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WEED SCIENCE

Influence of Irrigation and Application Timing on the Efficacy and Cotton Tolerance of Herbicide-Coated Fertilizer

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ABSTRACT

Irrigation and herbicide application timings can affect cotton (*Gossypium hirsutum* L.) tolerance and weed control when applying herbicide-coated fertilizers, especially herbicides not labeled in the crop, such as florpyrauxifen-benzyl. Experiments were conducted to (1) evaluate the influence of irrigation timing on Palmer amaranth (*Amaranthus palmeri* S. Wats.) and barnyardgrass control [*Echinochloa crus-galli* (L.) P. Beauv.], and (2) determine the effect of application timing on cotton injury and Palmer amaranth control with florpyrauxifen-benzyl–coated fertilizer. A greenhouse study was conducted assessing irrigation timings of 0, 3, and 10 d after application (DAA) and five herbicides, including florpyrauxifen-benzyl at 29 g ha^{-1}; fluometuron at 840 g ha^{-1}; fluridone at 168 g ha^{-1}; pyroxasulfone at 91 g ha^{-1}; and *S*-metolachlor at 1,388 g ha^{-1}. In a field trial at Marianna, AR, application timings comprised 1- to 2-leaf, 3- to 4-leaf, 6- to 8-leaf, and 10- to 12-node growth stages. Generally, activating any herbicide 10 DAA resulted in decreased weed control and increased weed density and biomass compared to 0 and 3 DAA. Under controlled conditions, florpyrauxifen-benzyl provided lowest barnyardgrass control compared to other herbicides. Control of Palmer amaranth was comparable among all herbicides in greenhouse conditions. Application at 1- to 2-leaf, 6- to 8-leaf, and 10- to 12-node growth stages resulted in comparable Palmer amaranth control across years, and injury was less than 20% for all timings. This research underscores the importance of soil moisture and application timing in obtaining optimal weed control and minimal cotton injury when coating herbicides on fertilizer.

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Weed management is essential in cotton (*Gossypium hirsutum* L.) production, as cotton quality and yield potential can decrease as weed interference increases (MacRae et al., 2013; Morgan et al., 2001; Norsworthy et al., 2016). For instance, the prolonged presence of Palmer amaranth (*Amaranthus palmeri* S. Wats) or barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] can reduce lint yield by up to 57 and 97%, respectively (Keeley and Thullen, 1991; MacRae et al., 2013). Weed presence also can adversely affect cotton canopy volume, biomass, and grade (Bagavathiannan et al., 2011; Keeley and Thullen, 1991; MacRae et al., 2013; Morgan et al., 2001). Palmer amaranth and barnyardgrass are just two examples of the many weed species in cotton production, and their impact highlights the importance of efficient weed management strategies.

The use of residual herbicides in cotton provides flexibility in subsequent applications by providing extended weed control. Residual herbicides also minimize weed interference until crop canopy formation (Price et al., 2008; Wilcut et al., 1997). These herbicides can be applied as preplant, preemergence (PRE), or postemergence (POST) applications. Because of the potential phytotoxicity of residual herbicides to cotton, only a few are labeled for POST over-the-top applications in the crop. One option to reduce crop injury is to coat herbicides onto fertilizers.

Herbicide-coated fertilizers have been tested in many cropping systems, such as wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), and rice (*Oryza sativa* L.) (Cotter, 2023; Koscelny and Peeper, 1996; Rabaey and Harvey, 1994). In cotton, nitrogen is typically applied just before squaring and at first bloom. Potassium is often applied before squaring due to a peak nutrient requirement at these stages (Kerby and Adams, 1985; Robertson et al., 2007; Wells and Green, 1991). Therefore, coating residual herbicides onto granular fertilizer and applying them at squaring would provide simultaneous prolonged weed control and required nutrients. Furthermore, coating herbicides onto fertilizer could potentially benefit cotton producers. For instance, if applied over the top, herbicides that cause phytotoxic effects to cotton could be applied more safely if coated onto fertilizer. Less injury could occur compared to herbicides applied with a water carrier due to decreased herbicide contact with foliage (Prasad and Cadogan, 1992).

Florpyrauxifen-benzyl is one potential herbicide that can be included in cotton weed control programs if coated onto fertilizers. This herbicide displays a strong relationship between soil moisture and weed control efficacy (Miller and Norsworthy, 2018a). Metabolism, translocation, and absorption of florpyrauxifen-benzyl in barnyardgrass were improved when the moisture content was increased, which makes this herbicide optimal for preflood applications in rice. Besides preflood applications, this herbicide is useful in non-flooded systems and has been tested across different cropping systems, such as cotton (Doherty et al., 2020; Wright et al., 2020). Florpyrauxifen-benzyl sprayed over the top of cotton at 3 g ai ha^{-1}, which is 10% of the full rate, caused up to 85% injury (Miller and Norsworthy, 2018b). However, when post-directed to 8-node cotton at 29 g ai ha^{-1}, no more than 11% injury to the crop has been reported (Doherty et al., 2020). Coating florpyrauxifen-benzyl onto fertilizers will likely reduce the injury further, and this herbicide and application method could potentially be implemented into cotton production systems.

To fully harness the potential of herbicide-coated fertilizers, it is paramount to understand how irrigation and application timing affect herbicide efficacy. Adequate moisture is essential to activate residual and soil-applied herbicides, as the time elapsed between application and irrigation or precipitation can greatly influence herbicide efficacy (Stewart et al., 2012). The amount of water applied and the activation timing can impact the control of weed species by herbicides such as florpyrauxifen-benzyl (Miller and Norsworthy, 2018a; Stewart et al., 2012). Additionally, when considering the potential of non-labeled herbicides, application timing must be considered, as it can influence the level of crop injury. With many herbicides, application timing can dictate the level of weed control and crop injury in response to certain herbicides. For instance, when 2,4-D exposure to cotton occurs during pre-bloom growth stages, increased injury can result compared to other growth stages (Byrd et al., 2016). Likewise, cotton can be more susceptible to injury at certain growth stages when florpyrauxifen-benzyl is applied as a coated fertilizer.

Herbicide-coated fertilizers can be a viable option in cotton production systems due to their practical advantages. By using this application technique, herbicides deemed unsafe to spray in over-the-top POST applications can be used without causing significant injury or yield reductions in cotton. Hence, research was conducted to (1) determine the influence of irrigation timing on the control of Palmer amaranth and barnyardgrass with herbicides coated onto fertilizer, and (2) assess how application timing affects cotton tolerance and Palmer amaranth control when including florpyrauxifen-benzyl coated onto fertilizer.

MATERIALS AND METHODS

Irrigation Timing. An experiment was conducted twice in greenhouses at the Milo J. Shult Agricultural Research and Extension Center in Fayetteville, AR. The soil used in both experimental runs was a Captina silt loam (Fine-silty, siliceous, active, mesic Typic Fragiudults) composed of 12.5% sand, 51.4% silt, 36.1% clay, and 2.3% organic matter with a pH of 7.1. Buckets 7.57 L in volume were filled with 5,920 g of soil and planted with 200 barnyardgrass seeds and 300 Palmer amaranth seeds and covered with 350 g of soil, which was air-dried in the greenhouse and dry to the touch. Greenhouse-controlled conditions ranged from 29 to 33 °C, with a 16/8h light/dark period.

The experiment was designed as a randomized complete block, with two factors and four replications. Blocking allowed for potential differences in light quantity at the bench top. The first factor was irrigation timing to activate the herbicides. Three irrigation timings were used: the same day as herbicide-coated fertilizer application [0 d after application (DAA)], 3 DAA, and 10 DAA. The second factor was herbicide, which consisted of five herbicide-coated fertilizer treatments: florpyrauxifen-benzyl at 29 g ha^{-1}; fluometuron at 840 g ha^{-1}; fluridone at 168 g ha^{-1}; pyroxasulfone at 91 g ha^{-1}; and *S*-metolachlor at 1,388 g ha^{-1} (Table 1). A nontreated check was provided for each irrigation timing to compare Palmer amaranth and barnyardgrass control, density, and biomass. BullsEye Blue Spray Pattern Indicator (SPI) (Milliken Chemical, Spartanburg, SC) at 0.112 L ha^{-1} was mixed with the herbicide

Table 1. Herbicide information and rates used as treatments in this experiment

Common name	Product name	Rate	Group number	Manufacturer	Address
		g ai ha^{-1}			
Florpyrauxifen-benzyl	Loyant®	29	4	Corteva Agriscience LLC	Indianapolis, IN
Fluometuron	Cotoran®	840	5	Syngenta Crop Protection LLC	Greensboro, NC
Fluridone	Brake®	168	12	SePRO Corp.	Carmel, IN
Pyroxasulfone	Zidua SC®	91	15	BASF Corp.	Research Triangle Park, NC
S-metolachlor	Dual Magnum®	1388	15	Syngenta Crop Protection LLC	Greensboro, NC

and fertilizer to ensure even coverage. The fertilizer blend consisted of urea at 196 kg ha^{-1} and muriate of potash at 112 kg ha^{-1}. The soil in each bucket was treated simultaneously and irrigated according to the respective irrigation timing with approximately 700 ml of water (equivalent to 2.35 mm ha^{-1}) using a hand-held garden hose containing a spray nozzle on the shower setting to mimic rainfall. After treatments were activated by irrigation, each bucket received 700 ml of water twice a week.

Palmer amaranth and barnyardgrass control were estimated at 14 and 28 d after treatment (DAT), using visible ratings on a scale of 0 to 100, with 0 representing no control and 100 representing no plants present (Frans et al., 1986). Palmer amaranth and barnyardgrass counts were obtained simultaneously with control. At 28 DAT, the above-ground biomass (g) of both weeds within each bucket was collected, separated by species, placed in paper bags, and dried at 60 °C for 1 wk. Percentage reduction was calculated by first calculating relative biomass and density (%), which were calculated from the respective nontreated check for both weed species using Equation 1, and then subtracting that value from 100.

$$\text{Relative density or biomass (\%)} = \left[\frac{\text{treated}}{\text{untreated}}\right] \times 100 \quad (1)$$

Application Timing. A two-year field experiment was performed at the Lon Mann Cotton Research Station in Marianna, AR (34.72629, -90.74001) in the summers of 2022 and 2023. The experiment was conducted on a Calloway silt loam (fine-silt, mixed, active, thermic Aquic Fraglossudalfs) composed of 11.8% sand, 70.2% silt, 18% clay, and 1.25% organic matter with a pH of 7.6. Fields were tilled and bedded before planting, and the beds were placed 97 cm apart. The trials were seeded with a four-row vacuum planter at a 1.3 cm depth and 99,000 seeds ha^{-1} to a three-gene Bt variety with resistance to glyphosate, glufosinate, and dicamba [Bollgard® 3 XtendFlex (DP2020B3XF) Bayer Crop Science, St. Louis, MO]. Each plot consisted of four rows and was 7.6 m in length.

The experiment was designed as a single-factor randomized complete block with four replications. Treatments consisted of four application timings: 1- to 2-leaf growth stage, 3- to 4-leaf growth stage, 6- to 8-leaf growth stage, and 10- to 12-node growth stage. Florpyrauxifen-benzyl coated onto a granular fertilizer blend at 29 g ai ha^{-1} was applied at each growth stage. The fertilizer blend comprised 196 kg ha^{-1} of urea and 112 kg ha^{-1} muriate of potash. A nontreated check was present for each application timing and received an application of untreated fertilizer. The fertilizer mixture was weighed out according to the target rate (308 kg ha^{-1} of the mixture) for each plot. No denitrification inhibitors were coated onto the urea, as the effect of the herbicide-coated fertilizer alone was to be tested. The herbicide-coated and uncoated fertilizer treatments were applied using a 2.7-kg, 5-setting GroundWork hand spreader (Tractor Supply Co, Brentwood, TN) set on the third setting. A blue dye, BullsEye Blue SPI, at 0.112 L ha^{-1} was mixed with the herbicide to ensure an even coating on fertilizer. The herbicide and fertilizer were mixed using a 0.64 m wide by 1.09 m deep concrete mixer (Central Machinery, Camarillo, CA). The person responsible for applying the herbicide-coated fertilizer walked at 4.8 km hour^{-1} through the three furrows of each plot, making two passes through each furrow.

Crop maintenance was practiced throughout the trial, consisting of applications of a plant growth regulator and irrigation. The trials were treated with mepiquat chloride formulated as Pix® Ultra Plant Regulator (BASF Corp, Research Triangle Park, NC) at 49 g ai ha^{-1} twice throughout the season. The experiments were irrigated when sufficient rainfall was absent (Table 2; Fig. 1).

Table 2. Irrigation/rainfall dates and precipitation (mm) for the activation of florpyrauxifen-benzyl applied at four different application timings for the application timing study

Application timing	Application date		Initial activation date		Precipitation[z]		Relative humidity	
	2022	2023	2022	2023	2022	2023	2022	2023
					-----------mm----------		----------%----------	
1- to 2-leaf	June 1	May 25	June 3	June 14	19	13	80	72
3- to 4-leaf	June 6	June 5	June 9	June 14	22	13	83	87
6- to 8-leaf	June 16	June 12	June 20	June 14	Irrigation[y]	13	69	43
10- to 12-node	June 27	July 5	June 27	June 8	14	22	78	59

[z]Precipitation received at the initial activation date

[y]Furrow irrigation applied to activate herbicides

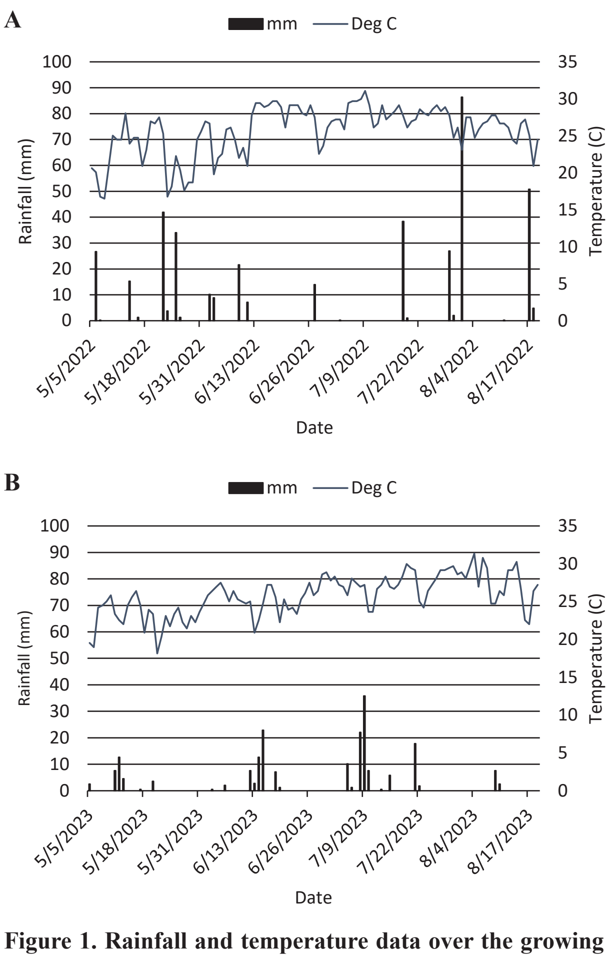

Figure 1. Rainfall and temperature data over the growing season in 2022 (A) and 2023 (B) at the Lon Mann Cotton Research Station, Marianna, AR. When rainfall was insufficient, supplemental irrigation was provided via furrow irrigation.

Following planting, a combination of fluometuron (Cotoran®, ADAMA, Raleigh, NC) at 1,120 g ai ha^{-1} plus paraquat (Gramoxone®, Syngenta Crop Protection, LLC, Greensboro, NC) at 700 g ai ha^{-1} was applied to the entire field for preemergence weed control. Clethodim (Select Max®, Valent, San Ramon, CA) at 85 g ai ha^{-1} was applied once throughout the season for grass control. A mixture of glyphosate (N-phosphonomethyl glycine; Roundup PowerMax3®, Bayer Crop Science, St. Louis, MO) at 1,260 g ae ha^{-1} and glufosinate-ammonium (Interline®, UPL NA Inc., King of Prussia, PA) at 656 g ai ha^{-1} was applied at different times, according to the application timing of the herbicide-coated fertilizer (Table 3). Nontreated checks also received the broadcast herbicide treatments. Spray applications were delivered using a hand-held CO_2-pressurized backpack sprayer with AIXR 110015 nozzles (TeeJet Technologies, Springfield, IL) at 140 L ha^{-1}.

Palmer amaranth control was evaluated 14 and 28 DAT for the 10- to 12-node growth stage on a scale of 0 to 100, with 0 representing no control and 100 representing no plants present (Frans et al., 1986). In addition, two, 1-m^2 quadrants were established in each plot, and Palmer amaranth plants were counted at 21 DAT. Cotton injury was rated at 14 and 28 DAT on a scale of 0 to 100, where 0 represented no injury and 100 represented complete plant death (Frans et al., 1986). Aerial images were taken using a DJI Mavic Mini Drone (SZ DJI Technology Co. Ltd, Nanshan, Shenzhen, China) at 14 DAT, and percentage groundcover was analyzed using the TurfAnalyzer companion FieldAnalyzer (Green Research Services LLC, Fayetteville, AR). Relative Palmer amaranth density was calculated (Eq. 1).

Data Analysis. Data were subjected to an analysis of variance using the GLIMMIX procedure in SAS 9.4 (SAS Institute, Cary, NC). Significant means were separated using Tukey's HSD post-hoc analysis ($\alpha = 0.05$). Data distribution was analyzed, and the Akaike Information Criterion was used to select the optimal distribution. The control data collected in the irrigation timing experiment did not fit a normal distribution. Thus, a beta distribution

Table 3. Application timing of glyphosate plus glufosinate to both the nontreated and treated plots for each florpyrauxifen-benzyl application timing

Florpyrauxifen-benzyl application timing	Glyphosate plus glufosinate timing[z]
1- to 2-leaf	1- to 2-leaf
3- to 4-leaf	3- to 4-leaf
6- to 8-leaf	1- to 2-leaf; 6- to 8-leaf
10- to 12-node	1- to 2-leaf; 6- to 8-leaf

[z]Glyphosate and glufosinate were applied at 1260 g ae ha^{-1} and 656 g ai ha^{-1}

was used (Gbur et al., 2012). Experimental runs were analyzed as random. Denominator degrees of freedom were adjusted to the Kenward and Roger (1997) approximation. For the application timing experiment, all data best fit a beta distribution. Data were analyzed by year because of a significant year effect when included as a fixed effect in the model.

RESULTS AND DISCUSSION

Irrigation Timing. There was no significant interaction between timing and herbicide at either 14 or 28 DAT regarding Palmer amaranth control (Table 4). Palmer amaranth control was primarily influenced by the timing of irrigation rather than the herbicide treatment. Averaged over all herbicides, delaying irrigation timing generally reduced Palmer amaranth control at 14 and 28 DAT. Specifically, herbicide effectiveness was reduced when irrigation was applied 10 DAA, with an average of 39% Palmer amaranth control at 14 DAT and 46% at 28 DAT. The other irrigation timings, 0 and 3 DAA, provided higher levels of control, which differed from each other at 14 DAT. The 0 and 3 DAA irrigation timings provided 98% and 92% Palmer amaranth control at 14 DAT, respectively. No differences were detected concerning Palmer amaranth control among the herbicides across all irrigation timings. Palmer amaranth can grow quickly, and if a residual herbicide is not activated before emergence, control levels will likely be decreased (Kouame et al., 2024).

The interaction between irrigation timing and herbicide timing was significant for barnyardgrass control at 14 and 28 DAT (Table 4). Overall, florpyrauxifen-benzyl was generally less effective at providing residual barnyardgrass control compared to the other herbicides at 14 and 28 DAT. All florpyrauxifen-benzyl treatments provided no more than 62% barnyardgrass control at 14 DAT and no more than 36% control by 28 DAT. *S*-metolachlor activated at 0 or 3 DAA resulted in no less than 83% barnyardgrass control through 28 DAT, indicating that it should be further evaluated under field conditions. These results indicate that barnyardgrass control can be significantly influenced by both irrigation timing and herbicide treatment.

At 28 DAT, barnyardgrass control was influenced by irrigation timing (Table 4). Herbicide effectiveness significantly decreased when herbicides were activated at 10 DAA, providing only 59% average control. However, when plots were irrigated at 0 or 3 DAA, efficacy was higher, with 87 and 82% control, respectively. The efficacy of herbicides in controlling redroot pigweed (*Amaranthus retroflexus* L.), green foxtail [*Setaria viridis* (L.) P. Beauv.], and common lambsquarters (*Chenopodium album* L.) are compromised when neither irrigation nor precipitation occurs within 7 d following preemergence application (Chomas and Kells, 2004; Stewart et al., 2012). Likewise, it is apparent that activating herbicide-coated fertilizers 10 DAA fails to achieve the same level of Palmer amaranth control at 14 and 28 DAT or barnyardgrass control at 28 DAT, compared to earlier irrigation timings.

Florpyrauxifen-benzyl exhibited the least barnyardgrass control among the herbicides tested when considering all irrigation timings combined at 28 DAT (Table 4). Florpyrauxifen-benzyl provided 39% barnyardgrass control at 14 DAT and 24% at 28 DAT. Similar to these results, whenever florpyrauxifen-benzyl is coated onto urea and applied preflood, barnyardgrass control averages 27% at 28 DAT (Cotter, 2023). However, whenever florpyrauxifen-benzyl is sprayed as broadcast at preflood, complete barnyardgrass control is observed. According to the results encountered in this study and those concluded by Cotter (2023), barnyardgrass control is greatly decreased when florpyrauxifen-benzyl is coated onto fertilizer.

The timing of irrigation was the only factor that influenced the relative density of Palmer amaranth (Table 5). The latest irrigation timing led to the highest presence of Palmer amaranth. Averaged over herbicides at 14 DAT, irrigation 10 DAA resulted in a 41% reduction in Palmer amaranth density, whereas there was a 97% reduction when irrigation occurred on the day of application. When plots were irrigated at 3 DAA, Palmer amaranth density was reduced by

Table 4. Palmer amaranth and barnyardgrass control in response to irrigation timing, herbicide treatment, and the interaction between irrigation timing and herbicide in a greenhouse trial

	Palmer amaranth control		Barnyardgrass control	
Factor	14 DAT[z]	28 DAT	14 DAT	28 DAT
Irrigation timing	----------	---------- % ----------	----------	----------
0 DAA	98	97a	80	87a
3 DAA	92	91a	74	82a
10 DAA	39	46b	68	59b
p-value[x]	<.0001	<.0001	0.5642	<.0001
Herbicide				
Florpyrauxifen-benzyl	81	88	39c	24c
Fluometuron	79	80	61bc	70b
Fluridone	84	81	73ab	83ab
Pyroxasulfone	94	84	85a	91ab
S-metolachlor	91	90	92a	95a
p-value	0.0617	0.2764	0.0270	0.0056
Irrigation timing × Herbicide				
0 DAA × Florpyrauxifen-benzyl	96	97	19d	10b
0 DAA × Fluometuron	96	93	60abcd	74a
0 DAA × Fluridone	95	94	76abc	89a
0 DAA × Pyroxasulfone	99	99	89ab	99a
0 DAA × *S*-metolachlor	99	99	99a	99a
3 DAA × Florpyrauxifen-benzyl	87	88	42cd	36ab
3 DAA × Fluometuron	87	92	62abcd	72a
3 DAA × Fluridone	88	82	83abc	94a
3 DAA × Pyroxasulfone	97	98	84abc	86a
3 DAA × *S*-metolachlor	94	91	83abc	95a
10 DAA × Florpyrauxifen-benzyl	33	57	62abcd	31ab
10 DAA × Fluometuron	28	36	61abcd	64a
10 DAA × Fluridone	44	45	54bcd	51ab
10 DAA × Pyroxasulfone	49	49	80abc	73a
10 DAA × S-metolachlor	47	44	76abc	75a
p-value	0.9679	0.9968	0.0251	0.0044

zAbbreviations: DAT, d after treatment, DAA, d after application

[y]Means within a column not containing the same lowercase letter are significantly different according to Tukey's HSD (α = 0.05)

[x]*P* values were generated using the GLIMMIX procedure in SAS 9.4 with a beta distribution

90% at 14 DAT and 93% at 28 DAT, which differed from the 0 and 10 DAA timings. When irrigated at 0 DAA, the reduction in Palmer amaranth density of all herbicides averaged 97% at 14 and 28 DAT. The main effect of herbicide did not impact Palmer amaranth density, which ranged from 77 to 92% reduction at 14 DAT and 81 to 91% at 28 DAT. Most herbicides depend on activation with moisture to be effective, and without activation, they can be lost via microbial decomposition, chemical decomposition, and photodegradation (Colquhoun, 2006). This research underscores the importance of activation before 10 DAA, as a significant amount of herbicide can be lost before irrigation.

The interaction between irrigation timing and herbicide was significant for barnyardgrass density reduction relative to the nontreated check (Table 5). When irrigated the day of application, *S*-metolachlor provided a 99% reduction in barnyardgrass density by 14 DAT, which was greater than the reduction for

Table 5. Palmer amaranth and barnyardgrass density and biomass relative to the nontreated check in response to herbicide-coated fertilizers applied preemergence in a greenhouse trial in Fayetteville, AR in 2023

	Weed Density				Weed Biomass	
	Palmer amaranth		Barnyardgrass		Palmer amaranth	Barnyardgrass
Factor	14 DAT[z]	28 DAT	14 DAT	28 DAT		
Irrigation timing	--------------------------------% reduction relative to nontreated---------------------------------					
0 DAA	97c[y]	97c	83	92b	99b	93
3 DAA	90b	93b	71	88b	85a	95
10 DAA	41a	28a	75	64a	75a	94
p-value[x]	<0.0001	<0.0001	0.3874	<0.0001	<0.0001	0.8683
Herbicide						
Florpyrauxifen-benzyl	80	88	53a	49a	97	47a
Fluometuron	77	82	65a	79b	94	95b
Fluridone	82	81	74ab	83b	88	96b
Pyroxasulfone	92	96	85b	94b	91	97b
S-metolachlor	89	91	93b	95b	88	98b
p-value	0.1186	0.0642	<0.0001	<0.0001	0.0924	<0.0001
Irrigation timing × Herbicide						
0 DAA × Florpyrauxifen-benzyl	95	96	27a	38ab	99c	15a
0 DAA × Fluometuron	95	92	63abc	89bcd	98c	94c
0 DAA × Fluridone	94	95	85abc	86bcd	99c	95c
0 DAA × Pyroxasulfone	99	99	90c	99e	99c	99c
0 DAA × *S*-metolachlor	98	98	99d	99e	99c	99c
3 DAA × Florpyrauxifen-benzyl	85	90	58abc	74abcd	94bc	57ab
3 DAA × Fluometuron	87	90	57abc	72abcd	98c	86c
3 DAA × Fluridone	85	85	78abc	94de	82abc	99c
3 DAA × Pyroxasulfone	95	98	85bc	92cd	74abc	96c
3 DAA × *S*-metolachlor	93	94	79abc	94de	35a	99c
10 DAA × Florpyrauxifen-benzyl	39	68	72abc	34a	93bc	76bc
10 DAA × Fluometuron	24	46	73abc	70abcd	57ab	98c
10 DAA × Fluridone	53	62	55ab	57abc	54ab	91c
10 DAA × Pyroxasulfone	45	53	81bc	79abcd	68ab	95c
10 DAA × *S*-metolachlor	47	69	87bc	77abcd	83abc	96c
p-value	0.3977	0.4388	0.0145	0.0259	0.0002	0.0004

[z]Abbreviations: DAT, d after treatment, DAA, d after application

[y]Means within a column for each location not containing the same lowercase letter are significantly different according to Tukey's HSD (α = 0.05)

[x]*P* values were generated using the GLIMMIX procedure in SAS 9.4 with a beta distribution

the 3 DAA irrigation timing. Irrigation at 10 DAA resulted in the lowest impact on barnyardgrass density at 28 DAT, with a 64% reduction relative to the nontreated when averaged over herbicides. Averaged over irrigation timing, the florpyrauxifen-benzyl treatment provided a 49% reduction of barnyardgrass 28 DAT, which was lower than all the other treatments.

Regarding relative biomass, the interaction between irrigation timing and herbicide treatment was significant in both species evaluated (Table 5). When irrigated at 0 DAA, Palmer amaranth biomass was reduced by 98% for all herbicides. Compared to 0 DAA, a slight increase in relative Palmer amaranth biomass was observed with most herbicides when plots were irrigated at 3 or 10 DAA. For irrigation timing, the activation at 0 DAA obtained the highest impact on Palmer amaranth biomass relative to the nontreated, with a reduction of 99%. Irrigation timing at 3 and 10 DAA caused an 85% and 75% reduction in Palmer amaranth biomass, respectively. Likewise, in wheat, both herbicide treatment and irrigation amount following application influence weed control, density, and biomass when treatments are sprayed (Verma et al., 2017).

For barnyardgrass, the treatment with florpyrauxifen-benzyl at 0 DAA obtained a 15% reduction in barnyardgrass biomass and was significantly increased when the herbicide was activated at 10 DAA (76%). Reduction in biomass ranged from 99 to 86% in the other treatments that did not include florpyrauxifen-benzyl. Overall, the treatment with florpyrauxifen-benzyl had the lowest reduction in biomass (47%), which was less than the reduction of biomass of the other herbicides (ranging from 98 to 95%). Whenever florpyrauxifen-benzyl is coated onto urea and applied to 2- to 3-leaf barnyardgrass, biomass was 87% relative to the nontreated check, which is a 13% reduction (Cotter, 2023). Therefore, it can be concluded that when applied as a coated fertilizer, florpyrauxifen-benzyl has a lower impact on barnyardgrass biomass compared to a broadcast spray application of this herbicide, regardless of irrigation timing.

Application Timing. Compared to the florpyrauxifen-benzyl coated onto fertilizer and applied at different cotton stages, Palmer amaranth control was lower when applied at the 3- to 4-leaf growth stage (Table 6). Palmer amaranth control was not different among the growth stage timings in 2022 and ranged from 65 to 92% at 14 DAT and from 55 to 86% at 21 DAT. Likewise, when florpyrauxifen-benzyl is sprayed post-directed to 8-node cotton, up to 99% Palmer amaranth control can occur (Doherty et al., 2020). However, in 2023, the herbicide-coated fertilizers applied at the 3- to 4-leaf growth stage obtained significantly lower Palmer amaranth control. Control was 38% and dropped to 14% at 21 DAT when this herbicide was applied at the 3- to 4-leaf growth stage. This treatment was only activated 9 d after application due to the lack of rainfall, which might have decreased Palmer amaranth control (Table 2). It has previously been shown that soil moisture can strongly affect florpyrauxifen-benzyl efficacy (Miller and Norsworthy, 2018a). Furthermore, the florpyrauxifen-benzyl label recommends that applications in rice should be made before flooding or activated within 5 DAA (Anonymous, 2023).

In 2023, the application at the 1- to 2-leaf cotton growth was not activated until 20 d later, yet Palmer amaranth control was optimal and comparable to the 6- to 8-leaf and 10- to 12-node stage applications. The high level of control provided could be attributed to the preemergence herbicide application that was made only 15 d before the 1- to 2-leaf growth stage application. The preemergence application contained fluometuron, a residual herbicide that can provide adequate Palmer amaranth control up to 28 DAT (Gardner et al., 2006; Hill et al., 2016). By the 6- to 8-leaf growth stage application, 33 d had passed, and by the 10- to 12-node growth stage, 55 d had passed, and the residual activity had broken. Thus, this residual application could explain the high level of Palmer amaranth control at the 1- to 2-leaf

Table 6. Palmer amaranth control and relative density in response to florpyrauxifen-benzyl-coated fertilizer at the 14 and 21 DAT evaluation dates in 2022 and 2023 for the application timing study

	Palmer amaranth control				Palmer amaranth density	
	2022		2023		2022	2023
Application timing	14 DAT[z]	21 DAT	14 DAT	21 DAT	21 DAT	21 DAT
	%-				% of nontreated check	
1- to 2-leaf	92	86	97a[y]	92a	47	17
3- to 4-leaf	65	55	38b	14b	83	48
6- to 8-leaf	82	81	88a	87a	95	83
10- to 12-node	88	75	88a	82a	71	26
p-value[x]	0.0652	0.0926	0.0001	0.0001	0.8361	0.5447

[z]Abbreviations: DAT, d after treatment

[y]Means within a column for each location not containing the same lowercase letter are significantly different according to Tukey's HSD (α = 0.05)

[x]*P* values were generated using the GLIMMIX procedure in SAS 9.4 with a beta distribution

growth stage despite the lack of irrigation to activate florpyrauxifen-benzyl.

Overall, relative Palmer amaranth density was not affected by florpyrauxifen-benzyl at any application timing (Table 6). Relative density ranged from 47 to 95% in 2022 and 17 to 83% in 2023. Palmer amaranth control was higher when florpyrauxifen-benzyl–coated fertilizer was added to the control program. Thus, adding florpyrauxifen-benzyl to an existing weed control program could improve Palmer amaranth management.

Cotton injury did not differ among the application timings at 14 or 21 DAT evaluation dates in 2023 (Table 7). However, differences were observed at 14 DAT in 2022. Except for the 1- to 2-leaf growth stage, all application timings had comparable amounts of injury in 2022. At 14 DAT, an application at the 1- to 2-leaf growth stage caused significantly less injury (4%) than the other timings (up to 20%). The highest injury observed (20%) was present when florpyrauxifen-benzyl–coated fertilizer was applied at the 6- to 8-leaf cotton growth stage. At 21 DAT, all applications caused comparable amounts of injury in both years, which ranged from 5 to 10%. The type of observed injury differed across the evaluation dates. In both years, the crop displayed epinasty at the 1- to 2-leaf and the 3- to 4-leaf growth stages (Fig. 2A). Conversely, cotton injury following the 6- to 8-leaf and 10- to 12-node applications consisted of small, prill-sized projections on the leaves (Fig. 2B). For both years, at 21 DAT, cotton injury by any florpyrauxifen-benzyl treatment was less than 10%. Thus, these results provide evidence that sustained damage to cotton does not occur when florpyrauxifen-benzyl is applied coated onto fertilizer at any growth stage. Although not assessed in this experiment, Pritchett et al. (2023) found that florpyrauxifen-benzyl–coated fertilizer applied over the top of cotton at the 6- to 8-leaf growth stage caused 17 and 21% injury 7 DAT, however there was no reduction in seed cotton yield. Additionally, Doherty et al. (2020) found no reduction in seed cotton yield when florpyrauxifen-benzyl was applied to 8-node cotton post-directed.

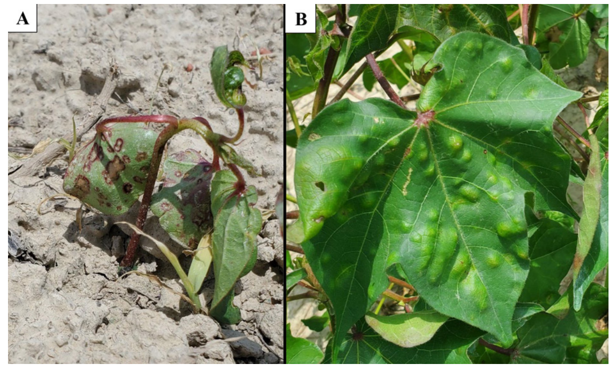

Figure 2. (A) Epinasty on cotton caused by florpyrauxifen-benzyl coated onto fertilizer applied to 1- to 2-leaf cotton 14 d after treatment and (B) prill-sized projections caused by florpyrauxifen-benzyl coated onto fertilizer applied to 6- to 8-leaf cotton 14 d after treatment.

Application timing did not affect cotton groundcover relative to the nontreated check for either 2022 or 2023 (Table 7). The injury caused to the crop by florpyrauxifen-benzyl did not result in decreased canopy size or groundcover. Additionally, Palmer amaranth plants in the plots did not cause differences between application timing treatments regarding relative cotton groundcover.

Table 7. Cotton injury and groundcover at the 14 and 21 DAT evaluation dates in both 2022 and 2023 for the application timing study

	Injury				Relative cotton groundcover			
	2022		2023		2022		2023	
Application timing	14 DAT[z]	21 DAT	14 DAT	21 DAT	14 DAT	21 DAT	14 DAT	21 DAT
	----------------------%----------------------				----------% of nontreated check----------			
1- to 2-leaf	4b[y]	10	5	4	93	70	79	106
3- to 4-leaf	8ab	5	2	3	112	111	97	99
6- to 8-leaf	20a	9	5	3	102	108	78	94
10- to 12-node	7ab	7	3	4	107	104	96	96
p-value[x]	0.0064	0.4366	0.3534	0.8367	0.5603	0.074	0.0886	0.9022

[z]Abbreviation: DAT, d after treatment

[y]Means within a column for each location not containing the same lowercase letter are significantly different according to Tukey's HSD (α = 0.05)

[x]*P* values were generated using the GLIMMIX procedure in SAS 9.4 with a beta distribution

CONCLUSIONS

Many factors influence weed control decisions, and when considering herbicide-coated fertilizers, it is essential to understand the impact of both irrigation and application timing on weed control and cotton tolerance. The results obtained here verify that delays in activating the herbicide-coated fertilizers with irrigation or rainfall will lower the expected level of weed control. Additionally, florpyrauxifen-benzyl coated onto fertilizer will not be a feasible option to control barnyardgrass, regardless of irrigation timing. However, applications of florpyrauxifen-benzyl coated on fertilizer could provide control of Palmer amaranth with minimal injury to cotton. There is a need for further research into the effect of application timing on florpyrauxifen-benzyl control of Palmer amaranth, where all treatments are activated within the same number of days. Because the number of days between application and irrigation was not the same for all application dates, these results are not conclusive. Further experimentation should be conducted to provide information on the effect of activation timing on cotton tolerance. In addition, other herbicides should be tested across the application timings evaluated here.

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