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# Soil residual activity of tetflupyrolimet and the influence of soil moisture and flood timeliness on barnyardgrass efficacy

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## Abstract

Tetflupyrolimet is the first herbicide with a novel site of action to be commercialized for use in agronomic crops in three decades. Direct-seed rice field experiments were conducted at research facilities near Stuttgart (silt loam), AR, and Keiser (clay), AR, to evaluate tetflupyrolimet as a preemergence herbicide versus commercial standards. Greenhouse experiments determined the influence of soil moisture on pre- and postemergence barnyardgrass control with tetflupyrolimet and clomazone and the impact of a delayed flood on efficacy when POST-applied. For the field experiments, clomazone, tetflupyrolimet, and quinclorac were applied individually PRE at 336 and 560, 134 and 224, and 336 and 560 g ai ha$^{-1}$, respectively, on a silt loam and clay soil, along with clomazone + tetflupyrolimet and clomazone + quinclorac at the same rates. The soil moisture experiment included a single PRE and a single POST application of clomazone at 336 g ai ha$^{-1}$, of tetflupyrolimet at 134 g ai ha$^{-1}$, and of a mixture at the respective rates on a silt loam soil at 50%, 75%, and 100% of field capacity. For the flood timing experiment, tetflupyrolimet was applied to 2- to 3-leaf barnyardgrass at 134 g ai ha$^{-1}$, and a flood was established at 4 h after treatment (HAT) and 5 and 10 d after treatment (DAT). Barnyardgrass control with a tetflupyrolimet and clomazone mixture was comparable to clomazone + quinclorac when averaged over all evaluations on silt loam and clay texture soils (≥91%). Soil moisture interacted with herbicide treatments for PRE and POST barnyardgrass efficacy when averaged over DAT, with tetflupyrolimet + clomazone generally providing the greatest and most consistent control across regimes. Flooding barnyardgrass at 4 HAT provided superior control to later flood timings. Tetflupyrolimet is an effective residual barnyardgrass herbicide, and the addition of clomazone will aid in providing consistent control across varying soil moisture conditions.

## Introduction

Tetflupyrolimet is the first herbicide with a novel site of action (SOA) for use in agronomic crops since the commercialization of hydroxyphenylpyruvate dioxygenase– and glutamine synthetase–inhibiting herbicides 30 yr ago (Duke 2012; Duke and Dayan 2022). Tetflupyrolimet is a Herbicide Resistance Action Committee/Weed Science Society of America Group 28, de novo pyrimidine biosynthesis inhibitor (orotate pathway) that targets the dihydroorotate dehydrogenase (DHODH) enzyme. The DHODH enzyme facilitates and catalyzes the oxidation reaction of dihydroorotate to orotate (Dayan 2019; Duke and Dayan 2022; Zrenner et al. 2006). Inhibition of DHODH prevents the downstream formation of uridine monophosphate from several precursors in the orotate pathway. It is lethal to most organisms due to the critical role of nucleotide production in plant growth and development. Inhibition activity of tetflupyrolimet on the DHODH enzyme was approximately 10-fold greater on *Setaria* spp. in comparison to rice; however, the selectivity for the latter is magnitudes greater than it is for sensitive weed species, suggesting that differences in metabolism may confer tolerance (Dayan 2019; Selby et al. 2023). The evaluated compounds of this new SOA have been documented to be specifically active toward monocotyledon weeds, with tetflupyrolimet having a high level of crop safety and effectiveness in paddy rice systems (Selby et al. 2023).

An extensive volume of direct-seeded and transplanted rice field experiments with tetflupyrolimet have been conducted in Brazil, India, Indonesia, Japan, the United States, and Vietnam with success in controlling economically important grass weed genera (*Echinochloa*, *Leptochloa*, and *Monochoria*) (Selby et al. 2023). Tetflupyrolimet exhibits preemergence (PRE) and postemergence (POST) control of sensitive grass species, although PRE applications are generally more effective. Tetflupyrolimet provides a high level of PRE weed control in paddy rice at 125 g ai ha$^{-1}$ and up to 90% POST efficacy at 250 g ai ha$^{-1}$ with no visible injury to rice (Selby et al. 2023). Furthermore, field and greenhouse data confirm the effectiveness of tetflupyrolimet on barnyardgrass and its excellent crop safety margin, which is not necessarily exclusive to rice (MCC, unpublished data).

FMC Corporation will likely position tetflupyrolimet as a PRE herbicide to be used in a mixture with clomazone both to preserve the longevity of SOAs and to broaden the spectrum of grass weed control. Mixing different SOAs has been proven to be one of the most effective chemical-based management strategies for mitigating the evolution of herbicide-resistant weeds, by alleviating selection pressure often imposed by a single SOA (Barbieri et al. 2022; Norsworthy et al. 2012). Since its commercialization in the early 2000s, clomazone has been widely adopted as a soil-applied herbicide in midsouthern U.S. rice production for effective control of imidazolinone-, propanil-, and quinclorac-resistant barnyardgrass populations despite a few fields having confirmed resistance to the herbicide (Baltazar and Smith 1994; Carey et al. 1995; Heap 2024; Norsworthy et al. 2007; Scherder et al. 2004). In addition to barnyardgrass, clomazone can effectively control broadleaf signalgrass [*Urochloa platyphylla* (Munro ex C. Wright) R.D. Webster], *Digitaria* spp., and *Panicum* spp. (Anonymous 2021). Unlike clomazone, a caveat to tetflupyrolimet is that its activity is primarily confined to, or is most effective on, *Echinochloa* species, which further identifies the need for and advantage of mixing with clomazone from an efficacy and herbicide resistance management perspective.

A major disadvantage of direct-seeded paddy rice systems is the length of time irrigation can take to uniformly cover an entire field, which may be ≥10 d, depending on rainfall, field size, and pumping capacity (JKN, personal communication, 2022). In some instances, rainfall is limiting, and irrigation must be used to activate soil-applied herbicides or allow the herbicide to be placed into the soil solution to become bioavailable. Suppose a field takes up to 10 d to receive adequate irrigation during dry weather; in that case, there may be variation in weed control in areas where activation was immediate, as opposed to those with delayed activation. The field experiments mentioned by Selby et al. (2023) indicated that the efficacy of tetflupyrolimet was not compromised under a variety of conditions, although the paper was not specific about the range of environmental parameters. It is common for delayed activation (generally <1.3 cm of irrigation or rainfall within 7 d after planting) to reduce the efficacy of soil-applied herbicides (Barnes and Oliver 2004), especially if weeds begin to germinate before irrigation or rainfall occurs (Anonymous 2022b), although there are some exceptions, such as dicamba (Anonymous 2022a; Shaner 2014).

Furrow-irrigated rice (FIR) has become an increasingly popular alternative production system in Arkansas to simplify crop rotation and management practices, accounting for approximately 18% of hectares as of 2022 (Hardke 2022). However, approximately 78% of the rice area is produced in a direct-seeded, delayed-flood system, with silt loam soils contributing to 56.9% of those hectares in Arkansas. Weed management programs can be particularly more challenging in FIR systems than in direct-seeded, delayed-flood systems. Frequent wetting and the absence of a permanent flood create an ideal environment for weed management to become more synonymous with row crop production and therefore more reliant on residual herbicides than is a typical paddy rice system (Norsworthy et al. 2008). The shift in the weed spectrum can make management more challenging, often leading to more herbicide applications. Because such an emphasis is placed on soil-applied herbicides in a FIR system, consistent performance is imperative across various soil moisture regimes.

As tetflupyrolimet nears commercial launch, it is important to understand the general efficacy of the herbicide as an individual component as well as the advantages of mixing it with clomazone, specifically on barnyardgrass, where management across the midsouthern United States can be challenging due to the prevalence of herbicide resistance (Talbert and Burgos 2007). Mixing tetflupyrolimet serves two purposes: mitigating herbicide resistance risk by combining two effective SOAs and increasing the spectrum of grass weed control. In addition to establishing the level of expected control with tetflupyrolimet as a stand-alone herbicide or in a mixture with clomazone, the impact of environmental conditions and management practices on efficacy must be evaluated to define expectations. Therefore experiments were designed (1) to evaluate the efficacy of tetflupyrolimet on barnyardgrass and other grass species compared to commercial standards based on a single PRE application; (2) to determine if soil moisture influences the level of control of tetflupyrolimet, clomazone, and the mixture on barnyardgrass PRE and POST; and (3) to determine if the variability of water movement across a paddy rice field influences POST performance of tetflupyrolimet.

## Materials and Methods

### *Soil Residual Activity Experiment*

To determine the effectiveness of tetflupyrolimet in comparison to other commercial PRE standards (clomazone, quinclorac, and clomazone + quinclorac) and to quantify the length of residual control over time, three field experiments were conducted from 2021 to 2023 on a clay and a silt loam soil. All silt loam experiments were conducted at the Rice Research and Extension Center, near Stuttgart, AR (34.464°N, 91.404°W), on a Dewitt silt loam soil (19% sand, 64% silt, and 17% clay with 1.1% organic matter) with pH 5.7. Experiments on the clay soil were at the Northeast Research and Extension Center in Keiser, AR (35.666°N, 90.082°W), on a Sharkey clay (41% sand, 1% silt, 58% clay, with 2.8% organic matter) with pH 5.5. Each field experiment was conducted once per year at the respective location and included four replications. Before planting, each field was subjected to conventional tillage events to prepare the seedbed. The experiment was arranged as a single-factor randomized complete-block design with four replications, and each plot measured 1.8 × 5.2 m. Herbicide treatments on the silt loam soil consisted of tetflupyrolimet at 134 g ai ha$^{-1}$, clomazone at 336 g ai ha$^{-1}$, quinclorac at 336 g ai ha$^{-1}$, tetflupyrolimet + clomazone (134 and 336 g ai ha$^{-1}$, respectively), and clomazone + quinclorac (both at 336 g ai ha$^{-1}$). The herbicide treatments were adjusted to the recommended rates for clay soil, where each respective rate was increased by a factor of 1.7.

The rice cultivar 'Diamond' (conventional, very short season, long grain, inbred) (University of Arkansas System Division of Agriculture, Little Rock, AR, USA) was planted at the silt loam site on May 14, 2021, April 30, 2022, and May 10, 2023. The same rice cultivar was planted at the clay site on May 20, 2021, May 10, 2022, and May 4, 2023. All applications were made immediately after planting using a hand-held backpack sprayer calibrated to deliver 140 L ha$^{-1}$ at 4.8 km h$^{-1}$ and equipped with TeeJet® AIXR 110015 nozzles (TeeJet® Technologies, Glendale Heights, IL, USA). Soil test potassium and phosphorus concentrations were addressed with

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samples collected in the fall before the start of each growing season and were amended before planting for each site-year. Immediately prior to flood establishment, the silt loam site received 168 kg $ha^{-1}$ of nitrogen, and an additional 30 kg $ha^{-1}$ was applied at the clay site in the form of urea (Roberts et al. 2016). Once rice in each experiment reached the 5-leaf growth stage or tillering, a permanent flood was established until harvest maturity. Nontarget broadleaf and sedge weeds were managed with the recommended rates of conventional rice herbicides with no activity on grass weed species, such as bentazon, halosulfuron, halosulfuron + prosulfuron, or 2,4-D.

Visible rice injury, visible barnyardgrass and broadleaf signalgrass control, and weed density (two 0.25-$m^2$ quadrats per experimental unit) assessments were collected at 21, 28, 35, and 42 d after treatment (DAT) following the PRE applications on the silt loam soil. The same assessments were collected at 14, 28, and 42 DAT on the clay soil; however, barnyardgrass was the only grass weed species evaluated on the clay soil. Each visible assessment was evaluated on a 0% to 100% scale, with 0% representing no injury or control and 100% representing crop death or complete control (Frans and Talbert 1977). Additionally, rice maturity was assessed by recording when at least 50% of the panicles within a plot were present. At full maturity, a 1.8-m-wide swath was harvested using a small-plot combine (ALMACO, Nevada, IA, USA), and grain yield was adjusted to 12% moisture.

For each location, site-year and replication were considered random to allow for generalizations to be drawn for visible rice injury, barnyardgrass and broadleaf signalgrass control, cumulative weed density, and rice grain yield. The silt loam and clay soil were analyzed independently due to differences in soil texture, weed species present, and herbicide rates. Excluding grain yield, a repeated-measures analysis, including herbicide and DAT as fixed effects, was conducted for all response variables at each location and was significant only for broadleaf signalgrass cumulative density (silt loam) and barnyardgrass cumulative density (clay). Values were averaged over all evaluation dates for response variables that had a main effect of herbicide treatment and did not have an interaction between herbicide treatment and DAT. A single-factor analysis (herbicide treatment) was used for rice grain yield because the response could be assessed only at a single point in time. All distributions were analyzed using the JMP PRO (version 17.1; SAS Institute, Cary, NC, USA) distribution platform (Avent et al. 2023), and residuals of the injury, weed control, and rice grain yield data assumed a normal distribution. Weed densities assumed a Poisson distribution (Gbur et al. 2012). All 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 honestly significant difference (HSD) ($\alpha = 0.05$).

### Soil Moisture Experiment

To evaluate the influence of soil moisture on the PRE and POST efficacy of tetflupyrolimet and clomazone individually, as well as the mixture of the two herbicides, two separate PRE and POST greenhouse experiments were initiated and repeated three times on a silt loam soil with three replications. Each experiment was conducted at the Milo J. Shult Research and Extension Center in Fayetteville, AR, in 2023 and 2024. A Captina silt loam soil (Fine-silty, siliceous, active, mesic Typic Fragiudults) with 20% sand, 66% silt, 14% clay, and 2.3% organic matter (Arkansas Agricultural Diagnostic Laboratory, Fayetteville, AR, USA) was collected and sieved to remove large pieces of residue and reduce the size of soil aggregates. The sieved soil was dried at 65 C for 2 wk, until no moisture was present. Once dried, 4,500 g of soil was added to 3.8-L buckets (no drainage). Soil bulk density and volumetric field capacity were calculated using Soil Plant Air Water (SPAW) software (U.S. Department of Agriculture Agricultural Research Service, Washington, DC, USA) using soil texture and organic matter inputs to determine the appropriate volume of water to maintain 50%, 75%, and 100% field capacity of the soil:

$$\mathrm{MW} = \frac{\mathrm{VFC}}{\mathrm{BD}} \times \%M \times \mathrm{MS} \qquad [1]$$

The methodology used to establish the desired soil moisture regimes was directly adapted from Avent et al. (2023), where MW represents the estimated mass of water required (1 g water = 1 ml water), VFC is the volumetric field capacity generated from SPAW, BD is the bulk density computed by SPAW using texture and organic matter, $\%M$ is the percent soil moisture established as the testing parameter, and MS is the mass of dried soil ($31.5\%/1.42 \times 100\% \times 4{,}500$ g = 998 g of water).

For each experiment, the greenhouse was set to provide a 14-h photoperiod with day and night temperatures of 32 C and 24 C, respectively. The 50%, 75%, and 100% of field capacity soil moisture regimes should reflect paddy or FIR production before the establishment of a permanent flood and provide an extreme scenario in instances when irrigation is limited or delayed in reaching certain areas of a field.

The buckets were filled with 4,250 g of soil brought to the appropriate moisture regime (based on 4,500 g of soil) and seeded with barnyardgrass at approximately 130 seeds $bucket^{-1}$. The remaining 250 g of soil was used to cover the exposed seed. Tetflupyrolimet and clomazone were applied individually and in a mixture at 134 and 336 g ai $ha^{-1}$ at the PRE and POST (2- to 3-leaf barnyardgrass) application timings. For POST applications, nonionic surfactant was added at 0.25% v/v to reduce the surface tension of the spray droplet. The PRE and POST experiments were conducted simultaneously for each run but were considered independent for statistical analysis. All PRE buckets received activating irrigation (1.3 cm) immediately following the herbicide application and were irrigated up to the appropriate moisture regime daily. The soil in buckets designated for POST treatments was also maintained daily in the respective moisture regimes. Each experiment was terminated 28 DAT. All herbicide treatments were applied using a motorized spray chamber calibrated to deliver 187 L $ha^{-1}$ with two TeeJet® 110067 flat-fan nozzles (TeeJet® Technologies).

Visible estimations of barnyardgrass control were recorded at 14 and 28 DAT on a 0% to 100% scale, with 0% representing no control and 100% representing complete control. The number of barnyardgrass plants in each bucket was recorded 28 DAT for PRE treatments. For POST treatments, barnyardgrass counts were recorded immediately before the herbicide application and again 28 DAT. The heights of three barnyardgrass plants per bucket were recorded at 28 DAT, and aboveground biomass was harvested, oven-dried to constant mass, and weighed.

Visual barnyardgrass control, density, biomass, and height data for the PRE and POST experiments were averaged over the three independent runs conducted from 2022 to 2024 and analyzed. Each experiment was initiated as a completely randomized design, and experimental run was considered a random effect, where block was nested within run. Herbicide treatment, moisture regime, and DAT were included in the model as fixed effects for a repeated-

**Table 1.** Broadleaf signalgrass and barnyardgrass percent control, rice visible injury, and rice grain yield collected at harvest.[a,b,c,d]

| Herbicide | Rate | Broadleaf signalgrass | Barnyardgrass | Rice | Grain yield |
|---|---|---|---|---|---|
| | g ai ha$^{-1}$ | ——— % control ——— | | % injury | kg ha$^{-1}$ |
| Silt loam | | | | | |
| Nontreated | | | | | 4,800 |
| Tetflupyrolimet | 134 | 90 bc | 93 ab | 3 b | 8,440 ab |
| Clomazone | 336 | 88 c | 90 b | 7 ab | 8,440 ab |
| Quinclorac | 336 | 92 b | 89 b | 8 ab | 7,120 b |
| Clomazone + tetflupyrolimet | 134 + 336 | 97 a | 97 a | 7 ab | 9,300 a |
| Clomazone + quinclorac | 336 + 336 | 97 a | 97 a | 9 a | 9,550 a |
| P-value | | <0.0001 | <0.0001 | 0.0200 | 0.0076 |
| Clay[e] | | | | | |
| Nontreated | | | | | 5,500 |
| Tetflupyrolimet | 228 | | 87 ab | 4 b | 8,890 ab |
| Clomazone | 570 | | 91 ab | 6 ab | 8,640 ab |
| Quinclorac | 570 | | 86 b | 4 b | 7,980 b |
| Clomazone + tetflupyrolimet | 228 + 570 | | 91 ab | 9 a | 9,300 a |
| Clomazone + quinclorac | 570 + 570 | | 94 a | 6 ab | 9,250 a |
| P-value | | | 0.0211 | 0.0020 | 0.0069 |

[a]All data were averaged over the 2021, 2022, and 2023 site-years at the silt loam and clay sites.
[b]Means within a column followed by the same letter are not different according to Tukey's HSD ($\alpha = 0.05$).
[c]Percent control was analyzed using repeated measures and averaged over 21, 28, 35, and 42 d after treatment.
[d]Nontreated control was not included in statistical analysis, but means were provided for grain yield.
[e]Broadleaf signalgrass was not present at the clay site.

measures analysis of percent barnyardgrass control. Barnyardgrass height, biomass, and mortality were analyzed as a two-factor factorial (Herbicide Treatment × Soil Moisture) because data collection of each response was assessed at a single point in time. All distributions were analyzed using the JMP PRO 17.1 distribution platform (Avent et al. 2023), and the residuals of all data assumed a normal distribution, excluding barnyardgrass densities, which assumed a Poisson distribution (Gbur et al. 2012). All data were analyzed in JMP PRO 17.1 and subjected to ANOVA using the fit model platform. Means were separated using Tukey's HSD ($\alpha = 0.05$).

### *Flood Timing Experiment*

A greenhouse experiment was conducted and replicated three times to assess the impact of flood timing on POST-applied tetflupyrolimet in scenarios where the timeliness of water movement across a field can be variable (up to 10 d). The experiment was arranged as a single-factor, completely randomized design with three replications conducted on silt loam soil (same soil, location, and greenhouse parameters as in the previous experiment). Barnyardgrass was planted into pots filled with sieved soil and thinned to five plants. The soil in pots was maintained at 80% of field capacity until a permanent flood was established. Tetflupyrolimet at 134 g ai ha$^{-1}$ plus non-ionic surfactant at 0.25% v/v was simultaneously applied POST (2- to 3-leaf) to all pots. Large metal containers were used for permanent flood establishment, maintaining 5 cm of clearance between the soil surface and the top of the container. Flood depth was monitored and replenished daily. One set of pots was flooded after allowing the herbicide to dry (approximately 4 h after application). The other two flood timing treatments were submersed to a 5-cm depth at 5 and 10 DAT until 28 d after the initial herbicide application.

Visible estimates of barnyardgrass control were recorded at 14 and 28 DAT, as described previously. At 28 DAT, live plants were counted in each pot, and aboveground biomass was harvested, oven-dried to constant mass, and weighed. Percent mortality was calculated because each pot was thinned to five plants.

Visible barnyardgrass control, biomass, and percent mortality were averaged over the three independent runs, with flood timing considered as the only fixed effect for percent mortality and biomass. A repeated-measures analysis was conducted for visible barnyardgrass control at 14 and 28 DAT to determine if efficacy increased over time, where flood timing and DAT were included in the model as fixed effects. Run was considered as a random effect and was not included in the model. Distributions were confirmed in JMP PRO 17.1 using the distribution platform (Avent et al. 2023), where the residuals assumed normality, and all data were subjected to ANOVA in JMP PRO 17.1 using the fit model platform. Means were separated using Fisher's protected least significant difference ($\alpha = 0.05$).

## Results and Discussion

### *Soil Residual Activity Experiment*

#### *Silt Loam Soil*

Visible injury to rice was comparable for each herbicide treatment, except for tetflupyrolimet (3%) and clomazone + quinclorac (9%), when averaged over 21, 28, 35, and 42 DAT for the repeated-measures analysis (Table 1). Visible injury from clomazone or mixtures that include clomazone typically manifests as transient bleaching (Zhang et al. 2005), and it is not surprising that greater numerical injury was observed on a silt loam soil in comparison to other treatments, as others have previously observed (Jordan et al. 1998). When averaged over DAT, all other herbicide treatments shared a similar level of damage to rice that ranged from 7% to 9%, indicating that injury remained minimal and was not different across evaluation dates. Injury to rice caused by tetflupyrolimet, if any, should exhibit a lack of root and shoot growth development (stunting) without the presence of chlorosis or necrosis (Selby et al. 2023); however, the only discernable symptomology was a

**Table 2.** Cumulative broadleaf signalgrass density at 21, 28, 35, and 42 d after treatment at the silt loam site.[a,b,c,d,e,f]

| Herbicide | Rate | Broadleaf signalgrass | | | | Barnyardgrass |
|---|---|---|---|---|---|---|
| | | 21 DAT | 28 DAT | 35 DAT | 42 DAT | |
| | g ai ha$^{-2}$ | plants m$^{-2}$ | | | | |
| Nontreated | | 230 | 270 | 294 | 294 | 272 |
| Tetflupyrolimet | 134 | 34 b–d | 42 bc | 58 a | 58 a | 20 ab |
| Clomazone | 336 | 38 bc | 40 bc | 46 ab | 46 ab | 22 a |
| Quinclorac | 336 | 20 e–g | 30 c–e | 40 bc | 40 bc | 28 a |
| Clomazone + tetflupyrolimet | 134 + 336 | 12 h | 12 gh | 20 e–g | 20 e–g | 8 c |
| Clomazone + quinclorac | 336 +336 | 10 h | 18 f–h | 24 d–f | 24 d–f | 10 bc |
| P-value | | 0.0032 | | | | <0.0001 |

[a]All data were averaged over the 2021, 2022, and 2023 site-years.
[b]Abbreviation: DAT, days after treatment.
[c]Means within a column followed by the same letter are not different according to Tukey's HSD (α = 0.05) for barnyardgrass.
[d]Barnyardgrass averaged over days after treatment.
[e]Repeated measures analysis was significant for interaction of density and days after treatment; therefore means can be compared across columns and rows according to Tukey's HSD (α = 0.05).
[f]Nontreated control was not included in the statistical analysis, but means are provided to show density.

negligible degree of stunting that was likely due to variability in the field.

According to the repeated-measures analysis, there were no differences in visible control of broadleaf signalgrass and barnyardgrass from 21 to 42 DAT, suggesting that efficacy remained consistent throughout the experiment for each weed species and could be averaged over DAT (Table 1). When averaged over DAT, the two mixtures that included clomazone provided the greatest broadleaf signalgrass control, where both were equal to 97%. Individual applications of tetflupyrolimet (90%) and clomazone (88%) were comparable, but quinclorac (92%) provided better control of broadleaf signalgrass than did clomazone. Like what was observed with broadleaf signalgrass, the repeated-measures analysis concluded that barnyardgrass control was consistent from 21 to 42 DAT (Table 1). The same trend was observed where the mixture of clomazone + tetflupyrolimet or clomazone + quinclorac provided 97% control of barnyardgrass. However, an individual application of tetflupyrolimet (93%) was comparable to the mixtures, which may allude to its specificity toward barnyardgrass, albeit the herbicide provided 90% visible control of broadleaf signalgrass at the silt loam location.

The repeated-measures analysis of cumulative broadleaf signalgrass densities further confirmed and reiterated the importance of mixing at least two compatible SOAs to increase weed control (Table 2). The two mixtures reduced the emergence of broadleaf signalgrass compared to any individual component by at least 4, 6, and 8 plants m$^{-2}$ across all evaluation dates. Unlike for broadleaf signalgrass, barnyardgrass cumulative densities did not increase or decrease over time but demonstrated an overall herbicide treatment effect when averaged across evaluation dates (Table 2). The individual applications of each herbicide ranged from 20 to 28 barnyardgrass escapes on average, as opposed to the two mixtures ranging from 8 to 10 m$^{-2}$. However, tetflupyrolimet was comparable to the clomazone + quinclorac mixture. Having 8 barnyardgrass escapes m$^{-2}$, the mixture of tetflupyrolimet and clomazone was more effective than all other individual treatments. Grain yield was similar for all treatments (≥8,440 kg ha$^{-1}$), excluding quinclorac (7,120 kg ha$^{-1}$), which may reflect poorer early-season barnyardgrass control relative to the other treatments in this experiment (Table 1).

This research indicates that quinclorac-resistant barnyardgrass was likely not prevalent during the three site-years on the silt loam soil. At this time, there is no supporting evidence from this experiment to conclude that a mixture of clomazone and tetflupyrolimet would be advantageous over a mixture of clomazone and quinclorac. However, given the current resistance status of barnyardgrass to quinclorac, there may be a benefit of mixing the novel SOA with clomazone. These potential implications underscore the importance of our research in the field of herbicide efficacy and weed control.

### *Clay Soil*

Visible injury to rice differed among herbicide treatments when averaged over 14, 28, and 42 DAT evaluations, although no estimation exceeded 9% and is likely biologically insignificant (Table 1). The mixture of clomazone + tetflupyrolimet or clomazone alone caused the highest levels of injury to rice at 14 DAT (9%) on the clay soil, comparable to clomazone alone at 6%. The visible injury caused by the mixture of clomazone and tetflupyrolimet was not greater than clomazone alone, indicating that the damage was likely associated with bleaching. The repeated-measures analysis (averaged over DAT) emphasized that tetflupyrolimet caused less numerical damage or was comparable to current PRE-applied commercial standards used in this experiment.

An initial concern was adequately adjusting the rate of tetflupyrolimet to optimize barnyardgrass control on clay soils because approximately 19% of rice hectarage is produced on a clay or clay loam soil in Arkansas (Hardke 2022). However, adjusting the rate of clomazone to 670 g ai ha$^{-1}$, which is greater than the herbicide rate used in this experiment, has proven to be sufficient on a clay soil without compromising weed control or increasing injury to rice (Zhang et al. 2005). Adjusting the rate of tetflupyrolimet by a factor of 1.7 from a silt loam soil (228 g ai ha$^{-1}$) provided a comparable level of barnyardgrass control to clomazone at 560 g ai ha$^{-1}$ and to the mixture with clomazone at the respective rates when averaged over DAT (Table 1). Shrinking and swelling of the clay soil surface often translates to a loss in residual control due to a comprised herbicide-rich barrier, where there is no longer contact with germinating weeds, and an opportunity for seeds to germinate at greater depths within soil openings; however, this phenomenon rarely translated into end-of-season escapes in plots treated with tetflupyrolimet based on early- and late-season visual observations. Cumulative barnyardgrass densities emphasized that more consistent control could be achieved over time (14 to 42 DAT) when mixing two SOAs, such as clomazone and tetflupyrolimet or clomazone and

**Table 3.** Cumulative barnyardgrass density at 14, 28, and 42 d after treatment at the clay site.[a,b,c,d]

| Herbicide | Rate | Barnyardgrass 14 DAT[c] | 28 DAT | 42 DAT |
|---|---|---|---|---|
| | g ai ha$^{-1}$ | plants m$^{-2}$ | | |
| Nontreated | | 254 | 456 | 480 |
| Tetflupyrolimet | 228 | 22 cd | 58 a | 60 a |
| Clomazone | 570 | 12 e | 42 b | 48 b |
| Quinclorac | 570 | 30 bc | 68 a | 80 a |
| Clomazone + tetflupyrolimet | 228 +570 | 16 de | 42 b | 46 b |
| Clomazone + quinclorac | 570 + 570 | 4 f | 24 c | 30 c |
| P-value | | | 0.0031 | |

[a]All data were averaged over the 2021, 2022, and 2023 site-years.
[b]Abbreviation: DAT, days after treatment.
[c]Repeated measures analysis was significant for interaction of density and days after treatment; therefore means can be compared across columns and rows according to Tukey's HSD (α = 0.05).
[d]Nontreated control was not included in the statistical analysis, but means are provided to show density.

quinclorac (Table 3). Excluding clomazone alone, by 42 DAT, plots treated with tetflupyrolimet and quinclorac had greater barnyardgrass densities than those treated with tank-mix partners with clomazone by 14 and 50 plants m$^{-2}$, respectively. Similar to the silt loam site, plots treated with quinclorac as a stand-alone herbicide had a lower grain yield on average than all other treatments, with higher infestations of barnyardgrass likely contributing to the observed reduction.

## *Soil Moisture Experiment*

### *Preemergence*

An interaction of herbicide and soil moisture regime was observed for barnyardgrass when averaged over the 14 and 28 DAT evaluation dates (Table 4). Barnyardgrass control with clomazone numerically decreased from 92% to 86% as soil moisture increased from 50% to 100% of field capacity, respectively, but was not significantly reduced. Plots treated with tetflupyrolimet demonstrated a contrasting effect compared to clomazone, where increased moisture increased barnyardgrass control. However, an increase in barnyardgrass control with tetflupyrolimet could be observed only between 50% (85% control) and 100% (93% control) of field capacity. A similar effect has been documented with PRE applications of amiben, atrazine, and *N*,*N*-dipropylthiocarbamate on a clay loam, where an increase in soil moisture resulted in greater performance (Stickler et al. 1969). Mixing clomazone and tetflupyrolimet provided effective and consistent barnyardgrass control, which never fell below 98% at the evaluated soil moisture regimes when averaged over 14 and 28 DAT. Repeated-measures analysis showed that there were differences in barnyardgrass control from 14 to 28 DAT when averaged over the soil moisture regime (Table 5). Barnyardgrass control decreased from 92% to 85% for clomazone from 14 to 28 DAT, respectively, while control increased by 10 percentage points from 84% for tetflupyrolimet in the same period. Mixing the two herbicides resulted in ≥98% barnyardgrass control at each evaluation date, emphasizing the importance of using them together in field situations for greater initial efficacy and persistence.

The same herbicide and soil moisture regime interaction was observed for barnyardgrass percent mortality, where percent mortality appeared to be reflective of visible estimations (Table 6). Tetflupyrolimet was the only herbicide treatment with which increasing soil moisture likewise led to an increase in barnyardgrass mortality. A 2-fold increase in soil moisture (50% to 100% of field capacity) resulted in a 20 percentage point differential in PRE barnyardgrass control (76% vs. 96% control). Despite increased PRE barnyardgrass control with tetflupyrolimet, the mixture of

**Table 4.** Influence of interaction of herbicide treatment and moisture regime at the preemergence and postemergence timings on barnyardgrass control.[a,b,c]

| Herbicide | Rate | Moisture regime | Control |
|---|---|---|---|
| | g ai ha$^{-1}$ | % of field capacity | % |
| Preemergence | | | |
| Clomazone | 336 | 50 | 92 a–d |
| Tetflupyrolimet | 134 | 50 | 85 d |
| Clomazone + tetflupyrolimet | 336 + 134 | 50 | 99 a |
| Clomazone | 336 | 75 | 87 cd |
| Tetflupyrolimet | 134 | 75 | 90 b–d |
| Clomazone + tetflupyrolimet | 336 + 134 | 75 | 98 ab |
| Clomazone | 336 | 100 | 86 cd |
| Tetflupyrolimet | 134 | 100 | 93 a–c |
| Clomazone + tetflupyrolimet | 336 + 134 | 100 | 99 a |
| P-value | | | 0.0051 |
| Postemergence[d] | | | |
| Clomazone | 336 | 50 | 57 c–e |
| Tetflupyrolimet | 134 | 50 | 64 b–e |
| Clomazone + tetflupyrolimet | 336 + 134 | 50 | 78 ab |
| Clomazone | 336 | 75 | 58 c–e |
| Tetflupyrolimet | 134 | 75 | 71 a–d |
| Clomazone + tetflupyrolimet | 336 + 134 | 75 | 74 ab |
| Clomazone | 336 | 100 | 51 e |
| Tetflupyrolimet | 134 | 100 | 73 a–c |
| Clomazone + tetflupyrolimet | 336 + 134 | 100 | 85 a |
| P-value | | | 0.04811 |

[a]All data were averaged over the three runs conducted in the greenhouse at the Milo J. Shult Research and Extension Center in Fayetteville, AR, in 2023 and 2024. The preemergence and postemergence experiments were analyzed independently.
[b]Means within a column followed by the same letter are not different according to Tukey's HSD (α = 0.05).
[c]Percent control was analyzed using repeated measures and averaged over 14 and 28 d after treatment.
[d]Included nonionic surfactant at 0.25% v/v.

**Table 5.** Influence of interaction of herbicide treatment and moisture regime at the preemergence timing on barnyardgrass mortality collected at 28 d after treatment.[a,b]

| Herbicide | Rate | Moisture regime | Mortality |
|---|---|---|---|
| | g ai ha$^{-1}$ | % of field capacity | % of nontreated |
| Clomazone | 336 | 50 | 92 ab |
| Tetflupyrolimet | 134 | 50 | 76 c |
| Clomazone + tetflupyrolimet | 336 + 134 | 50 | 98 ab |
| Clomazone | 336 | 75 | 87 a–c |
| Tetflupyrolimet | 134 | 75 | 84 bc |
| Clomazone + tetflupyrolimet | 336 + 134 | 75 | 98 ab |
| Clomazone | 336 | 100 | 87 a–c |
| Tetflupyrolimet | 134 | 100 | 96 ab |
| Clomazone + tetflupyrolimet | 336 + 134 | 100 | 99 a |
| P-value | | | 0.0073 |

[a]Data were averaged over the three experimental runs conducted in the greenhouse at the Milo J. Shult Research and Extension Center in Fayetteville, AR, in 2023 and 2024.
[b]Means within a column followed by the same letter are not different according to Tukey's HSD (α = 0.05).

**Table 6.** Visible barnyardgrass control at 14 and 28 d after treatment, including height and biomass collected at 28 DAT, for the preemergence experiment.[a,b,c,d]

| Herbicide | Rate | Control 14 DAT | Control 28 DAT | Height[e] | Biomass[f] |
|---|---|---|---|---|---|
| | g ai ha$^{-1}$ | — % of nontreated — | | — % reduction of nontreated — | |
| Clomazone | 336 | 92 b | 85 c | 58 a | 78 a |
| Tetflupyrolimet | 134 | 84 c | 94 ab | 93 b | 96 b |
| Clomazone + tetflupyrolimet | 336 + 134 | 98 a | 99 a | 95 b | 99 b |
| P-value | | <0.0001 | | <0.0001 | 0.0005 |

[a]Means are the average of three runs conducted in the greenhouse at the Milo J. Shult Research and Extension Center in Fayetteville, AR, in 2023 and 2024.
[b]Abbreviation: DAT, days after treatment.
[c]Repeated measures analysis was significant for interaction of control and days after treatment; therefore means can be compared across columns and rows according to Tukey's HSD ($\alpha = 0.05$).
[d]Means within a column followed by the same letter are not different according to Tukey's HSD ($\alpha = 0.05$).
[e]Mean barnyardgrass height of the nontreated control at 28 DAT was 37 cm.
[f]Mean barnyardgrass biomass of the nontreated control at 28 DAT was 12 g.

tetflupyrolimet and clomazone consistently remained above 98% barnyardgrass mortality across the three soil moisture regimes. If tetflupyrolimet is commercialized and applied as a stand-alone product, rice producers need to be mindful that maintaining a high level of soil moisture may aid in barnyardgrass management. However, clomazone would be an ideal tank-mix partner due to the increase in grass weed spectrum coupled with the consistent performance in the evaluated moisture regimes that are representative of field scenarios. In comparison to clomazone, barnyardgrass height and biomass were reduced by approximately 6-fold when tetflupyrolimet was applied alone or in a mixture (Table 6). Visually, plots treated with the mixture of clomazone and tetflupyrolimet displayed a combination of bleaching and stunting from the inhibition of 1-deoxy-D-xylulose 5-phosphate synthase and DHODH, where the latter explains the lack of growth and development of barnyardgrass (Selby et al. 2023).

Combining clomazone and tetflupyrolimet displayed consistency across all moisture regimes for each response, which again highlighted the advantage of mixing the two SOAs. The high level of barnyardgrass control and overall consistency would allow greater flexibility in FIR, where fields are divided into top, middle, and bottom (flooded) management zones with varying degrees of soil moisture (Chlapecka et al. 2021). If soil-applied herbicides needed to be activated in a conventional paddy rice system, it would likely take longer for each bay to receive adequate irrigation than the management zones in FIR. However, irrigation from flushing or flooding would potentially be more effective at distributing the herbicide over the surface layers of the soil and at increasing efficacy opposed to moistened soil (Russell et al. 1990).

### *Postemergence*

Clomazone, tetflupyrolimet, and the combination of the two herbicides displayed POST efficacy on barnyardgrass, albeit not to the extent of PRE applications (Table 4) (Selby et al. 2023). Although the herbicides evaluated in this experiment will not be advocated for POST applications as stand-alone treatments (A. Puri, Global Research and Development Product Manager, FMC Corporation, personal communication, 2023), it is important to identify the effectiveness of each on emerged weeds and if differing soil moisture regimes further influence efficacy. Tetflupyrolimet alone or in combination with clomazone will likely be mixed with other POST grass products to extend residual control of nonemerged weeds, and to date, there have been no incompatible herbicides identified that adversely impact the efficacy of actively growing barnyardgrass (MCC, unpublished data).

An interaction of herbicide treatment and soil moisture regime was also present for POST applications when averaging over the 14 and 28 DAT evaluation dates (Table 4). Barnyardgrass control with the individual herbicides or the mixture was not influenced by any change in soil moisture regime, although mixing clomazone and tetflupyrolimet was superior to clomazone by 21, 16, and 34 percentage points at 50%, 75%, and 100% of field capacity, respectively. Under greenhouse conditions, changes in soil moisture did not influence the control of red rice (*Oryza sativa* L.) or barnyardgrass from POST applications of imazethapyr (Zhang et al. 2001). From a POST standpoint, barnyardgrass control will be consistent across differing moisture regimes with a mixture of tetflupyrolimet and clomazone, which would provide greater flexibility in irrigation practices and ensure that efficacy would not be reduced if applied prior to establishment of a permanent flood.

Barnyardgrass height, biomass, and mortality were influenced by the POST herbicide applied, where the mixture of clomazone and tetflupyrolimet outperformed the individual components in two out of the three measured responses at 28 DAT (Table 7). Mixing the two SOAs reduced plant biomass by approximately 3- and 2-fold and increased percent mortality by a factor of roughly 3 and 6 over clomazone and tetflupyrolimet, respectively. Barnyardgrass height was similar between tetflupyrolimet alone and the mixture with clomazone, which is not surprising due to the downstream inhibition of pyrimidines needed for cellular reproduction caused by the new SOA. In PRE and POST applications, the addition of clomazone to tetflupyrolimet appeared to visibly compound symptomology from each respective SOA, where plants were stunted and bleached and demonstrated more rapid necrosis from loss of carotenoids leading to photooxidation.

## *Flood Timing Experiment*

Postemergence barnyardgrass control was improved by a range of 9 to 16 percentage points by establishing a permanent flood at 4 HAT as opposed to delaying until 5 or 10 DAT (Table 8). By 28 DAT, barnyardgrass control increased for all treatments; however, the 4 HAT flood was not improved statistically but was superior to the later flood timings. From 14 to 28 DAT evaluation dates, the 5 DAT flood timing saw the most improvement (16 percentage points) and was comparable to barnyardgrass in pots flooded at 10 DAT. At 28 DAT, the 4 HAT flood timing provided the highest level of POST barnyardgrass control (79%), which translated to

**Table 7.** Barnyardgrass height, biomass, and mortality collected at 28 d after treatment for the postemergence experiment.[a,b,c]

| Herbicide | Height[d] | Biomass[e] | Mortality |
|---|---|---|---|
| | —— % reduction of nontreated —— | | % of nontreated |
| Clomazone | 50 a | 66 a | 21 b |
| Tetflupyrolimet | 80 b | 74 a | 10 b |
| Clomazone + tetflupyrolimet | 85 b | 88 b | 59 a |
| P-value | <0.0001 | 0.0002 | <0.0001 |

[a]Means are the average of three runs conducted in the greenhouse at the Milo J. Shult Research and Extension Center in Fayetteville, AR, in 2023 and 2024.
[b]Means within a column followed by the same letter are not different according to Tukey's HSD (α = 0.05).
[c]Included non-ionic surfactant at 0.25% v/v.
[d]Mean barnyardgrass height of the nontreated control at 28 DAT was 49 cm.
[e]Mean barnyardgrass biomass of the nontreated control at 28 DAT was 21 g.

**Table 8.** Repeated-measures analysis of percent visible control of barnyardgrass at 14 and 28 days after treatment, as well as mortality and biomass as a percentage and as percent reduction of the nontreated control, respectively, at each flood timing.[a,b,c,d]

| Herbicide | Flood timing | Control | | Mortality | Biomass |
|---|---|---|---|---|---|
| | | 14 DAT | 28 DAT | | |
| | | —— % of nontreated —— | | | % reduction of nontreated |
| Tetflupyrolimet | 4 HAT | 70 a | 79 a | 26 a | 90 |
| | 5 DAT | 54 d | 70 b | 2 b | 89 |
| | 10 DAT | 61 c | 69 b | 10 ab | 92 |
| P-value | | 0.0058 | | 0.0108 | 0.2681 |

[a]All data were averaged over the three runs conducted in the greenhouse at the Milo J. Shult Research and Extension Center in Fayetteville, AR, in 2023.
[b]Abbreviations: DAT, days after treatment; HAT, hours after treatment.
[c]Repeated measures analysis was significant for the interaction of percent barnyardgrass control and days after treatment; therefore means can be compared across columns and rows according to Fisher's protected LSD (α = 0.05).
[d]Means within a column followed by the same letter are not different according to Fisher's protected LSD (α = 0.05).

the greatest percentage of plant mortality (26%), though it was comparable to flooding at 10 DAT (10%).

Despite the inconsistencies of POST barnyardgrass control at the 5 and 10 DAT flood timings, areas in the field where a permanent flood can be established at an earlier time appear to demonstrate a beneficial relationship and, at the least, should not adversely impact efficacy. Similar results have been documented with imazethapyr, where flooding 1 to 14 DAT maintained a higher level of red rice control at 28 d following a POST application (Avila et al. 2005). Although the flood timing experiment with tetflupyrolimet focused on POST efficacy, soil-applied herbicides generally improve performance when the activation is immediate and not excessive (Stewart et al. 2012). Further experiments will need to be conducted to determine if delaying herbicide activation influences PRE activity of tetflupyrolimet.

## Practical Implications

As with any herbicide, there are limitations to tetflupyrolimet, especially given the novelty of the SOA and the lack of published research specific to the herbicide. Results from these experiments demonstrate the effectiveness of tetflupyrolimet on barnyardgrass as a soil-applied residual herbicide in comparison to commercial standards, with the potential to aid in managing other grass weed species. Performance of tetflupyrolimet remained consistent in most instances compared to the evaluated commercial standards when adjusting the rate from a silt loam to a clay soil with minimal visible injury to rice. Mixing tetflupyrolimet with clomazone improved PRE and POST barnyardgrass efficacy across the range of dry to saturated environments that can be expected to occur in paddy rice and FIR systems. Furthermore, the addition of clomazone to tetflupyrolimet offers rice producers two effective SOAs to manage barnyardgrass, increase the grass weed spectrum, and minimize the selection placed on POST grass products in all available technologies. The consistency provided by a clomazone and tetflupyrolimet mixture should allow producers flexibility in time when using irrigation to activate the herbicides without compromising efficacy. Despite the effectiveness of both herbicides, making timely applications, using the appropriate rates, and incorporating a systems approach for weed management will aid in preserving longevity as new chemistries become available.

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## References

Anonymous (2021) Command® 3ME herbicide product label. Philadelphia: FMC Corporation. 27 p
Anonymous (2022a) XtendiMAX® herbicide product label. Research Triangle Park, NC: Bayer Crop Science. 24 p
Anonymous (2022b) Zidua® SC herbicide product label. Research Triangle Park, NC: BASF Corporation. 26 p
Avent TH, Norsworthy JK, Butts TR, Roberts TL, Bateman NR (2023) Rice tolerance to acetochlor with a fenclorim seed treatment. Weed Technol 36: 851–862

Avila LA, Senseman SA, McCauley GN, Chandler JM, O'Barr JH (2005) Effect of flood timing on red rice (*Oryza* spp.) control with imazethapyr applied at different dry-seeded rice growth stages. Weed Technol 19: 476–480

Baltazar AM, Smith RJ (1994) Propanil-resistant barnyardgrass (*Echinochloa crus-galli*) control in rice (*Oryza sativa*). Weed Technol 8, 576–581

Barbieri GF, Young BG, Dayan FE, Streibig JC, Takano HK, Merotto A Jr, Avila LA (2022) Herbicide mixtures: interactions and modeling. Adv Weed Sci 40, 1–25

Barnes JW, Oliver LR (2004) Preemergence weed control in soybean with cloransulam. Weed Technol 18, 1077–1090

Carey VF III, Hoagland RE, Talbert RE (1995) Verification and distribution of propanil-resistant barnyardgrass (*Echinochloa crus-galli*) in Arkansas. Weed Technol 9, 366–372

Chlapecka JL, Hardke JT, Roberts TL, Mann MG, Ablao A (2021) Scheduling rice irrigation using soil moisture thresholds for furrow irrigation and intermittent flooding. J Agron 113, 1258–1270

Dayan FE (2019) Current status and future prospects in herbicide discovery. Plants 8, 341

Duke SO (2012) Why have no new herbicide modes of action appeared in recent years? Pest Manag Sci 68, 505–512

Duke SO, Dayan FE (2022) The search for new herbicide mechanisms of action: is there a "holy grail"? Pest Manag Sci 78, 1303–1313

Frans RE, Talbert RE (1977) Design of field experiments and the measurement and analysis of plant responses. Pages 15–23 in Truelove B, ed. Research Methods in Weed Science. Auburn, AL, Southern Weed Science Society

Gbur EE, Stroup WW, McCarter KS, Durham SY, Young LJ, Christman M, West M, Kramer M (2012) Analysis of Generalized Linear Mixed Models in the Agricultural and Natural Resources Sciences. Madison, WI, American Society of Agronomy/Soil Science Society of America

Hardke JT (2022) Trends in Arkansas rice production. Pages 11–18 *in* Hardke J, Sha X, Bateman N, eds. B. R. Wells Arkansas Rice Research Studies 2022. Vol. 65. Fayetteville, University of Arkansas Agricultural Experiment Station

Heap I (2024) The International Survey of Herbicide Resistant Weeds. http://www.weedscience.com. Accessed: February 16, 2024

Jordan DL, Bollich PK, Burns AB, Walker DM (1998) Rice (*Oryza sativa*) response to clomazone. Weed Sci 46, 374–380

Norsworthy JK, Burgos NR, Scott RC, Smith KL (2007) Consultant perspectives on weed management needs in Arkansas rice. Weed Technol 21, 832–839

Norsworthy JK, Griffith GM, Scott RC (2008) Imazethapyr use with and without clomazone for weed control in furrow-irrigated, imidazolinone-tolerant rice. Weed Technol 22, 217–221

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60, 31–62

Roberts TL, Slaton N, Wilson C Jr, Norman R (2016) Soil fertility. Pages 69–102 *in* Arkansas Rice Production Handbook. Publication Number MP192. Fayetteville: University of Arkansas

Russell SG, Monaco TJ, Weber JB (1990) Influence of simulated rainfall and soil moisture on herbicidal activity of cinmethylin. Weed Sci 38, 267–272

Scherder EF, Talbert RE, Clark SD (2004) Rice (*Oryza sativa*) cultivar tolerance to clomazone. Weed Technol 18, 140–144

Selby TP, Satterfield AD, Puri A, Stevenson TM, Travis AD, Campbell MJ, Taggi AE, Hughes KA, Bereznak J (2023) Bioisosteric tactics in the discovery of tetflupyrolimet: a new mode-of-action herbicide. J Agric Food Chem 71, 18197–18204

Shaner DL (2014) Herbicide Handbook. 10th ed. Lawrence, KS: Weed Science Society of America, 513 p

Stewart CL, Soltani N, Nurse RE, Hamill AS, Sikkema PH (2012) Precipitation influences pre- and post-emergence herbicide efficacy in corn. Am J Plant Sci 3, 1193–1204

Stickler RL, Knake EL, Hinesly TD (1969) Soil moisture and effectiveness of preemergence herbicides. Weed Sci 17, 257–259

Talbert RE, Burgos NR (2007) History and management of herbicide-resistant barnyardgrass (*Echinochloa crus-galli*) in Arkansas rice. Weed Technol 21, 324–331

Zhang W, Webster EP, Blouin DC (2005) Response of rice and barnyardgrass (*Echinochloa crus-galli*) to rates and timings of clomazone. Weed Technol 19, 528–531

Zhang W, Webster EP, Selim HM (2001) Effect of soil moisture on efficacy of imazethapyr in greenhouse. Weed Technol 15, 355–359

Zrenner R, Stitt M, Sonnewald U, Boldt R (2006) Pyrimidine and purine biosynthesis and degradation in plants. Annu Rev Plant Biol 57, 805–836