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# WEED SCIENCE

# Impact of Mixing an Aqueous Capsule Suspension Formulation of Pendimethalin and Glyphosate on Growth and Yield of Second-Generation Glyphosate-Resistant Cotton

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## ABSTRACT

**Past research has shown that a postemergence (POST) mixture of a residual herbicide, such as *S*-metolachlor, with glyphosate can result in improved weed control and maximize cotton yield. Published research is limited on the tolerance of a POST mixture of an aqueous capsule suspension (ACS) formulation of pendimethalin with glyphosate applied at different growth stages to cotton. Research of this issue is important as producers continue to search for cost savings in cotton production, and the inclusion of residual herbicides such as pendimethalin in the planting regimen is needed to abate the expansion of glyphosate-resistant (GR) weeds. This research was conducted in 2006 and 2007 to evaluate the effects of POST combinations of glyphosate with an ACS formulation of pendimethalin on second-generation GR cotton growth, development, and yield. Treatments evaluated in the study included a factorial arrangement of herbicides [glyphosate (®Roundup Weathermax) at 1540 g $ha^{-1}$ alone or in combination with ACS pendimethalin (®Prowl $H_2O$) at 1064 or 2128 g $ha^{-1}$ or *S*-metolachlor (Dual Magnum) at 1064 or 2128 g $ha^{-1}$] and cotton growth stage (4- to 5- or 6- to 8-leaf). Ammonium sulfate at 2524 g $ha^{-1}$ was included with each treatment. Results indicated that visual crop response in the form of veinal yellowing and slight leaf malformation can be observed following a POST tank-mixture of pendimethalin with glyphosate. Response is limited to contacted leaves. Visual crop response following mixture of glyphosate with pendimethalin was minimal 21 d after both application timings and was not manifested in reductions in plant height or seedcotton yield compared to glyphosate applied alone.**

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Cotton cultivars resistant to glyphosate have been widely accepted in cotton producing states since commercialization (Sankula and Blumenthal, 2004). In 2008, 98% of the area devoted to cotton production in the southeastern and mid-southern U.S. was planted to glyphosate-resistant (GR) cotton cultivars (USDA, 2009a). Due to the increase in GR cotton hectares, the percentage of overall cotton hectares treated with glyphosate in the U.S. increased from 17% in 1996 to 82% in 2005 (USDA, 2009b). Widespread acceptance of the GR system in cotton stems from the fact that glyphosate controls a wide spectrum of grass and broadleaf weeds (Clewis et al., 2006), and a glyphosate-based weed management system in GR crops might require fewer herbicide applications, resulting in greater weed management flexibility (Culpepper and York, 1998).

The high adoption rate of GR crops has resulted in the widespread, and often exclusive, use of glyphosate for weed control (Heap and LeBaron, 2001; Powles, 2008), which is a prescription for weeds to develop herbicide resistance. In the U.S., resistance to glyphosate has been documented in common waterhemp (*Amaranthus rudis* Sauer), common ragweed (*Ambrosia artemisiifolia* L.), giant ragweed (*Ambrosia trifida* L.), horseweed [*Conyza Canadensis* (L.) Cronq.], Italian ryegrass [*Lolium perenne* L. spp. *multiflorum* (Lam.) Husnot], Palmer amaranth (*Amaranthus palmeri* S. Wats), and others (Heap, 2009). Another possible reason for the increasing number of GR weeds is the decrease in applications of herbicides with alternative modes of action, particularly herbicides with residual soil activity (Shaner, 2000; Young, 2006). To mitigate the development and spread of herbicide-resistant weeds, applications of herbicides with alternative modes of action are necessary.

Pendimethalin is a dinitroaniline herbicide that inhibits mitosis by binding to tubulin, the major microtubule protein, leading to a loss of microtubule structure and function (Sensemen, 2007). Pendimethalin can be applied preplant surface, preplant incorporated, preemergence (PRE), or postemergence-directed (PD) in cotton (Anonymous, 2009b). The addition of pendimethalin PD in cotton improved overall control of barnyardgrass [*Enchinochloa crus*-galli (L.) Beauv.] and yellow nutsedge (*Cyperus esculentus* L.), and reduced weed dry biomass at time of cotton harvest when compared to postemergence (POST) applications of glyphosate (Koger et al., 2007). Pendimethalin PRE increased control of annual grasses and *Amaranthus* species to greater than 90% and increased cotton yields 59 to 75% (Wilson et al., 2007). Richardson et al. (2007) observed increased control of annual grass species, smooth pigweed (*Amaranthus hybridus* L.) and common lambsquarters (*Chenopodium album* L.) from residual pendiemthalin control as compared to applications of trifloxysulfuron-sodium alone POST. Tank mixtures of glufosinate plus pendimethalin or flumioxazin provided residual control of horseweed 56 d after application (Steckel et al., 2006).

The use of herbicide combinations involving multiple modes of action can be an effective strategy to reduce the risks associated with the evolution of herbicide-resistant weeds (Kaushik et al., 2006). Past research has shown that a POST tank-mix of a residual herbicide, such as *S*-metolachlor, with glyphosate can result in improved weed control and maximize cotton yield (Clewis et al., 2006, 2008; Scroggs et al., 2007). POST applications of an aqueous capsule suspension (ACS) formulation of pendimethalin in second-generation GR cotton are allowed under supplemental labeling with rates ranging from 532 to 1064 g ha$^{-1}$ at the 4-through 8-leaf growth stage (Anonymous, 2009a). Published research investigating the effect of pendimethalin POST applications in cotton is limited. Dodds et al. (2010) reported no seedcotton yield reduction from a POST application of an oil or water-based formulation of pendimethalin at the 4-leaf growth stage. Research has shown that POST application of pendimethalin did not adversely injure corn (*Zea mays* L.), rice (*Oryza sativa* L.), and various turf species (Bond et al., 2009; Brecke et al., 2008; Prostko et al., 2006). Therefore, this research was conducted to evaluate the impact of a tank mixture of glyphosate and ACS pendimethalin applied at two growth stages on growth and yield of second-generation GR cotton.

## MATERIALS AND METHODS

Field experiments were conducted at the Northeast Research Station near St. Joseph, LA, in 2006 and 2007. The experimental design was a randomized complete block (RBC) with treatments replicated four times. The study was conducted in an area that is designated for crop tolerance and cotton defoliation research, and not traditional weed management studies, and is maintained weed-free with aggressive management each year. Therefore, weed populations are relatively low. To ensure minimal impacts from emerging weeds in the current research, limited hand-weeding was conducted. Production practices followed state extension recommendations for cotton production (Anonymous, 2010). Plots consisted of two rows 7.6 m long with a row spacing of 102 cm. Plots were planted to 'DP 164 B2RF' cotton on May 3 and May 1 in 2006 and 2007, respectively. Soil type was a Mhoon silt loam (fine-silty, mixed nonacid, thermic Typic Fluvaquent).

Treatments evaluated in the study included a factorial arrangement of herbicides (glyphosate (®Roundup Weathermax 5.5 SL; Monsanto Company, St. Louis, MO) at 1540 g ha$^{-1}$ alone or in combination with ACS pendimethalin (®Prowl $H_2O$ 3.8 ASC; BASF Ag Products, Research Triangle Park, NC) at 1064 or 2128 g ha$^{-1}$ or *S*-metolachlor (Dual Magnum 7.62 EC; Syngenta Crop Protection, Inc., Greensboro, NC) at 1064 or 2128 g ha$^{-1}$ and cotton growth stage (4- to 5- or 6- to 8-leaf). Ammonium sulfate at 2524 g ha$^{-1}$ was included with each treatment. Treatments were applied mid-morning in both years.

Applications were made using a tractor-mounted compressed air sprayer delivering 140 L ha$^{-1}$ at 220 kPa with four flat fan nozzles spaced 51 cm apart. Parameters measured included visual crop response, on a scale of 0 = no injury to 100 = plant death, and plant height at 7, 14, and 21 d after treatment (DAT). Plots were mechanically harvested following chemical defoliation to determine seedcotton yield.

Plant height data were analyzed as a RCB design with a factorial arrangement of treatments and growth stages with repeated measures over the evaluation intervals. All factor effects were considered fixed and within plot correlation was modeled using an auto-regressive error structure in SAS PROC MIXED. Estimates of means and standard errors were generated using least squares means statements. Experiments were run separately by year (as a fixed effect) due to differing rainfall patterns in these particular years. Means were separated using the Dunnett's adjustment (glyphosate alone compared with each chemical mixture) at the 0.05 level of significance. For yield data, PROC GLM was used because only a single yield observation was taken on each factor combination. Means were separated as described for the crop height variable.

For crop response data, there were a large fraction of 0 or non-injury responses in the data set, so the response could not be considered continuous. With binary variables defined as injury or no injury, injury ≤ 5 vs. above, injury ≤ 10 vs. above, or injury ≤ 20 or above, only the presence or absence definition created a split with enough power to detect any differences. Glyphosate alone was considered the baseline category for the treatment factor in modeling. A logistic regression repeated-measures model was performed using the repeated statement in PROC GENMOD in SAS 9.1. Autoregressive, unstructured, and independence error structures were investigated for modeling the within-plot correlation. Due to missing data and the limited combinations of factors, the estimated logistic models were similar across estimated error structures.

## RESULTS AND DISCUSSION

**Plant Height.** Repeated-measures analysis indicated no significant herbicide treatment by growth stage interactions with respect to plant height. Regardless of growth stage at time of application or evaluation interval, plant height was not reduced with tank mixture of glyphosate with pendimethalin or *S*-metolachlor compared with glyphosate applied alone (data not shown). Although height measurements were not recorded late season, visual observation of treatments immediately prior to harvest reflected a lack of significant height reductions observed with early season height data analysis. In contrast to the current findings, visual estimates of injury in the form of stunted growth in the range of 14 to 20% was observed 8 and 14 d following POST application of water-based pendimethalin at rates from 900 to 3400 g $ha^{-1}$ to 4-leaf cotton (Dodds et al., 2010). In that research, however, findings with respect to *S*-metolachlor agreed with findings in the current research.

**Crop Response.** Logistic regression repeated-measures analysis indicated no significant herbicide treatment by growth stage interactions with respect to crop response. A significant herbicide treatment by year interaction was noted. In 2006, analysis using the binary split of presence/absence of injury yielded not enough power to detect treatment differences (Table 1). In 2007, using the lower bounds of confidence intervals for the odds ratio, the odds of injury for pendimethalin tank mixed at the low and high rate were 5.8 and 19 times greater than for glyphosate applied alone, whereas the odds of injury for *S*-metolachlor co-applied at the low and high rate were 1.5 and 7.9 times greater than for glyphosate applied alone. Mixture of pendimethalin at the high and low rate averaged 3 and 7%, injury, respectively, whereas the low and high rate of *S*-metolachlor averaged 1 and 5%, respectively (Table 1). Crop visual response was primarily in the form of leaf blotching/necrotic spotting with *S*-metolachlor and yellowing of mid-veins and wavy leaf appearance following pendimethalin application. In both years, injury was limited to leaves present at time of herbicide application and was almost nonexistent (<2%) at the 21 DAT evaluation interval. Clewis et al. (2006, 2008) reported <4% visual injury 1 to 2 wk following POST combination of *S*-metolachlor at 1120 g $ha^{-1}$ with glyphosate at 1120 g $ha^{-1}$ to 3- to 4-leaf cotton. Observed injury was described as transient necrotic speckling on exposed leaves.

**Table 1. Cotton response following tank mixture of glyphosate and ACS pendimethalin at St. Joseph, LA.**

| Treatment[X] | Rate g $ha^{-1}$ | Injury 2006[Z] | Injury 2007[Z] |
|---|---|---|---|
| | | % | |
| glyphosate + pendimethalin | 1540 + 1064 | 4 | 3* |
| glyphosate + pendimethalin | 1540 + 2128 | 5 | 7* |
| glyphosate + *S*-metolachlor | 1540 + 1064 | 1 | 1* |
| glyphosate + *S*-metolachlor | 1540 + 2128 | 3 | 5* |
| glyphosate | 1540 | 0 | 0 |
| | | NS[Y] | |

[Z] Means analyzed using a repeated measures logistic regression model for the 7-, 14-, and 21-d after treatment visual crop response estimate. Response means followed by an asterisk (*) are significantly different from the response observed following treatment with glyphosate alone.

[X] Glyphosate (Roundup Weathermax, 5.5 SL); ACS pendimethalin (Prowl $H_2O$ 3.8 ASC); *S*-metolachlor (Dual Magnum 7.62 EC).

**Seedcotton Yield.** Data analysis indicated a significant herbicide treatment by growth stage interaction in 2006 only. In 2006, seedcotton yield for cotton receiving glyphosate alone averaged 3201 and 3264 kg ha$^{-1}$ following application at the 4- to 5- or 6- to 8-leaf growth stage, respectively (Table 2). At the initial growth stage application, glyphosate combined with pendimethalin at the high rate or either rate of *S*-metolachlor resulted in seedcotton yield of 3881, 3848, and 3874 kg ha$^{-1}$, respectively, which was greater than that observed with glyphosate alone. At the later growth stage, combination of glyphosate with pendimethalin at the low rate (3860 kg ha$^{-1}$) or *S*-metolachlor at the high rate (4015 kg ha$^{-1}$) resulted in greater yield than glyphosate alone. As mentioned earlier, weed populations were low and hand-weeding was performed. Yield increases observed, when compared to glyphosate applied alone, might have been the result of residual activity of herbicides evaluated preventing weed germination and emergence and possible competition prior to hand-weeding. Seedcotton yield was not reduced for tank mixtures when compared to that observed for glyphosate applied alone. In 2007, seedcotton yield for tank mixture with pendimethalin or *S*-metolachlor, averaged across growth stage at application, ranged from 2666 to 2900 kg ha$^{-1}$, which was similar to the 2867 kg ha$^{-1}$ observed following application of glyphosate alone (data not shown). Dodds et al. (2010) reported similar findings with no reduction in seedcotton yield following POST application of oil- or water-based pendimethalin formulations applied to 4-leaf cotton.

**Table 2. Seedcotton yield following tank mixture of glyphosate and ACS pendimethalin at St. Joseph, LA.**

| Treatment[X] | Rate g ha$^{-1}$ | Seedcotton yield 2006[Z] | | Seedcotton yield 2007 |
|---|---|---|---|---|
| | | 4- to 5-leaf | 6- to 8-leaf | |
| | | kg ha$^{-1}$ | | |
| glyphosate + pendimethalin | 1540 + 1064 | 3303 | 3860* | 2849 |
| glyphosate + pendimethalin | 1540 + 2128 | 3881* | 3408 | 2900 |
| glyphosate + *S*-metolachlor | 1540 + 1064 | 3848* | 3472 | 2787 |
| glyphosate + *S*-metolachlor | 1540 + 2128 | 3874* | 4015* | 2666 |
| glyphosate | 1540 | 3201 | 3264 | 2867 |
| | | | | NS[Y] |

[Z]**Means followed by an asterisk (*) are significantly different from the response observed following treatment with glyphosate alone using the Dunnett's adjustment (glyphosate alone compared with each chemical co-application) at the 0.05 level of significance.**

[Y]**NS: No significant difference among treatments.**

[X]**Glyphosate (Roundup Weathermax, 5.5 SL-); ACS pendimethalin (Prowl $H_2O$ 3.8 ASC); *S*-metolachlor (Dual Magnum 7.62 EC).**

Collectively, these results indicate that crop response following POST tank mix application of pendimethalin and glyphosate in the form of veinal yellowing and leaf malformation can be observed in second-generation GR cotton. The response is limited to leaves contacted upon application and was minimal 21 DAT for both application timings, nor did it result in negative effects on growth and yield. Results indicate that when applied according to the herbicide label, glyphosate/ACS pendimethalin combinations offer producers the ability to integrate POST and residual weed management strategies and limit application costs without sacrificing crop tolerance.

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