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Synergism with Imazamox Co-applications for Red Rice Control

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A study was conducted at three locations in Louisiana to evaluate the interactions of imazamox at 44 g ai ha^{-1} mixed with propanil, thiobencarb, or with a prepackaged mixture of propanil plus thiobencarb. A synergistic response was observed for red rice control for all treatments at 14 days after treatments (DAT); however, at 21 DAT a neutral response was observed for imazamox mixed with propanil or thiobencarb. A synergistic response occurred for red rice control when imazamox was mixed with propanil plus thiobencarb at 3360 g ai ha^{-1} for all evaluation dates; however, imazamox mixed with propanil plus thiobencarb at 1680 g ha^{-1} resulted in synergism at the same evaluations except at 35 DAT with neutral response. Synergism was observed for barnyardgrass control with imazamox mixed with propanil plus thiobencarb at 3360 g ha^{-1} at 35 and 49 DAT. The only antagonism observed for barnyardgrass control was at 42 DAT with imazamox plus propanil at 840 and 1680 g ha^{-1} or mixed with the prepackage mixture at 1680 g ha^{-1}. Rice treated with imazamox mixed with propanil plus thiobencarb at 3360 g ha^{-1} yielded 5770 kg ha^{-1}.
Nomenclature: Propanil; thiobencarb; barnyardgrass, *Echinochloa crus-galli* (L.) Beauv.; red rice, *Oryza sativa* L.; rice, *Oryza sativa* L.
Keywords: Antagonism; neutral response.

Weeds are a constant problem in rice production and can cause yield loss wherever rice is grown (Chisaka 1977; Zhang et al. 2003). Past research has demonstrated grain yield reduction from weed competition (Smith 1968), and red rice and barnyardgrass are some of the most common weeds of rice production worldwide (Estorninos et al. 2005; Gealy et al. 2003). Effective weed control is very important for successful rice production, and numerous herbicides are available for weed management in rice. In order to maximize rice yield, it is important to develop an effective herbicide program for red rice and barnyardgrass (Webster 2014).

Mixing or rotating herbicides with different modes of action can assist in weed control and reduce potential development of resistant weeds (Neve et al. 2011; Norsworthy et al. 2012). Mixing two or more herbicides can provide growers multiple benefits, such as a broader weed control spectrum and reduced costs (Hydrick and Shaw 1994). Research has been conducted on a vaiety of herbicide mixtures, including mixtures with varying spectra of control, different modes of action, and different combinations of postemergence and soil-applied herbicides. Weed control spectrum can be broadened by mixing a herbicide that controls only grasses with a herbicide that is active on broadleaf weeds (Blouin et al. 2010). Another practice is to mix a herbicide having nonselective postemergence activity on a stale seedbed production system with a herbicide possessing soil-residual activity (Webster and Shaw 1997).

An imidazolinone resistant (IR) rice (Clearfield® herbicide label, BASF Corporation, Research Triangle Park, NC 27709) production system consists of using rice cultivars resistant to the imidazolinone chemical family. Imazamox (Beyond® rice, BASF Corporation, Research Triangle Park, NC 27709) is labeled for control of red rice and other troublesome weeds when applied to IR cultivars, and it is an effective strategy for red rice management in rice production (Fish et al. 2016; Pellerin et al. 2004; Webster and Masson 2001).

Propanil has excellent selectivity between rice and barnyardgrass based on differential metabolism, and

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has been labeled as a broad-spectrum postemergence herbicide since 1961 (Shaner 2014). The selectivity between grass weeds and rice is based on physiological processes (Baltazar and Smith 1994; Smith 1961). Propanil has long been used to control annual grass and broadleaf weeds in southern US rice production (Smith 1965); however, there is documented propanil-resistant barnyardgrass in the midsouth (Carey at al. 1995).

Thiobencarb belongs to the thiocarbamate chemical family, and has activity on barnyardgrasses and red rice when applied preemergence and postemergence to three-leaf rice (Gressel and Valverdi 2009). Thiobencarb has been shown to have activity on *Leptochloa* spp., aquatic plants, and annual sedges. In the United States, thiobencarb is widely applied to rice fields in California, Louisiana, Florida, and Arkansas (Schmelzer et al. 2005).

It is generally understood that three types of responses can occur with herbicide mixtures: synergistic, antagonistic, and neutral (Colby 1967; Fish et al. 2015). Synergism occurs when the observed effect is higher than the isolated effect of each herbicide, and antagonism occurs when the effects of the herbicide mixture is less than the herbicidal effect of each herbicide applied alone (Blouin et al. 2004; Colby 1967). Antagonistic effects can imply levels of infestation that are higher after herbicides are applied. If herbicide interactions are not significant in either a synergistic or antagonistic response, a neutral response occurs (Fish et al. 2015, 2016).

A generalized expression for expected responses was given by Colby (1967), which when applied to means, yields the defining contrast for synergism and antagonism (Flint et al. 1988). Blouin et al. (2004) offered a third strategy employing nonlinear mixed-model methodology (NLMIXED) of SAS to perform tests of hypotheses (SAS Institute 2011), but its implementation became considerably more difficult and inefficient as the experimental design and analysis became more complex. Blouin's modified Colby's procedure can be used to separate the means of herbicide mixtures to determine if a synergistic, antagonistic, or neutral response occurs when mixing herbicides together in a single application for weed control (Blouin 2010).

In general, the use of herbicide mixtures results in an increased spectrum of weed control and the possibility of reducing the herbicide rate (Moss et al. 2007). In 2015, a synergistic response of red rice control with co-applications or mixtures of herbicides with imazethapyr was reported by Fish et al. (2015). Similar red rice control was observed when imazamox and propanil were mixed (Fish et al. 2016). The addition of clomazone with propanil plus thiobencarb promoted a synergistic response in barnyardgrass (Matzenbacher et al. 2015). Matzenbacher et al. (2015) reported that acetyl CoA carboxylase (ACCase) inhibitors mixed with acetolactate synthase (ALS) inhibitors, quinclorac, clomazone plus propanil, or thiobencarb resulted in antagonism with respect to barnyardgrass. Similar results were observed for the use fenoxaprop mixed with propanil plus molinate or bentazon for barnyardgrass control (Zhang et al. 2005).

The objective of this study was to evaluate the interaction of an imazamox mixture with propanil (RiceShot® herbicide label, RiceCo LLC, Memphis, TN 38137) or thiobencarb (Bolero® herbicide label, Valent USA Corp, Walnut Creek, CA 94596) or a prepackaged mixture of propanil plus thiobencarb (RiceBeaux® herbicide label, RiceCo LLC, Memphis, TN 38137) on red rice and barnyardgrass in rice production.

Materials and Methods

A field study was conducted at three locations: 1) the Louisiana State University Agricultural Center H. Rouse Caffey Rice Research Station (RRS) near Crowley, Louisiana, in 2011 and 2012 on a Crowley silt loam soil, with pH 6.4 and 1.4% organic matter (OM); 2) the Louisiana State University Agricultural Center Northeast Research Station (NERS) near St. Joseph, Louisiana, in 2012 on a Commerce silt loam with pH 6.1 and 2.2% OM; and 3) the Louisiana State University Agricultural Center Macon Ridge Research Station (MRRS) near Winnsboro, Louisiana, in 2012 on a Gigger silt loam with pH 5.8 and 1.3% OM.

Treatments were arranged as a two-factor factorial in a randomized complete block with four replications. Factor A consisted of imazamox at 0 or 44 g ai ha^{-1}. Factor B consisted of mixture herbicides: propanil at 840 or 1,680 g ai ha^{-1}, thiobencarb at 840 or 1,680 g ai ha^{-1}, a prepackaged mix of propanil plus thiobencarb at 1,680 or 3,360 g ai ha^{-1}, and no mixture herbicide. Propanil and thiobencarb rates applied alone were equal to the rates found in the prepackaged mixture of propanil plus thiobencarb. At all research

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locations, long-grain ‘CL 161’ IR rice was planted in 2011 and ‘CL 111’ IR rice was planted in 2012. Rice was drilled at 84 kg ha^{-1} in April with eight 19-cm rows, each 5.2 m long.

Herbicide applications were made using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 190 kPa. The spray boom consisted of five flat-fan 110015 nozzles (Flatfan AirMix® Venturi Nozzle, Greenleaf Technologies, Covington, LA 70434) with a 38-cm spacing. Crop oil concentrate at 1% (v/v) (Agri-Dex adjuvant label, Helena Chemical Company, Collierville, TN 38017) was added to imazamox when applied; however, no crop oil concentrate was added to any herbicide mixture that contained propanil and/or thiobencarb. Propanil and thiobencarb used in this research are emulsifiable concentrate (EC) formulations and require no adjuvant when mixed with imazamox. The initial treatment containing herbicide mixtures was applied on one- to three-leaf rice. In order to follow the IR rice stewardship program, the entire area at all locations received a second application of imazethapyr alone at 70 g ha^{-1} 14 days later to rice at the four-to five-leaf stage.

Data obtained from the studies included visual evaluation of weed control and injury based on chlorosis and necrosis of foliage and reduced plant height on a scale of 0% to 100%, where 0% indicates no injury or control and 100% indicates plant death. Rice plant height from the ground to the tip of the extended panicle was recorded immediately prior to harvest (data not shown), and rough rice yield was obtained for the primary crop with a small plot combine harvesting the center four rows of each plot, 3.9 m^{-2} of harvested area. Grain yield was adjusted to 12% moisture.

Treatments were applied at the RRS in the 2011 crop season on 2- to 8-cm red rice at the one- to three-leaf stage, 1- to 8-cm barnyardgrass at the one- to four-leaf stage, and, in 2012, on 5- to 10-cm red rice at the two- to three-leaf stage and 5- to 10-cm barnyardgrass at the two- to four-leaf stage. In 2012 at the NERS, applications were made to 1- to 8-cm barnyardgrass at the two- to six-leaf stage. In 2012, at the MRRS, applications were made to 3- to 5-cm barnyardgrass at the two- to four-leaf stage.

Red rice control was evaluated in 2011 and 2012 at the RRS at 14, 21, 35, and 49 days after initial treatment (DAT). Barnyardgrass control was evaluated in 2011 and 2012 at the RRS at 14, 21, 35, and 49 DAT, in 2012 at the NERS at 14, 21, and 49 DAT, and in 2012 at the MRRS at 21, 42, and 49 DAT.

Control data were analyzed under the guidelines described by Blouin et al. (2010), and rough rice yield data were analyzed with the use of the MIXED procedure of SAS (SAS 2008). The fixed effects for the model statement were the two rates of imazamox, mixture herbicides, DAT, and all interactions. The random effects for the RANDOM statement were locations, blocks within location, and treatment-by-block plots. The model used was described by Blouin et al. (2011). The dependent variables in separate analyses were red rice and barnyardgrass control, crop injury (data not shown), crop height, and rice yield. The analyses for control were by DAT. The analysis for yield used the Fisher’s Protected LSD ($P = 0.05$) to compare treatment means. Normality of plot effects over all DAT was checked using the UNIVARIANTE procedure of SAS (SAS 2011). Significant normality problems were not observed.

Results and Discussion

Treating red rice with a co-application of imazamox at 44 g ha^{-1} plus a prepackaged mixture of propanil plus thiobencarb at 3,360 g ha^{-1} resulted in a synergistic response across all evaluation dates. When red rice was treated with imazamox mixed with propanil plus thiobencarb at 1,680 g ha^{-1}, synergism occurred at 14, 21, and 49 DAT and a neutral response occurred at 35 DAT (Table 1). This indicates that no negative response occurred with this co-application.

When a co-application of propanil or thiobencarb was applied individually at the rates found in the prepackage mixture with imazamox a synergistic response was observed for red rice control at 14 DAT for propanil at 840 and 1,680 g ha^{-1} and for thiobencarb at 1,680 g ha^{-1} (Table 1). At all other evaluation dates a neutral response was observed. Similar results were reported by Fish et al. (2015). The synergistic response may be due to increased uptake and translocation of imazethapyr when mixed with propanil plus thiobencarb compared with imazethapyr alone. The prepackaged mixture is an EC formulation, and this formulation may be a better adjuvant system than a crop oil concentrate because it allows more efficient uptake and translocation of herbicide mixtures with propanil plus thiobencarb.

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Table 1. Red rice control with imazamox mixed with propanil and/or thiobencarb in 2011 and 2012 at the RRS[a]

Mixture herbicide[b]	Rate	Imazamox (g ai ha^{-1}) 0 Observed	44 Expected	44 Observed[c]	P-value
	g ai ha^{-1}	% Control			
14 DAT					
None	-	0	-	81	-
Propanil + thiobencarb	1,680	0	81	93+	0.0000
Propanil + thiobencarb	3,360	2	81	97+	0.0000
Propanil	840	0	81	87+	0.0134
Propanil	1,680	0	81	88+	0.0037
Thiobencarb	840	0	81	84	0.2103
Thiobencarb	1,680	0	81	86+	0.0324
21 DAT					
None	-	0	-	86	-
Propanil + thiobencarb	1,680	3	86	93+	0.0045
Propanil + thiobencarb	3,360	3	86	97+	0.0000
Propanil	840	5	86	84	0.3980
Propanil	1,680	3	86	86	0.9205
Thiobencarb	840	4	86	85	0.5453
Thiobencarb	1,680	8	87	84	0.3141
35 DAT					
None	-	0	-	84	-
Propanil + thiobencarb	1,680	4	84	89	0.0960
Propanil + thiobencarb	3,360	3	84	98+	0.0000
Propanil	840	4	84	85	0.7939
Propanil	1,680	4	84	85	0.7678
Thiobencarb	840	4	84	84	0.9256
Thiobencarb	1,680	4	84	86	0.2807
49 DAT					
None	-	0	-	76	-
Propanil + thiobencarb	1,680	0	76	89+	0.0025
Propanil + thiobencarb	3,360	0	76	96+	0.0000
Propanil	840	0	76	78	0.6519
Propanil	1,680	0	76	79	0.5476
Thiobencarb	840	0	76	80	0.4003
Thiobencarb	1,680	0	76	77	0.8804

[a] RRS, Louisiana State University AgCenter H. Rouse Caffey Rice Research Station near Crowley, LA.

[b] Evaluation date and respective herbicide mixture. DAT, days after treatment.

[c] Observed means followed by a plus (+) or a minus (–) are significantly different from Blouin's Modified Colby's expected responses at the 5% level, indicating a synergistic or an antagonistic response. No plus (+) or minus (–) indicates a neutral response.

Propanil or thiobencarb can be added with no negative impact on red rice control, and the grower can gain the benefits of a mixture containing multiple modes of action, allowing a greater spectrum of weed control and reducing the possibility of weed resistance.

A co-application of imazamox plus the prepackaged mixture applied at 3,360 g ha^{-1} to barnyardgrass resulted in a synergistic response at 35 and 49 DAT, and at all other evaluation dates a neutral response was observed (Table 2). The synergistic or neutral response shows that no negative impact was observed for barnyardgrass control with this co-application, and this is similar to results previously reported (Fish et al. 2015).

Barnyardgrass control 42 DAT was the only evaluation date where an antagonistic response was observed. Mixtures of imazamox with the lower rate of propanil plus thiobencarb or either rate of propanil were antagonistic for barnyardgrass control. The use of imazamox mixed with propanil plus thiobencarb allows the use of three different modes of

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Table 2. Barnyardgrass control with imazamox mixed with propanil and/or thiobencarb in 2011 at the RRS[a] and in 2012 at the RRS, NERS, and MRRS

Mixture herbicide[b]	Rate	Imazamox (g ai ha^{-1}) 0 Observed	44 Expected	44 Observed[c]	P-value
	g ai ha^{-1}	% Control			
14 DAT					
None	-	0	-	78	-
Propanil + thiobencarb	1,680	38	87	87	0.9870
Propanil + thiobencarb	3,360	52	90	92	0.5795
Propanil	840	36	86	84	0.7366
Propanil	1,680	41	87	86	0.8636
Thiobencarb	840	26	84	76	0.1219
Thiobencarb	1,680	35	86	82	0.4269
21 DAT					
None	-	0	-	74	-
Propanil + thiobencarb	1,680	43	85	91	0.3758
Propanil + thiobencarb	3,360	34	84	95	0.0849
Propanil	840	29	81	83	0.7166
Propanil	1,680	42	85	83	0.8779
Thiobencarb	840	22	80	82	0.7543
Thiobencarb	1,680	27	81	76	0.4480
35 DAT					
None	-	0	-	68	-
Propanil + thiobencarb	1,680	30	78	92	0.0934
Propanil + thiobencarb	3,360	30	78	98+	0.0218
Propanil	840	23	75	83	0.3723
Propanil	1,680	32	78	87	0.3042
Thiobencarb	840	23	75	67	0.3734
Thiobencarb	1,680	24	75	78	0.7360
42 DAT					
None	-	0	-	79	-
Propanil + thiobencarb	1,680	68	93	89–	0.0064
Propanil + thiobencarb	3,360	74	95	96	0.1381
Propanil	840	68	93	79–	0.0103
Propanil	1,680	63	92	79–	0.0056
Thiobencarb	840	34	86	78	0.7249
Thiobencarb	1,680	64	92	78	0.3961
49 DAT					
None	-	0	-	72	-
Table 2. Continued					
Propanil + thiobencarb	1,680	36	82	90	0.1670
Propanil + thiobencarb	3,360	47	85	97+	0.0320
Propanil	840	33	81	74	0.2053
Propanil	1,680	31	81	73	0.1491
Thiobencarb	840	25	79	75	0.5155
Thiobencarb	1,680	35	82	76	0.2845

[a] RRS, Louisiana State University AgCenter H. Rouse Caffey Rice Research Station near Crowley, LA; NERS, Louisiana State university AgCenter's Northeast Research Station near St. Joseph, LA; MERS, Louisiana State University AgCenter's Macon Ridge Research Station near Winnsboro, LA.

[b] Evaluation date and respective herbicide mixture. DAT, days after treatment.

[c] Observed means followed by a plus (+) or a minus (–) are significantly different from Blouin's Modified Colby's expected responses at the 5% level, indicating a synergistic or an antagonistic response. No plus (+) or minus (–) indicates a neutral response.

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Table 3. Rough rice yield of rice treated with imazamox mixed with propanil and thiobencarb at the RRS[a] in 2011 and 2012

Mixture herbicide[b]	Rate[c]	Imazamox (g ai ha^{-1}) 0	44
	g ai ha^{-1}	kg ha^{-1}	
None	-	2,280 e[d]	5,040 abc
Propanil + thiobencarb[c]	1,680	3,590 cde	5,480 ab
Propanil + thiobencarb	3,360	4,380 bcd	5,770 a
Propanil	840	3,850 bcde	5,080 abc
Propanil	1,680	3,330 cde	5,610 a
Thiobencarb	840	3,430 cde	4,680 abcd
Thiobencarb	1,680	3,030 de	5,570 ab

[a] RRS, Louisiana State University AgCenter H. Rouse Caffey Rice Research Station near Crowley, LA.

[b] Evaluation date and respective herbicide mixture. DAT, days after treatment.

[c] The products applied alone are equivalent to rates found in prepackaged mixture.

[d] Means followed by a common letter are not significantly different at $P = 0.05$ using PROC MIXED.

action in one application, and this has long been a suggested practice to help aid in delaying the development of herbicide resistant weeds (Fish et al 2015, 2016; Norsworthy et al. 2012). The observed barnyardgrass control with the single application of propanil plus thiobencarb applied at 1,680 g ha^{-1} was 68%, and that observed with propanil alone at 840 or 1,680 g ha^{-1} was 63% and 68%, respectively. The expected control for the imazamox co-applications was 92% to 93%; however, the observed control was 89% for imazamox plus propanil plus thiobencarb and 79% when mixed with either rate of propanil. An antagonistic response was observed for barnyardgrass control; however, the observed control was similar to control for barnyardgrass, 79%, when treated with imazamox alone at 44 g ha-1. This indicates that the mixture could still be beneficial in an overall weed management program because of the additional mode of action in the mix, even in the presence of a barnyardgrass infestation.

Rough rice yield was determined at the RRS in 2011 and 2012; an increase in rice yield was observed when imazamox was used in any herbicide program regardless of co-application product (Table 3). This indicates the importance of imazamox when red rice is present in an IR rice production system.

These findings provide producers an alternative to manage red rice in IR rice production, and the use of the herbicide mixtures evaluated in this research can lead to increased control of red rice and improved rice yield. Louisiana has localized populations of propanil and ALS-resistant barnyardgrass and ALS-resistant red rice; however, these are located in isolated areas. The mixtures evaluated in this research can be beneficial to the growers of Louisiana. Previous research further supports these conclusions and findings. Previous research shows the addition of multiple herbicide modes of action per individual application can help prevent or delay the development of herbicide-resistant weeds (Norsworthy et al. 2012). However, it is important to know that mixtures of herbicides can be used without antagonistic interactions. Fish et al. (2015, 2016) reported many benefits with the co-application of herbicides with multiple modes of action in an IR rice production system. These benefits include a broadened spectrum of control, economical application in a single spray solution versus the need for multiple applications to avoid antagonism, synergistic interactions with imazethapyr or imazamox co-applications, and the management and prevention of herbicide resistant weeds. More importantly, it is recommended that under high levels of weed pressure timely applications should also be employed to prevent yield loss (Webster et al. 2012).

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