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Grass Weed Control and Rice Response with Tetflupyrolimet-containing Programs

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ABSTRACT

Tetflupyrolimet is the first herbicide with a novel site of action labeled preemergence (PRE) and early postemergence for use in agronomic crops in the last three decades. Direct-seeded paddy rice field experiments were conducted near Stuttgart on a silt loam soil, AR, and Keiser on a clay soil, AR, to evaluate tetflupyrolimet-containing herbicide programs in comparison to commercial standards in conventional, imidazolinone-, and quizalofop-resistant rice systems. Additionally, a furrow-irrigated rice experiment was conducted near Colt, AR, on a silt loam soil, and Keiser to ensure clomazone and tetflupyrolimet mixtures compared to commercial standards. Twelve commonly planted rice cultivars were also evaluated in response to a single PRE or postemergence (POST) (2- to 3-leaf rice) application of tetflupyrolimet at 200 and 400 g ai ha^{-1} in a paddy rice system, near Colt. When averaged over soil texture and site-year, all herbicide programs, provided ≥98% barnyardgrass control at 56 d after (DA) the last application. Visible rice injury varied for each rice system. Still, injury rarely differed amongst herbicide programs, except at a single evaluation timing in the conventional (7 DA 3- to 4-leaf applications) and quizalofop-resistant (preflood) systems. All 12 rice cultivars displayed a high tolerance level to a single PRE or POST application of tetflupyrolimet at 200 and 400 g ai ha^{-1}. No visible injury, stand loss, or negative impact on rice maturity or reduced grain yield was observed for any cultivar. Tetflupyrolimet will be an effective alternative SOA in a program approach for barnyardgrass while maintaining excellent rice crop safety.

Nomenclature: Clomazone; quizalofop; tetflupyrolimet; barnyardgrass, *Echinochloa crus-galli* (L.) P. Beauv.; rice, *Oryza sativa* L.

Key words: Furrow-irrigated rice, herbicide programs, rice tolerance

INTRODUCTION

As of 2006, Arkansas accounted for approximately half of the total rice production in the US (Talbert and Burgos 2007: NASS 2024), signifying the economic importance of the crop to the state. Currently, Arkansas remains the number one producer of U.S. rice, planting almost an equivalent hectarage of rice to California, Louisiana, Mississippi, Missouri, and Texas combined (NASS 2024). About 82% of the rice hectares are produced within the mid-southern U.S. region, where herbicide-resistant *Echinochloa* species have been identified as the most difficult-to-manage grass weeds (Fischer et al. 2000; Van Wychen 2020; Butts et al. 2022; Silva et al. 2022) and can reduce grain yield up to 79% from season-long infestations (Norsworthy et al. 2013).

Barnyardgrass has historically been successful as a weedy pest in cultivated rice for centuries (King 1966) and likely migrated to other geographies from contaminated seed stock (Barrett 1983). Before the extensive use of pesticides, morphological similarities between early *Echinochloa crus-galli* biotypes and rice aided in the competitive nature of the weed. The ability of certain barnyardgrass biotypes (*Echinochloa crus galli* var. *oryzicola*) to germinate in anaerobic conditions, thrive in flooded rice culture, and mimic rice phenotypes are all evolutionary mechanisms responsible for the success of barnyardgrass in rice. However, the extensive use of pesticides in rice following the commercialization of propanil in 1959 has placed less selection towards the evolution of similar morphological and physiological characteristics and, instead, placed a greater emphasis on herbicide resistance (Barrett 1983). Since introducing chemical weed management strategies in rice, barnyardgrass has evolved resistance to six SOAs in Arkansas (HRAC/WSSA Groups 1, 2, 4, 5, 13, and 29), with some biotypes displaying multiple resistance (Heap 2024). Given the current resistance status, it is apparent that rice producing states have a need for novel chemical or management strategies.

Tetflupyrolimet is the first herbicide with a novel site of action (SOA) that will be commercialized for use in agronomic crops in the last 30 years [Herbicide Resistance Action Committee (HRAC)/Weed Science Society of America (WSSA) Group 28]. Tetflupyrolimet is anticipated to provide effective control of the most challenging grass weeds in rice (FMC Corporation 2023). To date, internal testing conducted by FMC has shown that tetflupyrolimet aims to provide season-long control of grass weeds and continues to be evaluated in other crops along with other analogs of the molecule, which include corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], sugarcane (*Saccharum officinarum* L.), and wheat (*Triticum aestivum* L.).

However, the novelty of tetflupyrolimet and limited published research create challenges in defining the true scope of the weed control spectrum, especially in its infancy prior to commercialization. Selby et al. (2023) and Lombardi and Al-Khatib (2024) provided some insight into a portion of the expected weed control spectrum from tetflupyrolimet due to the success of the herbicide in controlling *Echinochloa*, *Leptochloa*, and *Monochoria* in field trials conducted on direct-seeded and transplanted rice in Japan, Indonesia, India, Vietnam, Brazil, and the United States.

Tetflupyrolimet is classified as an aryl pyrrolinone anilide chemistry discovered in 2014 through high-volume greenhouse screenings (Gaines et al. 2021; Selby et al. 2023). The novel SOA targets de novo pyrimidine biosynthesis, which is one of the oldest and most essential metabolic pathways in plants and animals (Nara et al. 2000). Pyrimidines can be synthesized through salvage or de novo pathways, although the latter is more advantageous in eukaryotic organisms. When applied to sensitive species, tetflupyrolimet inhibits the functionality of dihydroorotate dehydrogenase (DHODH), an enzyme in the fourth step of de novo pyrimidine biosynthesis that facilitates the only redox reaction in the pathway. Disruption of DHODH leads to a lethal accumulation of dihydroorotate and a downstream deficiency of uridine-5’-monophosphate that deprives plants of pyrimidine bases needed for metabolism, gene expression, and deoxyribonucleic and ribonucleic acid biosynthesis (Nagy et al. 1992; Zrenner et al. 2006; Dayan 2019). In terms of selectivity of tetflupyrolimet between weeds and crops, inhibition of DHODH on *Setaria* sp. from tetflupyrolimet was 10-fold greater than rice, but tolerance of the crop appeared to be much greater than a magnitude of 10, suggesting that differential metabolism may be responsible for increased tolerance (Dayan 2019). Differential selectivity among various weed species or crops could also be attributed to organisms having significantly different enzymes in the six-step de novo pyrimidine biosynthesis pathway (Santosos and Thornburg 1998).

Tolerance to a specific herbicide can be variable and is dependent on the ability of a crop to metabolize and detoxify the compound (Cole 1994). Differential tolerance has also been documented amongst hybrid and inbred imidazolinone-resistant rice cultivars in response to applications of imazamox (Bond and Walker 2012). Recently, rice cultivars have been observed to have differing levels of sensitivity to florpyrauxifen-benzyl, particularly when applied to medium-grain and hybrid cultivars (Wright et al. 2021). Environmental conditions (temperature and soil moisture), herbicide rate, and growth stage are all parameters that can influence the degree of crop tolerance (Wright and Reick 1974; Burt and Akinsorotan 1976; Bond and Walker 2012).

With the arrival of tetflupyrolimet as the first novel SOA for use in agronomic crops in three decades, it is important to address the utility of the herbicide in all available rice production systems while maintaining a high degree of crop safety. The recent issues surrounding the commercialization of florpyrauxifen-benzyl in rice, specifically the variation in barnyardgrass efficacy and unforeseen injury to hybrid cultivars (Wright et al. 2021), emphasize the importance of extensive testing in those capacities. The objectives of these field experiments were to 1) evaluate the weed control efficacy of tetflupyrolimet and clomazone mixtures on medium- and fine-textured soils as residual herbicides in conventional, imidazolinone-resistant, and quizalofop-resistant rice systems and 2) evaluate rice response of tetflupyrolimet applied PRE and POST to commonly planted rice cultivars in the mid-southern region.

MATERIALS AND METHODS

Optimization of Tetflupyrolimet in Different Rice Production Systems. Eight field experiments were arranged as single-factor randomized complete block designs with four replications, focusing on weed control programs that included tetflupyrolimet on silt loam- and clay-textured soils. Herbicide treatments are shown in Tables 1, 2, 3, 4, 5, and 6. Each field experiment was conducted in 2021 and repeated in 2022. All silt loam paddy rice experiments were conducted near Stuttgart, AR, at the Rice Research and Extension Center (RREC) on a Dewitt silt loam soil (19% sand, 64% silt, and 17% clay with 1.1% organic matter) with a pH of 5.7. Furrow-irrigated silt loam experiments were conducted near Colt, AR, at the Pine Tree Research Station (PTRS) on a Calloway silt loam soil (17% sand, 68% silt, and 15% clay with 1.4% organic matter) with a pH of 6.7. All fine-textured field experiments were conducted near Keiser, AR, at the Northeast Research and Extension Center (NEREC) on a clay (41% sand, 1% silt, 58% clay, with 2.8% organic matter) with a pH of 5.5.

The rice cultivars ‘Diamond’ (conventional) (University of Arkansas System Division of Agriculture, Little Rock, AR), ‘FullPage 7521’ (imidazolinone-resistant) (RiceTec, Alvin, TX), and ‘PVL02’ (quizalofop-resistant) (Horizon Ag, Memphis, TN), were planted at the seeding rates found in Table 7 for the direct-seeded, delayed continuous flood experiments. ‘FullPage

7521' was also used to plant all furrow-irrigated rice (FIR) experiments. Rice was planted on May 14 ('Diamond'), May 15 ('FullPage 7521'), and May 15 ('PVL02'), in 2021, and all on April 30, in 2022, respectively at the silt loam location near Stuttgart, AR. Furrow-irrigated rice at the silt loam location, near Colt, AR, was planted on May 14 and May 17, in 2021 and 2022, respectively. At the fine-textured soil location, all paddy rice was planted on May 20, 2021, and May 10, 2022. Furrow-irrigated rice at the clay location was planted on June 1 and May 10, in 2021 and 2022, respectively. Paddy-rice experiments were conventionally drilled with 19-cm spacing into plots measuring 1.8- by 5.2-m with 1- m alleys. Each treatment for the FIR experiments consisted of two tilled and bedded rows with 97-cm spacing, which were conventionally drilled with the same 19-cm drill into plots measuring 1.9- by 6.1-m. All herbicide applications were made using a CO_2-pressurized backpack sprayer equipped with AIXR110015 flat fan nozzles (TeeJet, Glendale Heights, IL) that were calibrated to deliver a spray volume of 140 L ha^{-1} at 4.8 kph. Visible rice injury ratings were assessed at 7, 14, and 28 days after the most recent herbicide application. In addition to visible injury, weed control was visually evaluated at 14, 28, 42, and 56 days after the most recent application, with an emphasis on *Echinochloa crus-galli*. Visible injury and weed control ratings were assessed on a scale ranging from 0% to 100%, with 0% and 100% representing no injury or control and crop death or complete control, respectively (Frans and Talbert 1977).

Except for FIR, all other experiments were maintained as conventional paddy rice with the establishment of a permanent flood at the 5-leaf growth stage. Soil fertility was addressed specifically to each production system, soil texture, and rice cultivar planted according to the current Arkansas Rice Production Handbook (Roberts et al. 2016). Non-target broadleaf and sedge weeds were controlled with halosulfuron at 53 g ai ha^{-1}, halosulfuron at 70 g ai ha^{-1} plus prosulfuron at 40 g ai ha^{-1}, or 2,4-D at 1,120 g ai ha^{-1} prior to flood establishment. Unless otherwise specified, all methodology is the same.

All distributions were analyzed using the JMP PRO 17.1 (SAS Institute Inc., Cary, NC) distribution platform and all data assumed a normal distribution (Avent et al. 2022). Data were analyzed in JMP PRO 17.1 and subjected to analysis of variance (ANOVA) using the fit model platform. Means were separated using Tukey's honest significant difference (HSD) (α=0.05). Herbicide program, soil texture, and site-year were included in the initial model as fixed effects with block considered as random, to determine if barnyardgrass control and rice visible injury were different on a silt loam and clay soil. An interaction of the herbicide program and soil texture or herbicide program and site-year was not observed. Therefore, all data were averaged over site-year (random effect) and soil texture (random effect). Furrow-irrigated rice experiments were analyzed by soil texture due to differences in herbicide programs. Because there were no interactions between the herbicide program and soil texture for the paddy rice systems, the rate adjustments from silt loam to clay soil were assumed to be sufficient. In the final model for the conventional, imidazolinone-resistant, and quizalofop-resistant paddy rice systems, the herbicide program was considered as the only fixed effect, with site-year, soil texture, and block considered random effects. The final model for FIR systems included the herbicide program as a fixed effect by soil texture, with site-year and block as random effects.

Rice Tolerance to PRE- and POST-applied Tetflupyrolimet. To determine the response of 12 genetically different and commonly planted rice cultivars in Arkansas to a single PRE or POST application of tetflupyrolimet, field experiments were conducted at the Pine Tree Research Station near Colt, AR, on a Calloway silt loam soil in 2021, 2022, and 2023. Before planting, each field was subjected to conventional tillage events for preparation of the seedbed. The experiment was arranged as a two-factor randomized complete block design with four replications for each respective cultivar, and each plot measured 1.8 m wide by 5.2 m long (Table 7). All 12 cultivars were planted and treated on the same dates for each year with tetflupyrolimet at 0, 200, or 400 g ai ha^{-1} PRE or POST (2- to 3-leaf rice). Rice was planted and PRE applications were made on April 12, May 12, and April 12 in 2021, 2022, and 2023, respectively. Postemergence applications were made on May 26, June 6, and May 17 in 2021, 2022, and 2023, respectively. All applications were applied with a hand-held backpack sprayer equipped with AIXR110015 nozzles (TeeJet, Glendale Heights, IL) that was calibrated to deliver 140 L ha^{-1} at 4.8 km h^{-1} and non-ionic surfactant at 0.25% v/v was included in all POST herbicide treatments.

Before designated plots received a PRE application of tetflupyrolimet, all plots, including the nontreated control for each cultivar, received a broadcast application of clomazone plus quinclorac (Obey®) (FMC Corporation, Philadelphia, PA) at 900 g ai ha^{-1} to ensure that the experiment remained weed free. Immediately following the broadcast PRE application of clomazone plus quinclorac, the appropriate tetflupyrolimet-containing herbicide treatments were applied. Throughout the growing season, additional maintenance herbicide applications were made for the presence of any broadleaf weeds, grasses, or sedges. Depending on the weed species present, florpyrauxifen-benzyl (Loyant®) (Corteva Agriscience™, Indianapolis, IN) at 15 g ae ha^{-1}, halosulfuron (Permit®) (Gowan Company, Yuma, AZ) at 70 g ai ha^{-1}, or propanil (Stam M4®) (RiceCo LLC., Memphis, TN) at 4,500 g ai ha^{-1} were applied from early POST until the permanent flood was established.

Soil test potassium and phosphorus concentrations were determined from samples collected in the fall before the start of each growing season and soils were amended prior to planting for each site-year. The field also received a total of 150 kg ha^{-1} of nitrogen throughout the growing season, with 105 kg ha^{-1} urea (46-0-0) applied preflood, and the remaining when rice reached 1.3 cm internode elongation (Roberts et al. 2016). Once each experiment reached the 5-leaf growth stage or tillering, a permanent flood was established until harvest maturity.

Visible rice injury ratings were collected at 7, 14, 21, and 28 DAT for the PRE and POST applications and rice stand counts at 14 days after preemergence application (DAPRE). Aerial images were captured with a 4K RGB camera mounted on a Mavic Air II (DJI Innovations, Los Angeles, CA) drone to assess the percent canopy growth at 12, 7, and 13 weeks after planting (WAP). For each aerial image at the respective collection date, drone altitude was maintained at 30 m to minimize variability in image resolution for percent canopy growth analysis. Aerial images were analyzed for percent canopy growth and made relative to the nontreated control for each rice cultivar using FieldAnalyzer (Green Research Services LLC.). Rice maturity was assessed by recording 50% heading dates for each cultivar before harvest, which was determined when approximately 50% of the rice in each plot exhibited a panicle. At full maturity, a 1.5-m-wide swath out of the 1.8-m-wide plot was harvested using a small-plot combine (Almaco, Nevada, IA), and grain yield was determined by adjusting the harvested weights to 12% moisture.

Site-year, tetflupyrolimet rate, and application timing were included in the ANOVA model using JMP Pro 17.1 to determine the presence of significant interactions or main effects (α=0.05). Percent canopy growth was analyzed by site-year because the aerial images were collected at different evaluation timings (12, 7, and 13 weeks after PRE application in 2021, 2022, and 2023, respectively) relative to the PRE application. Site-year was the only significant main effect in the model (four out of 12 cultivars for relative grain yield). Dunnett's procedure was used when differences occurred between herbicide treatments and the nontreated control (α=0.05).

RESULTS AND DISCUSSION

Optimization of Tetflupyrolimet in Different Rice Production Systems. All conventional paddy rice programs maintained 96% barnyardgrass control with ≤10% visible phytotoxicity to rice at all evaluation dates in a two-pass system (two total herbicide applications) when averaged over site-year and soil texture (Table 2), which indicated that the rate adjustment for tetflupyrolimet rate was appropriate for fine-textured soils. Visible injury varied amongst herbicide programs due to bleaching from clomazone at 7 d after (DA) PRE but was overall minimal and transient in the weeks following the last application (data not shown). At 56 DA, the 3- to 4-leaf rice application, all herbicide programs exhibited ≥98% barnyardgrass control, and tetflupyrolimet-containing treatments did not display any advantage due to the high performance of all treatments.

The barnyardgrass population at each location likely did not exhibit resistance to HRAC/WSSA Groups 1, 2, 4, 13, or 29, which may explain the high efficacy of all programs that did not include tetflupyrolimet PRE but utilized clomazone as an alternative. In future field experiments, herbicide-resistant barnyardgrass needs to be over-seeded to determine if there are advantages when utilizing tetflupyrolimet in a program approach. The addition of tetflupyrolimet would potentially aid in the management of herbicide-resistant *Echinochloa crus-galli* biotypes due to its novelty and lack of prior exposure to the herbicide. A screening conducted in California on suspected herbicide-resistant grass weed populations collected from rice fields confirmed that tetflupyrolimet controlled all suspected herbicide-resistant samples (Becerra-Alvarez, unpublished data; Lombardi and Al-Khatib 2024). Lombardi and Al-Khatib (2024) mention that tetflupyrolimet provided effective control of bearded sprangletop [*Leptochloa fascicularis* (Lam.) Gray]. Bearded sprangletop and Amazon sprangletop [*Leptochloa panicoides* (J. Presl) Hitchc.] are the most prevalent *Leptochloa* species in the mid-southern U.S. and can be highly competitive and difficult to control in rice fields (Stauber et al. 1991; Tehranchian et al. 2016), reducing grain yield up to 36% (Smith 1988). In the mid-southern region, tetflupyrolimet will be marketed as a co-pack with clomazone (Richard Edmund of FMC, personal communication), which would increase the spectrum of grass control and introduce an effective and novel SOA into weed control programs. Tetflupyrolimet did effectively control Amazon sprangletop when present in plots, but the density was not sufficient to evaluate in multiple site-years; therefore, the data are not presented.

In the imidazolinone- and quizalofop-resistant paddy rice systems, each evaluated herbicide program offered highly effective season-long control of barnyardgrass regardless of whether tetflupyrolimet was included (Tables 3 and 4). There was no advantage for each technology when utilizing a two- or three-pass (three independent herbicide applications) system, although the latter approach would be recommended to mitigate the evolution of herbicide resistance (Norsworthy et al. 2012). It is important to note that a two-pass system was used to determine if programs that included tetflupyrolimet could be comparable to three separate herbicide applications without the herbicide. Still, all treatments provided exceptional barnyardgrass control (99% control at 56 DA the pre-flood treatment for imidazolinone- and quizalofop-resistant systems). Additionally, clomazone served as the PRE foundation in each herbicide program and is still considered a highly effective residual herbicide for barnyardgrass despite having confirmed resistance cases to the chemical in the mid-south (Heap 2024). Other research has demonstrated that clomazone can control barnyardgrass resistant to HRAC/WSSA Groups 2, 4, and 5, so it is not surprising that all herbicide programs in these experiments were successful (Wilson et al. 2014).

Traditional paddy rice is predominate in much of the mid-southern U.S. rice growing region, but a furrow-irrigated production system has become increasingly popular to simplify crop rotation and various management strategies (Hardke 2022). As of 2022, FIR accounts for approximately 18% of rice hectares in Arkansas. It is important to ensure that tetflupyrolimet-containing herbicide programs maintain consistent efficacy in the presence of aerobic and anaerobic conditions that exist at the same time in FIR systems. Weed management can be especially challenging in FIR due to an extended period of emergence and regrowth of escapes (Norsworthy et al. 2008). Visible barnyardgrass control averaged 99% at the silt loam and clay locations over the 2021 and 2022 site-years (Tables 5 and 6). Visible injury was not compared between the paddy rice and FIR systems, but the magnitude of early-season damage to rice appeared to be more extensive in FIR at the silt loam location than in other sites based on visual observations. Rice on top of beds exhibited more vigor, but plants in furrows were more prone to bleaching and necrosis, potentially resulting from standing water in the furrow. Rainfall or irrigation can reactivate clomazone and elicit crop symptomology (Anonymous 2021). At the 3-leaf application, the maximum observed visible injury was 9%, injury caused by clomazone was transient. Furrow-irrigated rice at the clay soil location displayed minimal early- or mid-season injury (at 7 and 6%, respectively).

Rice Response to PRE- and POST-applied Tetflupyrolimet. None of the rice cultivars displayed any symptoms associated with a single PRE or POST application of tetflupyrolimet at 200 or 400 g ai ha^{-1}, and therefore, visible injury data were not subject to statistical analysis. In addition to the lack of visible symptomology from a tetflupyrolimet application, none of the evaluated parameters (excluding percent canopy growth), such as rice stand, relative maturity, and relative grain yield, were reduced by the herbicide (Table 7). In only two instances, the percent canopy growth was different than the nontreated control. One of those instances involved the imidazolinone-resistant, inbred, long-grain cultivar, 'CLL16,' where percent canopy growth was greater than the nontreated control by 4 percentage points at 7 WAP in the 2022 site-year. Percent canopy growth was reduced by 7 percentage points at 12 WAP in the 2021 site-year for PVL02 (quizalofop-resistant, inbred, long-grain cultivar) but was comparable to the nontreated control for all other parameters.

Rice cultivars are known to respond differently to some herbicides, such as benzobicyclon and florpyrauxifen-benzyl, requiring thorough testing before commercialization of new herbicides. In the case of benzobicyclon, tolerance was conferred based on the presence of a functioning *HIS1* gene, and the level of expression was often dictated by the rice growth stage (Brabham et al. 2022). Similar studies were conducted prior to the commercialization of benzobicyclon, where *tropical japonica* cultivars maintained excellent crop safety while two *indica* cultivars ('Purple Marker' and 'Rondo') expressed severe phytotoxicity from the absence of a functioning *HIS1* gene (Kato et al. 2015; Young et al. 2017; Maeda et al. 2019). It would not be surprising if there was differential tolerance among the two subspecies of rice, but the research reported by Selby et al. (2023) indicates that tolerance to tetflupyrolimet is conferred in each subspecies.   In additional support of these data observed on 12 mid-south rice cultivars, a high level of tolerance with no impact to grain yield was also confirmed in six rice cultivars common to California rice production with different genetic backgrounds (one short- four medium-, and one long-grain) (Lombardi and Al-Khatib 2024). Considering there were no other differences for all other evaluated parameters for each cultivar, it is concluded that the evaluated mid-south rice cultivars have a high degree of tolerance to tetflupyrolimet like those documented by Selby et al. (2023).

Following the commercial launch of florpyrauxifen-benzyl, it was determined that some cultivars differed in sensitivity to the herbicide based on grain size and genotype (inbred and hybrid) (Wright et al. 2021; Anonymous 2023), although the mechanism responsible is not well understood. For this reason, the authors selected rice cultivars that encompassed a variety of differing genotypes for evaluation. Dihydroorotate dehydrogenase present in rice appears to confer broad tolerance to tetflupyrolimet, suggesting that the evaluated cultivars may carry a similar form of the enzyme or are able to effectively metabolize the herbicide.

PRACTICAL IMPLICATIONS

Tetflupyrolimet will provide rice producers with an alternative soil-applied herbicide SOA for control of barnyardgrass populations in the mid-southern U.S. Results from these experiments have demonstrated the overall effectiveness and versatility of tetflupyrolimet as a soil-applied herbicide on silt loam and clay soils for the management of barnyardgrass in conventional, imidazolinone-, and quizalofop-resistant rice production systems, which also include FIR. There is minimal injury from an individual PRE or POST application of tetflupyrolimet to the rice cultivars evaluated in a paddy rice system across three site-years. Visible injury to rice was only observed when tetflupyrolimet was mixed with other herbicides known to cause injury, such as clomazone, imidazolinone herbicides, penoxsulam, quinclorac, and quizalofop. Mixing clomazone and tetflupyrolimet will provide two effective SOAs to manage barnyardgrass and mitigate selection pressure placed on the already limited POST grass herbicides.

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Table 1. Sources of materials for cultivar response, conventional, furrow-irrigated, imidazolinone-resistant, quizalofop-resistant rice field experiments.

Common name	Trade name	Manufacturer
clomazone	Command 3ME	FMC Corporation, Philadelphia, PA
clomazone + pendimethalin	RiceOne	United Phosphorus Incorporated, King of Prussia, PA
clomazone + quinclorac	Obey	FMC Corporation, Philadelphia, PA
cyhalofop + penoxsulam	RebelEX	Corteva Agriscience, Indianapolis, IN
fenoxaprop	Ricestar HT	Bayer Crop Science, St. Louis, MO
imazamox	Postscript	Adama, Raleigh, NC
imazethapyr	Preface	Adama, Raleigh, NC
propanil	Stam M4	United Phosphorus Incorporated, King of Prussia, PA
quinclorac	Facet	BASF Corporation, Research Triangle Park, NC
quizalofop	Provisia	BASF Corporation, Research Triangle Park, NC
tetflupyrolimet	Dodhylex active	FMC Corp., Philadelphia, PA
crop oil concentrate	Agri-Dex	Helena Holding Company, Collierville, TN
non-ionic surfactant	Induce	Helena Holding Company, Collierville, TN

Table 2. Rice injury and barnyardgrass control of tetflupyrolimet applied with other herbicides preemergence and at 3- to 4-leaf stage rice in a conventional paddy rice system averaged across the silt loam and clay soil locations and across 2021 and 2022.[abc]

			Evaluation timing				
			14 DA, PRE		7 DA, 3- to 4-leaf		56 DA, 3- to 4-leaf
Herbicide	Timing	Rate[d]	Injury	ECHCG	Injury	ECHCG	ECHCG
		g ai ha^{-1}	--%--				
tetflupyrolimet	PRE	125, 175	4	96	4 b	96	99
clomazone	PRE	313, 438					
tetflupyrolimet	3-4 leaf rice	125, 75					
clomazone	3-4 leaf rice	313, 188					
penoxsulam + cyhalofop	3-4 leaf rice	320, 320					
tetflupyrolimet	PRE	125, 175	7	98	8 ab	98	99
clomazone	PRE	313, 438					
tetflupyrolimet	3-4 leaf rice	125, 75					
clomazone	3-4 leaf rice	313, 188					
propanil	3-4 leaf rice	4,488, 4,488					
tetflupyrolimet	PRE	125, 175	9	98	10 a	98	99
clomazone	PRE	313, 438					
tetflupyrolimet	3-4 leaf rice	125, 75					
clomazone	3-4 leaf rice	313, 188					
fenoxaprop	3-4 leaf rice	122, 122					
clomazone	PRE	337, 671	6	98	5 ab	98	99
quinclorac	PRE	421, 565					
pendimethalin	3-4 leaf rice	1,066, 1,066					
penoxsulam + cyhalofop	3-4 leaf rice	320, 320					

Table 2 continued. Rice injury and barnyardgrass control of tetflupyrolimet applied with other herbicides preemergence and at 3- to 4-leaf stage rice in a conventional paddy rice system averaged across the silt loam and clay soil locations and across 2021 and 2022.[abc]

			Evaluation timing					
			14 DA, PRE		7 DA, 3- to 4-leaf			56 DA, 3- to 4-leaf
Herbicide	Timing	Rate[d]	Injury	ECHCG	Injury		ECHCG	ECHCG
		g ai ha^{-1}	---		%		---	
clomazone	PRE	337, 570						
quinclorac	PRE	421, 565						
pendimethalin + clomazone	3-4 leaf rice	1,114, 1,114	9	98	9	ab	98	99
propanil	3-4 leaf rice	4,488, 4,488						
clomazone	PRE	337, 671						
quinclorac	3-4 leaf rice	421, 421	8	99	5	ab	98	98
fenoxaprop	3-4 leaf rice	122, 122						
P-value			0.2044	0.4289	0.0378		0.2493	0.3658

[a] Means within a column and crop followed by the same letter are not different according to Tukey's HSD (α=0.05).

[b] Abbreviations: ECHCG, barnyardgrass; DA, d after; PRE, preemergence.

[c] Silt loam location, Rice Research and Extension Center, near Stuttgart, AR; clay location, Northeast Research and Extension Center, near Keiser, AR

[d] Silt loam rate, clay rate

Table 3. Rice injury and barnyardgrass control of tetflupyrolimet applied with other herbicides preemergence and at 2-to 3-leaf, 3-to 4-leaf, and preflood stage rice in a imidazolinone-resistant paddy rice system averaged across the silt loam and clay soil locations and across 2021 and 2022.[abc]

			Evaluation timing				
			2- to 3-leaf		Preflood		56 DA preflood
Herbicide	Timing	Rate[d]	Injury	ECHCG	Injury	ECHCG	ECHCG
		g ai ha^{-1}	--		-% -		--
tetflupyrolimet	PRE	125, 175	13	97	7	97	99
clomazone	PRE	313, 438					
imazethapyr	PRE	105, 105					
tetflupyrolimet	3-4 leaf rice	125, 75					
clomazone	3-4 leaf rice	313, 188					
imazethapyr	3-4 leaf rice	105, 105					
tetflupyrolimet	PRE	125, 175	12	96	11	96	99
clomazone	PRE	313, 438					
tetflupyrolimet	2-3 leaf rice	125, 75					
clomazone	2-3 leaf rice	313, 188					
imazethapyr	2-3 leaf rice	105, 105					
imazamox	PREFLD	44, 44					
tetflupyrolimet	PRE	125, 175	15	98	14	97	99
clomazone	PRE	313, 438					
tetflupyrolimet	2-3 leaf rice	125, 75					
clomazone	2-3 leaf rice	313, 188					
imazethapyr	2-3 leaf rice	44, 44					
imazamox	PREFLD	44, 44					

Table 3 continued. Rice injury and barnyardgrass control of tetflupyrolimet applied with other herbicides preemergence and at 2-to 3-leaf, 3- to 4-leaf, and preflood stage rice in a imidazolinone-resistant paddy rice system averaged across the silt loam and clay soil locations and across 2021 and 2022.[abc]

			Evaluation timing				
			2- to 3-leaf		Preflood		56 DA preflood
Herbicide	Timing	Rate[d]	Injury	ECHCG	Injury	ECHCG	ECHCG
		g ai ha^{-1}	--	--	%	--	--
tetflupyrolimet	PRE	125, 175	18	96	9	93	99
clomazone	PRE	313, 438					
tetflupyrolimet	3-4 leaf rice	125, 75					
clomazone	3-4 leaf rice	313, 188					
penoxsulam + cyhalofop	3-4 leaf rice	320, 320					
clomazone	PRE	337, 671	18	98	10	96	99
imazethapyr	PRE	105, 105					
pendimethalin	3-4 leaf rice	1,066, 1,066					
imazethapyr	3-4 leaf rice	105, 105					
clomazone	PRE	337, 671	12	98	7	98	99
quinclorac	PRE	421, 565					
pendimethalin	2-3 leaf rice	1,066, 1,066					
imazethapyr	2-3 leaf rice	105, 105					
imazamox	PREFLD	44, 44					
P-value			0.5876	0.7674	0.1557	0.2887	1.0000

[a] Means within a column and crop followed by the same letter are not different according to Tukey's HSD (α=0.05).

[b] Abbreviations: ECHCG, barnyardgrass; DA, d after; PRE, preemergence; PREFLD, preflood.

[c] Silt loam location, Rice Research and Extension Center, near Stuttgart, AR; clay location, Northeast Research and Extension Center, near Keiser, AR

[d] Silt loam rate, clay rate

Table 4. Rice injury and barnyardgrass control of tetflupyrolimet applied with other herbicides preemergence and at 2-to 3-leaf, 3-to 4-leaf, and preflood stage rice in a quizalofop-resistant paddy rice system averaged across the silt loam and clay soil locations and across 2021 and 2022.[abc]

			Evaluation timing				
			2- to 3-leaf		Preflood		56 DA Preflood
Herbicide	Timing	Rate[d]	Injury	ECHCG	Injury	ECHCG	ECHCG
		g ai ha^{-1}	-----%				-----%
tetflupyrolimet	PRE	125, 175	7	98	4 ab	98	99
clomazone	PRE	313, 438					
quizalofop	2-3 leaf rice	120, 120					
quizalofop	PREFLD	120, 120					
tetflupyrolimet	PRE	125, 175	7	98	2 b	98	99
clomazone	PRE	313, 438					
tetflupyrolimet	3-4 leaf rice	125, 75					
clomazone	3-4 leaf rice	313, 188					
quizalofop	3-4 leaf rice	120, 120					
tetflupyrolimet	PRE	125, 175	8	98	5 ab	99	99
clomazone	PRE	313, 438					
tetflupyrolimet	3-4 leaf rice	125, 75					
clomazone	3-4 leaf rice	313, 188					
fenoxaprop	3-4 leaf rice	122, 122					
clomazone	PRE	337, 671	8	98	5 ab	99	99
quinclorac	PRE	421, 565					
quizalofop	2-3 leaf rice	120, 120					
quizalofop	PREFLD	120, 120					

Table 4 continued. Rice injury and barnyardgrass control of tetflupyrolimet applied with other herbicides preemergence and at 2- to 3-leaf, 3- to 4-leaf, and preflood stage rice in a quizalofop-resistant paddy rice system averaged across the silt loam and clay soil locations and across 2021 and 2022.[abc]

			Evaluation timing					
			2-3 leaf		Preflood			56 DA Preflood
Herbicide	Timing	Rate[d]	Injury	ECHCG	Injury		ECHCG	ECHCG
		g ai ha^{-1}	---%---					
clomazone	PRE	337, 671	8	97	8	a	98	99
quinclorac	PRE	421, 565						
pendimethalin	3-4 leaf rice	1,066, 1,066						
quizalofop	3-4 leaf rice	120, 120						
P-value			0.9303	0.4085	0.0186		0.6548	0.4134

[a] Means within a column and crop followed by the same letter are not different according to Tukey's HSD (α=0.05).

[b] Abbreviations: ECHCG, barnyardgrass; DA, d after; PRE, preemergence; PREFLD, preflood.

[c] Silt loam location, Rice Research and Extension Center, near Stuttgart, AR; clay location, Northeast Research and Extension Center, near Keiser, AR

[d] Silt loam rate, clay rate

Table 5. Rice injury and barnyardgrass control of tetflupyrolimet applied with other herbicides preemergence, 3-leaf, and tillering rice in a conventional furrow-irrigated rice system averaged across 2021 and 2022 at the silt loam location.[abc]

			Evaluation timing				
			14 DA PRE		3 leaf		56 DA tillering
Herbicide	Timing	Rate	Injury	ECHCG	Injury	ECHCG	ECHCG
		g ai ha^{-1}	%				
tetflupyrolimet	PRE	125	20	99	6	99	99
clomazone	PRE	313					
tetflupyrolimet	3 leaf rice	125					
clomazone	3 leaf rice	313					
penoxsulam + cyhalofop	3 leaf rice	320					
tetflupyrolimet	PRE	125	20	99	9	99	99
clomazone	PRE	313					
tetflupyrolimet	3 leaf rice	125					
clomazone	3 leaf rice	313					
penoxsulam + cyhalofop	3 leaf rice	320					
fenoxaprop	Tillering rice	122					
clomazone	PRE	337	18	99	6	99	99
quinclorac	PRE	421					
pendimethalin + clomazone	3 leaf rice	1,114					
penoxsulam + cyhalofop	3 leaf rice	320					
clomazone	PRE	337	26	99	8	99	99
quinclorac	PRE	421					
pendimethalin + clomazone	3 leaf rice	1,114					
penoxsulam + cyhalofop	3 leaf rice	320					
fenoxaprop	Tillering rice	122					

Table 5 continued. Rice injury and barnyardgrass control of tetflupyrolimet applied with other herbicides preemergence, 3-leaf, and tillering rice in a conventional furrow-irrigated rice system averaged across 2021 and 2022 at the silt loam location.[abc]

			Evaluation timing				
			14 DA PRE		3 leaf		56 DA tillering
Herbicide	Timing	Rate	Injury	ECHG	Injury	ECHG	ECHG
		g ai ha^{-1}	--	---%	---		
P-value			0.1286	1.0000	0.6374	1.0000	1.0000

[a] Means within a column and crop followed by the same letter are not different according to Tukey’s HSD (α=0.05).

[b] Abbreviations: ECHCG, barnyardgrass; DA, d after; PRE, preemergence.

[c] Silt loam location, Pine Tree Research and Extension Center, near Colt, AR

Table 6. Rice injury and barnyardgrass control of tetflupyrolimet applied with other herbicides preemergence, 3-leaf, and tillering rice in a conventional furrow-irrigated rice system averaged across 2021 and 2022 at the clay location.[abc]

			Evaluation timing				
			14 DA PRE		3 leaf		56 DA tillering
Herbicide	Timing	Rate	Injury	ECHCG	Injury	ECHCG	ECHCG
		g ai ha^{-1}	%				
tetflupyrolimet	PRE	175	6	99	4	99	99
clomazone	PRE	438					
tetflupyrolimet	3 leaf rice	75					
clomazone	3 leaf rice	788					
penoxsulam + cyhalo.	3 leaf rice	320					
tetflupyrolimet	PRE	175	4	99	4	99	99
clomazone	PRE	438					
tetflupyrolimet	3 leaf rice	75					
clomazone	3 leaf rice	188					
penoxsulam + cyhalofop	3 leaf rice	320					
fenoxaprop	Tillering rice	122					
clomazone	PRE	671	7	99	6	99	99
quinclorac	PRE	565					
pendimethalin + clomazone	3 leaf rice	1,066					
penoxsulam + cyhalofop	3 leaf rice	320					
clomazone	PRE	671	7	99	5	99	99
quinclorac	PRE	565					
pendimethalin + clomazone	3 leaf rice	1,066					
penoxsulam + cyhalofop	3 leaf rice	320					
fenoxaprop	Tillering rice	122					

Table 6 continued. Rice injury and barnyardgrass control of tetflupyrolimet applied with other herbicides preemergence, 3-leaf, and tillering rice in a conventional furrow-irrigated rice system averaged across 2021 and 2022 at the clay location.[abc]

			Evaluation timing				
			14 DA PRE		3 leaf		56 DA tillering
Herbicide	Timing	Rate	Injury	ECHCG	Injury	ECHCG	ECHCG
		g ai ha^{-1}	--%--				
P-value			0.1838	0.5501	0.2003	0.4098	0.8444

[a] Means within a column and crop followed by the same letter are not different according to Tukey's HSD (α=0.05).

[b] Abbreviations: ECHCG, barnyardgrass; DA, d after; PRE, preemergence.

[c] Clay location, Northeast Research and Extension Center, near Keiser, AR

Table 7. List of rice cultivars selected to determine respective response to a single preemergence or postemergence application of tetflupyrolimet at a 200 or 400 g ai ha^{-1} rate for the 2021, 2022, and 2023 site-years.[a]

Cultivar	Genetics	Technology	Grain type	Seeding rate
				seeds m^{-1} row
CLL15	inbred	imidazolinone-resistant	Long	72
CLL16	inbred	imidazolinone-resistant	Long	72
Diamond	inbred	conventional	Long	72
Jupiter	inbred	conventional	Medium	72
Lynx	inbred	conventional	Medium	72
Titan	inbred	conventional	Medium	72
Jewel	inbred	conventional	Long	72
RT7231MA	inbred	quizalofop-P-resistant	Long	52
PVL02	inbred	quizalofop-P-resistant	Long	65
RT7321FP	hybrid	imidazolinone-resistant	Long	36
RT7521FP	hybrid	imidazolinone-resistant	Long	36
RTXP753	hybrid	conventional	Long	36

[a] Lynx cultivar was not available for the 2023 site-year.

Table 8. Rice stand counts, percent canopy growth, rice maturity, and relative grain yield after a preemergence or postemergence application of tetflupyrolimet, averaged in 2021, 2022, and 2023, at the Pine Tree Research Station, near Colt, AR. All data excluding canopy growth were averaged over site-year.[a]

Cultivar	Rate	Timing	Stand 14 DAPRE[b]	Canopy growth[c]			Maturity[d]	Relative yield[ef]
				2021	2022	2023		
	g ai ha^{-1}		plants row m^{-1}	------------%------------			days	% (kg ha^{-1})
CLL15	0		36	97	89	78	0	100 (6,920)
	200	PRE	35	95	86	70	1	116
	400	PRE	37	97	86	75	1	118
	200	POST		98	90	77	1	118
	400	POST		97	90	82	1	119
CLL16	0		34	92	88	88	0	100 (8,440)
	200	PRE	37	90	89	87	1	96
	400	PRE	37	91	88	86	1	101
	200	POST		92	90	82	-1	97
	400	POST		92	92*	87	1	90
Diamond	0		38	92	72	91	0	100 (7,680)
	200	PRE	34	93	54	96	2	103

	400	PRE	37	88	71	96	0	99
	200	POST		94	54	96	2	104
	400	POST		90	67	95	1	106
Jewel	0		44	85	70	96	0	100 (7,120)
	200	PRE	44	86	67	95	-1	103
	400	PRE	45	88	71	95	-2	94
	200	POST		86	74	96	-1	100
	400	POST		86	65	93	-1	98

Table 8. Rice stand counts, percent canopy growth, rice maturity, and relative grain yield after a preemergence or postemergence application of tetflupyrolimet, averaged in 2021, 2022, and 2023, at the Pine Tree Research Station, near Colt, AR. All data excluding canopy growth were averaged over site-year.[a]

				Canopy growth[c]				
Cultivar	Rate	Timing	Stand 14 DAPRE[b]	2021	2022	2023	Maturity[d]	Relative yield[ef]
	g ai ha^{-1}		plants row m^{-1}	------------%------------			days	% (kg ha^{-1})
Jupiter	0	----	39	84	76	97	0	100 (7,480)
	200	PRE	38	80	81	83	0	112
	400	PRE	37	79	68	96	0	117
	200	POST		80	79	98	0	113
	400	POST		79	80	88	0	122

Lynx	0	----	24	90	97		0	100 (5,410)
	200	PRE	17	90	93		1	90
	400	PRE	16	88	95		0	103
	200	POST		90	94		0	106
	400	POST		89	92		-1	100
PVL02	0	----	42	81	67	56	0	100 (5,610)
	200	PRE	43	76	73	67	0	110
	400	PRE	44	74*	74	66	0	104
	200	POST		79	71	70	0	107
	400	POST		78	66	64	0	97
RT7321FP	0	----	20	89	94	82	0	100 (10,210)
	200	PRE	21	89	96	88	-1	103
	400	PRE	21	90	93	86	0	102
	200	POST		91	96	90	0	100
	400	POST		91	96	85	-1	106

Table 8. Rice stand counts, percent canopy growth, rice maturity, and relative grain yield after a preemergence or postemergence application of tetflupyrolimet, averaged in 2021, 2022, and 2023, at the Pine Tree Research Station, near Colt, AR. All data excluding canopy growth were averaged over site-year.[a]

				Canopy growth[c]				

Cultivar	Rate	Timing	Stand 14 DAPRE[b]	2021	2022	2023	Maturity[d]	Relative yield[ef]
	g ai ha^{-1}		plants row m^{-1}	------------%------------			days	% (kg ha^{-1})
RT7521FP	0	----	23	85	100	70	0	100 (10,810)
	200	PRE	25	81	99	77	0	98
	400	PRE	23	82	99	72	0	98
	200	POST		86	99	81	0	100
	400	POST		82	99	78	0	96
RT7231MA	0	----	28	81	88	80	0	100 (8,240)
	200	PRE	27	80	84	83	0	102
	400	PRE	26	80	92	82	0	106
	200	POST		81	91	77	0	112
	400	POST		79	88	84	0	111
RTXP753	0	----	22	96	98	70	0	100 (10,510)
	200	PRE	21	96	99	77	0	110
	400	PRE	21	95	98	75	0	104
	200	POST		95	98	85	0	108
	400	POST		96	99	74	0	110

Table 8. Rice stand counts, percent canopy growth, rice maturity, and relative grain yield after a preemergence or postemergence application of tetflupyrolimet, averaged in 2021, 2022, and 2023, at the Pine Tree Research Station,

near Colt, AR. All data excluding canopy growth were averaged over site-year.[a]

				Canopy growth[c]				
Cultivar	Rate	Timing	Stand 14 DAPRE[b]	2021	2022	2023	Maturity[d]	Relative yield[ef]
	g ai ha^{-1}		plants row m^{-1}	------------%------------			days	% (kg ha^{-1})
Titan	0	----	43	88	74	73	0	100 (7,170)
	200	PRE	43	90	69	81	0	110
	400	PRE	43	91	66	76	-1	108
	200	POST		90	71	80	1	119
	400	POST		88	75	80	1	108

[a] Asterisks denote significance from the nontreated control using Dunnett's procedure (α=0.05). For rice canopy growth, any difference observed is only within the respective site-year.

[b] Abbreviation: DAPRE, days after preemergence application.

[c] Percent canopy growth collected at 12, 7, and 13 weeks after preemergence treatment in 2021, 2022, and 2023, respectively.

[d] Maturity measured in days relative to the nontreated control when 50% of rice in each plot exhibited panicles.

[e] Grain yield was not collected for Lynx and PVL02 cultivars in the 2023 site-year, data were averaged over 2021 and 2022.

[f] Grain yield of the nontreated control is presented in parentheses in kg ha^{-1}.