypogaea* L.) and controls a broad spectrum of weed species (Cantwell et al. 1989; Grichar 1994; Richburg et al. 1993). Imazethapyr is an acetolactate synthase (ALS; EC 2.2.1.6) inhibitor (Anonymous 2011). ALS herbicides catalyze the first step of biosynthesis of the branched-chain amino acids, valine, leucine, and isoleucine, that are essential for plant development (Stidham 1991; White et al. 2003). ALS-inhibiting herbicides were first introduced in 1982 and have become important tools for weed control in many of the major agronomic crops (White et al. 2003).

Clearfield® rice is currently produced on approximately 55 to 64% of rice hectarage in Mississippi (MSU-ES 2014b; Norsworthy et al. 2013). Imazethapyr is commonly used to control grass weeds such as barnyardgrass, broadleaf signalgrass (*Urochloa platyphylla* Nash.), and red rice (*Oryza sativa* L.). (Bollich et al. 2002; Masson and Webster 2001; Noldin et al. 1999; Ottis et al. 2003; Pellerin et al. 2004), however, additional herbicides are commonly mixed with imazethapyr for increased control of broadleaf weed species, such as hemp sesbania and Palmer amaranth (MSU-ES 2014b; Norsworthy et al. 2008; Zhang et al. 2006). Pellerin et al. (2004) reported $\leq$ 10% control of hemp sesbania from imazethapyr applied alone, but control was increased to $\geq$ 84% when bentazon plus acifluorfen, carfentrazone, halosulfuron, propanil plus molinate, triclopyr, or bispyribac-sodium were mixed with imazethapyr POST. Zhang et al. (2006) reported that the addition of bispyribac-sodium, carfentrazone, or propanil plus molinate to imazethapyr POST improved overall weed control and resulted in greater grain yields than imazethapyr applied alone. Tank mixes for improved weed control spectrum with imazethapyr are common; however, cautions should be taken when mixing imazethapyr with other herbicides. Antagonism from mixing imazethapyr with some herbicides has been reported (Li et al. 2002).

Saflufenacil is labeled for broadleaf weed control in grain crops and has potential to be used in rice (Camargo et al. 2012). Hemp sesbania and Palmer amaranth are among the most common and troublesome weeds of rice in Mississippi (Webster 2012). Broadleaf weeds can be controlled with applications of saflufenacil alone and in mixtures with other rice herbicides (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 could be a useful tool in rice production because it controls Palmer amaranth (Anonymous 2013; Camargo et al. 2012), the most troublesome broadleaf weed species in Mississippi (Webster 2012). Herbicides labeled for control of this weed in rice are limited (MSU-ES 2014b; Norsworthy et al. 2010). Camargo et al. (2012) observed that saflufenacil caused rice injury but the observed injury did not reduce yield. Saflufenacil was recently labeled for POST applications in rice (Anonymous 2014b). The objective of this research was to compare the efficacy and crop injury of saflufenacil to other broadleaf herbicides applied in mixture with imazethapyr in a Clearfield® weed control program.

Materials and Methods

A study to compare the efficacy of saflufenacil to other broadleaf herbicides applied in mixtures with imazethapyr in a Clearfield rice® system was conducted in 2012 (33.44ºN, 90ºW) and 2013 (33.45ºN, 90.90ºW) at the Mississippi State University Delta Research and Extension Center in Stoneville, MS. Soil series was a Sharkey clay (very-fine, smectitic, thermic Chromic Eqiaquerts) with a pH of 8.2 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, barnyardgrass, hemp sesbania, Palmer amaranth, and ivyleaf morningglory [*Ipomoea hederacea* (L.) Jacq.] were surface-seeded prior to 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 both years, the study was surface-irrigated as needed, and a 6 to 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 and Bond 2008). Nitrogen fertilizer was applied as urea at approximately 165 kg ha^{-1} immediately prior to flood establishment. Standard agronomic practices were used during the growing season (Buehring 2008). After the final weed control 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) crop oil concentrate (Agri-Dex, a 99% crop-oil concentrate, Helena Chemical Co., 5100 Poplar Ave., Memphis, TN 38137) was applied as a broadcast spray twice, approximately 7 days apart, to control of hemp sesbania and facilitate mechanical harvest.

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 early-postemergence (EPOST) treatments applied to rice in the one- to two-leaf stage, and late-postemergence (LPOST) treatments applied to rice in the four-leaf to one-tiller stage. The second factor was broadleaf herbicide and consisted of no broadleaf herbicide, saflufenacil at 50 g ha^{-1}, carfentrazone at 35 g ha^{-1}, a prepacked mixture of halosulfuron plus thifensulfuron at 35 plus 4 g ha^{-1}, and a prepacked mixture of propanil plus thiobencarb 2,240 plus 2,240 g ha^{-1}. Imazethapyr at 70 g ha^{-1} was applied to all plots at both the EPOST and LPOST timing and the broadleaf herbicide was applied in mixture with imazethapyr at the designated timing. The no broadleaf herbicide treatment consisted of imazethapyr alone applied at each application timing. A nontreated check was included for comparison. All treatments were mixed crop oil concentrate at 1% v/v (Agri-Dex, a 99% crop-oil concentrate, Helena Chemical Co., 5100 Poplar Ave., Memphis, TN 38137). Treatments were applied with a CO_2-pressurized backpack sprayer and hand-held boom 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 barnyardgrass, hemp sesbania, ivyleaf morningglory, and Palmer amaranth were visually estimated at 7, 14, and 28 days application (DAT) on a scale of 0 to100% where 0=no rice injury or weed control and 100=complete plant death. Barnyardgrass populations were 110 and 30 plants m^{-2} EPOST and LPOST, respectively, in 2012 and 11 and 33 plants m^{-2} EPOST and LPOST, respectively, in 2013. Barnyardgrass plants were 3 and 8 cm in height at the respective timings both site years. Hemp sesbania populations were 43 plants m^{-2} at each timing 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, 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} EPOST and LPOST, respectively, in 2012 and 22 and 11 plants m^{-2} 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. The number of days to 50% heading was recorded as an indication of rice maturity by calculating the time period from seedling emergence until 50% of rice plants in an individual plot had visible panicles. Plots were drained approximately 2 wk before harvest maturity was reached. 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

The square roots of visual injury and control estimates were arcsine transformed. The transformation did not improve homogeneity of variance based on visual inspection of plotted residuals; therefore, nontransformed data were used in analyses. Data from the nontreated control were deleted prior to analysis of visual crop injury and weed control estimates to stabilize variance. Yield data were analyzed in comparison to 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. Nontransformed data were subjected to the Mixed Procedure (Statistical software Release 9.3, SAS Institute Inc., 100 SAS Campus Drive, 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 application timing, broadleaf herbicide, and the interaction between these variables. 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).

Results and Discussion

The main effects of application timing and broadleaf herbicide, and the interaction of these variables were not significant for rice injury at any evaluation (Table 3.1). A main effect of application timing was observed for barnyardgrass control 28 DAT and hemp sesbania and ivyleaf morningglory control 14 DAT (Table 3.2). Pooled across broadleaf herbicide treatment, barnyardgrass control was increased from 76% when a broadleaf herbicide was included with imazethapyr LPOST to 84% when a broadleaf herbicide was included EPOST (Table 3.3). However, hemp sesbania and ivyleaf morningglory control were higher when a broadleaf herbicide was included with imazethapyr at the LPOST timing.

The main effect of broadleaf herbicide was significant for barnyardgrass, Palmer amaranth, hemp sesbania, and ivyleaf morningglory at the 7 and 14 DAT rating interval (Tables 3.2, 3.4 and 3.5). Pooled across application timing, the addition of saflufenacil and propanil plus thiobencarb improved control of barnyardgrass over that of imazethapyr alone. Saflufenacil or propanil plus thiobencarb in combination with imazethapyr provided the greatest control 7 and 14 DAT (≥ 85% and 81%, respectively). Barnyardgrass control with imazethapyr was not influenced by the addition of carfentrazone or halosulfuron plus thifensulfuron. Saflufenacil does not control grass weed species (Anonymous 2013); however, previous research has reported that saflufenacil causes yield reducing injury to other grass crops such as barley, corn, Proso millet, and wheat (Frihauf et al. 2010; Lyon and Kniss 2010; Moran et al. 2011; Sikkema et al. 2008). Also, the saflufenacil formulation used in this research was an emulsifiable concentrate (EC). Emulsifiable concentrate herbicide formulations can cause increased crop and weed responses compared with other formulations of the same herbicide (Fish et al. 2014). The combination of these factors increased barnyardgrass injury and may possibly explain why saflufenacil mixed with imazethapyr improved control compared to that of imazethapyr alone. The increase in control barnyardgrass control from propanil plus thiobencarb was because this herbicide exhibits barnyardgrass control (MSU-ES 2014b).

Palmer amaranth (Table 3.4), hemp sesbania (Table 3.5), and ivyleaf morningglory (3.5) control with treatments that included saflufenacil, propanil plus thiobencarb, and carfentrazone was greater 7 and 14 than with treatments that included halosulfuron plus thifensulfuron or imazethapyr alone. The low Palmer amaranth control with imazethapyr or halosulfuron plus thifensulfuron was attributed to the ALS-resistant Palmer amaranth that was present at the research site (MSU-ES 2014a; Nandula et al. 2012).

A significant effect of broadleaf herbicide was also detected for hemp sesbania and ivyleaf morningglory control 28 DAT (Table 3.6). Hemp sesbania control 28 DAT was greater with all treatments that included a broadleaf herbicide compared with imazethapyr alone. Saflufenacil, propanil plus thiobencarb, and carfentrazone controlled more hemp sesbania than halosulfuron plus thifensulfuron or imazethapyr alone. Ivyleaf morningglory control was similar among all treatments that included a broadleaf herbicide; however, saflufenacil, propanil plus thiobencarb, and carfentrazone provided greater control than that of imazethapyr alone.

Rough rice yield was influenced by broadleaf herbicide treatment, but not application timing (Table 3.6). Rough rice yields were greatest in plots treated with saflufenacil or propanil plus thiobencarb. Yields following carfentrazone and halosulfuron plus thifensulfuron were greater than that of imazethapyr alone, but less than that in plots treated with saflufenacil or propanil plus thiobencarb. Low yields following imazethapyr alone and halosulfuron plus thifensulfuron treatments were attributed to poor weed control compared with the other treatments. Hemp sesbania and ivyleaf morningglory control was similar with saflufenacil, propanil plus thiobencarb, and carfentrazone; however, carfentrazone only provided 78% control of Palmer amaranth in comparison to 96% and 92% from saflufenacil and propanil plus thiobencarb treatments, respectively. Although grass weed species are generally more competitive than broadleaf weed species, high densities of broadleaf weed species can cause negative impacts on rice yield (Smith 1988). Early-season Palmer amaranth interference has also been documented to cause reductions in rice yield (Meyer et al. 2014). The differences in yield following carfentrazone compared with saflufenacil or propanil plus thiobencarb could be partially explained by the numeric differences in control of Palmer amaranth among these treatments.

Camarago et al. (2012) reported that saflufenacil caused rice injury that did not cause a reduction in yield. Results of the current research indicate that injury from saflufenacil is similar to that of other herbicides currently in use in rice production systems. Barnyardgrass and Palmer amaranth are currently the two most common and troublesome weeds of rice in Mississippi (Webster 2012). These species can cause detrimental impacts on rice yield when allowed to compete with rice (Meyer et al. 2014; Ottis and Talbert 2007; Smith 1988). Saflufenacil at 50 g ha^{-1}, in combination with imazethapyr applied EPOST or LPOST, provided similar or improved control of barnyardgrass, hemp sesbania, ivyleaf morningglory, and Palmer amaranth compared with other broadleaf herbicides that are used in rice and caused no negative impact on rice maturity or rough rice yields. Results indicate that saflufenacil is an effective, safe tool for broadleaf weed control in Clearfield® rice.

Table 3.1 Significance of the main effects of application timing and broadleaf herbicide treatment and the interaction among the main effects for rice injury and maturity from broadleaf herbicides applied in mixtures with imazethapyr.

	Rice Injury[a]			
Effects	7 DAT	14 DAT	28 DAT	Maturity[b]
	p-value			
Application timing	0.9099	0.3218	0.8120	0.0939
Broadleaf herbicide	0.2075	0.4157	0.7979	0.1816
Application timing* broadleaf herbicide	0.9712	0.4157	0.9456	0.4259

[a] Abbreviation: DAT, days after treatment.
[b] Rice maturity was determined by calculating the number of days from rice emergence until 50% of the plants in each plot had a visible panicle.

Table 3.2 Significance of the main effects of application timing and broadleaf herbicide treatment and interaction among the main effects for barnyardgrass, hemp sesbania, and ivyleaf morningglory, and Palmer amaranth control at 7, 14, and 28 days after treatment (DAT) with broadleaf rice herbicides applied in mixtures with imazethapyr[a].

Effects	Barnyardgrass			Hemp sesbania			Ivyleaf morningglory			Palmer amaranth		
	7	14	28	7	14	28	7	14	28	7	14	28
	p-value											
Application timing	0.257	0.796	0.013	0.140	0.004	0.564	0.108	0.042	0.489	0.803	0.495	0.107
Broadleaf herbicide	0.018	0.030	0.055	<.001	<.001	<.001	0.001	0.002	0.010	<.001	0.004	0.115
Application timing* broadleaf herbicide	0.170	0.303	0.228	0.163	0.613	0.430	0.029	0.054	0.370	0.085	0.162	0.288

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

Table 3.3 Barnyardgrass, hemp sesbania, and ivyleaf morningglory control at different evaluation intervals with imazethapyr-based herbicide mixtures applied at two application timings in Stoneville, MS, in 2012 and 2013[a, b, c].

Application timing	Barnyardgrass control	Hemp sesbania control	Ivyleaf morningglory control
	28 DAT	14 DAT	14 DAT
		%	
EPOST	84 a	77 b	79 b
LPOST	76 b	81 a	91 a

[a] Data are pooled across five herbicide treatments (imazethapyr applied alone at 70 g ai ha^{-1} and in combination with saflufenacil at 50 g ai ha^{-1}, propanil plus thiobencarb at 2,240 plus 2,240 g ai ha^{-1}, carfentrazone at 35 g ai ha^{-1}, and halosulfuron plus thifensulfuron at 35 plus 4 g ai ha^{-1}
[b] Abbreviations: EPOST, early-postemergence (1-2 leaf rice growth stage). LPOST, late-postemergence (4-leaf-1-tiller rice growth stage); DAT, days after treatment.
[c] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$.

Table 3.4 Barnyardgrass and Palmer amaranth control 7 and 14 days after treatment (DAT) with imazethapyr applied alone and in mixtures with broadleaf herbicides in Stoneville, MS in 2012 and 2013[a, b].

Herbicide	Barnyardgrass control		Palmer amaranth control	
	——%		———	
	7 DAT	14 DAT	7 DAT	14 DAT
Imazethapyr alone	70c	70 c	31 b	38 b
Carfentrazone	76 bc	74 bc	83 a	78 a
Halosulfuron plus thifensulfuron	73 c	74 bc	32 b	41 b
Propanil plus thiobencarb	88 a	87 a	93 a	92 a
Saflufenacil	85 ab	81 ab	95 a	96 a

[a] Data pooled across two application timings and two experiments. Application timings were to one- to two-leaf rice and to four-leaf to one-tiller rice.
[b] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$.

Table 3.5 Control of hemp sesbania and ivyleaf morningglory control 7 and 14 days after treatment (DAT) with broadleaf herbicides at Stoneville, MS, in 2012 and 2013[a, b, c].

Herbicide treatment	Hemp sesbania control		Ivyleaf morningglory control	
	7 DAT	14 DAT	7 DAT	14 DAT
	%			
Imazethapyr alone	24 c	19 c	51 c	60 c
Carfentrazone	94 a	96 a	97 a	96 a
Halosulfuron plus thifensulfuron	78 b	89 b	64 b	77 b
Propanil plus thiobencarb	95 a	94 a	90 a	94 a
Saflufenacil	96 a	95 a	97 a	97 a

[a] Data are pooled across two application timings and two experiments. Application timings were to one- to two-leaf rice and to four-leaf to one-tiller rice. All plots were treated with imazethapyr at each application timing. Broadleaf herbicide treatments were mixed with imazethapyr and applied at the proper application timing.
[c] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$.

Table 3.6 Control of hemp sesbania and ivyleaf morningglory 28 days after treatment (DAT) and rough rice yield from broadleaf herbicides applied in mixtures with imazethapyr from Stoneville, MS in 2012 and 2013[a, b].

Herbicide	Hemp sesbania control 28 DAT	Ivyleaf morningglory control 28 DAT	Yield
	——————%——————		kg ha^{-1}
Imazethapyr alone	14 c	86 b	7720 c
Carfentrazone	93 a	97 a	10389 b
Halosulfuron + thifensulfuron	85 b	92 ab	10080 b
Propanil+thiobencarb	92 a	97 a	12778 a
Saflufenacil	94 a	98 a	11865 a

[a] Data are pooled across two application timings and two experiments. Application timings were applied to one- to two-leaf rice and to four-leaf to one-tiller rice. All plots were treated with imazethapyr at each application timing. Broadleaf herbicide treatments were mixed with imazethapyr and applied at the proper application timing.
[b] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$.

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CHAPTER IV

RESPONSE OF COMMERCIAL RICE CULTIVARS TO IN-SEASON APPLICATIONS OF SAFLUFENACIL

Abstract

Labeling for saflufenacil was recently updated to include in-season applications to rice, but no research has been published on differential rice cultivar response to POST applications of saflufenacil. Research was conducted in 2012 and 2013 at the Delta Research and Extension Center in Stoneville, MS, to evaluate the response of five commercial rice cultivars to in-season applications of saflufenacil. Rice cultivars included ‘Cheniere’, ‘CL151’, ‘Caffey’, ‘CL261’, and ‘CLXL745’. Treatments included a nontreated control, saflufenacil at 50 g ai ha^{-1}, and carfentrazone at 35 g ai ha^{-1} applied mid-postemergence (MPOST) to rice in the three- to four-leaf stage. Differences in tolerance among rice cultivars were observed; however, injury with saflufenacil was similar to that of carfentrazone for all cultivars. Pooled across cultivars, injury was greatest at 3 and 7 days after treatment (DAT; 21 and 17%, respectively). At the 14 DAT evaluation, rice injury was only 5% and by 28 DAT injury was 1%. 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 NDVI, maturity, mature plant height, and rice yield between treated and nontreated plots.

Results indicate that, even though visual rice injury occurs following application, saflufenacil is safe for application to rice cultivars currently grown in the southern U.S. rice-producing area.

Introduction

Rice (*Oryza sativa* L.) 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 ai of herbicides in comparison to 117,000 kg ai 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 today are barnyardgrass [*Echinochloa crus-galli* (L.) Beauv], Palmer amaranth (*Amaranthus palmeri* S. Wats), and hemp sesbania [*Sesbania herbacea* (P. Mill.) McVaugh] (Webster 2012). Weeds compete with crops 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 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, 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 new protoporphyrinogen IX oxidase (PPO)-inhibiting herbicide marketed by BASF (Grossman et al. 2010). Saflufenacil 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 (Grossman et al. 2010). 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 through 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 (NIS), crop oil concentrate (COC), or methylated seed oil (MSO) 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 this problem. 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 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 preplant-only applications in rice (Anonymous 2013b, 2014b). Saflufenacil is commonly utilized 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 (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). Hemp sesbania and Palmer amaranth are among the most common and troublesome weeds of rice in Mississippi (Webster 2012). Saflufenacil applied alone and in mixtures with other rice herbicides controls broadleaf weed species 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 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), the most common and troublesome broadleaf weed species in Mississippi (Webster 2012).

Camargo et al. (2012) reported that saflufenacil POST caused rice injury, but this injury did not reduce yield. Rice cultivar and growth stage can impact 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 et al. 2004; Zhang and Webster 2002). 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, the most common and troublesome broadleaf weed of rice in Mississippi, 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 differential cultivar tolerance to this herbicide. The objective of this research was to compare the response of five commercial rice cultivars to POST applications of saflufenacil and compare the response following saflufenacil to that from 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 (33.40ºN, 90.94ºW) and twice in 2013 (33.43ºN, 90.90ºW; 33.41ºN, 90.93ºW) at the Mississippi State University Delta Research and Extension Center in Stoneville, MS. Soil at all sites was a Skarkey 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 kg ai ha^{-1} in November for control of GR Italian ryegrass (Bond et al. 2014). Emerged vegetation was controlled prior to planting using glyphosate (Roundup Weathermax, herbicide, Monsanto Company, 800 N. Lindburgh 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 (‘Cheniere’ [Reg. No. CV-120-120, PI 634719), ‘CL151’ (Reg. No. CV-133PI 654463]), two inbred, medium-grain (‘Caffey’ [Reg. No. CV-138, PI 665059], 'CL261' [pending regulatory approval]) and one hybrid ('CLXL745') rice cultivar were planted on May 9, 2012, April 9, 2013, and April 30, 2013. All cultivars were seeded at 95 kg ha^{-1} (400 to 450 seed/m^2) except 'CLXL745', which is a hybrid. Because of its heterosis, a seeding a rate of 28 kg ha^{-1} (125 seed/m^2) was utilized for 'CLXL 745' 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 rows measuring 4.6 m in length. 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 five commercial rice cultivars (previously described). The second factor was herbicide and consisted of no herbicide treatment (control), 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 carfentrazone has a range of use rates (Anonymous 2013a), 35 g ha^{-1} was chosen because it represents twice the rate typically utilized by producers in Mississippi (J. A. Bond, personal communication). 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 (XR 11002 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% (rice 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. Normalized difference vegetative index (NDVI) was assessed using a hand-held crop sensor (GreenSeeker, crop sensing system, Trimble Navigation Limited, 935 Stewart Drive, Sunnyvale, CA 94085) 4 w after flood establishment as an indication of plant health. 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 (4.76mm) 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 years, locations, and replications nested within years by location (Blouin et al. 2011). Considering year and location 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 were acrsine 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, mature rice height, and yield (rough, total or whole milled), and evaluation interval was not included as a factor in analyses of these parameters. 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, which is a macro for converting mean separation output letter groupings (Saxton 1998).

Results and Discussion

The main effects of cultivar and herbicide and the interaction of these variables were not significant for NDVI, days to 50% heading, mature rice height, or yield (rough, total milled, and whole milled) (Table 4.1). No differences in injury with saflufenacil or carfentrazone were observed on individual cultivars, however cultivars responded differently. Pooled across herbicides and rating intervals, CLXL745 (13%) was injured more than CL151 or Cheniere (10% and 9%, respectively) (Table 4.2). Cheniere was more tolerant than Caffey or CL261. Injury was similar at 3 and 7 d after treatment regardless of cultivar or herbicide treatment (Table 4.3). Injury declined to 5% at 14 DAT, and by 28 DAT, injury was only 1%.

Previous research reports varied 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 susceptibile to fenoxaprop than long-grain cultivars 'Tebonnet' and 'Lamont' (Griffin and Baker 1990). Lanclos et al. (2003) reported that glufosinate applications to medium-grain glufosinate-resistant cultivars delayed heading 7 to 15 d, but heading of long-grain glufosinate-resistant cultivars were only delayed 3 to 5 d. 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 hybrid long-grain cultivar XL723 (Bond and Walker 2012). Although differences in level of injury were noted among the cultivars evaluated in the current research, injury from saflufenacil was similar to that of carfentrazone, a herbicide currently labeled for applications to rice (Anonymous 2013a). Inbred long-grain cultivars CL151 and Cheniere were more tolerant to both herbicides than hybrid long-grain cultivar CLXL745 based on visual estimates of injury. Tolerance of medium-grain cultivars CL261 and Caffey was similar to that of CL151. However, Cheniere was injured less than Caffey (Table 4.2). 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.

Since the confirmation of a GR biotype of Palmer amaranth in 2004, this species has become extremely problematic in GR cotton, corn, and soybean (Barnett et al. 2013; Bond and Oliver 2006; Ward et al. 2013). Recently, Palmer amaranth has also become problematic in Mississippi rice production. Palmer amaranth is currently the most common and troublesome broadleaf weed species of rice in Mississippi (Webster 2012). Available herbicides do not provide adequate control of this weed creating a niche for a new broadleaf herbicide in rice (Norsworthy et al. 2010). Control of *Amaranthus* ssp. 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 traditionally used in rice, carfentrazone and acifluorfen, provide less than acceptable control of this weed (Grichar 2007; Norsworthy et al. 2008; Norsworthy et al. 2010). There is currently a need for a herbicide to control Palmer amaranth in rice (Norsworthy et al. 2010). Saflufenacil controls Palmer amaranth and other broadleaf weed species (Geier et al. 2009). Similar to other research, hybrid and inbred medium-grain cultivars were injured more than inbred, long-grain cultivars.

However, with all cultivars evaluated, the injury observed following saflufenacil did not negatively impact 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.

Table 4.1 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)

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

Table 4.2 Response of five commercial rice cultivars to PPO-inhibiting herbicides at Stoneville, MS, in 2012 and 2013.

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

[a] Means for each cultivar are 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 days 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 4.3 Injury of commercial rice cultivars from two PPO-inhibiting herbicides at 4 evaluation intervals in Stoneville, MS in 2012 and 2013.[a]

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

[a] Injury data at each evaluation interval are 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 $p \leq 0.05$.

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