ABSTRACT

DEAN, BROCK ALAN. Integration of Herbicide-Coated Fertilizer for Residual Weed Control in Cotton (*Gossypium hirsutum*). (Under the direction of Dr. Charles W. Cahoon).

Due to the increasing prevalence of multiple herbicide-resistant weed species and the subsequent rise in weed control costs, there is great need for additional weed management strategies in cotton production. Residual herbicide-coated granular ammonium sulfate (AMS) fertilizer could offer growers an economical alternative for managing multiple herbicide-resistant weed biotypes. Experiments were conducted to investigate the utility and efficacy of residual herbicide-coated fertilizer and its integration into North Carolina cotton production.

Palmer amaranth is one of the most troublesome weeds infesting North Carolina cotton. An experiment was conducted in 2022 and 2023 to evaluate herbicide-coated fertilizer for cotton tolerance and Palmer amaranth control. Treatments included acetochlor; atrazine; dimethenamid-*P*; diuron; flumioxazin; fluometuron; fluridone; fomesafen; linuron; metribuzin; pendimethalin; pyroxasulfone; pyroxasulfone + carfentrazone; *S*-metolachlor; and sulfentrazone. Each herbicide was individually coated on granular AMS (321 kg ha^{-1}) and top-dressed onto 5- to 7-leaf cotton. All herbicides resulted in transient cotton injury, except metribuzin. In 2022, metribuzin caused 11 to 39% and 8 to 17% injury at Clayton and Rocky Mount, respectively. In 2023, metribuzin caused 13 to 32% injury at Clayton and 73 to 84% injury at Rocky Mount. Pyroxasulfone (91%), pyroxasulfone + carfentrazone (89%), fomesafen (87%), fluridone (86%), flumioxazin (86%), and atrazine (85%) controlled Palmer amaranth ≥ 85%. Pendimethalin and fluometuron were the least effective treatments, resulting in 58% and 62% control, respectively. As anticipated, early season metribuzin injury resulted in cotton yield loss; plots treated with metribuzin yielded 640 kg ha^{-1} and were only comparable to linuron (790 kg ha^{-1}). This research suggests, with the exception of metribuzin, residual herbicides coated on AMS may fit cotton production, providing growers with additional modes of action for late season control of multiple herbicide-resistant Palmer amaranth.

Two additional experiments were conducted in 2022 and 2023 to determine the optimal granular AMS rate and application timing for pyroxasulfone-coated AMS. In the rate study, AMS rates included 161, 214, 267, 321, 374, 428, and 481 kg ha^{-1}, equivalent to 34, 45, 56, 67, 79, 90, and 101 kg N ha^{-1}, respectively. All rates were coated with pyroxasulfone at 118 g ai ha^{-1} and top-dressed onto 5- to 7-leaf cotton. In the timing study, pyroxasulfone (118 g ai ha^{-1}) was coated on AMS and top-dressed at 321 kg ha^{-1} (67 kg N ha^{-1}) onto 5- to 7-leaf, 9- to 11-leaf, and first bloom cotton. In both experiments, weed control and cotton tolerance to pyroxasulfone-coated AMS were compared to pyroxasulfone applied postemergence (POST) and postemergence-directed (POST-directed). Pyroxasulfone applied POST was the most injurious treatment in both experiments (8 to 16%), while pyroxasulfone-coated AMS resulted in ≤ 4% cotton injury. With exception of the lowest rate of AMS (161 kg ha^{-1}; 79%), all AMS rates coated with pyroxasulfone controlled Palmer amaranth ≥ 83%, comparable to pyroxasulfone applied POST (92%) and POST-directed (89%). In the timing study, the method of application did not affect Palmer amaranth control, but the mid- and late-timing applications outperformed early applications. These results indicate that pyroxasulfone-coated AMS can control Palmer amaranth comparable to pyroxasulfone applied POST and POST-directed, with minimal risk of cotton injury. However, application timing may warrant an additional POST treatment to achieve adequate late-season weed control.

Integration of Herbicide-Coated Fertilizer for Residual Weed Control in Cotton (*Gossypium hirsutum*)

by
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DEDICATION

I dedicate this thesis to my fiancé, family, and Dr. Brent Rogers. To my fiancé, I owe a debt of gratitude for your unwavering love and support throughout this process. You have been my sounding board, proofreader, and the anchor keeping me from veering off course. To my family, leaving home was never my intention nor an easy decision to make. Despite the challenges, you stood by me and supported every step I took, and for that, I am eternally grateful. Lastly, I would like to express my sincerest gratitude to Dr. Brent Rogers for his mentorship and guidance. Without your belief in me, I would not be where I am today.

BIOGRAPHY

Brock Dean grew up in the small town of Greenfield, Ohio, where he spent time around his family's farm. He was involved on the family farm and soon realized he had a passion for agriculture. After graduating from Greenfield McClain High School in 2018, he attended Morehead State University to pursue a bachelor's degree in agronomy and agricultural business. While at Morehead State University, Brock discovered his interest in field research and weed science while conducting research on industrial hemp. Upon graduating from Morehead State University in 2021, Brock sought an internship with SynTech Research in California to further his experience in both field and greenhouse research. In 2022, he began graduate school at North Carolina State University, focusing on cotton weed management under the direction of Dr. Charlie Cahoon. Brock enjoys spending time with his fiancé and dog in his free time, watching NC State and Notre Dame football, and turkey hunting, all when he isn't looking at weeds.

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CHAPTER I

Literature Review

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INTRODUCTION

In recent years, cotton producers have navigated high production costs, which increased $459 ha^{-1} between 2018 and 2022 (USDA-ERS 2023a). This increase is partly due to the prevalence of multiple herbicide-resistant (HR) weed biotypes, like Palmer amaranth (*Amaranthus palmeri* S. Watson; Washburn 2024). Extensive herbicide programs, sophisticated application technology, and the price of herbicide-tolerant cottonseed have further exposed the true cost of managing multiple HR weed biotypes (Devore et al. 2012; Korres et al. 2019; Ofosu et al. 2023; Shaner et al. 2014). Since 1990, herbicide-tolerant cottonseed prices have increased 463% (USDA-ERS 2023b), and in 2023, 97% of US cotton was planted to cultivars with at least one herbicide-tolerant trait (USDA-NASS 2023). In addition to weed control, fertilizer prices have contributed to the rise in production costs, increasing 39% since 2018 (USDA-ERS 2023a).

Several characteristics, including rapid growth (Horak and Loughin 2000), immense fecundity (Ehleringer 1983), extended germination (Ward et al. 2013), and wide genetic variability (Chandi et al. 2013), contribute to the weediness of Palmer amaranth (Cardina 2021; Van Wychen 2022). When coupled with widespread herbicide resistance, these traits can adversely affect cotton yield and harvest efficiency (Fast et al. 2009; Norsworthy et al. 2014). At densities of 3 and 8 plants m^{-1}, Palmer amaranth can reduce cotton yield by as much as 28 and 92%, respectively (MacRae et al. 2013; Morgan et al. 2001; Rowland et al. 1999). If left unmanaged, Palmer amaranth densities of 1,300 weeds ha^{-1} can reduce harvest efficiency by as much as 2 hours (Smith et al. 2000). Managing Palmer amaranth continues to worsen where biotypes have evolved resistance to many of the herbicides registered in cotton (Heap 2024).

After the introduction of herbicide-tolerant cotton, it was common to manage Palmer amaranth by concurrently using herbicide-tolerant cultivars and POST herbicides. However, glyphosate- and acetolactate synthase (ALS)-resistant Palmer amaranth is now commonplace in every cotton-producing state in the U.S. and continues to evolve resistance to additional modes of action (MOAs; Bond et al. 2006; Culpepper et al. 2006; Norsworthy et al. 2008; Poirier et al. 2014). Palmer amaranth biotypes have developed resistance to 2,4-D in Kansas (Kumar et al. 2019), dicamba in Tennessee (Foster and Steckel 2022), and glufosinate in Arkansas and North Carolina (Jones 2022; Priess et al. 2022). In addition to the looming threat of resistance, a Federal district court in Arizona recently issued an order to vacate the labels for dicamba products registered for POST over-the-top (OTT) use in cotton and soybean (Cahoon 2024; Everman 2024; Messina 2024). This raises concerns, especially where dicamba remains effective in controlling Palmer amaranth. With resistance and regulatory concerns, many growers have returned to an integrated approach to weed management (Culpepper et al. 2010).

Residual herbicides in cotton

Before the advent of glyphosate-tolerant cotton, it was common practice to layer residual herbicides with multiple effective MOAs (Keeling and Abernathy 1989; Laws 2016). A standard recommendation would have included pendimethalin or trifluralin applied pre-plant incorporated, followed by a preemergence application of a photosystem II (PSII)-inhibitor, such as diuron or fluometuron. If warranted, a postemergence-directed (POST-directed) application, including cyanazine, diuron, fluometuron, or prometryn plus MSMA or DSMA, would follow to ensure adequate late-season weed control (Wilcut et al. 1995). Utilizing layered soil-residual herbicides and multiple effective MOAs can prevent weed emergence throughout the growing season and further delay the evolution of herbicide-resistant weed biotypes (Busi et al. 2020; Chahal et al. 2021; Neve et al. 2011; Robinson 2017). Like the aforementioned strategy, similar programs are currently advised by extension weed specialists to effectively manage multiple herbicide-resistant Palmer amaranth and other weeds (Cahoon and York 2024; Culpepper 2019).

Among residual herbicides registered for PRE use in cotton, fomesafen, a protoporphyrinogen oxidase (PPO)-inhibitor, is commonly used for its effectiveness against Palmer amaranth (Bauman et al. 1998; Everman et al. 2009; Gardner et al. 2006). When timely activating rainfall is received, fomesafen has been observed to control Palmer amaranth 74 to 99% (Sweat et al. 1998; Whitaker et al. 2011). In addition to fomesafen, the PSII-inhibitors, diuron and fluometuron, are routinely applied PRE to control Palmer amaranth in cotton. Previous research by Whitaker et al. (2011) reported diuron and fluometuron controlled Palmer amaranth 55 to 91% and 49 to 86%, respectively. However, both diuron and fluometuron are under review by the Environmental Protection Agency, bringing to question the longevity of these critical chemistries as tools for controlling Palmer amaranth (Haigwood 2022). In the potential absence of diuron and fluometuron, additional options, including the very-long-chain-fatty-acid (VLCFA)-inhibitor acetochlor and the phytoene desaturase-inhibitor fluridone, remain available. Earlier studies found acetochlor and fluridone controlled Palmer amaranth 84 and 97%, respectively (Braswell et al. 2016; Cahoon et al. 2015a).

Residual herbicides registered for POST OTT use in cotton are relatively limited; the VLCFA-inhibitors, including acetochlor, dimethenamid-*P*, and *S*-metolachlor, are the predominate options. These herbicides provide effective residual control of Palmer amaranth, but do not control emerged weeds (Geier et al. 2006; Hay 2017; Knezevic et al. 2009; Riar et al. 2012). On this account, these products are often applied in combination with glufosinate, glyphosate, dicamba, or 2,4-D (Cahoon and York 2024; Culpepper and Vance 2023, 2021). While glyphosate-resistant Palmer amaranth is commonplace in North Carolina, the herbicide remains valuable for controlling many broadleaf and grass weeds. Previous research reported *S*-metolachlor plus glyphosate and 2,4-D to control Palmer amaranth 95% (Houston et al. 2020). Additional research by Cahoon et al. (2015b) reported 94% control of Palmer amaranth when acetochlor and *S*-metolachlor were applied with glufosinate. Postemergence OTT applications of VLCFA-inhibitors can, and frequently do, result in moderate cotton injury (Cahoon et al. 2014; Collie et al. 2014). Despite moderate injury, symptoms are generally absent 21 days after treatment (DAT) and cotton yield is unaffected (Everman et al. 2007; Inman et al. 2014).

In 2024, transgenic cotton cultivars with tolerance to 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides were commercially launched. Following the release of Alite™ 27, the cotton formulation of the HPPD-inhibiting herbicide isoxaflutole, growers will gain an additional tool for managing herbicide-resistant weeds PRE and/or early POST (Farr et al. 2022; Joyner et al. 2022; Unglesbee 2020). Earlier studies evaluated isoxaflutole PRE and reported 61 to 99% control of Palmer amaranth four weeks after application (WAA), but like the VLCFA-inhibitors, isoxaflutole does not effectively control emerged weeds (Foster et al. 2022; Joyner 2021; Stephenson and Bond 2012). The ALS-inhibiting herbicides, including trifloxysulfuron and pyrithiobac, provide additional POST residual options in cotton. However, Palmer amaranth biotypes resistant to ALS-inhibiting herbicides are widespread, ultimately hindering their use (Molin et al. 2016; Nakka et al. 2017; Nandula et al. 2012; Norsworthy et al. 2008). Aside from the aforementioned herbicides, no other POST OTT residual herbicides are available in cotton production.

Despite limited POST OTT residual herbicides, there are additional options through POST-directed lay-by and hooded sprayer applications. These options include the PSII-inhibitors diuron, fluometuron, and prometryn, the VLCFA-inhibitors (acetochlor, *S*-metolachlor, and pyroxasulfone), and the PPO-inhibitors fomesafen and flumioxazin (Cahoon and York 2024; Everman et al. 2009; Wilcut et al. 1995). Previous studies evaluated cotton tolerance to POST applications of fluometuron, pyroxasulfone, and flumioxazin. When applied POST to cotyledon and 2- to 4-leaf cotton, fluometuron caused nearly 40% injury (Kendig et al. 2007). Research on cotton tolerance to pyroxasulfone has generally varied. Eure et al. (2013) reported 30 to 40% cotton injury and 19 to 25% yield loss, whereas Kroger et al. (2008) observed 13 to 17% cotton injury and yield was unaffected. Stephenson IV et al. (2019) evaluated reduced rates of flumioxazin applied POST in cotton and reported 69 to 97% injury.

Of the herbicides registered for POST-directed use in cotton, pyroxasulfone, flumioxazin, and fomesafen are among the most efficacious in controlling Palmer amaranth (Barkley et al. 2016; Grey et al. 2013; Janak and Grichar 2016; Stephenson et al. 2017). Previous research by Whitaker et al. (2011) found fomesafen and flumioxazin more effective than diuron, fluometuron, and prometryn. Other studies found flumioxazin and pyroxasulfone to control Palmer amaranth 82 to 100% and 96 to 100%, respectively (Cahoon et al. 2015c; Doherty et al. 2014; Steele et al. 2005). Although numerous residual herbicides are registered for POST-directed use in cotton, these products are seldom used in this capacity. This is partly because POST-directed applications are time- and labor-intensive, and following the commercialization of glyphosate-tolerant cotton, many growers replaced such methods of weed control for simple and cost-effective POST-only programs (Duke and Powles 2008; Webster and Sosonskie 2010). In addition, POST-directed applications require a height differential between the cotton and targeted weeds to prevent crop injury, which is particularly difficult to obtain due to the robust growth of Palmer amaranth (Askew et al. 2002, Askew and Wilcut 1999).

Due to the infrequent use of POST-directed herbicides, selection pressure for weed biotypes resistant to the few POST OTT residual options has intensified. Currently, Palmer amaranth biotypes have evolved resistance to both HPPD- and VLCFA-inhibitors, bringing to question the longevity of these important MOAs (Brabham et al. 2019; Heap 2024; Jhala et al. 2014; Mahoney et al. 2020). It is therefore imperative to investigate additional weed management tactics (Beckie and Harker 2017; Duke and Heap 2017; Kniss 2018).

Residual herbicides beyond cotton

Aside from cotton production, various residual herbicides have proven effective in controlling Palmer amaranth. These options include the PSII-inhibitors atrazine, metribuzin, and linuron, as well as the PPO-inhibitor sulfentrazone. Atrazine has long been considered a staple PRE and POST product in corn and has been reported to control glyphosate-resistant Palmer amaranth 100% 28 DAT (Norsworthy et al. 2008; Swanton et al. 2007; Williams et al. 2010). Apart from its efficacy, atrazine is cost-effective and offers growers compatibility in tank-mixes (Rodriguez et al. 2023; Walsh et al. 2012). Previous studies evaluated metribuzin in sweetpotato and reported 100 and 77% control of Palmer amaranth 4 and 10 WAA, respectively (Meyers et al. 2017). Moore et al. (2021) observed similar control with linuron in sweetpotato, with control ranging from 86 to 98% 4 WAA. In soybean and peanut production systems, sulfentrazone has been reported to control Palmer amaranth 77 to 97% (Belfry et al. 2015; Grey and Wehtje 2005).

Although effective in controlling Palmer amaranth, the use of metribuzin and linuron is prohibited on coarse-textured soils typical of North Carolina cotton production due to injury concerns (Anonymous 2024b, 2024e). In addition to soil texture, crop tolerance to metribuzin and linuron depends on the timing and rate of rainfall following application (Shaner 2014). Coble and Schrader (1973) reported greater soybean sensitivity to metribuzin after heavy rainfall was received within the first 10 days following application on coarse-textured soil with low organic matter. Conversely, research from VanGessel et al. (2017) indicated that substantial rainfall on sandy soil may have leached metribuzin beneath the upper soil profile, thus resulting in greater wheat tolerance to metribuzin. If heavy rain occurs after linuron is applied PRE to corn, soybeans, carrots, parsnips, and potatoes, severe injury could result (Anonymous 2024b). Use restrictions also apply to atrazine as the herbicide has demonstrated the ability to cause injury on coarse-textured soils, especially when applied PRE to sorghum (Anonymous 2024a).

Despite these herbicides not being registered for use in cotton, the lack of POST OTT residual herbicides and the infrequent use of POST-directed herbicides have heightened the need for alternative weed management strategies. This is further compounded by the increasing prevalence of multiple HR Palmer amaranth and the subsequent rise in weed control costs. An economical alternative could be the use of the aforementioned herbicides coated on fertilizer.

Nitrogen fertility in cotton

In a typical growing season, recommended rates of nitrogen range from 34 to 89 kg ha^{-1} for non-irrigated systems (Gatiboni and Hardy 2024). However, recommended fertilizer rates and application timings vary by location, soil texture, and estimated yield potential. On deep, sandy textured soils, typical of the southeastern cotton production region, many growers find it appropriate to apply a split or replacement application of nitrogen due to leaching potential (Edmisten and Collins 2024; Hons et al. 2004). Since cotton is less responsive to nitrogen early in the growing season, the bulk of nitrogen should be applied at match-head square. When a replacement application is necessary, the applied nitrogen rate should not exceed 34 kg ha^{-1}. It is generally optimal to side-dress nitrogen 2- to 3-weeks after first bloom to ensure adequate nitrogen is accessible at early bloom (Gatiboni and Hardy 2024). On well-irrigated soils capable of yielding 2- to 3-bale cotton, some growers may apply upwards of 112 kg nitrogen ha^{-1} (Gatiboni and Hardy 2024). Even then, most farmers apply the bulk of fertilizer when flower buds begin to set. Of the available nitrogen sources, nitrogen solutions, ammonium nitrate, ammonium sulfate, and urea are most regularly used. For herbicide-coated fertilizer, nitrate-based fertilizers are not recommended as they do not absorb herbicide (Anonymous 2024d; 2024f).

Utility of herbicide-coated fertilizer

The practice of impregnating and/or coating granular fertilizer with liquid herbicide began around 1955 and was commonly employed through the mid- to late-1990s (Folckemer et al. 1955; Furtick 1968; Hoyt 1995). A survey conducted by Rabaey and Harvey (1994) estimated 43,300 ha^{-1} were treated with herbicide-coated fertilizer in Wisconsin between 1992 and 1993. During this time, many growers favored herbicide-coated fertilizer due to the convenience of applying both fertilizer and herbicide in a single operation, thereby reducing time, labor, and soil compaction (Albright and Harvey 1997; Buhler 1987; Meyer et al. 1973). Herbicide-coated fertilizer has been top-dressed in conventional tillage systems due to its ability to penetrate a crop canopy and residue more effectively than a spray (Kells and Meggitt 1985).

In turfgrass and container nurseries, herbicide-coated fertilizer, often called “weed and feed” material, was commonly used to prevent herbicide volatility and run-off and to increase efficiency (Case et al. 2005; Derr 1994; Yelverton 1998). Postflood aerial applications of quinclorac and bensulfuron in rice were occasionally applied via granular fertilizer to mitigate off-target movement to cotton and soybean, which are typically grown in the Southern rice production region (Braverman 1995). Cotter (2023) discovered florpyrauxifen-benzyl coated urea reduced rice injury compared to spray applications when applied at rates exceeding label recommendations. One could expect less crop injury by herbicide-coated fertilizer since less herbicide would be intercepted by foliage compared to standard liquid spray applications.

Although various studies have investigated herbicide-coated fertilizer, there are concerns pertaining to its use. Overall, limited distribution centers are processing herbicide-coated fertilizer, bringing to question the availability of this material to growers. Top-dressing herbicide-coated fertilizer with a broadcast spreader is generally less precise than a foliar spray, which could adversely affect weed control and crop response (Wells and Green 1991). If herbicide-coated fertilizer is used in the early growing season with a low fertilizer rate, there are concerns of achieving adequate ground coverage to optimize weed control. With nitrogen being applied at various timings within a growing season and a lack of research evaluating herbicide-coated fertilizer at these different timings, concerns arise regarding its utility in cotton. Despite these concerns, herbicide-coated fertilizer has demonstrated effective residual weed control.

Efficacy of herbicide-coated fertilizer

In wheat, diammonium phosphate fertilizer proved to be an effective carrier for triasulfuron and was more efficacious controlling henbit than triasulfuron sprayed POST (Koscelny and Peeper 1996). Braverman (1995) observed greater duckweed control in rice when using granular fertilizer as a carrier for bensulfuron. Oxadiazon coated on controlled-released fertilizer effectively suppressed prostrate spurge and large crabgrass (Crossan et al. 1997). One study, conducted by Yelverton (1998), reported effective weed control with herbicide-coated fertilizer depended on particle coverage and application timing. This is further supported by Skoglund and Gandrund (1984), which reported herbicide-coated fertilizer generally provides weed control consistent with standard spray applications if applied at appropriate fertilizer rate.

Another study determined propachlor, alachlor, naptalam, and chloramben controlled annual grasses and broadleaved weeds in container-grown stock when coated on dicalcium phosphate fertilizer. However, effective control depended upon the amount of treated fertilizer placed in each container (Ruizzo et al. 1983). In corn, alachlor- and cyanazine-coated fertilizer controlled giant foxtail (*Setaria faberi* Herrm.) at least 89%, comparable to control observed by each herbicide applied pre-plant incorporated (Rabaey and Harvey 1994). Additional research, conducted by Grey et al. 2010, reported fomesafen-coated fertilizer controlled Palmer amaranth comparable to a standard spray application.

Herbicide-coated fertilizer in cotton

Currently, pendimethalin and pyroxasulfone are the only herbicides registered to be applied coated on granular fertilizer in cotton (Anonymous 2024c, 2024f). Pendimethalin-coated fertilizer has been shown to control Texas millet (*Urochloa texana* R. Webster) similarly to pendimethalin sprayed at planting (Grey et al. 2008). Although previous work evaluated pendimethalin-coated fertilizer, minimal research has investigated pyroxasulfone-coated fertilizer in cotton (Steckel 2021). Pyroxasulfone is registered to be coated on non-nitrate-based fertilizers and applied at rates ranging from 225 to 785 kg ha^{-1}. Applications can be made on cotton from 5-leaf to beginning bloom stage (Anonymous 2024f). With pyroxasulfone rarely POST-directed in cotton and given its efficacy and length of residual activity against Palmer amaranth (Mueller 2017; Mueller and Steckel 2011; Westra 2012), it is imperative to optimize pyroxasulfone-coated fertilizer in cotton. Additionally, concerns regarding the appropriate fertilizer rate and application timing when utilizing herbicide-coated fertilizer warrants additional research.

The primary objectives of this research were to evaluate herbicide-coated granular ammonium sulfate (AMS) for cotton tolerance and Palmer amaranth control. This research assessed the optimal application timing and AMS rate for pyroxasulfone-coated AMS and evaluated various other residual herbicides to determine if herbicides not labeled for POST OTT use in cotton could be integrated via herbicide-coated fertilizer.

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CHAPTER II

Optimizing Pyroxasulfone-Coated Granular Ammonium Sulfate in Cotton (*Gossypium hirsutum*)

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ABSTRACT

Two experiments were conducted in 2022 and 2023 near Rocky Mount and Clayton, NC, to determine the optimal granular ammonium sulfate (AMS) rate and application timing for pyroxasulfone-coated AMS. In the rate study, AMS rates included 161, 214, 267, 321, 374, 428, and 481 kg ha^{-1}, equivalent to 34, 45, 56, 67, 79, 90, and 101 kg N ha^{-1}, respectively. All rates were coated with pyroxasulfone at 118 g ai ha^{-1} and top-dressed onto 5- to 7-leaf cotton. In the timing study, pyroxasulfone (118 g ai ha^{-1}) was coated on AMS and top-dressed at 321 kg ha^{-1} (67 kg N ha^{-1}) onto 5- to 7-leaf, 9- to 11-leaf, and first bloom cotton. In both experiments, weed control and cotton tolerance to pyroxasulfone-coated AMS was compared to pyroxasulfone applied postemergence (POST) and postemergence-directed (POST-directed). The check in both experiments received non-herbicide treated AMS (321 kg ha^{-1}). Prior to treatment applications, all plots (including the check) were maintained weed free with glyphosate and glufosinate; no residuals were used prior to applications. In both experiments, pyroxasulfone applied POST was the most injurious (8 to 16%), while pyroxasulfone-coated AMS resulted in ≤ 4% injury. Additionally, no differences in cotton lint yield were observed in both experiments. With exception of the lowest rate of AMS (161 kg ha^{-1}; 79%), all AMS rates coated with pyroxasulfone controlled Palmer amaranth ≥ 83%, comparable to pyroxasulfone applied POST (92%) and POST-directed (89%). In the timing study, the method of application did not affect Palmer amaranth control, but the mid- and late-timing applications outperformed early applications. These results indicate that pyroxasulfone-coated AMS can control Palmer amaranth comparable to pyroxasulfone applied POST and POST-directed, with minimal risk of cotton injury. However, application timing may warrant a follow-up POST treatment to achieve adequate late-season weed control.

Nomenclature: pyroxasulfone; cotton, *Gossypium hirsutum* L.

Keyword: Cotton tolerance; fertilizer; impregnated

INTRODUCTION

Palmer amaranth (*Amaranthus palmeri* S. Watson) has become one of the most troublesome weeds across the southern US cotton (*Gossypium hirsutum* L.) production region (Van Wychen 2022). If left unmanaged, Palmer amaranth at 3 and 8 plants m^{-1} can reduce cotton yield by as much as 28 and 92%, respectively (MacRae et al. 2013; Morgan et al. 2001; Rowland et al. 1999). In addition to adversely affecting cotton yield, Palmer amaranth densities of 1,300 weeds ha^{-1} can reduce harvest efficiency by as much as 2 hours (Smith et al. 2000). Management concerns continue to rise where Palmer amaranth biotypes have evolved resistance to many of the chemical control options registered in cotton production (Heap 2024).

In recent years, cotton producers have had to navigate high production costs, which increased an estimated \$459 ha^{-1} from 2018 to 2022 (USDA-ERS 2023a). A portion of these expenses are attributed to fertilizers, insecticides, and other agrichemicals for early-season cotton development and crop maintenance (Edmisten and Collins 2024). However, the increasing prevalence of multiple herbicide-resistant (HR) weed biotypes, like Palmer amaranth, has rendered weed control one of the more expensive components of cotton production (Washburn 2024). The costs associated with managing multiple HR weed biotypes have been exacerbated through extensive herbicide programs, sophisticated application technology, and the price of herbicide-tolerant cottonseed, which increased 463% between 1990 and 2020 (Devore et al. 2012; USDA-ERS 2023b). Timely pesticide and fertilizer applications are critical for maximizing cotton yield; however, this is generally difficult to achieve due to the complexities of cotton weed management (Tariq et al. 2020). Given the importance of efficiency and the necessity to effectively manage multiple HR Palmer amaranth, there is great need to incorporate alternative weed management strategies to control this troublesome species.

In 2020, pyroxasulfone, a very-long-chain-fatty-acid-(VLCFA)-inhibitor, received an amended label allowing it to be coated on granular fertilizer and top-dressed onto cotton (Anonymous 2024). Before the label amendment, pyroxasulfone could only be postemergence-directed (POST-directed) in cotton. This posed challenges, as many growers are ill-equipped or hesitant to apply herbicides POST-directed. Such applications are time- and labor-intensive and require a height differential between the cotton and the targeted weeds, which is often difficult to achieve (Askew et al. 2002; Wilcut et al. 1995). However, pyroxasulfone-coated fertilizer offers growers an alternative to POST-directed lay-by applications and the potential to conserve inputs. Previous research has shown that a simultaneous application of herbicide and granular fertilizer can reduce fuel and labor costs, as well as soil compaction (Buhler 1987).

In addition to the ease of application and the ability to minimize inputs with pyroxasulfone-coated fertilizer, pyroxasulfone has been reported to control Palmer amaranth well. Studies evaluating pyroxasulfone applied preemergence (PRE) and postemergence (POST) reported 100 and 96% control 21 and 28 days after treatment (DAT), respectively (Cahoon et al. 2015; Steele et al. 2005). Aside from Palmer amaranth, pyroxasulfone has also demonstrated activity on troublesome grasses in cotton, including Texas millet [*Urochloa texana* R. Webster.], goosegrass [*Eleusine indica* (L.) Gaertn.], and barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.]; (Kharel et al. 2022; Steele et al. 2005; Stephenson et al. 2017; Van Wychen 2022). Although research on pyroxasulfone-coated fertilizer is limited, other studies have demonstrated effective weed control in row crop production systems using herbicide-coated fertilizer (Grey et al. 2008; Grey and Webster 2013; Rabaey and Harvey 1994). One study, conducted by Yelverton

(1998), reported effective weed control with herbicide-coated fertilizer depended on particle coverage and the timing of application.

Currently, pyroxasulfone is registered to be coated on non-nitrate-based fertilizers and applied at rates ranging from 225 to 785 kg ha^{-1}. Applications can be made on cotton from 5-leaf to beginning bloom stage (Anonymous 2024). However, recommended fertilizer rates and application timings vary by location, soil texture, and estimated yield potential. On deep, sandy textured soils, typical of the southeastern cotton production region, many growers find it appropriate to apply a split or replacement application of nitrogen due to leaching potential (Hons et al. 2004). These applications generally result in small amounts of nitrogen being applied early in the growing season, with the remainder applied at match-head square (Gatiboni and Hardy 2024). Depending on the timing of application, pyroxasulfone-coated fertilizer may be well-suited for these situations, as it could provide necessary late-season residual following residuals applied at earlier growth stages (Matthew Inman, BASF Corporation, personal communication). However, there are concerns if pyroxasulfone is applied coated on a low rate of fertilizer, the lack of distribution of the herbicide may jeopardize weed control (Anonymous 2024). Due to frequent applications of low fertilizer rates and variability in application timing, it is imperative to optimize pyroxasulfone-coated fertilizer in cotton production.

The objectives of this research were to determine (1) the optimal granular ammonium sulfate (AMS) rate for applying pyroxasulfone-coated AMS and (2) the optimal application timing for pyroxasulfone-coated AMS to effectively control Palmer amaranth in cotton.

Materials and Methods

Shared Methodology for Both Experiments

Two separate experiments were conducted in 2022 and 2023 at the Upper Coastal Plains Research Station near Rocky Mount, NC (35.89, 77.68), and the Central Crops Research Station near Clayton, NC (35.67, 78.51). The soil at Rocky Mount consisted of an Aycock very fine sandy loam (Fine-silty, siliceous, subactive, thermic Typic Paleudults) with 0.3 to 0.4% humic matter and pH of 6.0 to 6.1. The soil at Clayton consisted of a Dothan loamy sand (Loamy, kaolinitic, thermic Arenic Kandiudults) with 0.3 to 0.4% humic matter and pH of 5.5 to 6.0 (Mehlich 1984).

Fields at both locations were prepared using conventional tillage and then bedded into 91 and 97-cm rows at Rocky Mount and Clayton, respectively. In both years and at both locations, plots were 4 rows by 9.1-m. Deltapine® cotton cultivar 'DP 2115 B3XF' (Bayer CropScience, Research Triangle Park, NC) was planted on May 11, 2022, at Rocky Mount and May 12, 2022, at Clayton. In 2023, 'DP 2115 B3XF' cotton cultivar was planted at Rocky Mount on May 9, whereas Deltapine® ThryvOn™ cotton cultivar 'DP 2211 B3TXF' was planted at Clayton on May 11. Cotton was seeded at approximately 107,637 seeds ha^{-1} to a depth of 2-2.5 cm. All pesticide and fertilizer applications required for crop maintenance were applied in accordance with recommendations from North Carolina Cooperative Extension (Edmisten et al. 2024).

In both experiments, pyroxasulfone (Zidua® SC herbicide, BASF Corp., Research Triangle Park, NC) was applied at 118 g ai ha^{-1} across all treatments. Pyroxasulfone-coated AMS (21-0-0-24; FCI Agri Service Co., Raeford, NC) was prepared by mixing the desired rate of herbicide, water, and 1 ml of blue dye in an electric powered concrete mixer (Sears, Roebuck and Co, USA.) that contained the appropriate rate of granular AMS. The proportion of water-to-AMS was 473 ml water/113 kg AMS, which was suggested as the optimal ratio for pyroxasulfone-coated AMS (Matthew Inman, personal communication, BASF corporation). The blue dye (1 ml) was included in the mixture to provide a means for visually estimating coverage throughout the mixing process. In both experiments, the check received 321 kg ha^{-1} of nontreated AMS as a grower standard for comparison. All treatments containing fertilizer were evenly applied within three cotton row middles using 1.89 L plastic containers (ULINE Company, U.S.A.) with lids that had equally spaced and sized (5/32 drill bit) holes. In addition to a check, both experiments included pyroxasulfone applied POST and POST-directed for comparison. All spray applications were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 207 kPa. Backpack sprayers were outfitted with AIXR11002 flat-fan nozzles (TeeJet Air Induction XR Flat Spray Tips, TeeJet Technologies, Wheaton, IL) when applying POST applications, and POST-directed applications were made using a single flood nozzle (TK-VS2 wide angle FloodJet, TeeJet Technologies, Wheaton, IL).

Prior to treatment applications, all plots (including the check) were treated with glyphosate (Roundup PowerMAX® 3 Herbicide, Bayer CropScience, St. Louis, MO) at 1,345 g ae ha^{-1} and glufosinate (Liberty® 280 SL Herbicide, BASF Corporation, Research Triangle Park, NC) at 656 g ai ha^{-1} to control previously emerged weeds. No residual herbicides were used prior to treatment applications. All study locations were naturally infested with Palmer amaranth.

All data were subject to analysis of variance using the GLIMMIX procedure of SAS 9.4 (SAS institute Inc., Cary, NC) ($\alpha = 0.05$). The weedy check was excluded from the statistical analyses for cotton lint yield and weed control in both experiments. Treatment means were separated using Tukey's honestly significant difference test ($P \leq 0.05$) where appropriate. In both experiments, location, year, replication, and their interactions were considered random effects to allow inferences to be made across broader environmental conditions and locations (Blouin et al. 2011; Moore and Dixon 2015).

Rate Study

Pyroxasulfone (118 g ai ha^{-1}) was coated on granular AMS rates of 161, 214, 267, 321, 374, 428, and 481 kg ha^{-1}, equivalent to 34, 45, 56, 67, 79, 90, and 101 kg N ha^{-1}, respectively. Weed control and cotton tolerance to pyroxasulfone-coated AMS was compared to pyroxasulfone applied POST and POST-directed. All applications were made on 5- to 7-leaf cotton on June 17, 2022, and June 21, 2023. Treatments were arranged in a randomized complete block design (RCBD) with four replications. Visual estimates of weed control and cotton injury were made bi-weekly until 70 days after treatment (DAT)(Frans 1986), and late season Palmer amaranth density was recorded prior to cotton defoliation. At the conclusion of the season, the center two rows of each plot were mechanically harvested and weighed to determine yield. For statistical analyses, treatment was considered a fixed effect. The accumulated rainfall received for herbicide activation in both years and at both locations is reported in Table 1.

Timing Study

Treatment structure was a 4 by 3 factorial including 3 application methods plus a check at 3 application timings. Treatments were arranged in a RCBD with four replications. For application methods, pyroxasulfone was applied via coated AMS (321 kg ha^{-1}), POST over-the-top, and POST-directed. Application timings included 5- to 7-leaf, 9- to 11-leaf, and first bloom cotton. For each timing, visual estimates of cotton injury were collected 3 and 7 DAT. At 14 days after late application (DA LA), visual estimates of weed control and cotton injury were collected for each timing and were continued on a bi-weekly schedule until 70 DA LA. In addition to cotton injury and weed control, late season Palmer amaranth density was collected prior to cotton defoliation, and the center two rows of each plot were mechanically harvested and weighed to determine cotton lint yield at the conclusion of the season. For statistical analyses, application method, application timing, and their interaction were considered fixed effects. Application dates and accumulated rainfall in both years and at both locations is reported in Table 4.

Results and Discussion

Rate Study

Main effect of treatment was significant for cotton injury 3 and 14 DAT. As anticipated, pyroxasulfone applied POST was the most injurious treatment, resulting in 8 to 12% cotton injury (Table 2). Although these results demonstrate minimal injury with pyroxasulfone applied POST, research on cotton tolerance to pyroxasulfone has widely varied. For instance, Eure et al. (2013) observed significant cotton injury and a 19 to 35% yield loss after pyroxasulfone was applied POST, whereas Kroger et al. (2008) observed no yield loss and only 13 to 17% cotton injury when pyroxasulfone was applied onto 4-leaf cotton.

For treatments containing AMS, all injury was in the form of cotton necrotic leaf speckling and mostly caused by AMS granules adhering to damp foliage at time of application. Regardless of the AMS rate coated with pyroxasulfone, all injury was ≤ 4% and comparable to injury observed from non-herbicide treated AMS (321 kg ha^{-1}) applied to the check (3%; Table 2). These results are further supported by research from Tennessee, which also reported minimal cotton injury with the use of pyroxasulfone-coated fertilizer in cotton (Steckel 2021). At 3 DAT, pyroxasulfone applied POST-directed (7%) was more injurious than every AMS rate coated with pyroxasulfone (≤ 2%). At 14 DAT, pyroxasulfone POST-directed (5%) remained more injurious than pyroxasulfone coated on 161 to 320 kg ha^{-1}(≤ 3%) of AMS but was comparable to pyroxasulfone coated on 374 to 481 kg ha^{-1} (4%) of AMS. These findings suggest that regardless of the AMS rate, pyroxasulfone-coated AMS can likely result in cotton injury that is less than or comparable to pyroxasulfone applied POST-directed. With exception of pyroxasulfone applied

POST (3%), cotton injury was absolved by 28 DAT (data not shown). No differences in cotton lint yield were observed, with yield ranging from 1,040 to 1,210 kg lint ha^{-1} (Table 2).

Palmer amaranth Control

Treatment was significant for Palmer amaranth control and density (Table 3). In both years and locations, adequate rainfall was received for herbicide activation (Table 1). No differences in control were observed between pyroxasulfone applied POST (92%) and POST-directed (89%). Additionally, every treatment controlled Palmer amaranth comparable to pyroxasulfone applied POST-directed (89%). Despite no differences, it is notable that there was a 10% difference in control between pyroxasulfone applied POST-directed (89%) and coated on 161 kg ha^{-1} of AMS (79%; Table 3). Given the competitive nature of Palmer amaranth and its ability to produce immense amounts of seed (Bensch et al. 2003; Schwartz et al. 2016), this difference may warrant the use of higher rates of AMS when pyroxasulfone is coated on the fertilizer.

With exception of the lowest rate of AMS (161 kg ha^{-1}), all treatments controlled Palmer amaranth comparable to pyroxasulfone applied POST (Table 3). These results support earlier research by Skoglund and Gandrud (1984), which reported herbicide-coated fertilizer generally provides weed control consistent with standard spray applications if applied at appropriate fertilizer rate. Across all AMS rates coated with pyroxasulfone, no differences in Palmer amaranth control were observed. Despite differences in visual estimates of Palmer amaranth control, no differences in density were observed across treatments. However, all treatments reduced Palmer amaranth density 63 to 88% compared to the check (Table 3).

Timing Study

Main effects of application method and application timing were significant for cotton injury. The interaction was significant; therefore, cotton injury data are presented by application method and application timing (Table 5). As anticipated, pyroxasulfone applied POST was the most injurious treatment at each timing. However, pyroxasulfone applied POST at the early (16%) and mid (14%) timings was more injurious than when applied at the late timing (8%). Between the early (9%), mid (6%), and late (3%) applications, cotton injury from pyroxasulfone POST-directed followed a consistent trend, with total injury decreasing the later applications were made (Table 5). This is likely attributed to cotton maturity as taller plants generally receive less herbicide contact during POST-directed lay-by applications (Altom et al. 2000; Ferrell et al. 2007). Pyroxasulfone-coated AMS (3%) caused less injury compared to pyroxasulfone applied POST-directed (9%) at the early timing, thus suggesting it may be a safer alternative for growers considering 5- to 7-leaf POST-directed lay-by applications.

In addition, pyroxasulfone-coated AMS (321 kg ha^{-1}) caused greater injury when applied at the mid timing (4%) compared to the late timing (1%; Table 5). However, regardless of which timing pyroxasulfone-coated AMS (321 kg ha^{-1}) was applied, all injury was ≤ 4% and comparable to injury observed from non-herbicide treated AMS (321 kg ha^{-1}) applied to the check (≤ 4%). At 14 DA LA, no cotton injury was observed from applications made at the early or mid timings (Table 5). It is important to note that at 14 DA LA, 42 and 28 d had passed since the early and mid timing applications of pyroxasulfone, respectively. These results suggest that there is no adverse cotton response due to these applications being made at different timings. This is further supported by cotton lint yield data, which indicates no differences across all application timings and methods (Table 5).

Palmer amaranth Control

Main effect of application timing was significant for Palmer amaranth control. The main effect of application method and the two-way interaction of application timing and application method was not significant. However, it is still important to understand Palmer amaranth control across application methods. Therefore, data for Palmer amaranth control are presented for application timings averaged over application methods and application methods averaged over application timings. Data for Palmer amaranth density are averaged over application timings. Both locations received adequate rainfall for herbicide activation in both years (Table 4).

Averaged over application timings, there were no differences in Palmer amaranth control across application methods, with all methods controlling the weed 90 to 91% 42 DAT (Table 6). Reductions in Palmer amaranth density follow similar trends to visual estimates of control, in which all treatments resulted in 88% fewer plants compared to the check (Table 6). These findings further suggest that pyroxasulfone-coated AMS (321 kg ha^{-1}, 90%) has potential to control Palmer amaranth similar to pyroxasulfone applied POST (91%) and POST-directed (90%). Palmer amaranth control by pyroxasulfone is unsurprising as previous research reports the herbicide to control Palmer amaranth ≥ 90% (Cahoon et al. 2015; Doherty et al. 2014, Geier et al. 2006; Janak and Grichar 2016; Steele et al. 2005).

At 42 DA LA, pyroxasulfone applied at the mid timing (93%) controlled Palmer amaranth similar to pyroxasulfone applied at the late timing (95%; Table 7). However, at the same time, early applications (83%) were less effective than both the mid (93%)- and late (95%)- applications. It is important to note that at 42 DA the late timing, 70 and 56 d had passed since the early and mid timing applications of pyroxasulfone, respectively. Dissipation studies estimate the residual half-life (DT_{50}) of pyroxasulfone between 8 and 71 days, which may explain reduced control observed by early timing applications compared to later applications (Mueller 2017; Mueller and Steckel 2011; Westra 2012). Following pyroxasulfone applied at the early timing, an additional POST application, including another residual herbicide, would be needed to ensure adequate late-season weed control (Cahoon and York 2024; Culpepper and Vance 2023;

Culpepper and Vance 2021). It is important to note that glyphosate and glufosinate were applied POST before treatments at each timing. When considering this, a POST application followed by pyroxasulfone-coated AMS at the mid timing (9- to 11-leaf cotton) could potentially achieve adequate late-season control of Palmer amaranth, especially if used in combination with a strong preemergence herbicide program.

Practical Implications

Given the complexities of cotton weed management and the continued rise in weed control costs, there is great need for alternative weed management strategies in cotton production. Since being registered in cotton in 2020, limited research has been conducted to optimize pyroxasulfone-coated fertilizer in cotton production systems. This research provides evidence that pyroxasulfone-coated AMS ($\geq$ 214 kg ha^{-1}) has potential to control Palmer amaranth comparable to pyroxasulfone applied POST and POST-directed, with minimal risk of cotton injury. When applied onto 5- to-7-leaf cotton, pyroxasulfone-coated AMS was less injurious than pyroxasulfone POST-directed; thus, suggesting it may be a safer option for growers considering early-season POST-directed lay-by applications. This research also indicates that when pyroxasulfone is applied to 5- to 7-leaf cotton, an additional POST application may be necessary to achieve season-long control of Palmer amaranth, regardless of the application method. Aside from the results in these experiments, it is important that pyroxasulfone-coated AMS be applied in compliance with current label recommendations (Anonymous 2024), as additional research is warranted to further explore the efficacy and usability of pyroxasulfone-coated fertilizer in cotton production.

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Table 1. Dates of application and accumulated rainfall.

		Application	Days After Application			
Location	Year	Date	0-8	9-16	17-24	25-32
			----------cm----------			
Clayton	2022	June 17	0.66	0.59	7.54	0.97
	2023	June 21	3.21	4.52	5.96	0.08
Rocky Mount	2022	June 17	1.6	0.05	6.1	0.46
	2023	June 21	4.52	1.48	8.03	0.23

Table 2. Cotton injury and yield after pyroxasulfone was applied POST, POST-directed, and coated on differing rates of granular ammonium sulfate fertilizer.[a,b]

			Cotton Injury		
Herbicide[c,d]	Treatment[e,f]	AMS Rate	3 DAT	14 DAT	Lint Yield
		kg ha^{-1}	-------%-------		kg ha^{-1}
None	AMS	321	2 c	3 c	—
Pyroxasulfone	AMS	161	1 c	2 c	1,100 a
Pyroxasulfone	AMS	214	1 c	3 c	1,080 a
Pyroxasulfone	AMS	267	1 c	3 c	1,200 a
Pyroxasulfone	AMS	321	3 c	3 c	1,040 a
Pyroxasulfone	AMS	374	2 c	3 c	1,100 a
Pyroxasulfone	AMS	428	2 c	3 c	1,040 a
Pyroxasulfone	AMS	481	2 c	4 bc	1,130 a
Pyroxasulfone	POST	321	12 a	8 a	1,070 a
Pyroxasulfone	POST-directed	321	7 b	5 b	1,060 a

[a]Means followed by the same letter are not different according to Tukey's honestly significant difference ($P < 0.05$). For columns beginning with NS, means are not statistically different.

[b]Abbreviations: DAT, days after treatment; POST, postemergence; POST-directed, postemergence-directed; AMS, ammonium sulfate.

[c]Pyroxasulfone was applied at 118 g ai ha^{-1}.

[d]Applications were made onto 5- to 7-leaf cotton.

[e]Non-herbicide treated AMS was applied at 321 kg ha^{-1} in the check and where pyroxasulfone was applied POST and POST-directed.

[f]Prior to applications, all plots (including the check) were treated with glyphosate at 1,345 g ae ha^{-1} and glufosinate at 656 g ai ha^{-1}.

Table 3. Palmer amaranth control and density as influenced by pyroxasulfone applied POST, POST-directed, and coated on differing rates of granular ammonium sulfate fertilizer.[a,b]

			Control	
			Palmer amaranth	
Herbicide[c,d]	Treatment[e,f]	AMS Rate	42 DAT	Density
		kg ha^{-1}	---%---	plants m^{-2}
None	AMS	321	—	8 a
Pyroxasulfone	AMS	161	79 b	2 b
Pyroxasulfone	AMS	214	83 ab	1 b
Pyroxasulfone	AMS	267	84 ab	2 b
Pyroxasulfone	AMS	321	85 ab	3 b
Pyroxasulfone	AMS	374	88 ab	2 b
Pyroxasulfone	AMS	428	88 ab	1 b
Pyroxasulfone	AMS	481	88 ab	2 b
Pyroxasulfone	POST	321	92 a	2 b
Pyroxasulfone	POST-directed	321	89 ab	2 b

[a]Means followed by the same letter are not different according to Tukey's honestly significant difference ($P < 0.05$). For columns beginning with NS, means are not statistically different.

[b]Abbreviations: DAT, days after treatment; POST, postemergence; POST-directed, postemergence-directed; AMS, ammonium sulfate.

[c]Pyroxasulfone was applied at 118 g ai ha^{-1}.

[d]Applications were made onto 5- to- 7-leaf cotton.

[e]Non-herbicide treated AMS was applied at 321 kg ha^{-1} in the check and where pyroxasulfone was applied POST and POST-directed.

[f]Prior to applications, all plots (including the check) were treated with glyphosate at 1,345 g ae ha^{-1} and glufosinate at 656 g ai ha^{-1}.

Table 4. Dates of application and accumulated rainfall.

Application Timing	Location	Year	Application Date	Days After Application 0-8	9-16	17-24	25-32
				---------------cm---------------			
Early	Clayton	2022	June 10	0.71	0.46	0.97	7.17
		2023	June 21	3.21	4.52	5.96	0.08
	Rocky Mount	2022	June 10	4.09	0.56	0.05	7.21
		2023	June 21	4.52	1.48	8.03	0.23
Mid	Clayton	2022	June 24	0.59	7.55	0.97	0.08
		2023	July 3	6.27	4.65	0.08	0.13
	Rocky Mount	2022	June 24	0.05	7.21	0.47	1.12
		2023	July 3	4.53	5.06	1.12	0.28
Late	Clayton	2022	July 6	7.2	0.94	2.57	0.81
		2023	July 17	0.08	0.13	2.42	4.39
	Rocky Mount	2022	July 6	7.24	0.44	5.11	2.57
		2023	July 17	1.15	0	0.61	3.26

Table 5. Cotton injury and yield after pyroxasulfone was applied POST, POST-directed, and coated on granular ammonium sulfate fertilizer at different application timings.[a,b]

Herbicide[c]	Application Timings[d]	Application Methods[e,f]	AMS Rate	Cotton Injury 3 DAT		Cotton Injury 14 DA LA		Lint Yield	
			kg ha^{-1}	--------%--------				kg ha^{-1}	
None	Early	AMS	321	3	ef	0	c	—	
Pyroxasulfone		Coated	321	3	ef	0	c	1,000	a
Pyroxasulfone		POST	321	16	a	0	c	1,000	a
Pyroxasulfone		POST-directed	321	9	b	0	c	1,070	a
None	Mid	AMS	321	4	de	0	c	—	
Pyroxasulfone		Coated	321	4	de	0	c	1,060	a
Pyroxasulfone		POST	321	14	a	0	c	1,050	a
Pyroxasulfone		POST-directed	321	6	cd	0	c	1,100	a
None	Late	AMS	321	1	f	1	b	—	
Pyroxasulfone		Coated	321	1	f	1	b	1,130	a
Pyroxasulfone		POST	321	8	bc	9	a	1,020	a
Pyroxasulfone		POST-directed	321	3	ef	1	b	1,110	a

[a]Means followed by the same letter are not different according to Tukey's honestly significant difference ($P < 0.05$). For columns beginning with NS, means are not statistically different.

[b]Abbreviations: DAT, days after treatment; DA LA, days after late application; POST, postemergence; POST-directed, postemergence-directed; AMS, ammonium sulfate.

[c]Pyroxasulfone was applied at 118 g ai ha^{-1}.

[d]Application timings: Early, 5- to 7-leaf; Mid, 9- to 11-leaf; Late, 1st bloom.

[e]Non-herbicide treated AMS was applied at 321 kg ha^{-1} in the check and where pyroxasulfone was applied POST and POST-directed.

[f]Prior to applications, all plots (including the check) were treated with glyphosate at 1,345 g ae ha^{-1} and glufosinate at 656 g ai ha^{-1}.

Table 6. Palmer amaranth control and density as influenced by pyroxasulfone applied POST, POST-directed, and coated on granular ammonium sulfate fertilizer.[a,b]

Herbicide[c,d]	Application Methods[e,f]	AMS Rate	Control Palmer amaranth 42 DAT (NS)	Density
		kg ha^{-1}	--%--	plants m^{-2}
None	AMS	321	—	16 a
Pyroxasulfone	Coated	321	90 a	2 b
Pyroxasulfone	POST	321	91 a	2 b
Pyroxasulfone	POST-directed	321	90 a	2 b

[a]Data are averaged over application timings. Means followed by the same letter are not different according to Tukey's honestly significant difference ($P < 0.05$). For columns beginning with NS, means are not statistically different.

[b]Abbreviations: DAT, days after treatment; POST, postemergence; POST-directed, postemergence-directed; AMS, ammonium sulfate.

[c]Pyroxasulfone was applied at 118 g ai ha^{-1}.

[d]Application timings: Early, 5- to 7-leaf; Mid, 9- to 11-leaf; Late, 1st bloom.

[e]Non-herbicide treated AMS was applied at 321 kg ha^{-1} in the check and where pyroxasulfone was applied POST and POST-directed.

[f]Prior to applications, all plots (including the check) were treated with glyphosate at 1,345 g ae ha^{-1} and glufosinate at 656 g ai ha^{-1}.

Table 7. Influence of application timing on Palmer amaranth control.[a]

Application Timings[b,c,d,e]	Control Palmer amaranth 42 DA LA	
	--%--	
Early (70 DAT)	83	b
Mid (56 DAT)	93	a
Late (42 DAT)	95	a

[a]Data are averaged over application methods. Means followed by the same letter are not different according to Tukey's honestly significant difference at ($P < 0.05$). For columns beginning with NS, means are not statistically different.

[b]Abbreviations: DAT, days after treatment; DA LA, days after late application.

[c]Application timings: Early, 5- to 7-leaf; Mid, 9- to 11-leaf; Late, first bloom.

[d]Pyroxasulfone (118 g ai ha^{-1}) was applied POST, POST-directed, and coated on granular ammonium sulfate fertilizer (321 kg ha^{-1}) at each timing.

[e]Prior to applications, all plots (including the check) were treated with glyphosate at 1,345 g ae ha^{-1} and glufosinate at 656 g ai ha^{-1}.

CHAPTER III

Residual Weed Control in Cotton (*Gossypium hirsutum*) Utilizing Herbicide-Coated Fertilizer

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ABSTRACT

An experiment was conducted in 2022 and 2023 near Rocky Mount and Clayton, NC, to evaluate residual herbicide-coated fertilizer for cotton tolerance and Palmer amaranth control. Treatments included acetochlor; atrazine; dimethenamid-*P*; diuron; flumioxazin; fluometuron; fluridone; fomesafen; linuron; metribuzin; pendimethalin; pyroxasulfone; pyroxasulfone + carfentrazone; *S*-metolachlor; and sulfentrazone. Each herbicide was individually coated on granular ammonium sulfate (AMS) and top-dressed at 321 kg ha^{-1} (67 kg N ha^{-1}) onto 5- to 7-leaf cotton. The check received the equivalent rate of non-herbicide treated AMS. Prior to top-dress, all plots (including the check) were treated with glyphosate and glufosinate to control previously emerged weeds. All herbicides resulted in transient cotton injury, except metribuzin. Cotton response to metribuzin varied by year and location. In 2022, metribuzin caused 11 to 39% and 8 to 17% injury at Clayton and Rocky Mount, respectively. In 2023, metribuzin caused 13 to 32% injury at Clayton and 73 to 84% injury at Rocky Mount. Pyroxasulfone (91%), pyroxasulfone + carfentrazone (89%), fomesafen (87%), fluridone (86%), flumioxazin (86%), and atrazine (85%) controlled Palmer amaranth ≥ 85%. Pendimethalin and fluometuron were the least effective treatments, resulting in 58% and 62% control, respectively. As anticipated, early season metribuzin injury translated into yield loss; plots treated with metribuzin yielded 640 kg ha^{-1} and were only comparable to linuron (790 kg ha^{-1}). This research suggests that, with the exception of metribuzin, residual herbicides coated on AMS may be suitable and effective in cotton production, providing growers with additional modes of action for late season control of multiple herbicide-resistant Palmer amaranth.

Nomenclature: pyroxasulfone; pyroxasulfone + carfentrazone; *S*-metolachlor; dimethenamid-*P*; acetochlor; pendimethalin; fomesafen; flumioxazin; sulfentrazone; fluridone; diuron;

fluometuron; linuron; atrazine; metribuzin; glyphosate; glufosinate; cotton, *Gossypium hirsutum* L.

Key Words: cotton tolerance; impregnated

INTRODUCTION

In recent years, cotton producers battled high production costs, increasing an estimated \$459 ha^{-1} between 2018 and 2022 (USDA-ERS 2023). This rise is partly due to the prevalence of multiple herbicide-resistant (HR) weed species, like Palmer amaranth (*Amaranthus palmeri* S. Watson). Extensive herbicide programs, sophisticated application technology, and the price of herbicide-tolerant cottonseed have further exposed the true cost of managing multiple HR weed biotypes (Devore et al. 2012; Korres et al. 2019; Ofosu et al. 2023; USDA-ERS 2023b). In the past, growers could simply and cost-effectively manage Palmer amaranth by concurrently using postemergence (POST) herbicides and herbicide-tolerant cultivars. However, Palmer amaranth biotypes have evolved resistance to many of the POST herbicides available in cotton (Culpepper et al. 2006; Foster and Steckel 2022; Jones, 2022; Kumar et al. 2019), thus necessitating more focus on integrated weed management and alternative control tactics (Duke and Heap 2017).

Prior to herbicide-tolerant cotton cultivars, it was common to layer residual herbicides preemergence (PRE), POST, and postemergence-directed (POST-directed) (Culpepper et al. 2010; Prostko et al. 2001; Westberg et al. 1989; Wilcut et al. 1995; Young 2006). Like the aforementioned strategy, similar programs are currently advised by extension weed specialists to effectively manage multiple HR Palmer amaranth and to further delay the evolution of herbicide-resistance (Busi et al. 2020; Cahoon and York 2024; Culpepper and Vance 2023; Neve et al. 2011). Soil residual herbicides routinely applied PRE to control Palmer amaranth in cotton include the protoporphyrinogen oxidase (PPO)-inhibitor fomesafen, the very-long-chain-fatty-acid (VLCFA)-inhibitor acetochlor, and the photosystem II (PSII)-inhibitors diuron and fluometuron (Whitaker et al. 2011). However, both diuron and fluometuron are under review by the Environmental Protection Agency, bringing into question the longevity of these herbicides for managing Palmer amaranth (Haigwood 2022). In the potential absence of diuron and fluometuron, alternative options, including the phytoene desaturase-inhibitor fluridone and the microtubule-inhibitor pendimethalin, remain available.

Residual herbicides registered for POST over-the-top (OTT) use in cotton are relatively limited; the VLCFA-inhibitors, including acetochlor, dimethenamid-*P*, and *S*-metolachlor, are the predominate options. These herbicides provide effective residual control of Palmer amaranth, but do not control emerged weeds (Geier et al. 2006; Hay 2017; Knezevic et al. 2009; Riar et al. 2012). In 2024, transgenic cotton cultivars with tolerance to 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides were commercially launched. Following the release of Alite™ 27, the cotton formulation of the HPPD-inhibiting herbicide isoxaflutole, growers will gain an additional tool for managing Palmer amaranth PRE and/or early POST (Barber et al. 2021; Farr et al. 2022; Joyner et al. 2022). Like the VLCFA-inhibitors, isoxaflutole does not effectively control emerged Palmer amaranth (Joyner 2021; Stephenson and Bond 2012). The ALS-inhibiting herbicides, including trifloxysulfuron and pyrithiobac, provide additional POST residual options in cotton. However, Palmer amaranth biotypes resistant to ALS-inhibiting herbicides are widespread, ultimately hindering their use (Molin et al. 2016; Nakka et al. 2017; Nandula et al. 2012; Norsworthy et al. 2008). Beyond the aforementioned herbicides, no other POST OTT residual herbicides are available in cotton production.

Despite limited POST OTT residual herbicides, there are additional options through the use of POST-directed lay-by and hooded sprayer applications. These options include the PSII-inhibitors diuron, fluometuron, and prometryn, the VLCFA-inhibitors (acetochlor, *S*-metolachlor, and pyroxasulfone), and the PPO-inhibitors fomesafen and flumioxazin (Cahoon and York 2024, Wilcut et al. 1995). Fomesafen, flumioxazin, and pyroxasulfone have been proven efficacious in controlling Palmer amaranth and are generally more effective than diuron, fluometuron, and prometryn (Cahoon et al. 2015; Doherty et al. 2014; Steele et al. 2005; Stephenson et al. 2017; Whitaker et al. 2011). Although numerous residual herbicides are registered for POST-directed use in cotton, these products are seldom used in this capacity. This is partly because POST-directed applications are time- and labor-intensive, and following the commercialization of glyphosate-tolerant cotton, many growers replaced such methods of weed control for simple and cost-effective POST-only programs (Duke and Powles 2008; Webster and Sosonskie 2010). In addition, POST-directed applications require a height differential between the cotton and targeted weeds to prevent crop injury, which is particularly difficult to obtain due to the robust growth of Palmer amaranth (Askew et al. 2002, Askew and Wilcut 1999).

Due to the infrequent use of POST-directed herbicides, greater selection pressure for resistance has been imposed on the few POST OTT residual options. Currently, Palmer amaranth biotypes resistant to HPPD- and VLCFA-inhibitors have been discovered, bringing to question the longevity of these important MOAs (Brabham et al. 2019; Heap 2024; Jhala et al. 2014; Mahoney et al. 2020). With weed control costs continuing to rise and the rate of herbicide discovery at a near standstill (Beckie and Harker 2017; Duke 2012; Washburn 2023), there is a pressing need for alternative weed control strategies that have potential to integrate additional herbicides into cotton weed management.

Given that growers frequently apply fertilizer within a growing season (Edmisten and Collins 2024; Hons et al. 2004), especially on the sandy soils typical of the southern U.S. cotton production region (Gatiboni and Hardy 2024), one potential weed management strategy is residual herbicide-coated fertilizer. Buhler (1987) reported that herbicide-coated fertilizer had potential to reduce time and labor costs, as well as soil compaction. In turfgrass and container nurseries, herbicide-coated fertilizer is commonly used to prevent herbicide volatility and to reduce the risk of injury (Derr 1994; Yelverton 1998). For cotton producers, herbicide-coated fertilizer could provide growers with an alternative to POST-directed lay-by applications (Steckel 2021). Considering less crop foliage would be exposed to herbicide compared to standard spray applications, herbicide-coated fertilizer may have the potential to integrate additional residual herbicides in cotton.

Currently, pendimethalin and pyroxasulfone are the only herbicides registered to be applied coated on granular fertilizer in cotton (Anonymous 2024a, 2024c). Pendimethalin-coated fertilizer has been shown to control Texas millet (*Urochloa texana* R. Webster) similarly to pendimethalin sprayed at planting (Grey et al. 2008). Research in North Carolina found pyroxasulfone-coated granular ammonium sulfate (AMS) to control Palmer amaranth comparable to pyroxasulfone applied POST and POST-directed (Dean et al. 2023). Although some studies evaluated herbicide-coated fertilizer in cotton, there is need to further investigate efficacy and utility of additional herbicides applied coated on AMS fertilizer in cotton. The objectives of this research were to evaluate cotton tolerance to various herbicides applied top-dress, coated on AMS fertilizer, and associated Palmer amaranth control.

Materials and Methods

An experiment was conducted in 2022 and 2023 at the Upper Coastal Plains Research Station near Rocky Mount, NC (35.89, 77.68), and the Central Crops Research Station near Clayton, NC (35.67, 78.51). The soil at Rocky Mount consisted of an Aycock very fine sandy loam (Fine-silty, siliceous, subactive, thermic Typic Paleudults) with 0.3 to 0.4% humic matter and pH of 6.0 to 6.1. The soil at Clayton consisted of a Dothan loamy sand (Loamy, kaolinitic, thermic Arenic Kandiudults) with 0.3 to 0.4% humic matter and pH of 5.5 to 6.0 (Mehlich 1984).

Fields at both locations were prepared using conventional tillage and then bedded into 91-cm rows at Rocky Mount and 97-cm rows at Clayton. Plots were 4 rows wide by 9.1-m long. Deltapine® cotton cultivar 'DP 2115 B3XF' (Bayer CropScience, Research Triangle Park, NC) was planted on May 11, 2022, at Rocky Mount and May 12, 2022, at Clayton. In 2023, 'DP 2115 B3XF' cotton cultivar was planted at Rocky Mount on May 9, whereas Deltapine® ThryvOn™ cotton cultivar 'DP 2211 B3TXF' was planted at Clayton on May 11. Cotton was seeded at approximately 107,637 seeds ha^{-1} to a depth of 2-2.5 cm. All pesticide and fertilizer applications required for crop maintenance were applied in accordance with recommendations from North Carolina Cooperative Extension (Edmisten et al. 2024).

Treatments included 15 residual herbicides plus a check. Herbicides and application rates are reported in Table 1. Treatments were arranged in a randomized complete block design with four replications. Each herbicide was coated on granular AMS (21-0-0-24; FCI Agri Service Company, Raeford, NC) and applied at 321 kg ha^{-1} (67 kg N ha^{-1}) onto 5- to 7-leaf cotton. The check received the equivalent rate of non-herbicide treated AMS for comparison. Herbicide-coated AMS was prepared by mixing the desired rate of herbicide, water, and 1 ml of blue dye (45 ml of total solution) in an electric powered concrete mixer (Sears, Roebuck and Co, USA.) that contained the appropriate rate of granular AMS. The blue dye (1 ml) was included in the mixture to provide a means for visually estimating coverage throughout the mixing process. All treatments were evenly applied within three cotton row middles using 1.89 L plastic containers (ULINE Company, U.S.A.) with lids that had equally spaced and sized (5/32 drill bit) holes.

Prior to applications, all plots (including the check) were treated with glyphosate (Roundup PowerMAX® 3 Herbicide, Bayer CropScience, St. Louis, MO) at 1,345 g ae ha^{-1} and glufosinate (Liberty® 280 SL Herbicide, BASF Corporation, Research Triangle Park, NC) at 656 g ai ha^{-1} to control previously emerged weeds. No residual herbicides were used prior to treatment applications. Spray applications were made using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 207 kPa. Backpack sprayers were equipped with AIXR 11002 flat-fan nozzles (TeeJet® Air Induction Extended Range spray nozzles; TeeJet Technologies, Wheaton, IL). Application dates and accumulated rainfall at both locations in both years are reported in Table 2.

All locations were naturally infested with Palmer amaranth. Visual estimates of cotton injury and weed control were made bi-weekly until 70 days after treatment (DAT; Frans 1986), and late-season Palmer amaranth density was recorded before cotton defoliation. At the conclusion of the season, the center two rows of each plot were mechanically harvested and weighed to determine cotton lint yield. All data were subject to analysis of variance using the GLM procedure of SAS software (version 9.4; SAS Institute Inc., Cary, NC) ($\alpha = 0.05$). Treatment means were separated using Fisher's Protected LSD ($P \leq 0.05$) where appropriate. For all analyses, treatment, year, location, and their interactions were considered fixed effects, while replication was considered a random effect.

Results and Discussion

Cotton Response

Main effects of treatment, year, and location were significant for cotton injury. The three-way interaction of the main effects was significant; thus, data for cotton injury are presented by location. Most injury was in the form of cotton necrotic leaf specking and resulted from AMS granules adhering to damp foliage at time of application. However, interveinal and marginal leaf chlorosis was notable in response to the PSII-inhibitors, including diuron, fluometuron, linuron, atrazine, and metribuzin. These herbicides are apoplastically translocated (moving upward through the plant from the soil) throughout the plant and can be absorbed through foliage or roots (Ross and Childs 1996). When soil-applied, plant roots can readily absorb these herbicides, causing chlorophyll synthesis inhibition and degradation of cell membranes (Neal et al. 2015).

At 7 DAT in 2022, sulfentrazone was the most injurious at both locations, resulting in 18 and 11% cotton injury at Clayton and Rocky Mount, respectively (Table 3). Like sulfentrazone, metribuzin and fomesafen elicited greater cotton response at Clayton than at Rocky Mount. At Clayton, metribuzin and fomesafen resulted in 11 and 12% cotton injury, respectively. Meanwhile, both caused 8% injury at Rocky Mount. At Clayton, metribuzin (11%), acetochlor (7%), pyroxasulfone + carfentrazone (7%), flumioxazin (6%), and linuron (6%) were more injurious than all other treatments. With the exception of sulfentrazone (11%), metribuzin (8%), and fomesafen (8%), pyroxasulfone + carfentrazone (6%) was the only other treatment that caused injury greater than the non-herbicide treated AMS (4%) at Rocky Mount. Notably, atrazine (1%), acetochlor (2%), diuron (2%), fluometuron (1%), and pendimethalin (2%) resulted in injury less than the non-herbicide treated AMS (4%) at this location (Table 3). Differences in cotton injury between the two locations was likely attributed to rainfall, with Clayton and Rocky Mount accumulating 0.66 and 2.44 cm between 0 and 8 DAT, respectively (Table 2). Due to lower rainfall at Clayton, AMS granules likely remained on cotton foliage for an extended period after top-dress, thus causing slightly greater injury.

By 28 DAT in 2022, all treatments, except metribuzin, resulted in cotton injury comparable to the injury observed from non-herbicide treated AMS (3%). Once again, cotton response to metribuzin was greater at Clayton (18%) than Rocky Mount (12%). This was further evident 42 DAT, where metribuzin caused 39 and 17% cotton injury at Clayton and Rocky Mount in 2022, respectively (Table 3). Differences between locations were likely due to rainfall and soil texture. Soil texture at Clayton is a loamy sand, while Rocky Mount is a very-fine sandy loam. Between 17 and 40 DAT, Clayton received 2.59 cm more precipitation than Rocky Mount (Table 2). Given the coarser textured soil at Clayton plus the additional rainfall, metribuzin could have leached into the cotton root zone, thus causing greater root absorption and injury (Kleemann and Gill 2008; Moomaw and Martin, 1978). These findings are further supported by Coble and Schrader (1973), who reported greater soybean sensitivity to metribuzin after rainfall was received on coarse-textured soil with low organic matter. In general, these results are unsurprising, as metribuzin cannot be applied to soybeans or many other crops on coarse-textured soil with less than 2% organic matter (Anonymous 2024b). Aside from metribuzin, no other herbicide injured cotton 42 DAT at either location.

Similar to 2022, relatively minor cotton injury was observed at Rocky Mount and Clayton in 2023, except for metribuzin (Table 4). However, cotton tolerance to metribuzin differed in 2023, particularly at Rocky Mount. At 7 DAT, metribuzin accounted for 32 and 73% cotton injury at Clayton and Rocky Mount, respectively. This response was likely influenced by extensive rainfall that was received at Clayton (2.67 cm) and Rocky Mount (2.74 cm) the first two days following top-dress. By 28 and 42 DAT at Rocky Mount, metribuzin caused 84 and 81% injury, respectively, whereas at Clayton, 15 and 13% injury was observed, respectively. Between 9 and 24 DAT, Clayton accumulated 1.74 cm greater rainfall than Rocky Mount (Table 2). While rainfall likely initiated a cotton response to metribuzin, the greater rainfall at Clayton could have leached metribuzin beneath the root zone, resulting in less herbicide available for root absorption (Shaner 2014). Similar thoughts were reported by VanGessel et al. (2017), suggesting substantial rainfall on coarse-textured soil may have increased wheat tolerance to metribuzin.

Aside from metribuzin, there was overall less cotton injury in 2023 (Table 4). At Clayton, acetochlor, atrazine, dimethenamid-*P*, diuron, fluometuron, pendimethalin, pyroxasulfone, *S*-metolachlor, and the non-herbicide treated AMS caused no injury (Table 4). This is contrary to results observed in 2022 where these treatments caused 4 to 7% cotton injury (Table 3). Similar to 2022, pyroxasulfone (0%), *S*-metolachlor (1%), acetochlor (2%), atrazine (0%), fluometuron (1%), pendimethalin (1%), and dimethenamid-*P* (2%) all caused cotton injury comparable to the non-herbicide treated AMS at Rocky Mount.

Over two growing seasons, cotton response to diuron and fluridone was consistent across locations, accounting for 1 to 3% and 3 to 4% cotton injury, respectively. However, cotton response to flumioxazin varied by year. In 2022, flumioxazin caused 6 and 4% injury at Clayton and Rocky Mount, respectively. Meanwhile, in 2023, flumioxazin resulted in 13% injury at Clayton and 11% at Rocky Mount (Table 4). At Clayton, sulfentrazone resulted in less injury in 2023 (11%) than in 2022 (18%). At Rocky Mount, cotton response to sulfentrazone remained consistent, with 11% cotton injury observed both years. Contrary to 2022, no treatment injured cotton 28 DAT in 2023, except metribuzin. At both locations, cotton response to metribuzin remained evident 42 DAT (Table 4).

Acetochlor, *S*-metolachlor, and pyroxasulfone applied POST OTT of cotton are reported to cause ≥ 19% cotton injury (Cahoon et al. 2014; Collie et al. 2014; Eure et al. 2013). However, when coated on granular AMS and applied OTT of 5- to 7-leaf cotton, these herbicides injured cotton ≤ 7%. Previous research from Tennessee also reported minimal injury when pyroxasulfone-coated fertilizer was top-dressed in cotton (Steckel 2021). Fluometuron applied

POST OTT to cotyledon and 2- to 4-leaf cotton has been reported to cause 40% cotton injury (Kendig et al. 2007). However, when applied on granular AMS, fluometuron only accounted for 1 to 4% injury. Likewise, low-doses of flumioxazin applied POST OTT to simulate spray drift causes 69 to 97% cotton injury (Stephenson IV et al. 2019). However, flumioxazin-coated AMS caused no greater than 13% cotton injury. Research by Morgan et al. (2011a, 2011b) found that POST-directed lay-by applications of diuron, linuron, and fomesafen effectively controlled volunteer cotton. These same herbicides applied coated on AMS fertilizer in this study resulted in ≤ 12% cotton injury.

Palmer amaranth Control

Main effect of treatment was significant for Palmer amaranth control and density; main effects of year and location were not significant. Furthermore, interactions among main effects were not detected; therefore, data for Palmer amaranth control and density were averaged over years and locations (Table 5). Adequate rainfall was received for herbicide activation in both years at both locations (Table 2).

At 42 DAT, all treatments controlled Palmer amaranth ≥73% with the exception of pendimethalin and fluometuron, which controlled the weed 58 and 62%, respectively. These results are unsurprising as pendimethalin and fluometuron have historically provided inconsistent control of Palmer amaranth (Culpepper and York 2000; Grichar 2008). Conversely, pyroxasulfone (91%) was more efficacious than every other treatment, except pyroxasulfone + carfentrazone (89%), fomesafen (87%), fluridone (86%), flumioxazin (86%), and atrazine (85%; Table 5). Similarly, previous research reports excellent (≥ 90%) Palmer amaranth control by pyroxasulfone (Cahoon et al. 2015; Doherty et al. 2014, Geier et al. 2006; Janak and Grichar 2016; Steele et al. 2005). With the exception of fluridone (56%), all the aforementioned herbicides reduced late-season Palmer amaranth density by at least 78% compared to the nontreated check (Table 5).

Pyroxasulfone + carfentrazone (89%), fomesafen (87%), fluridone (86%), and flumioxazin (86%) were more efficacious than metribuzin (78%), linuron (77%), diuron (76%), sulfentrazone (74%), *S*-metolachlor (73%), and dimethenamid-*P* (73%). Earlier work by Whitaker et al. (2011) reported that fomesafen generally provides more effective control of Palmer amaranth than diuron. In general, reductions in Palmer amaranth density followed similar trends as estimates of visual control, with plots treated with diuron containing 56% fewer plants than the nontreated check, whereas plots treated with fomesafen had 89% less plants (Table 5). Additionally, atrazine (85%) proved more effective in controlling Palmer amaranth than sulfentrazone (74%), *S*-metolachlor (73%), and dimethenamid-*P* (73%). However, sulfentrazone (74%), *S*-metolachlor (73%), and dimethenamid-*P* (73%) controlled Palmer amaranth comparable to acetochlor (80%), metribuzin (78%), linuron (77%), and diuron (76%). Houston et al. (2019) reported similar Palmer amaranth control with *S*-metolachlor, acetochlor, diuron, sulfentrazone, and metribuzin.

Cotton Yield

Main effect of treatment was significant for cotton yield; main effects were not significant for year and location. No significant interactions were detected; therefore, data for cotton yield are presented averaged over years and locations (Table 5). Numerically, cotton treated with diuron (960 kg ha^{-1}) and fomesafen (950 kg ha^{-1}) produced the greatest yield. All other treatments, except metribuzin, linuron, and *S*-metolachlor, produced similar yield to plots treated with diuron or fomesafen. While plots treated with *S*-metolachlor yielded less than plots treated with diuron and fomesafen, yield was still comparable to all other treatments. As expected, due to early season visual injury, cotton treated with metribuzin (640 kg ha^{-1}) yielded the lowest and was only comparable to linuron (790 kg ha^{-1}). Despite yielding similarly to cotton treated with metribuzin, linuron was comparable in yield to all other treatments. It should be noted the objectives of this research were to evaluate cotton tolerance to various herbicides applied top-dress, coated on AMS fertilizer, and associated residual weed control; conducting this experiment under weed-free conditions may be more appropriate to evaluate treatment effects on cotton yield. However, yield reductions in response to metribuzin are likely as significant visual injury was observed earlier in the season.

Practical Implications

Due to the increasing prevalence of multiple HR Palmer amaranth and the continuous rise in weed control costs, alternative weed management strategies are needed. Our results provide evidence that herbicide-coated AMS may allow integration of additional residual herbicides for late season weed control in cotton with minimal injury risk. This is important, considering POST residual options in cotton are limited. Integration of additional residual herbicides using this application technique may reduce selection pressure on Group 15 herbicides, a mode of action cotton producers have long depended on. Furthermore, considering many growers are ill-equipped or hesitant to apply herbicides POST-directed, residual herbicide-coated AMS may provide farmers with a more efficient avenue for applying late season residual herbicides. Simultaneously applying a residual herbicide and fertilizer in a single pass has potential to reduce time, labor, and fuel costs. Although this research proves many herbicides not currently labeled for OTT use in cotton can be safely used when coated on AMS fertilizer, additional research is warranted to further quantify cotton tolerance and potential yield effects under weed-free conditions.

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Table 1. Residual herbicide treatments applied top-dress, coated on granular ammonium sulfate fertilizer.[a]

Herbicides[b]	Trade names	Formulation concentration	Application Rate	Manufacturer
		g ai L^{-1}	g ai ha^{-1}	
acetochlor	Warrant®	360	1,260	Bayer CropScience
atrazine	Atrazine® 4L	480	1,120	Adama US
dimethenamid-*P*	Outlook®	719	630	BASF Corporation
diuron	Direx®	480	840	Makhteshim Agan of North America
flumioxazin	Valor® EZ	480	52	Valent U.S.A
fluometuron	Cotoran® 4L	480	1,120	Adama US
fluridone	Brake®	144	221	SePRO Corporation
fomesafen sodium salt	Reflex®	240	280	Syngenta Crop Protection
linuron	Linex® 4L	480	840	NovaSource, Inc
metribuzin	TriCor®	75%	420	UPL NA, Inc
pendimethalin	Prowl® H20	455	1,064	BASF Corporation
pyroxasulfone	Zidua® SC	500	118	BASF Corporation
pyrox + carfen-ethyl	Anthem® Flex	447 + 32	118 + 9	FMC Corporation
S-metolachlor	Dual Magnum®	913	1,067	Syngenta Crop Protection
sulfentrazone	Spartan®	480	210	FMC Corporation

[a]Specimen labels for each product and mailing addresses and website of each manufacturer can be found at www.cdms.net.

[b]Abbreviations: Pyrox + carfen-ethyl, pyroxasulfone + carfentrazone-ethyl.

Table 2. Top-dress application dates and accumulated rainfall after applications.

Locations	Years	Application Dates	Days following application					
			0-8	9-16	17-24	25-32	33-40	40-48
			cm					
Rocky Mount	2022	June 16	2.44	0.02	6.1	0.46	0.08	6.55
	2023	June 21	4.52	1.48	8.03	0.23	0.97	0.36
Clayton	2022	June 17	0.66	0.58	7.54	0.97	0.08	3.3
	2023	June 21	3.21	5.29	5.96	0.08	0.06	1.84

Table 3. Cotton injury as affected by residual herbicide-coated granular ammonium sulfate fertilizer, 2022.[a]

Herbicides[b,c,d,e]	Cotton Injury					
	Clayton			Rocky Mount		
	7 DAT	28 DAT	42 DAT	7 DAT	28 DAT	42 DAT
	%					
none	4 ef	3 b	0 b	4 d	3 bc	0 b
acetochlor	7 c	4 b	0 b	2 gh	3 bc	0 b
atrazine	3 f	3 b	0 b	1 h	3 bc	0 b
dimethenamid-*P*	5 de	5 b	0 b	3 d-g	3 bc	0 b
diuron	3 f	3 b	0 b	2 gh	3 bc	0 b
flumioxazin	6 cd	4 b	0 b	4 de	3 bc	0 b
fluometuron	3 f	4 b	0 b	1 h	2 c	0 b
fluridone	4 ef	4 b	0 b	3 d-g	2 c	0 b
fomesafen	12 b	7 b	0 b	8 b	5 b	0 b
linuron	6 cd	7 b	0 b	4 d	5 bc	0 b
metribuzin	11 b	18 a	39 a	8 b	12 a	17 a
pendimethalin	5 cde	3 b	0 b	2 gh	3 bc	0 b
pyroxasulfone	4 ef	3 b	0 b	4 d	3 bc	0 b
pyrox + carfen	7 cd	4 b	0 b	6 c	4 bc	0 b
S-metolachlor	5 cde	4 b	0 b	4 def	2 c	0 b
sulfentrazone	18 a	7 b	0 b	11 a	5 bc	0 b

[a]Data are presented by year and location. Means within a column followed by the same letter are not statistically different according to Fisher's Protected LSD ($P \leq 0.05$). For columns beginning with NS, means are not statistically different.

[b]Abbreviations: DAT, days after treatment; pyrox + carfen, pyroxasulfone + carfentrazone; AMS, ammonium sulfate.

[c]Each herbicide was coated on granular AMS and top-dressed at 321 kg ha^{-1} onto 5- to 7-leaf cotton.

[d]The check received non-herbicide treated granular AMS at 321 kg ha^{-1}.

[e]Prior to top-dress, all plots (including the check) were treated with glyphosate at 1,345 g ae ha^{-1} and glufosinate at 656 g ai ha^{-1}.

Table 4. Cotton injury as affected by residual herbicide-coated granular ammonium sulfate fertilizer, 2023.[a]

Herbicides[b,c,d,e]	Cotton Injury					
	Clayton			Rocky Mount		
	7 DAT	28 DAT	42 DAT	7 DAT	28 DAT	42 DAT
			%			
none	0 d	0 b	0 a	0 g	0 b	0 b
acetochlor	0 d	0 b	0 a	2 efg	0 b	0 b
atrazine	0 d	0 b	0 a	0 g	0 b	0 b
dimethenamid-*P*	1 d	0 b	0 a	2 efg	0 b	0 b
diuron	1 d	0 b	0 a	3 e	0 b	0 b
flumioxazin	13 b	0 b	0 a	11 b	0 b	0 b
fluometuron	0 d	0 b	0 a	1 efg	0 b	0 b
fluridone	3 cd	0 b	0 a	3 ef	0 b	0 b
fomesafen	9 bc	0 b	0 a	9 cd	0 b	0 b
linuron	8 bc	0 b	0 a	9 cd	0 b	0 b
metribuzin	32 a	15 a	13 b	73 a	84 a	81 a
pendimethalin	0 d	0 b	0 a	1 efg	0 b	0 b
pyroxasulfone	0 d	0 b	0 a	0 g	0 b	0 b
pyrox + carfen	8 bc	0 b	0 a	7 d	0 b	0 b
S-metolachlor	0 d	0 b	0 a	1 efg	0 b	0 b
sulfentrazone	11 b	0 b	0 a	11 bc	0 b	0 b

[a]Data are presented by year and location. Means within a column followed by the same letter are not statistically different according to Fisher's Protected LSD ($P \leq 0.05$). For columns beginning with NS, means are not statistically different.

[b]Abbreviations: DAT, days after treatment; pyrox + carfen, pyroxasulfone + carfentrazone; AMS, ammonium sulfate.

[c]Each herbicide was coated on granular AMS and top-dressed at 321 kg ha^{-1} onto 5- to 7-leaf cotton.

[d]The check received non-herbicide treated granular AMS at 321 kg ha^{-1}.

[e]Prior to top-dress, all plots (including the check) were treated with glyphosate at 1,345 g ae ha^{-1} and glufosinate at 656 g ai ha^{-1}.

Table 5. Influence of residual herbicide-coated granular ammonium sulfate fertilizer on Palmer amaranth control and density, and cotton lint yield.[a]

	Control		Density			
	Palmer amaranth					
Herbicides[b,c,d,e]	42 DAT		Palmer amaranth		Yield	
	%		plants m^{-2}		Kg ha^{-1}	
none[d]	–		9	a	860	ab
acetochlor	80	b-e	1	e	860	ab
atrazine	85	a-d	2	de	820	ab
dimethenamid-*P*	73	e	2	de	910	ab
diuron	76	de	4	bcd	960	a
flumioxazin	86	abc	1	e	840	ab
fluometuron	62	f	6	ab	880	ab
fluridone	86	abc	4	bcd	830	ab
fomesafen	87	abc	1	e	950	a
linuron	77	cde	2	de	790	bc
metribuzin	78	cde	2	de	640	c
pendimethalin	58	f	5	bc	850	ab
pyroxasulfone	91	a	1	e	850	ab
pyrox + carfen	89	ab	1	e	930	ab
S-metolachlor	73	e	3	b-e	800	b
sulfentrazone	74	e	3	b-e	820	ab

[a]Data are averaged over years and locations. Means followed by the same letter are not different according to Fisher's Protected LSD ($P \leq 0.05$). For columns beginning with NS, means are not statistically different.

[b]Abbreviations: pyrox + carfen, pyroxasulfone + carfentrazone; DAT, days after treatment; AMS, ammonium sulfate.

[c]Each herbicide was coated on granular AMS and top-dressed at 321 kg ha^{-1} onto 5- to 7-leaf cotton.

[d]The check received non-herbicide treated granular AMS at 321 kg ha^{-1}.

[e]Prior to top-dress, all plots (including the check) were treated with glyphosate at 1,345 g ae ha^{-1} and glufosinate at 656 g ai ha^{-1}.