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Short Title: Control with fluridone

Palmer amaranth (*Amaranthus palmeri*) Control in Furrow-Irrigated Rice with Fluridone

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Abstract

Herbicide-resistant Palmer amaranth is creating additional challenges for producers choosing to adopt a furrow-irrigated rice production system due to the absence of a sustained flood, enabling extended weed emergence. Fluridone has been shown to control Palmer amaranth effectively in cotton production systems and was recently registered for use in rice. Experiments were initiated in 2022 and 2023 to evaluate 1) Palmer amaranth control and rice tolerance to preemergence- and postemergence-applied fluridone at a 0.5x (84 g ai ha^{-1}) and 1x rate (168 g ai ha^{-1}) on a silt loam soil and 2) the effect of various herbicide programs containing fluridone on Palmer amaranth biomass, seed production, and rough rice grain yield. Preemergence applications of fluridone at a 1x rate in combination with clomazone resulted in 84% control of Palmer amaranth 21 d after treatment (DAT). Fluridone, in combination with clomazone preemergence, caused up to 36% rice injury 21 DAT; however, early season injury did not negatively affect rice yields. Palmer amaranth biomass and fecundity were reduced with herbicide programs that included fluridone plus florpyrauxifen-benzyl, and, in some instances, there was no Palmer amaranth biomass or seed production following multiple applications of both herbicides. Fluridone- and florpyrauxifen-benzyl-based herbicide programs achieved effective control of Palmer amaranth when applied timely, but injury to hybrid rice is enhanced with preemergence applications of fluridone that are not permitted with the current label.

Nomenclature: Florpyrauxifen-benzyl; fluridone; Palmer amaranth, *Amaranthus palmeri* (S.) Watson; cotton, *Gossypium hirsutum* L.; rice, *Oryza sativa* L.

Key Words: chemical control, crop injury, herbicides, seed production, weed control

Introduction

In the mid-southern U.S., rice is typically produced in a flooded system, which requires straight or contour levees to help maintain a permanent flood throughout the growing season (Hardke et al. 2022). However, furrow-irrigated rice has gained popularity in recent years, and in 2022, 18% of the total rice hectares in Arkansas were furrow-irrigated. While flood-irrigated rice involves establishing a continuous flood at the V5 stage of rice until maturity, furrow-irrigated rice is made possible by creating raised beds with furrows between the hipped rows, allowing the movement of water via gravity from the top end of the field (Counce et al. 2020; Lunga et al. 2021). Not only have producers lauded the idea of furrow-irrigated rice potentially decreasing water and equipment use (Chlapecka et al. 2021), but it also makes for an efficient transition into a rice-soybean [*Glycine max* (L.) Merr.] crop rotation, which is a frequent practice in Arkansas (Nalley et al. 2022). A major benefit of crop rotation is being able to integrate herbicide programs targeting troublesome grass species in a broadleaf crop (Burgos et al. 2021). However, the different water management practices associated with these two systems influence the emergence pattern and spectrum of weeds within a field (Kraehmer et al. 2016).

As of 2022, the most troublesome weed species in flood-irrigated rice included barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], sedge species (*Cyperus* spp.) and weedy rice (*Oryza sativa* L.), while barnyardgrass, Palmer amaranth, and sedges were among the most problematic weeds in a furrow-irrigated rice system (Butts et al. 2022). The permanent flood established by conventional paddy rice can help alleviate weed emergence, especially from terrestrial weeds that cannot survive in anaerobic conditions (Bagavathiannan et al. 2011). Furrow-irrigated rice allows typical upland crop weeds, such as Palmer amaranth, to thrive throughout the growing season due to the aerobic conditions creating a favorable environment for weed emergence and survival (Beesinger et al. 2022; Norsworthy et al. 2011).

Palmer amaranth has historically been among the five most troublesome weeds in major row crop production systems in the Midsouth (Norsworthy et al. 2014; Van Wychen 2020; Webster and Nichols 2012). While the influence of Palmer amaranth emergence on rice yields is unknown, some studies display its negative impact on soybean, cotton, and corn (*Zea mays* L.) yields (Klingaman and Oliver 1994; Massinga et al. 2001). Previous research has shown that Palmer amaranth densities $\leq$ 8 plants m^{-1} of row can reduce soybean and cotton yields by 78% and 70%, respectively (Bensch et al. 2003; Rowland et al. 1999). Considering Palmer amaranth

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has the potential to severely impact crop yields and furrow-irrigated rice hectares are increasing, more research is needed to create management strategies aimed at reducing the growth and development of the weed.

With herbicide-resistant populations of Palmer amaranth being widespread, effective chemical control options for Palmer amaranth are scarce. Typically, herbicides are used to control the most problematic weeds because they are easily accessible and convenient to apply (Priess et al. 2022). However, in Arkansas, Palmer amaranth has evolved resistance to eight sites of action, which is why it is recommended for producers to overlap multiple herbicide chemistries to help slow the evolution of herbicide-resistant weed species (Bagavathiannan et al. 2013; Barber et al. 2015; Heap 2024). Among those sites of action previously mentioned, microtubule assembly inhibitors [Herbicide Resistance Action Committee (HRAC)/Weed Science Society of America (WSSA) Group 3], acetolactate synthase inhibitors (ALS, HRAC/WSSA Group 2), and protoporphyrinogen oxidase inhibitors (PPO, HRAC/WSSA Group 14) are used in rice but are no longer effective due to confirmation of herbicide-resistant Palmer amaranth populations (Bond et al. 2006; Gossett et al. 1992; Varanasi et al. 2019). Florpyrauxifen-benzyl (Loyant™, Corteva Agriscience, Wilmington, DE 19805) and 2,4-D, both synthetic auxins (HRAC/WSSA Group 4), are generally effective at controlling Palmer amaranth in a furrow-irrigated rice system, but there is also confirmed resistance to 2,4-D (Hwang et al. 2023). Additionally, strict application regulations have been placed on both herbicides due to injury to adjacent susceptible crops from off-target movement (ASPB 2020; Barber et al. 2023; Wright et al. 2020). The adoption of novel herbicide sites-of-action for Palmer amaranth control would be beneficial given the status of current common chemical weed control options.

Fluridone (Brake, SePRO Corporation, Carmel, IN 46032), a phytoene desaturase inhibitor (PDS, WSSA Group 12), has been commonly used as a soil-applied, preemergence (PRE) herbicide in cotton for control of broadleaf and grass species (Hill et al. 2016). Fluridone is highly effective at controlling Palmer amaranth, especially on silt loam soils (Banks and Merkle 1979). The previous study also showed fluridone having prolonged activity in clay soils, with the herbicide being detected up to 250 days after application. Since most Arkansas rice hectares are composed of silt loam soils (Hardke et al. 2022), fluridone has potential value in furrow-irrigated rice production systems. However, before recommending fluridone in furrow-irrigated rice, rice tolerance and herbicidal efficacy must be assessed.

Since 2016, studies have been conducted to evaluate rice injury from fluridone carryover, with one study showing that fluridone applied PRE at 224 g ai ha^{-1} prior to cotton caused no more than 5% injury to rice the following year (Hill et al. 2016). Conversely, a 16 and 22% reduction in rice stand was observed with fluridone at 448 and 900 g ai ha^{-1}, respectively. As of 2023, fluridone was labeled for postemergence (POST) use in dry-seeded rice beginning at the 3-leaf rice growth stage at a maximum annual use rate of 168 g ai ha^{-1} (Anonymous 2023). Therefore, the objectives of this research were to (1) assess Palmer amaranth control and rice tolerance to PRE- and POST-applied fluridone at a 0.5x and 1x label rate on a silt loam soil and (2) evaluate the effect of various herbicide programs including fluridone on Palmer amaranth biomass, seed production, and rice grain yield.

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Materials and Methods

Palmer amaranth Control and Rice Injury with Single Applications of Fluridone

Field experiments were initiated in 2022 and 2023 at the Pine Tree Research Station near Colt, Arkansas (35.10887° N, 90.94066° W), on a Calhoun silt loam (fine-silty, mixed, active, thermic Typic Glossaqualfs) consisting of 11% sand, 68% silt, 21% clay, and 1.6% organic matter with a pH of 7.2. In 2022 and 2023, an additional site was located at the Milo J. Shult Research and Extension Center in Fayetteville, Arkansas (36.09366° N, 94.17344° W), on a Leaf silt loam (fine, mixed, active, thermic Typic Albaquults) comprised of 18% sand, 69% silt, 13% clay, and 1.6% organic matter with a pH of 6.7. The field experiment was designed to evaluate rice tolerance and Palmer amaranth control with a single fluridone application at a 1x label rate (168 g ai ha^{-1}) applied in combination with clomazone (Command 3ME, FMC Corporation, Philadelphia, PA 19104) PRE or florpyrauxifen-benzyl POST in a furrow-irrigated rice system (Table 1). The experiment was conducted as a randomized complete block design with four replications. Before planting, the test site was field cultivated and hipped into 91-cm and 76-cm wide beds in Fayetteville and Colt, respectively. The trials were kept free of grass weeds and sedge spp. using fenoxaprop (Ricestar HT, Gowan Company, Yuma, AZ 85364) and halosulfuron (Permit®; Gowan Company), and hand weeding when necessary. Three split nitrogen applications, as urea (460 g N kg^{-1}), were applied at 135 kg N ha^{-1} in two-week intervals following the V5 growth stage. Other nutrients were supplied preplant based on recommendations from the University of Arkansas System Division of Agriculture Marianna Soil Test Lab. Unless rainfall occurred, the experimental area was irrigated twice weekly following the V5 rice stage.

At all sites, a hybrid, long-grain rice cultivar 'Full Page RT7321FP' (RiceTec Inc., Alvin, TX 77512) was planted at 35 kg ha^{-1} at a 1-cm depth and 19-cm between rows. Plot dimensions were 3.7 m (four beds) wide by 5.2 m long and 3.1 m wide (four beds) by 5.2 m long in Fayetteville and Colt, respectively. The experiment consisted of seven treatments, including a nontreated control for comparison, with application timings occurring PRE, early postemergence at 3-leaf rice (EPOST), and mid-postemergence at rice tillering (MPOST). Herbicide treatments were made using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 276 kPa using four 110015 AIXR nozzles spaced 48 cm apart (TeeJet Technologies, Springfield, IL 62703) (Table 2).

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Visible estimations of rice injury and Palmer amaranth control were rated on a 0 to 100 scale, with zero being no plant symptomology and 100 representing complete plant mortality. Ratings were recorded 21 d after PRE (DAPRE), 7 d after early-POST (DAEPOST), and 14 and 28 d after mid-POST (DAMPOST). Before rice harvest, Palmer amaranth aboveground biomass was collected from a 1 m^2 quadrat within the center of each plot. All harvested biomass was placed in an oven at 66 C for two weeks, dried to constant mass, and dry biomass weight was recorded. Afterward, each female Palmer amaranth plant was threshed, and the ground plant material was separated from the seeds using a 20-mesh sieve and a vertical air column seed cleaner (Miranda et al. 2021). After cleaning, a 200-seed subsample from three random plots was weighed, and the average weight was used to calculate the number of seeds produced in the m^2 quadrat. Rough rice grain yield was determined by harvesting the center of each plot using a Kincaid 8-XP (Kincaid, Haven, KS 67543) small-plot combine equipped with a 1.8 m wide header. The grain yield was adjusted to 12% moisture.

Palmer amaranth Control and Rice Injury with Single and Multiple Applications of Fluridone

A field experiment was conducted at the Lon Mann Cotton Research Station in Marianna, AR (34.72549° N, 90.73423° W), in 2022 and the Milo J. Shult Research and Extension Center in Fayetteville, AR, in 2023 to assess Palmer amaranth control and rice injury with single and multiple applications of fluridone in combination with clomazone PRE or florpyrauxifen-benzyl POST. The experiment was conducted as a randomized complete block design with four replications. The soil at the Marianna site was a Convent silt loam consisting of 9% sand, 80% silt, 11% clay, and 1.8% organic matter with a pH of 6.5. In Fayetteville, the soil was a Leaf silt loam comprised of 18% sand, 69% silt, 13% clay, and 1.6% organic matter with a pH of 6.6. Before planting, the soil was tilled and hipped into 96-cm and 91-cm wide beds in Marianna and Fayetteville, respectively.

In both years, a hybrid, long-grain rice cultivar ‘Full Page RT 7321FP’ (RiceTec Inc., Alvin, TX 77512) was sown at 35 kg ha^{-1} at a 1-cm depth with 19-cm between rows. Plot dimensions were 1.9 m (two beds) wide by 5.2 m long and 1.8 m (two beds) wide by 5.2 m long in Marianna and Fayetteville, respectively. A natural population of Palmer amaranth was allowed to germinate after rice planting was completed. The trials were kept free of other undesirable weed species using applications of fenoxaprop or mechanical methods if necessary. The soil for each trial was amended for fertility preplant based on soil test values from the University of

Arkansas System Division of Agriculture Marianna Soil Test Lab fertility recommendations. Once the rice reached the V5 growth stage, irrigation water was delivered every two days unless rainfall occurred. Nitrogen, as urea (460 g N kg^{-1}), was applied at 135 kg N ha^{-1} in three separate applications in two-week intervals beginning at the 5-leaf stage of rice. This trial consisted of nine treatments, including a nontreated control, with application timings occurring PRE, MPOST, and late-postemergence at 42 d after planting (DAP) (Table 3). Herbicide treatments were made using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 276 kPa using four 110015 AIXR nozzles spaced 48 cm apart (TeeJet Technologies, Springfield, IL 62703) (Table 4).

Visible Palmer amaranth control and rice injury ratings were recorded 21 DAPRE, 14 DAMPOST, and 14 and 28 d after late-POST (DALPOST). Visual ratings were based on the same 0 to 100 scale mentioned in the previous experiment. Likewise, Palmer amaranth biomass, weed seed production, and rice grain yield data collection used the same parameters as the single fluridone application experiment.

Data Analysis

All data were analyzed in R studio version 4.3.2 (R Core Team, Vienna, Austria) using the 'glmmTMB' function (glmmTMB package; Brooks et al. 2017). Data were checked to determine whether the assumptions of normality and homogenous variance were met using the Shapiro-Wilks test and Levene's test. Rice injury, Palmer amaranth control, Palmer amaranth biomass, Palmer amaranth seed production, and rice grain yield were fitted to a generalized linear mixed-effect model (Stroup 2015). All injury and control data were analyzed using a beta distribution by evaluation timing, while Palmer amaranth biomass and seed production at harvest were analyzed using a Poisson distribution (Gbur et al. 2012). After the residuals failed to violate the Shapiro-Wilks and Levene's test, rice grain yield was analyzed using a Gaussian or normal distribution. Analysis of variance (ANOVA) was performed on each model using the 'car' package with Type III Wald chi-square test (Fox and Weisberg 2019). For each herbicide program, estimated marginal means (Searle et al. 1980) were obtained using the 'emmeans' package. The Sidak method was utilized to adjust for multiple pairwise comparisons (Midway et al. 2020), and the 'multcomp' package was used to generate a compact letter display to visually distinguish differences among treatments (Hothron et al. 2008). In both experiments, site year and block nested within site year were treated as random effects to draw general conclusions over diverse environments (McLean et al. 1991; Midway 2022), and herbicide treatment was considered a fixed effect (Blouin et al. 2011).

Results and Discussion

Palmer amaranth Control and Rice Injury with Single Applications of Fluridone

There were differences among herbicide treatments for visible estimations of Palmer amaranth control 21 DAPRE when averaged over four site years (P = 0.0002, Table 5). At 21 DAPRE, Palmer amaranth control ranged from 40% to 86% among herbicide treatments. Across all site years, Palmer amaranth control was ≥ 83% with clomazone + fluridone PRE at 21 DAPRE, which is similar to other research reporting 70 to 94% Palmer amaranth control three weeks after cotton planting with PRE applications of fluridone at rates ranging from 224 to 448 g ai ha^{-1} (Hill et al. 2017). However, the fluridone rates in the previously mentioned study are higher than the maximum annual use rate of 168 g ai ha^{-1} in rice. In most instances, PRE treatments that included clomazone + fluridone provided greater Palmer amaranth control than clomazone alone 21 DAPRE. Norsworthy et al. (2008) also reported reduced control of Palmer amaranth when clomazone was applied alone PRE.

Similarly, rice injury differed among herbicide treatments 21 DAPRE (P < 0.0001, Table 5). Both clomazone and fluridone disrupt pigment formation in the plant cells of susceptible species, leading to a bleached appearance on plant leaves (Anderson and Roberston 1960; Duke et al. 1991). Although rice has acceptable tolerance to clomazone, severe rice injury may still occur under various climatic conditions (Zhang et al. 2005); hence, the bleaching symptomology was greater when fluridone was mixed with clomazone. As a result, PRE treatments containing clomazone alone caused 10 to 16% injury to rice, while fluridone with clomazone resulted in 29 to 33% injury 21 DAPRE. These findings are similar to those observed by Martin et al. (2018), who reported PRE applications of clomazone and fluridone, each alone, causing 12 and 18% injury to rice four weeks after treatment at higher rates, respectively. Based on results, PRE treatments containing fluridone + clomazone caused a 2-fold increase in rice injury.

Herbicide treatment was significant for Palmer amaranth control ratings taken 7 DAEPOST (P < 0.0001, Table 6). Palmer amaranth control ranged from 76 to 92%, and PRE treatments containing clomazone and fluridone provided greater control than clomazone PRE followed by florpyrauxifen-benzyl EPOST. Waldrep and Taylor (1976) reported that fluridone provides prolonged residual control of *Amaranthus* species; hence, greater control of Palmer

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amaranth was observed at this timing even in the absence of a POST herbicide application. Additionally, applying fluridone with florpyrauxifen-benzyl EPOST did not enhance Palmer amaranth control, which is likely attributed to fluridone having minimal POST activity on established weeds (Waldrep and Taylor 1976).

At 7 DAEPOST, rice injury evaluations differed among herbicide treatments ($P < 0.0001$, Table 6). Treatments that included clomazone + fluridone PRE were more injurious to rice than clomazone PRE followed by florpyrauxifen-benzyl EPOST. Based on the injury data from similar treatments, clomazone + fluridone PRE caused 27 to 30% injury to rice, while injury from clomazone PRE followed by florpyrauxifen-benzyl EPOST ranged from 8 to 13%. Moreover, fluridone applied EPOST with florpyrauxifen-benzyl did not cause additional injury to rice compared to herbicide treatments containing clomazone PRE followed by florpyrauxifen-benzyl EPOST. Hence, rice injury can be minimized with an EPOST fluridone application while achieving greater Palmer amaranth control.

The final treatment was applied MPOST, and visible estimations of Palmer amaranth control were significant 14 ($P = 0.0169$) and 28 ($P = < 0.0001$) d after treatment (DAT) (Table 7). Regardless of the rate or timing of application, all programs containing a POST application of florpyrauxifen-benzyl had similar levels of Palmer amaranth control 14 DAT (90 to 92%). A previous study also reported similar Palmer amaranth control levels 21 DAT with florpyrauxifen-benzyl applied at 15 and 30 g ae ha^{-1} (Beesinger et al. 2022). At 28 DAT, herbicide programs that included either a single application of florpyrauxifen-benzyl at 30 g ae ha^{-1} POST or sequential applications of the herbicide at 15 g ae ha^{-1} EPOST and MPOST provided 97 to 98% Palmer amaranth control. Clomazone applied PRE followed by an EPOST fluridone application and sequential applications of florpyrauxifen-benzyl at EPOST and MPOST provided 98% control of Palmer amaranth, indicating that control can be optimized with labeled fluridone applications with florpyrauxifen-benzyl. Additionally, these findings support the need for effective POST herbicides in combination with soil-applied residuals for extended Palmer amaranth control, as noted by Hill et al. (2017).

Similarly, rice injury differed among herbicide programs 14 ($P = 0.0034$) and 28 ($P = 0.0232$) days after the final application (Table 7). At 14 DAT, clomazone PRE followed by florpyrauxifen-benzyl EPOST and a MPOST application of fluridone + florpyrauxifen-benzyl caused less injury to rice than programs including clomazone + fluridone PRE and clomazone +

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fluridone PRE followed by florpyrauxifen-benzyl MPOST at 15 g ae ha^{-1}, with injury being 7, 15, and 17%, respectively. These results display minimal injury to rice with mid-season fluridone applications mixed with florpyrauxifen-benzyl. As a result, producers can achieve residual Palmer amaranth control later in the growing season with POST fluridone applications while mitigating severe injury to the crop caused by a PRE application. At 28 DAT, clomazone + fluridone PRE followed by florpyrauxifen-benzyl MPOST at 30 g ae ha^{-1} caused 8% injury to rice. Rice injury was reduced to 3% when fluridone was applied MPOST or excluded from the herbicide program, suggesting that rice is more tolerant to fluridone at later growth stages and when applied foliarly (Waldrep and Taylor 1976).

Over four site years, the herbicide program affected rough rice grain yield ($P = 0.0044$, Table 8). Rice yield in the nontreated control was lowest compared to the other evaluated treatments. For all other herbicide programs, rice yields were similar and ranged from 6,380 to 6,600 kg ha^{-1}. High levels of Palmer amaranth control were achieved early in the season; thus, there was a lack of interference from Palmer amaranth and subsequent impact on grain yield throughout the remainder of the growing season. The yield data observed here indicates that POST fluridone applications in rice do not impact rough rice grain yield; hence, Palmer amaranth control can be achieved with labeled fluridone applications while not affecting grain development.

Conversely, Palmer amaranth biomass production differed as a function of the herbicide program averaged over the four site years, and weed biomass ranged from 0.2 to 350 g m^{-2} ($P < 0.0001$, Table 8). Compared to the nontreated control, all herbicide programs reduced Palmer amaranth biomass production. However, POST treatments containing florpyrauxifen-benzyl or florpyrauxifen-benzyl + fluridone caused the greatest reduction in Palmer amaranth biomass production, indicating the importance of applying effective POST herbicides in rice. The clomazone + fluridone PRE followed by florpyrauxifen-benzyl at 30 g ae ha^{-1} MPOST treatment allowed Palmer amaranth to produce similar quantities of biomass compared to a PRE application of clomazone with sequential POST applications of florpyrauxifen-benzyl at 15 g ae ha^{-1}. These findings indicate that PRE fluridone applications may not be necessary to effectively suppress Palmer amaranth biomass production in a furrow-irrigated rice system.

Regarding Palmer amaranth seed production, the herbicide program impacted the quantity of weed seed produced ($P < 0.0001$, Table 8). Compared to the nontreated control,

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clomazone + fluridone PRE allowed Palmer amaranth to produce the highest quantity of seed at approximately 23,500 seed m^{-2}. Sequential POST applications had the greatest impact on Palmer amaranth seed production relative to treatments that included a single POST application. The seed production data reported here is supported by Beesinger et al. (2022), who found that sequential florpyrauxifen-benzyl applications reduced Palmer amaranth seed production to a greater extent than a single application. Additionally, weed seed production was similar among programs where fluridone was applied either EPOST or MPOST with florpyrauxifen-benzyl, which may be attributed to the herbicide preventing additional weed emergence and subsequent offspring additions to the soil seedbank.

Palmer amaranth Control and Rice Injury with Single and Multiple Applications of Fluridone

Averaged over site year, herbicide treatment affected Palmer amaranth control when it was recorded 21 DAPRE ($P < 0.0001$, Table 9). At 21 DAPRE, Palmer amaranth control improved when fluridone was applied at either 84 or 168 g ai ha^{-1} in a mixture with clomazone, providing 84 to 91% control across the evaluated herbicide treatments. Weed control was greatest when clomazone was applied PRE with fluridone at 84 and 168 g ai ha^{-1}. Herbicide applications containing clomazone + fluridone at 84 or 168 g ai ha^{-1} resulted in 84 to 91% Palmer amaranth control, while clomazone applied alone resulted in only 43% control. These results indicate that adding fluridone PRE increases Palmer amaranth control relative to clomazone applied alone, as an approximate 2-fold increase in control was observed 21 DAT.

There were also differences in visible injury to rice among herbicide treatments 21 DAPRE ($P = 0.0472$, Table 9). Relative to the nontreated control, rice injury was greatest with treatments containing clomazone + fluridone at 168 g ai ha^{-1}. When applied PRE, clomazone + fluridone at 168 g ai ha^{-1} caused 32 to 36% injury to rice, which was greater than the 18% injury caused by clomazone applied alone. These results indicate that PRE fluridone applications, sprayed at a 1x rate, have a greater impact on rice than treatments excluding the herbicide. Although rice injury from treatments containing clomazone + fluridone at 84 g ai ha^{-1} was not statistically different than clomazone alone, producers should not apply fluridone until rice reaches the V3 growth stage (Anonymous 2023).

At 14 DAMPOST, visible evaluations of Palmer amaranth control differed among herbicide treatments ($P < 0.0001$, Table 10). Clomazone + fluridone at 84 g ai ha^{-1} PRE followed by florpyrauxifen-benzyl was superior to clomazone alone followed by florpyrauxifen benzyl in controlling Palmer amaranth, with each treatment providing 93 and 87% control, on average, respectively. In the absence of a POST florpyrauxifen-benzyl application, Palmer amaranth control ranged from 69 to 94%. Based on the data, integrating fluridone into herbicide programs will add value when targeting Palmer amaranth. However, fluridone is not currently labeled for PRE use in rice production systems. Additionally, these results display the need for effective POST herbicides, such as florpyrauxifen-benzyl, for enhanced Palmer amaranth control in a furrow-irrigated rice system.

Herbicide treatment also impacted rice injury 14 DAMPOST, with injury ranging from 13 to 39% ($P < 0.0001$, Table 10). Rice injury was greatest when fluridone was applied at 168 g ai ha^{-1} in combination with clomazone PRE. Fluridone was less injurious to rice when applied at a rate of 84 g ai ha^{-1}, even if the treatment included a sequential application of the herbicide MPOST at the same rate. A previous study conducted on a precision-leveled field also reported greater rice injury with fluridone applied at a 1x rate to 3-leaf rice than a 0.5x rate four weeks after application (Butts et al. 2024). Additionally, PRE applications of fluridone at the 0.5x rate in combination with clomazone followed by florpyrauxifen-benzyl MPOST does not increase rice injury compared to PRE treatments excluding fluridone. There were also no differences in injury with clomazone + fluridone PRE treatments compared to an identical PRE treatment followed by an MPOST application of florpyrauxifen-benzyl. Overall, greater rice injury was observed with fluridone applied at a 1x rate, which may be attributed to the extensive persistence of the herbicide in the soil, as reported by others (Banks et al. 1979).

The final herbicide application timing occurred LPOST, and visible Palmer amaranth control ratings differed as a function of herbicide program 14 and 28 DALPOST (Table 11). At 14 DALPOST, herbicide programs containing sequential florpyrauxifen-benzyl applications achieved 90% to 96% Palmer amaranth control. Relative to those treatments, PRE clomazone applications with fluridone followed by a single LPOST florpyrauxifen-benzyl application were less effective. These results suggest that multiple applications of fluridone or florpyrauxifen-benzyl should be used to optimize Palmer amaranth control. At 28 DALPOST, herbicide programs that utilized multiple applications of fluridone and florpyrauxifen-benzyl achieved 97 to 98% control of Palmer amaranth. Hence, applying multiple herbicides with different modes of action (MOA) is among the best management practices when targeting problematic weed species, such as Palmer amaranth (Norsworthy et al. 2012).

Herbicide programs containing multiple applications of fluridone and florpyrauxifen-benzyl caused up to 29% rice injury 14 DAT, comparable to all other programs evaluated in the experiment (Table 11). Similarly, sequential fluridone applications did not exacerbate rice injury compared to treatments with single applications of fluridone and florpyrauxifen-benzyl 28 DAT. These injury data suggest extended weed control can be achieved with more herbicide applications without causing additional rice injury compared to commercial standards.

Averaged across site years, rough rice yields differed among the herbicide programs (Table 12). Rice in the nontreated control had the lowest yield among treatments at 3,580 kg ha^{-1}. For all other herbicide programs, rice yields were similar and ranged from 7,540 to 8,260 kg ha^{-1}. The consistent grain yield across treatments is likely attributed to each program having an LPOST florpyrauxifen-benzyl application. Another study also observed maximum rice grain yield with LPOST applications of florpyrauxifen-benzyl in a furrow-irrigated rice system (Wright et al. 2020). Since fluridone provides effective early-season control of Palmer amaranth (Grichar et al. 2020; Hill et al. 2017), rice will likely have a competitive advantage in suppressing additional Palmer amaranth seedlings due to canopy formation. Hence, fewer POST herbicides may be required to control the weed sufficiently. Additionally, the visual injury observed with both fluridone and florpyrauxifen-benzyl did not have a long-term effect on rice yield by the end of the growing season.

Palmer amaranth biomass accumulation differed among the herbicide programs (Table 12). Compared to the nontreated control, all herbicide programs successfully reduced Palmer amaranth biomass production. Additionally, those programs that included a PRE and POST application of fluridone and sequential POST applications of florpyrauxifen-benzyl had the greatest impact on Palmer amaranth biomass production, allowing no weeds to escape in those plots at the time of rice harvest in both site years. These results are unsurprising, considering fluridone and florpyrauxifen-benzyl exhibited noteworthy control of Palmer amaranth when applied PRE and POST, respectively.

Likewise, the herbicide program affected Palmer amaranth seed production (Table 12), and the nontreated control allowed for the greatest Palmer amaranth seed production at 30,700 seed m^{-2}. In recent years, a zero-tolerance threshold approach has been widely recommended for long-term management of Palmer amaranth and preserving herbicide efficacy (Bagavathiannan and Norsworthy 2012; Norsworthy et al. 2012), in which no weeds are allowed to escape control

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and produce seed (Norris 2007; Norsworthy et al. 2014). Considering there was no Palmer amaranth present in plots where multiple applications of fluridone and florpyrauxifen-benzyl were made, no offspring were produced at rice harvest for those treatments. Conversely, Beesinger et al. (2022) found that sequential florpyrauxifen-benzyl applications still allowed Palmer amaranth to produce viable seeds by rice harvest. Therefore, findings from this research indicate that multiple applications of fluridone in combination with sequential POST applications of florpyrauxifen-benzyl will be advantageous in reducing the quantity of weed seed returned to the soil seedbank, further supporting the zero-tolerance threshold approach.

Practical Implications

This research highlights the ability of fluridone to provide excellent Palmer amaranth control when integrated into herbicide programs targeting the weed in a furrow-irrigated rice system. However, PRE fluridone applications caused greater rice injury than herbicide treatments excluding the herbicide; therefore, producers should not apply fluridone until the V3 rice growth stage, as stated on the herbicide label. Both experiments were placed at the higher end of the field with drier relative conditions; therefore, potential rice injury may be less with reduced moisture compared to the bottom end of the field. Severe injury from fluridone may occur in areas of the field where water from irrigation or rainfall is not removed due to its high persistence on a silt loam soil (Banks et al. 1979) and in fields that have been previously precision-leveled (Butts et al. 2024). Overall, the results reported here display the flexible application timing of fluridone when applied as a POST, residual herbicide with florpyrauxifen-benzyl for Palmer amaranth on a silt loam soil. Furthermore, using fluridone at labeled rates does not appear to translate into persistent season-long rice injury, yet it effectively controls Palmer amaranth while preserving rice yields. Although Palmer amaranth biomass and seed production was reduced with herbicide programs that included fluridone, the weed was still present at harvest in most instances; hence, producers must remain aware of the offspring and sufficient seedbank replenishment potential of the weed, which facilitates the spread of herbicide-resistant genes in future growing seasons.

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Competing Interests

The authors declare none.

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Table 1. Herbicide treatment, timing, and rate for the different programs evaluated in the single fluridone application experiment at Fayetteville, AR and Colt, AR in 2022 and 2023.[a]

Herbicide treatment	Timing	Rate
		g ai/ae ha^{-1}
Clomazone	Preemergence	336
Fluridone	Preemergence	168
Clomazone	Preemergence	336
Fluridone	Preemergence	168
Florpyrauxifen-benzyl	Mid-postemergence	15
Clomazone	Preemergence	336
Fluridone	Preemergence	168
Florpyrauxifen-benzyl	Mid-postemergence	30
Clomazone	Preemergence	336
Florpyrauxifen-benzyl	Early-postemergence	15
Florpyrauxifen-benzyl	Mid-postemergence	15
Clomazone	Preemergence	336
Fluridone	Early-postemergence	168
Florpyrauxifen-benzyl	Early-postemergence	15
Florpyrauxifen-benzyl	Mid-postemergence	15
Clomazone	Preemergence	336
Florpyrauxifen-benzyl	Early-postemergence	15
Fluridone	Mid-postemergence	168
Florpyrauxifen-benzyl	Mid-postemergence	15

[a] All florpyrauxifen-benzyl applications included 0.58 L ha^{-1} methylated seed oil

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Table 2. Dates for planting and herbicide applications.[a]

Location	Planting	Preemergence	EPOST	MPOST
Fayetteville, AR	June 1, 2022	June 1, 2022	Jun 23, 2022	July 1, 2022
	May 2, 2023	May 3, 2023	June 1, 2023	June 13, 2023
Colt, AR	May 17, 2022	May 18, 2022	June 9, 2022	June 15, 2022
	May 3, 2023	May 3, 2023	May 26, 2023	June 6, 2023

[a] Abbreviations; EPOST, early-postemergence; MPOST, mid-postemergence

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Table 3. Herbicide treatments, timings, and rates evaluated for the multiple fluridone application experiment at Marianna, AR, and Fayetteville, AR, in 2022 and 2023.[a]

Herbicide treatment	Timing	Rate
		g ai/ae ha^{-1}
Clomazone	Preemergence	336
Florpyrauxifen-benzyl	Mid-postemergence	15
Florpyrauxifen-benzyl	Late-postemergence	15
Clomazone	Preemergence	336
Fluridone	Preemergence	84
Florpyrauxifen-benzyl	Mid-postemergence	15
Florpyrauxifen-benzyl	Late-postemergence	15
Clomazone	Preemergence	336
Fluridone	Preemergence	168
Florpyrauxifen-benzyl	Mid-postemergence	15
Florpyrauxifen-benzyl	Late-postemergence	15
Clomazone	Preemergence	336
Fluridone	Preemergence	84
Florpyrauxifen-benzyl	Mid-postemergence	15
Fluridone	Mid-postemergence	84
Florpyrauxifen-benzyl	Late-postemergence	15
Clomazone	Preemergence	336
Fluridone	Preemergence	84
Florpyrauxifen-benzyl	Mid-postemergence	15
Florpyrauxifen-benzyl	Late-postemergence	15
Fluridone	Late-postemergence	84
Clomazone	Preemergence	336
Fluridone	Preemergence	84
Florpyrauxifen-benzyl	Late-postemergence	15
Clomazone	Preemergence	336
Fluridone	Preemergence	168
Florpyrauxifen-benzyl	Late-postemergence	15
Clomazone	Preemergence	336
Fluridone	Preemergence	84
Florpyrauxifen-benzyl	Late-postemergence	15
Fluridone	Late-postemergence	84

[a] All florpyrauxifen-benzyl applications included 0.58 L ha^{-1} methylated seed oil

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Table 4. Dates for planting and herbicide applications.[a]

Location	Planting	Preemergence	MPOST	LPOST
Marianna, AR	May 10, 2022	May 10, 2022	June 6, 2022	June 21, 2022
Fayetteville, AR	May 2, 2023	May 3, 2023	June 1, 2023	June 13, 2023

[a] Abbreviations: MPOST, mid-postemergence; LPOST, late-postemergence

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Table 5. Visible Palmer amaranth control and rice injury for the single fluridone application experiment at 21 DAPRE, averaged over four site-years.[ab]

Herbicides	Rate	AMAPA control		Rice injury	
	g ai ha^{-1}	-------------% of nontreated----------------			
Clomazone + fluridone	336 + 168	86	a	30	a
Clomazone + fluridone	336 + 168	83	a	33	a
Clomazone + fluridone	336 + 168	84	a	29	a
Clomazone	336	45	b	10	b
Clomazone	336	40	b	16	b
Clomazone	336	69	ab	10	b
P-value		0.0002		<0.0001	

[a] Means within a column followed by the same letter are not different according to Sidak method (α=0.05)

[b] Abbreviations: DAPRE, d after preemergence; AMAPA, Palmer amaranth

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Table 6. Visible Palmer amaranth control and rice injury for the single fluridone application experiment 7 DAEPOST, averaged over four site-years.[abc]

Herbicides	Timing	Rate	AMAPA control		Rice injury	
		g ai/ae ha^{-1}	----------% of nontreated-----------			
Clomazone +	PRE	336	92	a	30	a
Fluridone	PRE	168				
Clomazone +	PRE	336	91	a	32	a
Fluridone	PRE	168				
Clomazone +	PRE	336	88	ab	27	a
Fluridone	PRE	168				
Clomazone	PRE	336	76	b	12	b
Florpyrauxifen-benzyl	EPOST	15				
Clomazone	PRE	336	82	ab	13	b
Fluridone +	EPOST	168				
Florpyrauxifen-benzyl	EPOST	15				
Clomazone	PRE	336	77	b	8	b
Florpyrauxifen-benzyl	EPOST	15				
P-value			<0.0001		<0.0001	

[a] Means within a column followed by the same letter are not different according to Sidak method (α=0.05)

[b] Abbreviations: DAEPOST, d after early-postemergence; AMAPA, Palmer amaranth; PRE, preemergence; EPOST, early-postemergence

[c] All florpyrauxifen-benzyl applications included 0.58 L ha^{-1} methylated seed oil

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Table 7. Visible Palmer amaranth control and rice injury for the single fluridone application experiment 14 and 28 DAMPOST, averaged over four site-years.[ab]

Herbicides	Timing	Rate	AMAPA control				Rice injury			
			14 DAT		28 DAT		14 DAT		28 DAT	
		g ai/ae ha^{-1}	-----------------% of nontreated-----------------							
Clomazone +	PRE	336	69	b	73	c	15	a	5	ab
Fluridone	PRE	168								
Clomazone +	PRE	336	90	a	94	b	17	a	5	ab
Fluridone	PRE	168								
Florpyrauxifen-benzyl	MPOST	15								
Clomazone +	PRE	336	91	a	97	ab	14	ab	8	a
Fluridone	PRE	168								
Florpyrauxifen-benzyl	MPOST	30								
Clomazone	PRE	336	91	a	97	ab	10	ab	3	b
Florpyrauxifen-benzyl	EPOST	15								
Florpyrauxifen-benzyl	MPOST	15								
Clomazone	PRE	336	92	a	98	a	11	ab	4	ab
Fluridone +	EPOST	168								
Florpyrauxifen-benzyl	EPOST	15								
Florpyrauxifen-benzyl	MPOST	15								
Clomazone	PRE	336	90	a	97	ab	7	b	3	b
Florpyrauxifen-benzyl	EPOST	15								
Fluridone +	MPOST	168								
Florpyrauxifen-benzyl	MPOST	15								
P-value			0.0169		<0.0001		0.0034		0.0232	

[a] Means within a column followed by the same letter are not different according to Sidak method (α=0.05)

[b] Abbreviations: DAMPOST, d after mid-postemergence; AMAPA, Palmer amaranth; DAT, d after treatment PRE, preemergence; EPOST, early-postemergence; MPOST, mid-postemergence

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Table 8. The influence of herbicide programs utilizing single fluridone applications on Palmer amaranth seed production, Palmer amaranth biomass, and rice grain yield, averaged over four site-years.[abc]

Herbicides	Timing	Rate	SP		Biomass		Yield	
		g ai/ae ha^{-1}	seed m^{-2}		g m^{-2}		kg ha^{-1}	
Nontreated	-	-	72,380	a	350	a	4,020	b
Clomazone +	PRE	336	23,496	b	218	b	6,600	a
Fluridone	PRE	168						
Clomazone +	PRE	336	1,285	c	9	c	6,560	a
Fluridone	PRE	168						
Florpyrauxifen-benzyl	MPOST	15						
Clomazone +	PRE	336	921	d	0.2	e	6,520	a
Fluridone	PRE	168						
Florpyrauxifen-benzyl	MPOST	30						
Clomazone	PRE	336	520	e	2.0	de	6,380	a
Florpyrauxifen-benzyl	EPOST	15						
Florpyrauxifen-benzyl	MPOST	15						
Clomazone	PRE	336	151	f	3.6	d	6,540	a
Fluridone +	EPOST	168						
Florpyrauxifen-benzyl	EPOST	15						
Florpyrauxifen-benzyl	MPOST	15						
Clomazone	PRE	336	86	f	5.8	cd	6,590	a
Florpyrauxifen-benzyl	EPOST	15						
Fluridone +	MPOST	168						
Florpyrauxifen-benzyl	MPOST	15						
P-value			<0.0001		<0.0001		0.0044	

[a] Abbreviation: SP, seed production; PRE, preemergence; EPOST, early-postemergence; MPOST, mid-postemergence

[b] Means within the same column followed by the same letter are not different according to Sidak method (α=0.05); the absence of letters indicates no treatment difference was present

[c] All florpyrauxifen-benzyl applications included 0.58 L ha^{-1} methylated seed oil

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Table 9. Visible Palmer amaranth control and rice injury for the multiple fluridone application experiment 21 DAPRE, averaged over 2022 and 2023.[ab]

Herbicides	Rate	AMAPA control		Rice injury	
	g ai ha^{-1}	-------------% of nontreated--------------			
Clomazone	336	43	b	18	b
Clomazone + fluridone	336 + 84	85	a	29	ab
Clomazone + fluridone	336 + 168	88	a	32	a
Clomazone + fluridone	336 + 84	84	a	26	ab
Clomazone + fluridone	336 + 84	85	a	28	ab
Clomazone + fluridone	336 + 84	85	a	27	ab
Clomazone + fluridone	336 + 168	90	a	36	a
Clomazone + fluridone	336 + 84	91	a	27	ab
P-value		<0.0001		0.0472	

[a] Means within a column followed by the same letter are not different according to Sidak method (α=0.05); the absence of letters indicates no treatment difference was present

[b] Abbreviations: DAPRE, d after preemergence; AMAPA, Palmer amaranth; PRE, preemergence

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Table 10. Visible Palmer amaranth control and rice injury for the multiple fluridone application experiment 14 DAMPOST, averaged over 2022 and 2023.[abc]

Herbicides	Timing	Rate	AMAPA control		Rice injury	
		g ai/ae ha^{-1}	------------% of nontreated------------			
Clomazone	PRE	336	87	b	13	c
Florpyrauxifen-benzyl	MPOST	15				
Clomazone + fluridone	PRE	336 + 84	94	ab	16	bc
Florpyrauxifen-benzyl	MPOST	15				
Clomazone + fluridone	PRE	336 + 168	96	a	39	a
Florpyrauxifen-benzyl	MPOST	15				
Clomazone + fluridone	PRE	336 + 84	92	ab	25	b
Florpyrauxifen-benzyl + fluridone	MPOST	15 + 84				
Clomazone + fluridone	PRE	336 + 84	92	ab	17	bc
Florpyrauxifen-benzyl	MPOST	15				
Clomazone + fluridone	PRE	336 + 84	68	c	14	bc
Clomazone + fluridone	PRE	336 + 168	94	ab	37	a
Clomazone + fluridone	PRE	336 + 84	75	c	20	bc
P-value			<0.0001		<0.0001	

[a] Means within a column followed by the same letter are not different according to Sidak method (α=0.05)

[b] Abbreviations: DAMPOST, d after mid-postemergence; AMAPA, Palmer amaranth; PRE, preemergence; MPOST, mid-postemergence

[c] All florpyrauxifen-benzyl applications included 0.58 L ha^{-1} methylated seed oil

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Table 11. The main effect of herbicide program on visible Palmer amaranth control and rice injury 14 and 28 DALPOST, averaged over 2022 and 2023.[abc]

Herbicides	Timing	Rate	AMAPA control				Rice injury			
			14 DAT		28 DAT		14 DAT		28 DAT	
		g ai/ae ha^{-1}	----------------% of nontreated-----------------							
Clomazone	PRE	336	90	abc	92	bc	16	b	12	b
Florpyrauxifen-benzyl	MPOST	15								
Florpyrauxifen-benzyl	LPOST	15								
Clomazone +	PRE	336	92	abc	96	ab	13	b	20	ab
Fluridone	PRE	84								
Florpyrauxifen-benzyl	MPOST	15								
Florpyrauxifen-benzyl	LPOST	15								
Clomazone +	PRE	336	96	a	96	ab	35	a	26	ab
Fluridone	PRE	168								
Florpyrauxifen-benzyl	MPOST	15								
Florpyrauxifen-benzyl	LPOST	15								
Clomazone +	PRE	336	94	ab	97	a	29	ab	25	ab
Fluridone	PRE	84								
Florpyrauxifen-benzyl +	MPOST	15								
Fluridone	MPOST	84								
Florpyrauxifen-benzyl	LPOST	15								
Clomazone +	PRE	336	94	ab	98	a	26	ab	17	ab
Fluridone	PRE	84								
Florpyrauxifen-benzyl	MPOST	15								
Florpyrauxifen-benzyl +	LPOST	15								
Fluridone	LPOST	84								
Clomazone +	PRE	336	80	d	87	c	20	ab	13	b
Fluridone	PRE	84								
Florpyrauxifen-benzyl	LPOST	15								

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Clomazone +	PRE	336	85	cd	93	abc	36	a	33	a
Fluridone	PRE	168								
Florpyrauxifen-benzyl	LPOST	15								
Clomazone +	PRE	336	88	bcd	93	abc	17	b	18	ab
Fluridone	PRE	84								
Florpyrauxifen-benzyl +	LPOST	15								
Fluridone	LPOST	84								
P-value			<0.0001		0.0022		0.0267		0.0409	

[a] Means within a column followed by the same letter are not different according to Sidak method (α=0.05)

[b] Abbreviations: DALPOST, d after late-postemergence; AMAPA, Palmer amaranth; DAT, d after treatment; PRE, preemergence; MPOST, mid-postemergence; LPOST, late-postemergence

[c] All florpyrauxifen-benzyl applications included 0.58 L ha^{-1} methylated seed oil

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Table 12. Influence of different herbicide programs utilizing single and multiple applications of fluridone on Palmer amaranth seed production, Palmer amaranth biomass, and rice grain yield averaged over 2022 and 2023.[abc]

Herbicides	Timing	Rate	SP		Biomass		Yield	
		g ai/ae ha^{-1}	seed m^{-2}		g m^{-2}		kg ha^{-1}	
Nontreated	-	-	30,700	a	166	a	3,580	b
Clomazone	PRE	336	8,273	b	39	b	7,890	a
Florpyrauxifen-benzyl	MPOST	15						
Florpyrauxifen-benzyl	LPOST	15						
Clomazone	PRE	336	8,216	b	25	bc	7,860	a
Fluridone	PRE	84						
Florpyrauxifen-benzyl	MPOST	15						
Florpyrauxifen-benzyl	LPOST	15						
Clomazone	PRE	336	8,019	b	17	cd	7,740	a
Fluridone	PRE	168						
Florpyrauxifen-benzyl	MPOST	15						
Florpyrauxifen-benzyl	LPOST	15						
Clomazone	PRE	336	0	f	0	d	7,540	a
Fluridone	PRE	84						
Florpyrauxifen-benzyl	MPOST	15						
Fluridone	MPOST	84						
Florpyrauxifen-benzyl	LPOST	15						
Clomazone	PRE	336	0	f	0	d	8,110	a
Fluridone	PRE	84						
Florpyrauxifen-benzyl	MPOST	15						
Florpyrauxifen-benzyl	LPOST	15						
Fluridone	LPOST	84						

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Clomazone	PRE	336	1,355	e	12	cd	8,120	a
Fluridone	PRE	84						
Florpyrauxifen-benzyl	LPOST	15						
Clomazone	PRE	336	1,722	d	13	cd	7,580	a
Fluridone	PRE	168						
Florpyrauxifen-benzyl	LPOST	15						
Clomazone	PRE	336	5,642	c	41	b	8,260	a
Fluridone	PRE	84						
Florpyrauxifen-benzyl	LPOST	15						
Fluridone	LPOST	84						
P-value			<0.0001		<0.0001		<0.0001	

[a] Abbreviations: SP, seed production; PRE, preemergence; MPOST, mid-postemergence; LPOST, late-postemergence

[b] Means within the same column followed by the same letter are not different according to Sidak method (α=0.05)

[c] All florpyrauxifen-benzyl applications included 0.58 L ha^{-1} methylated seed oil

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