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# HPPD-resistant cotton response to isoxaflutole applied preemergence and postemergence

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## Abstract

Studies were conducted in 2019 and 2020 in Lewiston, NC, to determine the crop response of 4-hydroxyphenylpyrivate dioxygenase (HPPD)-resistant cotton to isoxaflutole (IFT) and other cotton herbicides as part of a cotton weed management program that included herbicides applied preemergence, early postemergence (EPOST), and mid-postemergence (MPOST). IFT was applied PRE at 105 g ha$^{-1}$ alone and in various combinations with acetochlor, diuron, fluometuron, fluridone, fomesafen, pendimethalin, and pyrithiobac. EPOST treatments included IFT at 53 or 105 g ha$^{-1}$ alone or in combination with glyphosate or glufosinate, or dimethenamid-*P* + glufosinate. Glyphosate + glufosinate was applied MPOST to all treatments except the nontreated control. Cotton injury from IFT applied PRE was minimal (0% to 3%). Injury following EPOST application of dimethenamid-*P* + glufosinate ranged from 3% to 5% and 6% to 9% in 2019 and 2020, respectively. In both years, injury from IFT applied PRE followed by IFT applied EPOST never exceeded injury from IFT applied PRE followed by dimethenamid-*P* + glufosinate. Isoxaflutole applied PRE followed by IFT applied EPOST at 105 g ha$^{-1}$ resulted in 0% to 2% cotton injury, indicating that IFT can be applied either PRE or EPOST with minimal risk to cotton. Late-season cotton height and cotton lint yield were not affected by any herbicide treatment. The experimental HPPD-resistant cotton cultivar was minimally injured by IFT applied PRE and EPOST, it tolerated standard cotton herbicides, and yield loss was not observed. Given these results, HPPD-resistant cotton and IFT may be integrated into cotton weed management systems with minimal risk for cotton injury and provide an additional effective mechanism of action for managing troublesome weeds in cotton.

## Introduction

In 2020, 96% of U.S. cotton acreage included genetically engineered resistance to one or more herbicides (USDA-NASS 2020). This trend began with rapid adoption of glyphosate-resistant (GR) cotton, which allowed cotton growers to control troublesome weeds postemergence (POST) with minimal risk for crop injury (Gianessi 2008). Extensive use of glyphosate hastened the evolution of GR weeds, thus creating need for a return to integrated weed control systems and the establishment of additional management tools (Duke and Heap 2017; Kniss 2018).

Before GR cotton was widely adopted, producers used several soil-residual herbicides with multiple effective mechanisms of action (MOAs). A typical recommendation of the time would have included application of a preplant-incorporated (PPI) herbicide, such as pendimethalin or trifluralin, followed by a photosystem II–inhibiting herbicide applied preemergence (PRE), such as diuron or fluometuron. In some instances, application of a postemergence (POST)-directed herbicide would follow to provide additional late-season control (Wilcut et al. 1995). Like the aforementioned strategy, which uses multiple effective MOAs and layered soil-residual herbicides, similar programs are once again encouraged by extension weed scientists to control GR Palmer amaranth (*Amaranthus palmeri* S. Watson; Cahoon and York 2020; Culpepper 2019). Soil-residual herbicides are a critical component of an integrated approach to weed management (Culpepper et al. 2010; Norsworthy et al. 2014; Whitaker et al. 2011; Wiggins et al. 2016) and can delay further evolution of herbicide-resistant weed biotypes (Busi et al. 2020; Neve et al. 2011). In recent years, fluridone, an inhibitor of phytoene desaturase and a new MOA to cotton (Bartels and Watson 1978; Cahoon et al. 2015b; Chamovitz et al. 1993; Kowalczyk-Schroder and Sandmann 1992), was commercialized specifically for controlling herbicide-resistant Palmer amaranth (Anonymous 2019a; York 2014; York 2016). Protoporphyrinogen oxidase (PPO) inhibitors applied preplant and/or PRE, and very long chain fatty acid (VLCFA) inhibitors applied PRE and/or early POST (EPOST) also control GR Palmer amaranth (Bond et al. 2006; Cahoon et al. 2015a; Cahoon and York 2020; Culpepper 2019; Whitaker et al. 2010). However, Palmer amaranth biotypes resistant to PPO and VLCFA inhibitors have been discovered in Tennessee and Arkansas, respectively, bringing into question the longevity of these important MOAs as tools for managing Palmer amaranth (Brabham et al. 2019; Copeland et al. 2018; Copeland et al. 2019; Varanasi et al. 2018; Ward et al. 2013). With the looming threat of additional herbicide resistance and the pace of herbicide discovery at a near standstill (Beckie and Harker 2017; Dayan 2019; Duke 2012), a great need exists to incorporate new effective weed control strategies into cotton production.

Research is underway in anticipation of the commercialization of cotton resistant to 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides, for which commercial launch is projected by 2023 (G Baldwin, BASF Corporation, personal communication). In addition to tolerance to the HPPD-inhibiting herbicide isoxaflutole (IFT), these cultivars are anticipated to have tolerance to glyphosate, glufosinate, and dicamba. Isoxaflutole is being evaluated for use both PRE and EPOST. Cotton tolerance to HPPD-inhibiting herbicides was achieved by insertion of an HPPD protein from *Pseudomonas fluorescens*. A single substitution of glycine for tryptophan at position 336 allows for reduced sensitivity to IFT (Boudec et al. 2001; Matringe et al. 2005; USDA-APHIS 2017).

Isoxaflutole is presently labeled for use in corn (*Zea mays* L.) for control of broadleaf and grass weeds and can be used PPI, PRE, or EPOST (Anonymous 2019b; Anonymous 2019c) and in transgenic HPPD-resistant soybean [*Glycine max* (L.) Merr.] PPI or PRE (Anonymous 2019d). Considerable corn injury has been documented following applications of IFT (Wicks et al. 2007; Wilson et al. 1999), which in some cases, have been attributed to coarse soil texture, low organic matter content, and elevated soil pH (Vrabel 1996; Wicks et al. 2007). The propensity of IFT to injure corn in coarse soils with low organic matter raises concern for future use in cotton, because these soil characteristics are common to cotton production in the southeastern United States (Garcia et al. 2011; NASA 2016; USDA-NASS 2019).

Isoxaflutole could be valuable for managing *Amaranthus* species in cotton, as previous research reports effective residual control (Knezevic et al. 1998; Starkey et al. 2016; Stephenson and Bond 2012; Zhao et al. 2017). Outside of *Amaranthus* species, IFT has also demonstrated activity on other weeds, some of which are troublesome in cotton. Smith (2019) reported that IFT controlled common lambsquarters (*Chenopodium album* L.), common ragweed (*Ambrosia artemisiifolia* L.), and velvetleaf (*Abutilon theophrasti* Medik.). Zhao et al. (2017) noted that IFT has the potential to control large-seeded weeds more effectively than VLCFA-inhibiting herbicides. Some of the most common and troublesome weeds in cotton include grasses, such as barnyardgrass (*Echinochloa crus-galli* L.), johnsongrass (*Sorghum halepense* L.), and goosegrass (*Eleusine indica* L.; Van Wychen 2019). Data suggest that each of these troublesome weeds may be controlled by IFT applied PRE (Bhowmik et al. 1999; Stephenson and Bond 2012; Takano et al. 2018).

Reports of IFT efficacy on weeds following POST application is limited. Starkey et al. (2016) evaluated IFT for POST control of Palmer amaranth and found that control was highly dependent upon weed size. Palmer amaranth ≤10 cm was controlled ≥94%. Young and Hart (1998) reported that methylated seed oil (MSO) applied in combination with IFT improved adsorption and translocation of the herbicide in giant foxtail (*Setaria faberi* Herrm.). Weed control by IFT applied POST could be a tool for managing emerged weeds in reduced-tillage cotton while still providing residual control. Similar assertions were made regarding potential use of IFT in no-till corn (Armel 2002; Vrabel et al. 1996).

Following commercialization of HPPD-resistant crops, careful stewardship of HPPD-inhibiting herbicides will be needed to avoid evolution of HPPD-resistant weed biotypes. Currently, resistance to HPPD-inhibiting herbicides has evolved in biotypes of Palmer amaranth and tall waterhemp (Heap 2021). Most notably, a recent North Carolina survey found that nearly 40% of screened Palmer amaranth populations contained survivors following mesotrione applied POST at 105 g ai ha$^{-1}$ (Mahoney et al. 2020). Confirmation of HPPD-resistant Palmer amaranth in the southeastern United States brings into question the longevity of this MOA.

The main objective of this research was to determine how IFT would integrate into cotton weed management systems in North Carolina. The goal was to evaluate cotton tolerance following PRE and POST applications of IFT alone and in combination with commonly used cotton herbicides in HPPD-resistant cotton.

## Materials and Methods

A weed-free experiment was conducted at the Peanut Belt Research Station near Lewiston-Woodville, NC (36.14°N, 77.16°W) in 2019 and 2020. Soil in 2019 was a Goldsboro sandy loam (fine-loamy, siliceous, subactive, thermic Aquic Paleudults) with 1.1% humic matter and pH 6.0, whereas the soil in 2020 was a Lynchburg sandy loam (fine-loamy, siliceous, thermic Aeric Paleaquults) with 0.7% humic matter and pH 6.0 (Mehlich 1984).

Sites were prepared using conventional tillage and then bedded on 91-cm rows, with plots of four 7.6-m rows in 2019 and four 9-m rows in 2020. The experimental design was a randomized complete block with four replications. An experimental 'GLIXTP' cotton cultivar (BASF Corporation, Research Triangle Park, NC) with tolerance to dicamba, IFT, glufosinate, and glyphosate was planted on May 14, 2019, and May 13, 2020. Cotton was seeded at a rate of 107,500 and 123,500 seeds ha$^{-1}$ at a depth of 2 and 2.5 cm in 2019 and 2020, respectively. Fertilizers, insecticides, growth regulators, and harvest aids were applied in accordance with recommendations from North Carolina Cooperative Extension.

Treatments consisted of IFT alone or in combination, PRE, and EPOST compared to commercial standards. A nontreated control was included for comparison. All treatments, except the nontreated control, received glyphosate + glufosinate + ammonium sulfate (AMS) mid-POST (MPOST). Application dates and rainfall data are presented in Table 1; herbicides, adjuvants, and rates can be found in Table 2; and herbicide treatments can be found in Table 3.

PRE herbicides were applied immediately following planting with a $CO_2$-pressurized backpack sprayer equipped with flat-fan nozzles (TTI TeeJet® Turbo TeeJet Induction Flat Spray Tips; TeeJet Technologies, Wheaton, IL) delivering 140 L ha$^{-1}$ at 207 kPa. In 2019, EPOST treatments were applied 31 d after planting (DAP) when cotton was 3- to 4-leaf, whereas MPOST herbicides were applied to 10-leaf cotton 18 d after (DA) EPOST. In 2020, EPOST treatments were applied to 1- to 2-leaf cotton (26 DAP); MPOST herbicides were applied to 6-leaf cotton (15 DA EPOST). POST herbicides were applied using a $CO_2$-pressurized backpack sprayer delivering 140 L ha$^{-1}$ equipped with DG 11002 (TeeJet® Drift Guard flat spray nozzles; TeeJet Technologies) and AIXR 11002 (TeeJet® Air Induction Extended Range spray nozzles; TeeJet Technologies) nozzles in 2019 and 2020, respectively. To avoid weed interference influencing cotton development and yield, hand-weeding was employed as necessary.

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**Table 1.** Planting and herbicide application dates and rainfall following preemergence herbicides applied at cotton planting.[a]

| | Planting | Herbicide application date | | | Rainfall | |
|---|---|---|---|---|---|---|
| Year | Date | PRE | EPOST | MPOST | 0–7 DAP | 8–14 DAP |
| | | | | | cm | |
| 2019 | May 14 | May 14 | June 14 | July 18 | 0.4 | 0 |
| 2020 | May 13 | May 13 | June 8 | July 23 | 1.1 | 1.6 |

[a]Abbreviations: DAP, days after planting; EPOST, early postemergence; MPOST, mid-postemergence; PRE, preemergence.

**Table 2.** Herbicides and adjuvants used preemergence and postemergence.[a]

| Herbicides and adjuvants | Trade names | Formulation concentration | Manufacturer |
|---|---|---|---|
| Acetochlor | Warrant® | 360 g ai $L^{-1}$ | Bayer CropScience |
| Ammonium sulfate | Amaze Gold® | 34% | Loveland Products, Inc. |
| Crop oil concentrate | Agri-Dex® | 99% | Helena Chemical Co. |
| Dimethenamid-P | Outlook® | 719 g ai $L^{-1}$ | BASF Corporation |
| Diuron | Direx® 4L | 480 g ai $L^{-1}$ | Makhteshim Agan of North America |
| Fluometuron | Cotoran® 4L | 480 g ai $L^{-1}$ | Adama US |
| Fluridone | Brake® | 144 g ai $L^{-1}$ | SePRO Corporation |
| Fomesafen sodium salt | Reflex® | 240 g ai $L^{-1}$ | Syngenta Crop Protection |
| Glufosinate | Liberty® 280 SL | 280 g ai $L^{-1}$ | BASF Corporation |
| Glyphosate | Roundup PowerMAX® II | 660 g ae $L^{-1}$ | Bayer Crop Science |
| Isoxaflutole | Alite 27® | 479 g ai $L^{-1}$ | BASF Corporation |
| Pendimethalin | Prowl® H2O | 395 g ai $L^{-1}$ | BASF Corporation |
| Pyrithiobac sodium | Staple® LX | 384 g ai $L^{-1}$ | Corteva Agriscience |

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

Cotton stand was evaluated 21 DAP by counting all emerged cotton in the two center rows of each plot. Visual estimates of cotton injury (Frans et al. 1986) were collected 9 to 14 DAP, 21 DAP, 7 and 15 to 18 DA EPOST, and 13 to 14 and 27 to 28 DA MPOST. In addition, cotton height was collected 15 DA EPOST and just prior to harvest by measuring the height of 10 plants from the two center rows of each plot. The center two rows of each plot were mechanically harvested and weighed to determine seedcotton yield. Seedcotton grab samples from each plot were collected and ginned using a tabletop gin to calculate lint percentage and thus determine lint yield. To evaluate effects of herbicide treatments on fiber length, fiber length uniformity, fiber strength, and micronaire, 10-g lint subsamples were subjected to high-volume instrumentation analysis (Sasser 1981). All data were subjected to ANOVA using the GLIMMIX procedure of SAS software (version 9.4; SAS Institute Inc., Cary, NC) and means were separated using Fisher's protected LSD at $P = 0.05$ where appropriate. Main effects of herbicide treatment and year-by-herbicide treatment interactions were observed only for visual estimates of cotton injury. Therefore, all data, except cotton injury, are presented pooled over years.

## Results and Discussion

### Cotton Stand

Cotton stand in the nontreated control was 10 plants m $row^{-1}$ 21 DAP (Table 3). Cotton stand in plots treated with a residual herbicide PRE ranged from 9 to 10 plants m $row^{-1}$. Residual herbicides applied PRE, including the grower standard of acetochlor + diuron + fomesafen, IFT alone, and IFT + acetochlor, diuron, diuron + pendimethalin, fluometuron, fluridone, fomesafen, and pyrithiobac, had no effect on cotton stand.

### Cotton Response

Year-by-herbicide treatment interactions for cotton injury 9 to 14 DAP, 7 and 15 to 18 DA EPOST were significant; therefore, data are presented by year (Table 4). The grower standard PRE treatment, acetochlor + diuron + fomesafen (4%), caused the greatest injury 9 to 14 DA PRE in 2019. At this same time, only IFT + diuron and IFT + diuron + pendimethalin caused similar injury to cotton as that of acetochlor + diuron + fomesafen. All other treatments, including IFT alone (0%), were less injurious than the grower standard applied PRE. Cotton injury observed PRE in 2020 was less than in 2019 and ranged just 0% to 2%. It is important to note, like 2019, IFT alone caused 0% cotton injury 9 to 14 DA PRE. Cotton injury observed in this study is similar to that observed by Cahoon et al. (2015a) and Foster (2021). Previous research carried out in North Carolina found that cotton was injured ≤3% 18 to 27 DA PRE by acetochlor, diuron, fomesafen, and fluometuron and two- and three-way combinations of the residual herbicides (Cahoon et al. 2015a). Foster (2021) evaluated HPPD-resistant cotton in Texas and reported 1% injury 14 DA PRE from IFT + fluometuron and IFT + pendimethalin.

Despite little cotton response to IFT and other PRE herbicides in 2019 and 2020, PRE rates required for effective weed control can sometimes injure cotton, especially when growing conditions are less than ideal (Schrage et al. 2012). Culpepper et al. (2012) reported that seedling vigor, rainfall/irrigation intensity, and/or planting depth influenced cotton response to diuron, fomesafen, pyrithiobac, and pendimethalin in Georgia. For example, under

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**Table 3.** Cotton stand as affected by isoxaflutole alone and isoxaflutole combinations applied preemergence and early postemergence.[a]

| Herbicides and application times[b],[c] | | Cotton stand 21 DAP |
|---|---|---|
| PRE | EPOST[d] | plants m row$^{-1}$ |
| None | None | 10 NS |
| Acet + diuron + fome | dimet + gluf | 9 |
| IFT + diuron | dimet + gluf | 10 |
| IFT + pendi | dimet + gluf | 10 |
| IFT + diuron + pendi | dimet + gluf | 10 |
| IFT | dimet + gluf | 10 |
| IFT + acet | dimet + gluf | 10 |
| IFT + fome | dimet + gluf | 10 |
| IFT + fluometuron | dimet + gluf | 10 |
| IFT + fluridone | dimet + gluf | 10 |
| IFT + pyrithiobac | dimet + gluf | 10 |
| None[e] | IFT LR[f] | 10 |
| None[e] | IFT HR[f] | 10 |
| None[e] | IFT HR + glyph | 10 |
| None | IFT HR + gluf | 10 |
| IFT | IFT HR[f] | 10 |

[a]Data are averaged over 2 yr. Means within a column followed by the same letter are not different according to Fisher's protected LSD test at P = 0.05. For columns beginning with NS, means are not statistically different.
[b]Abbreviations: Acet, acetochlor; Fome, fomesafen; IFT, isoxaflutole; Pendi, pendimethalin; Dimet, dimethenamid-P; Gluf, glufosinate; Glyph, glyphosate; NS, no significant difference; PRE, preemergence; EPOST, early postemergence; DAP, days after planting; HR, high rate; LR, low rate.
[c]Acetochlor, diuron, fomesafen, fluometuron, fluridone, isoxaflutole, pendimethalin, and pyrithiobac applied at 1,261, 560, 210, 1,121, 168, 105, 925, and 59 g ha$^{-1}$ PRE. Dimethenamid-P, glufosinate, isoxaflutole low rate, and isoxaflutole high rate applied at 841, 881, 53, and 105 g ha$^{-1}$ EPOST. Glyphosate applied at 1,734 g ae ha$^{-1}$ EPOST.
[d]All treatments, except the nontreated control, received glufosinate at 881 g ha$^{-1}$ plus glyphosate at 1,734 g ae ha$^{-1}$ mid-POST.
[e]Treatments received no PRE herbicide in 2019, and acetochlor at 1,261 g ha$^{-1}$ PRE in 2020.
[f]Isoxaflutole applied alone EPOST included crop oil concentrate at 1% vol/vol; no adjuvant was included when IFT was applied in combination with glufosinate or glyphosate. Glufosinate and/or IFT applied EPOST included ammonium sulfate at 2.5 kg ha$^{-1}$.

ideal conditions (normal planting depth and normal irrigation), cotton was injured 4% by fomesafen, whereas the herbicide caused 33% to 41% injury under adverse conditions (i.e., shallow planting depth and intense irrigation). Similarly, Main et al. (2012) observed up to 24% reduction in cotton stand 5 to 7 DA after a PRE application of fomesafen when rainfall coincided with cotton emergence. Because various factors including seedling vigor, environmental conditions, and planting depth can influence injury from residual herbicides, further evaluation of HPPD-resistant cotton across varying environments and production practices is warranted.

In 2019, cotton injury 7 DA EPOST was minimal across all treatments (0% to 5%), but cotton injury was greater from dimethenamid-*P* + glufosinate (3% to 5%), regardless of PRE treatment, compared to low rate of IFT (LR; 53 g ha$^{-1}$) or high rate of IFT (HR; 105 g ha$^{-1}$), which injured cotton 1% and 2%, respectively. Note that dimethenamid-*P* + glufosinate was applied only to treatments receiving a PRE, whereas IFT HR applied EPOST followed no PRE or IFT PRE. However, we can directly compare IFT PRE followed by (fb) dimethenamid-*P* + glufosinate or IFT HR EPOST. Following IFT PRE, dimethenamid-*P* + glufosinate EPOST injured cotton 4% 7 DA EPOST compared to only 2% injury from IFT PRE fb IFT HR EPOST. In the absence of a PRE, IFT HR + glyphosate (0%) and IFT HR + glufosinate (2%) were no more injurious than IFT alone 7 DA EPOST. IFT alone applied EPOST included crop oil concentrate and AMS; when IFT was applied in combination with glyphosate or glufosinate, only AMS was added. Regardless of adjuvant or herbicide partner, cotton response to IFT applied EPOST was minimal. In 2020, similar trends in cotton injury were observed. Regardless of IFT rate or herbicide combination, cotton was injured 0% to 1%, with the exception of IFT HR + glufosinate, which resulted in 4% injury to cotton. No injury was observed from IFT PRE fb IFT HR EPOST in 2020, again confirming the safety of IFT when applied both PRE and EPOST. Notably, injury from dimethenamid-*P* + glufosinate was greater in 2020 than 2019 and ranged from 6% to 9%. When making a direct comparison between IFT PRE fb dimethenamid-*P* + glufosinate or IFT HR EPOST, cotton injury from dimethenamid-*P* + glufosinate (7%) again exceeded injury from IFT HR (0%) EPOST. Conditions were favorable for cotton growth in both 2019 and 2020; however, increased cotton response to dimethenamid-*P* + glufosinate in 2020 may be attributed to higher air temperature and relative humidity, and greater soil moisture at the time of EPOST applications (data not shown). Cahoon and York (2020) noted increased cotton response to *S*-metolachlor, another VLCFA inhibitor (Weed Science Society of America Group 15), when applications coincide with high temperatures and increased soil moisture.

In 2019, injury 15 to 18 DA EPOST ranged between 2% and 3% across all treatments and was not significant. Contrarily, herbicide treatments did affect cotton injury at this timing in 2020, though injury was less than that observed 7 DA EPOST. Dimethenamid-*P* + glufosinate resulted in 2% to 4% injury to cotton, whereas IFT applied EPOST resulted in just 0% to 2% injury to cotton. The lower and higher rates of IFT applied EPOST resulted in 0% and 1% cotton injury 15 to 18 DA EPOST, respectively. IFT HR + glyphosate (0%) and IFT + glufosinate (2%) applied at the same timing also caused little injury. Additionally, IFT PRE fb IFT HR EPOST again caused minimal injury (1%) and resulted in less injury than cotton treated with IFT PRE fb dimethenamid-*P* + glufosinate EPOST (3%). When cotton was 6- to 10-leaf (MPOST), glyphosate + glufosinate was applied to all treatments, except the nontreated control (data not shown), injuring cotton ≤1%.

Cotton response to EPOST treatments containing dimethenamid-*P* is unsurprising. EPOST applications of VLCFA inhibitors can cause cotton injury, but even in cases in which moderate or severe early season injury has been documented, cotton lint yield remains unaffected (Cahoon et al. 2014; Eure et al. 2013; Everman et al. 2007, 2009; Inman et al. 2014; Samples 2020). In Texas, Foster (2021) observed similar response of HPPD-resistant cotton to EPOST applications of dimethenamid-*P* + glufosinate, which resulted in 6% to 10% cotton injury 14 DA EPOST across 4-site years. However, Foster (2021) reported greater cotton injury following IFT + glufosinate (6% to 9%) applied EPOST compared to 2% to 4% injury from the combination in this study.

### Cotton Height

Cotton in the nontreated control plots averaged 19 cm in height 15 DA EPOST; all herbicide treatments resulted in reduced cotton height compared to the nontreated control at that time. Cotton in plots treated with IFT PRE fb dimethenamid-*P* + glufosinate, acetochlor fb IFT LR, and IFT fb IFT HR averaged 18 cm in height. Cotton was shortest in plots treated with pendimethalin PRE (14 cm). In general, residual combinations applied PRE fb dimethenamid-*P* resulted in shorter cotton compared to treatments that did not include dimethenamid-*P*. Despite early season differences in height, cotton recovered, and by the date that harvest aids were applied, no difference in cotton height was observed. Final cotton height across all treatments ranged 75 to 81 cm.

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**Table 4.** Cotton injury from isoxaflutole alone and isoxaflutole combinations applied preemergence and early postemergence.[a]

| | | Cotton injury | | | | | |
|---|---|---|---|---|---|---|---|
| | | 2019 | | | 2020 | | |
| | | 9 to 14 DA | 7 DA | 15 to 18 DA | 9 to 14 DA | 7 DA EPOST | 15 to 18 DA |
| Herbicides and application times[b,c] | | PRE | EPOST | EPOST | PRE | EPOST | EPOST |
| PRE | EPOST[d] | % | | | | | |
| Acet + diuron + fome | dimet + gluf | 4 a | 5 a | 2 | 2 a | 8 ab | 4 a |
| IFT + diuron | dimet + gluf | 3 ab | 4 b | 2 | 1 b | 6 bc | 3 ab |
| IFT + pendi | dimet + gluf | 2 b | 5 a | 2 | 0 c | 9 a | 4 a |
| IFT + diuron + pendi | dimet + gluf | 3 ab | 3 c | 2 | 0 c | 7 ab | 2 bc |
| IFT | dimet + gluf | 1 cd | 4 b | 3 | 0 c | 7 ab | 3 ab |
| IFT + acet | dimet + gluf | 1 cd | 3 c | 2 | 1 b | 7 ab | 3 ab |
| IFT + fome | dimet + gluf | 1 cd | 4 b | 2 | 2 a | 7 ab | 3 ab |
| IFT + fluometuron | dimet + gluf | 1 cd | 4 b | 2 | 0 c | 7 ab | 4 a |
| IFT + fluridone | dimet + gluf | 2 bc | 4 b | 2 | 1 b | 6 bc | 4 a |
| IFT + pyrithiobac | dimet + gluf | 1 cd | 4 b | 2 | 0 c | 7 ab | 4 a |
| None[e] | IFT LR[f] | — | 2 d | 3 | — | 0 d | 0 d |
| None[e] | IFT HR[f] | — | 1 e | 3 | — | 1 d | 1 c |
| None[e] | IFT HR + glyph | — | 0 f | 2 | — | 1 d | 0 d |
| None | IFT HR + gluf | — | 2 d | 2 | — | 4 c | 2 bc |
| IFT | IFT HR[f] | 0 d | 2 d | 2 | 0 c | 0 d | 1 c |

[a]Data are averaged over 2 yr. Means within a column followed by the same letter are not different according to Fisher's protected LSD test at P = 0.05. For columns beginning with NS, means are not statistically different.
[b]Abbreviations: Acet, acetochlor; Fome, fomesafen; IFT, isoxaflutole; Pendi, pendimethalin; Dimet, dimethenamid-P; Gluf, glufosinate; Glyph, glyphosate; PRE, preemergence; EPOST, early postemergence; HR, high rate; LR, low rate.
[c]Acetochlor, diuron, fomesafen, fluometuron, fluridone, isoxaflutole, pendimethalin, and pyrithiobac applied at 1,261, 560, 210, 1,121, 168, 105, 925, and 59 g $ha^{-1}$ PRE. Dimethenamid-P, glufosinate, isoxaflutole low rate, and isoxaflutole high rate applied at 841, 881, 53, and 105 g $ha^{-1}$ EPOST. Glyphosate applied at 1,734 g ae $ha^{-1}$ EPOST.
[d]All treatments, except the nontreated control, received glufosinate at 881 g $ha^{-1}$ plus glyphosate at 1,734 g ae $ha^{-1}$ mid-POST.
[e]Treatments received no PRE herbicide in 2019, and acetochlor at 1,261 g $ha^{-1}$ PRE in 2020.
[f]Isoxaflutole applied alone EPOST included crop oil concentrate at 1% vol/vol; no adjuvant was included when IFT was applied in combination with glufosinate or glyphosate. Glufosinate and/or IFT applied EPOST included ammonium sulfate at 2.5 kg $ha^{-1}$.

**Table 5.** Cotton height and yield as affected by isoxaflutole alone and isoxaflutole combinations applied preemergence and early postemergence.[a]

| | | Cotton height | | |
|---|---|---|---|---|
| Herbicides and application times[b,c] | | 15 DA EPOST height | Final plant height | Yield |
| PRE | EPOST[d] | cm | | kg $ha^{-1}$ |
| None | None | 19 a | 80 | 1,470 |
| Acet + diuron + fome | dimet + gluf | 15 e | 78 | 1,340 |
| IFT + diuron | dimet + gluf | 16 d | 76 | 1,370 |
| IFT + pendi | dimet + gluf | 14 f | 75 | 1,370 |
| IFT + diuron + pendi | dimet + gluf | 14 f | 76 | 1,300 |
| IFT | dimet + gluf | 18 b | 81 | 1,440 |
| IFT + acet | dimet + gluf | 16 d | 76 | 1,340 |
| IFT + fome | dimet + gluf | 16 d | 76 | 1,380 |
| IFT + fluometuron | dimet + gluf | 17 c | 75 | 1,430 |
| IFT + fluridone | dimet + gluf | 17 c | 77 | 1,400 |
| IFT + pyrithiobac | dimet + gluf | 16 d | 76 | 1,340 |
| None[e] | IFT LR[f] | 18 b | 77 | 1,440 |
| None[e] | IFT HR[f] | 17 c | 79 | 1,470 |
| None[e] | IFT HR + glyph | 17 c | 76 | 1,470 |
| None | IFT HR + gluf | 17 c | 76 | 1,380 |
| IFT | IFT HR[f] | 18 b | 81 | 1,430 |

[a]Data are averaged over 2 yr. Means within a column followed by the same letter are not different according to Fisher's protected LSD test at P = 0.05. For columns beginning with NS, means are not statistically different.
[b]Abbreviations: Acet, acetochlor; Fome, fomesafen; IFT, isoxaflutole; Pendi, pendimethalin; Dimet, dimethenamid-P; Gluf, glufosinate; Glyph, glyphosate; PRE, preemergence; EPOST, early postemergence; HR, high rate; LR, low rate.
[c]Acetochlor, diuron, fomesafen, fluometuron, fluridone, isoxaflutole, pendimethalin, and pyrithiobac applied at 1,261, 560, 210, 1,121, 168, 105, 925, and 59 g $ha^{-1}$ PRE. Dimethenamid-P, glufosinate, isoxaflutole low rate, and isoxaflutole high rate applied at 841, 881, 53, and 105 g $ha^{-1}$ EPOST. Glyphosate applied at 1,734 g ae $ha^{-1}$ EPOST.
[d]All treatments, except nontreated control, received glufosinate at 881 g $ha^{-1}$ plus glyphosate at 1,734 g ae $ha^{-1}$ mid-POST.
[e]Treatments received no PRE herbicide in 2019 and acetochlor at 1,261 g $ha^{-1}$ PRE in 2020.
[f]Isoxaflutole applied alone EPOST included crop oil concentrate at 1% vol/vol; no adjuvant was included when IFT was applied in combination with glufosinate or glyphosate. Glufosinate and/or IFT applied EPOST included ammonium sulfate at 2.5 kg $ha^{-1}$.

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### Cotton Yield

Cotton lint yield ranged from 1,300 to 1,470 kg ha$^{-1}$ (Table 5), and no treatment differences were observed. Like cotton yield, herbicide treatments did not affect micronaire, fiber length, fiber length uniformity, or fiber strength (data not shown).

The HPPD-resistant cotton cultivar used in this experiment demonstrated excellent tolerance to IFT PRE and EPOST. IFT, applied alone or in combination with other herbicides, caused minimal cotton injury, thus demonstrating potential for safe use at either timing. These findings are further reinforced by research conducted in Arkansas and Texas, which also reported no decrease in cotton stand, minimal injury, and no reductions in lint yield from IFT applied PRE or EPOST when used alone or combined with other herbicides (Fleming et al. 2021; Foster 2021). Additionally, the experimental cotton cultivar demonstrated tolerance to commonly used cotton herbicides PRE and POST.

Despite considerable evidence that HPPD-resistant cotton responds minimally to IFT applied PRE and EPOST at rates up to 105 g ha$^{-1}$, further research is warranted to explore the response of HPPD-resistant cultivars to higher rates of IFT. Presently, 105 g ha$^{-1}$ is expected to be the 1× rate of IFT for use in cotton (J Sanderson, BASF Corporation, personal communication); however, evaluation of cotton response exceeding this rate is needed to ensure a considerable margin of crop safety is present.

Although further research is required, tolerance of the experimental HPPD-resistant cultivar observed in this experiment indicates that IFT can likely be integrated safely into cotton weed management systems and used alongside common PRE and POST cotton herbicides with minimal risk to producers, while providing another effective MOA for controlling troublesome weeds in cotton.

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