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Research Article

Response of Sesame to Selected Herbicides Applied Early in the Growing Season

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Growth chamber experiments were conducted to evaluate the response of sesame to PRE and POST applications of soil residual herbicides. PRE applications of acetochlor and *S*-metolachlor at 1.26 and 1.43 kg ai·ha^{-1} showed little or no sesame injury (0 to 1%) 4 wks after herbicide treatments (WAT). POST treatments of acetochlor and trifluralin made 3 wks after planting (WAP) resulted in greater sesame injury (40%) compared to applications at bloom (18%). Field studies were conducted in Texas and Oklahoma during the 2014 and 2015 growing seasons to determine sesame response to clethodim, diuron, fluometuron, ethalfluralin, quizalofop-P, pendimethalin, pyroxasulfone, trifluralin, and trifloxysulfuron-sodium applied 2, 3, or 4 weeks after planting (WAP). Late-season sesame injury with the dinitroaniline herbicides consisted of a proliferation of primary branching at the upper nodes of the sesame plant (in the shape/form of a broom). Ethalfluralin and trifluralin caused more "brooming" effect than pendimethalin. Some yield reductions were noted with the dinitroaniline herbicides. Trifloxysulfuron-sodium caused the greatest injury (up to 97%) and resulted in yield reductions from the untreated check. Early-season diuron injury (leaf chlorosis and necrosis) decreased as application timing was delayed, and late-season injury was virtually nonexistent with only slight chlorosis (<4%) still apparent on the lower leaves. Sesame yield was not consistently affected by the diuron treatments. Fluometuron caused early-season injury (stunting/chlorosis), and a reduction of yield was observed at one location. Pyroxasulfone applied 2 WAP caused up to 25% sesame injury (stunting) but did not result in a yield reduction. Quizalofop-P caused slight injury (<5%) and no reduction in yield.

1. Introduction

Sesame production has typically occurred in China and India using dehiscent varieties that are prone to capsule shattering during harvest; therefore, hand harvesting is nearly compulsory to minimize seed loss [1]. Sesame was introduced to the US from Africa and was called beni/benne/benni. Betts [2] quotes letters from Thomas Jefferson that document his trials with sesame between 1808 and 1824. Jefferson stated that sesame ". . .is among the most valuable acquisitions our country has ever made. . . . I do not believe before that there existed so perfect a substitute for olive oil." He talks about the rule of thumb that still exists today that sesame will do well where cotton (*Gossypium hirsutum* L.) does well. Nondehiscent varieties were developed in the US during the 1950's to allow mechanized harvest [3], and this development has allowed hectarage to increase substantially [1].

The presence of weeds is a major obstacle in sesame production [1, 4–8] and can negatively influence sesame yield. Kropff and Spitters [9] reported that the major factor influencing sesame yield loss in a competitive situation between the crop and weed is the ratio between the relative leaf area of the weed and the crop at the time of crop canopy closure. The effects of weeds on sesame establishment and growth have been well documented. Balyan [10], Gurnah [11], and Singh et al. [12] reported weed-induced reductions of sesame yield up to 74% and a need for a critical weed-free period up to 50 days after planting. Babiker et al. [13] reported that unrestricted weed growth reduced sesame grain yield by 30% and keeping the sesame crop weed free for 2, 4, 6, and 8 weeks after planting increased the grain yield by 8, 37, 40, and 43%, respectively. They concluded that the critical period of weed control in sesame appeared to be between 2 and 6 weeks after planting. Zuhair et al. [14] found that insufficient weed control during the early growth period of sesame caused 35 to 70% yield reductions, and they added that the critical period of weed control in sesame is 2 to 3 weeks after crop emergence.

With weak seedling vigor, limited competitive ability, and a lack of inexpensive and affordable labor, the use of preemergence (PRE) and/or postemergence (POST) herbicides is essential for commercially mechanized sesame production, especially in the US [7]. Also, the long growing season for sesame requires that herbicides provide season-long control [4, 6, 7]. Currently, *S*-metolachlor is the only herbicide registered for PRE use in the US but has caused sesame injury under certain conditions [15]. In Texas, *S*-metolachlor resulted in 9 to 29% sesame stand reduction at one location, while at another location, stand reduction was ≤8% [15]. At other locations, *S*-metolachlor provided 99% weed control and no injury [6]. Regardless of early-season injury issues, sesame yield from the application of *S*-metolachlor was often greatest of all herbicides tested [6].

Herbicide tolerance may be affected by many factors including application timing [1]. *S*-metolachlor-applied PRE can cause up to 47% injury to cotton on sandy soils; however, applications made after cotton emergence did not affect cotton stand [16]. Kendig et al. [17] reported that POST applications of *S*-metolachlor to cotton at the four-leaf stage caused less reduction in cotton biomass than the application at the cotyledon stage. Jefferies et al. [18] reported that, in chickpea (*Cicer arietinum* L.), the combination of imazethapyr plus imazamox caused a height reduction and decreased node development at all growth stages; however, an application at the 9 to 12 node stage caused the most severe delay.

All POST herbicides that control broadleaf weeds in sesame have caused some sesame injury or yield reduction [5, 7]. For broadleaf weed problems in sesame, the use of soil-applied herbicides still appears to be the only option [4, 6, 7]. However, since sesame hectares are increasing in areas of the US, there is a critical need to find more herbicides which can be used in sesame cultivation to extend weed control especially during the early portion of the growing season [13, 14]. Studies were undertaken to determine sesame tolerance to various PRE and POST herbicides that could be applied early in the growing stage to extend weed control and cause little sesame injury.

2. Materials and Methods

The growth chamber and field studies were conducted to compare sesame response to commonly used PRE and POST herbicides applied up to five weeks after sesame planting.

2.1. Growth Chamber Experiments. Two growth chamber experiments to evaluate the response of sesame to PRE and POST applications of soil residual herbicides were conducted in 2017 at Texas A&M University Weed Science Research Facility, College Station, TX. Each PRE and POST experiment was repeated 2x under similar growth chamber conditions and data pooled over time.

2.1.1. Sesame Variety and Soil. Five seeds of "S-39" sesame variety were planted in 15 cm diameter plastic pots, and the pots were watered as needed. In the POST-response experiment, three healthy sesame plants were maintained at the time of herbicide application. The soil used in this study was collected from Brazos Valley Research Farm near College Station, TX, with no history of residual herbicide use. The soil texture was silty clay loam with pH 8.0 and 1.2% organic matter. The growth chamber was maintained at 27/21°C day/night temperature with 14 hours of photoperiod using artificial lights.

2.1.2. Plot Design, Herbicides, and Application. The growth chamber experiments were laid out in a randomized complete-block design with four replications. The PRE herbicides were applied the day following sesame planting, while POST applications of the herbicides were made at two growth stages: 3 wks after planting (WAP) when sesame growth stage was 3-4 leaf pairs and at bloom approximately 5 WAP. The PRE applications of acetochlor (Warrant®, Monsanto Company, St. Louis, MO, 63167) at 1.26 and 2.52 kg ai·ha^{-1}, pethoxamid (not commercialized yet; FMC Corp., Philadelphia, PA, 19104) at 1.12 and 2.24 kg ai·ha^{-1}, and *S*-metolachlor (Dual II Magnum®, Syngenta Crop Protection, LLC, Greensboro, NC, 27419) at 1.43 and 2.86 kg ai·ha^{-1} were applied at 1x and 2x of the labeled US doses, whereas acetochlor at 1.26 kg ai·ha^{-1} and trifluralin (Treflan®, Helena Chemical Company, Collierville, TN, 38017) at 1.68 kg ai·ha^{-1} were applied at the 1x dose in POST-response experiment. Herbicides were applied using a single-tip spray chamber (DeVries Manufacturing Corp., Hollandale, MN, 56045) fitted with an XR110015 nozzle (TeeJet® Technologies, Spraying Systems Co., Wheaton, IL, 60139) calibrated to deliver 140 L·ha^{-1} spray volume at 207 kPa pressure at a speed of 4.8 km·h^{-1}. These studies were done twice over time.

2.1.3. Sesame Injury Evaluations and Analysis. Visual injury was evaluated at 2 and 4 wks after herbicide treatment (WAT) using a 0 to 100% scale, where 0% means no injury and 100% means complete death. Data were arcsine square root transformed before analysis; however, back-transformed real mean values are presented based on the interpretation from the transformed data. In the PRE study, ANOVA was performed using SAS 9.4 (SAS Institute. 1998. SAS user's guide. SAS Inst., Cary, NC) to evaluate the significance of herbicide treatments on sesame response. The Fishers Protected LSD at 0.05 level of probability was used for separation of mean differences. The nontreated control was included for comparison. *A priori* orthogonal contrasts (single degree of freedom) were used to compare the sesame injury following the POST herbicide applications at two growth stages (3 WAP versus bloom).

2.2. Field Research Sites. Field studies were conducted in 2014 and 2015 in south Texas near Knippa (29.396713°N, 99.609378°W), in east central Texas near College Station (30.372965°N, 96.199284°W), in the High Plains of Texas near Hale Center (34.07590°N, 102.04642°W in 2014; 34.0699°N, 101.9415°W in 2015), and in southeastern Oklahoma near Lane (34.29861°N, 95.98806°W) to evaluate sesame response to herbicides applied POST at 2, 3, and 4 WAP. Soil type near Knippa was a Winterhaven silty clay loam (fine silty, carbonatic, hyperthermic Fluventic Ustochrepts) with less than 1.0% organic matter and pH 7.8. Soil type near Hale Center was a Amarillo sandy clay loam (fine loamy, mixed, thermic Aridic Paleustalf) with 0.8% organic matter and pH 7.8, while at College Station, the soil type was a Westwood silty clay loam (fine silty, mixed, superactive, thermic Udifluventic Haplustepts) with 1.2% organic matter and pH 8.0. At Lane, the soil type was a Bosville fine sandy loam (fine, mixed, active, thermic Albaquic Paleudalfs) with 0.6% organic matter and pH 6.3.

2.2.1. Plot Design, Herbicides, and Adjuvant. A randomized complete-block experimental design was used, and treatments were replicated three to four times depending on location. Treatments consisted of a factorial arrangement of eight herbicide treatments in 2014 including clethodim (Select Max®, Valent USA Corp., Walnut Creek, CA, 94595) at 0.15 kg ai·ha^{-1}, diuron (Direx®, Alligare, LLC, Opelika, AL, 36801), fluometuron (Cotoran®, Adama USA, Raleigh, NC, 27604) at 1.12 kg·ha^{-1}, quizalofop-P (Assure II®, E. I. duPont de Nemours and Company, Wilmington, DE, 19805) at 0.08 kg·ha^{-1}, ethalfluralin (Sonalan®, Dow AgroSciences LLC, Indianapolis, IN, 46268) at 0.84 kg ai·ha^{-1}, trifluralin (Treflan EC®, Dow AgroSciences LLC, Indianapolis, IN 46268) at 0.85 kg ai·ha^{-1}, pendimethalin (Prowl H_20®, BASF Corp., Research Triangle Park, NC, 27709) at 1.06 kg ai·ha^{-1}, and pyroxasulfone (Zidua®, BASF Corp., Research Triangle Park, NC, 27709) at 0.12 kg ai·ha^{-1}. In 2015, ten herbicide treatments were evaluated including trifluralin at 0.85 and 1.7 kg ai·ha^{-1}, pendimethalin at 1.06 and 2.12 kg ai·ha^{-1}, ethalfluralin at 0.84 and 1.68 kg ai·ha^{-1}, fluometuron at 1.12 kg ai·ha^{-1}, pyroxasulfone at 0.12 kg ai·ha^{-1}, diuron at 1.12 kg ai·ha^{-1}, and trifloxysulfuron-sodium (Envoke®, Syngenta Crop Protection, LLC, Greensboro, NC, 27419) at 0.008 kg ai·ha^{-1}. The doses of the dinitroaniline herbicides (ethalfluralin, pendimethalin, and trifluralin) represent 1x and 2x of the labeled US dose, while the doses of all other herbicides represent 1x of the labeled US dose. Three POST application timings (2, 3, and 4 WAP) were used in both years. At the Lane location in 2014, herbicide applications were actually made 3, 4, and 5 WAP. A nontreated control was included for comparison at all locations.

Crop oil concentrate (Agri-Dex®, Helena, Collierville, TN, 38017) at 1.0% v/v was added to the clethodim, diuron, fluometuron, and quizalofop-P treatments. No type of adjuvant was added to the other herbicide treatments since they are considered soil-applied herbicides and have little or no foliar weed control activity.

2.2.2. Herbicide Application. Herbicides were applied in water using a CO_2-pressurized backpack sprayer with either TeeJet 11002DG, TurboTee 110015AIXR, or Turbo TeeJet 11002 flat fan spray nozzle tips (TeeJet Spraying Systems Co., P.O. Box 7900, Wheaton, IL, 60188) depending on location. Sprayers were calibrated to deliver 190 L·ha^{-1} at 207 kPa at Knippa, 140 L·ha^{-1} at 207 kPa at College Station and Hale Center, and 93.5 L·ha^{-1} at 131 kPa at the Lane location.

2.2.3. Plot Size. Each plot in south Texas was five rows (76 cm apart) by 9.1 m long and four rows (101 cm apart) by 7.3 m long in College Station, Hale Center, and Lane. Only the two middle rows were sprayed, and the other rows were untreated and served as buffers.

2.2.4. Sesame Plantings, Observations, and Harvest. The sesame variety "S-35" was planted at Knippa, Hale Center, and Lane in both years, while "S-39" was planted at College Station in 2015. Planting dates at Knippa were June 13, 2014, and July 16, 2015; at Hale Center, June 19, 2014, and July 6, 2015; at Lane, June 19, 2014, and June 20, 2015; and at College Station, June 24, 2015. The sesame cultivars were seeded approximately 1.0 to 2.0 cm deep at 9 kg·ha^{-1} at all locations. At maturity, sesame in the plots was hand harvested, dried, and threshed with a stationary harvester.

Sesame injury was evaluated 6 to 9 WAP (early season) and 11 to 19 WAP (late season) based on a scale of 0 (no sesame injury) to 100 (complete sesame death). Injury consisted of stunting, leaf chlorosis and necrosis, and brooming effect. The brooming effect is a proliferation of primary branching at the upper nodes of the sesame plant (in the shape/form of a broom). Branching typically does not occur from these nodes since they are primarily flowering nodes. When branching at these nodes does occur, flowers are not formed [19]. These branches are not typically long (<25 cm) and support 5 to 10 capsules as opposed to the primary branches found lower on the plant which can be almost a meter long and support up to 10x as many capsules [19].

2.2.5. Data Analysis. An analysis of variance was performed using the ANOVA procedure for SAS (SAS Institute. 1998. SAS user's guide. SAS Inst., Cary, NC) to evaluate the significance of herbicides and application timing on sesame response and yield. Fishers Protected LSD at the 0.05 level of

Table 1: Sesame injury with PRE and POST applications of soil residual herbicides in growth chamber experiments conducted at College Station, TX, in 2017[a].

Herbicide	Dose (kg ai·ha^{-1})	Application timing	Sesame injury[b,c] 2 WAT (%)	4 WAT
PRE application				
Nontreated control	—	—	0	0
Acetochlor	1.26	PRE	10[d]	0[c]
Acetochlor	2.52	PRE	15[c]	11[b]
Pethoxamid	1.12	PRE	10[d]	7[b]
Pethoxamid	2.24	PRE	30[a]	39[a]
S-metolachlor	1.43	PRE	10[d]	1[c]
S-metolachlor	2.86	PRE	26[b]	46[a]
POST application				
Nontreated control	—	—	0	0
Acetochlor	1.26	3 WAP	16[b]	19[b]
Acetochlor	1.26	At bloom	6[b,c]	15[b]
Trifluralin	1.68	3 WAP	40[a]	60[a]
Trifluralin	1.68	At bloom	3[c]	20[b]
Contrasts[d]				
POST: 3 WAP versus at bloom			28 versus 5**	40 versus 18**

[a]WAP, weeks after sesame planting; WAT, weeks after herbicide treatment; [b]means presented within each column with no common letter(s) are significantly different at $\alpha = 0.05$; [c]data were arcsine square root transformed before analysis; however, back-transformed real mean values are presented based on the interpretation from the transformed data; [d]a priori orthogonal contrast, **significant ($P < 0.01$).

probability was used for separation of mean differences. The untreated check was used for sesame injury ratings and yield comparison but was only included in yield data analysis.

3. Results and Discussion

3.1. Growth Chamber Results

3.1.1. Sesame Injury with PRE Herbicides. The PRE application of acetochlor, pethoxamid, and *S*-metolachlor at the 1x dose resulted in 10% sesame injury 2 WAT, whereas 15 to 30% injury was observed with these herbicides applied at the 2x dose (Table 1). Similarly, in a study conducted in Florida, Sperry et al. [1] reported that PRE application of *S*-metolachlor at 1.42 and 2.78 kg ai·ha^{-1} resulted in 41 and 65% reduction in sesame plant height, respectively. At 4 WAT, slight or no injury was observed with the PRE applications of *S*-metolachlor and acetochlor at 1.43 and 1.26 kg ai·ha^{-1}, respectively; however, pethoxamid at 1.12 kg ai·ha^{-1} resulted in 7% sesame injury (Table 1). At the 2x dose, pethoxamid and *S*-metolachlor caused the greatest injury (39–46%), while acetochlor was less injurious (11%). Injury symptoms consisted of sesame plant stunting and curling of the leaves.

3.1.2. Sesame Injury with POST Herbicides. The POST application of trifluralin (1.68 kg ai·ha^{-1}) at 3 WAP showed a higher level (≥40%) of sesame injury at 2 and 4 WAT compared to the other POST treatments (Table 1). No difference in sesame response was noted with acetochlor applied 3 WAP or at sesame bloom. Averaged across all POST herbicide treatments, when evaluated 2 and 4 WAT, sesame injury was 28 and 40%, respectively, when POST applications were made 3 WAP, compared with 5 and 18% injury, respectively, with POST applications made at sesame bloom stage. Shorter internode length of the sesame plants resulted in the stunted growth following the POST application of these herbicides.

3.2. Field Research Results

3.2.1. 2014 Results

(1) Herbicide Injury. Early-season clethodim injury at any location was no greater than 5% when applied 2 to 3 WAP; however, the 4 WAP application of clethodim caused 18% injury at the Hale Center location (Table 2). No late-season injury with clethodim was noted at Knippa with any application timings, while 5% injury was noted with the 4 WAP application at Hale Center. At Lane, when evaluated 12 WAP, injury ranged from 1 to 5% but was not different than the untreated check. Clethodim has proven equally good at controlling both annual and perennial grasses, particularly Johnsongrass (*Sorghum halepense* (L.) Pers.) in sesame [5]. There is a label in the US for clethodim (Select Max®) use in sesame which allows spraying at all growth stages except flowering [19]. Clethodim applied during flowering has resulted in lack of capsule formation along the main stem of the plant and is commonly referred to as “cap gap” [19].

Diuron caused considerable leaf necrosis and chlorosis at both Texas locations but little to no injury was observed at the Lane location when rated early season, while late-season injury was 4% or less at all locations (Table 2). Grichar et al. [6], in an earlier study, reported that diuron applied PRE at 1.12 kg·ha^{-1} reduced sesame stands and caused sesame injury in one year in the Hale Center area; however, in south Texas no adverse effects with diuron were seen in the two-year study. Typically, diuron injury with POST applications to sesame is transient, and by late-season, only slight leaf chlorosis may be noted on lower leaves [7].

Table 2: Early- and late-season sesame injury with selected herbicides applied 2, 3, or 4 weeks after planting at Knippa, Hale Center (Texas), and Lane (Oklahoma) in 2014.

Herbicide[a]	Dose (kg ai·ha)	Application timing WAP[b]	Early season Knippa	Early season Hale Center	Early season Lane	Late season Knippa	Late season Hale Center	Late season Lane
			WAP 6	6	8	19	11	12
			(%)					
Clethodim	0.15	2	0	3	1	0	0	1
		3	0	2	5	0	0	5
		4	3	18	3	0	5	3
Diuron	1.12	2	48	17	4	3	2	4
		3	50	13	4	3	3	4
		4	23	20	1	2	2	1
Fluometuron	1.12	2	—	17	3	—	2	1
		3	47	20	5	3	0	4
		4	12	27	1	2	3	1
Quizalofop-P	0.08	2	0	0	5	0	0	5
		3	0	0	5	0	0	5
		4	3	0	5	0	0	5
Ethalfluralin	0.84	2	5	5	3	2	0	1
		3	3	10	0	0	3	0
		4	3	2	1	8	0	1
Trifluralin	0.85	2	3	3	4	0	0	3
		3	5	7	1	0	0	1
		4	7	0	4	50	0	1
Pendimethalin	1.06	2	7	37	5	2	3	4
		3	2	28	0	0	2	0
		4	3	7	1	0	0	1
Pyroxasulfone	0.12	2	25	—	3	2	—	3
		3	5	—	1	0	—	2
		4	2	—	4	0	—	0
Untreated	—	—	0	0	0	0	0	0
LSD (0.05)			4	7	NS	8	5	NS

[a]Agridex at 1.0% v/v added to clethodim, diuron, fluometuron, and quizalofop-P treatments; [b]WAP, weeks after planting.

Fluometuron provided similar results to diuron with 12 to 47% early-season injury in Texas but <5% injury at the Oklahoma location when evaluated early season or late season. Grichar et al. [6] reported that fluometuron at 1.12 kg·ha^{-1} applied PRE in the High Plains region of Texas reduced sesame stand and caused injury in one of the two years, while no stand reduction or injury was noted at the south Texas location.

Sesame injury from quizalofop-P was 5% or less at all locations. Sesame injury from this herbicide has been virtually nonexistent at any rates or application timings (author's personal observation).

Ethalfluralin injury to sesame was the greatest with the 2 WAP application at Knippa (5%) and the 3 WAP application at Hale Center (10%) with little to no injury at Lane (Table 2). This injury is typically in the form of stunting and leaf malformation. Late-season injury was only noted with the 4 WAP application at Knippa. This injury manifested itself as the brooming effect which was mainly seen on the upper portion of the plant and is only seen late season.

Early-season trifluralin injury (stunting and leaf malformation) at Knippa was greatest with the 3 and 4 WAP application, while at Hale Center, the 3 WAP application caused the greatest injury. No significant injury was noted at Lane. Late-season injury at Knippa was 50% with the 4 WAP application with no injury noted at the other locations (Table 2). The injury at Knippa was in the form of the brooming effect noted earlier. This type of injury is only seen with the dinitroaniline herbicides.

Pendimethalin injury early season at Knippa was the greatest with the 2 WAP application, while at Hale Center, all application timings resulted in significant injury. This injury, in the form of stunting and leaf malformation, decreased as the sesame plant aged. No injury was noted at Lane. Late-season injury was virtually nonexistent (≤4%), and little to no brooming effect was noted.

Typically, the dinitroaniline herbicides are applied preplant incorporated (PPI) or PRE; however, POST applications of these herbicides may be used to extend residual weed control throughout the growing season [20]. Since the dinitroaniline herbicides have lower water solubility and can volatilize and photodecompose on the soil surface over time, these herbicides need to be mechanically incorporated or need rainfall or irrigation to move these herbicides into the weed seed zone [21–24]. Uptake of these herbicides is primarily through roots and emerging shoots [25]. Parker [26]

Table 3: Sesame yield at Knippa, Hale Center (Texas), and Lane (Oklahoma) as influenced by selected herbicides applied 2, 3, or 4 weeks after planting in 2014.

Herbicide[a]	Dose (kg ai·ha)	Appl timing WAP[b]	Yield (kg·ha)		
			Knippa	Hale Center	Lane
Clethodim	0.15	2	1770	597	923
		3	1759	639	1051
		4	1773	544	760
Diuron	1.12	2	1734	636	1000
		3	1435	549	1010
		4	1787	454	902
Fluometuron	1.12	2	—	615	1085
		3	1563	602	946
		4	1559	537	983
Quizalofop-P	0.08	2	1873	611	841
		3	1869	569	926
		4	1767	560	732
Ethalfluralin	0.84	2	1805	416	923
		3	1832	630	933
		4	1893	436	749
Trifluralin	0.85	2	1713	520	655
		3	1680	608	817
		4	1730	613	732
Pendimethalin	1.06	2	1817	238	1048
		3	1802	241	936
		4	1872	560	943
Pyroxasulfone	0.12	2	1897	—	847
		3	1782	—	916
		4	1780	—	702
Untreated	—	—	1943	613	905
LSD (0.05)			270	108	214

[a]Agridex at 1.0% v/v added to clethodim, diuron, fluometuron, and quizalofop-P treatments; [b]WAP, weeks after planting.

showed that trifluralin was more inhibitory to grain sorghum (*Sorghum bicolor* (L.) Moench) when absorbed through roots than emerging shoots. It is possible that the dinitroaniline herbicides will be concentrated in the extreme upper portions of the soil profile and weed seed may be able to germinate below the zone where dinitroaniline herbicides are located [27]. In this case, emerging shoots pass through treated soil, whereas developing roots would be below the herbicide treated soil. The effectiveness of soil-applied herbicides is dependent upon several factors, including movement of the herbicide into the soil either through water provided by rainfall or irrigation or by mechanical incorporation [28, 29].

Early-season pyroxasulfone injury was greatest with the 2 and 3 WAP application at Knippa, while no injury was noted at Lane. No late-season pyroxasulfone injury was noted at any location (Table 2). Pyroxasulfone is a newly registered herbicide in the US for either preplant (PP), PPI, PRE, or early postemergence (EPOST) used in corn, cotton, soybean (*Glycine max* L.), and wheat (*Triticum aestivum* L.) and application timing is crop specific [30–32]. Pyroxasulfone controls *Amaranthus* spp., *Lolium* spp., *Urochloa* spp., goosegrass (*Eleusine indica* L.), crowfootgrass (*Dactyloctenium aegyptium* L.), and *Digitaria* spp. [33–39]. Although pyroxasulfone has a similar weed control spectrum as *S*-metolachlor and dimethenamid-P, it has a higher specific activity allowing for use rates approximately eight times lower than dimethenamid-P [40]. Pyroxasulfone inhibits very long chain fatty acid synthesis similar to chloroacetamide, oxyacetamide, and tetrazolinone herbicides [33].

(2) Sesame Yield. At Knippa, sesame yield was reduced from the untreated check with diuron and trifluralin applied 3 WAP and fluometuron applied 3 and 4 WAP (Table 3). At Hale Center, sesame yield was reduced when compared to the untreated check with diuron applied 4 WAP, ethalfluralin applied 2 and 4 WAP, and pendimethalin applied 2 and 3 WAP. At the Lane location, only trifluralin applied 2 WAP reduced sesame yield relative to the untreated check. The yield reductions noted with diuron at Knippa and Hale Center were probably due to the early-season injury (>13%) noted at those locations.

Grichar et al. [6] concluded that it was best if the dinitroaniline herbicides were applied PRE due to severe sesame injury when applied PPI. Of the dinitroaniline herbicides, only pendimethalin (formulated as Prowl H_20) can be applied PRE [41]; however, annual grass control following pendimethalin applied PRE is often poor [42]. Hussien et al. [43] reported that trifluralin at rates greater than 0.84 kg·ha^{-1} was harmful to sesame, while Schrodter and Rawson [44] reported that pendimethalin at 1.5 and 3.0 kg·ha^{-1} and trifluralin at 0.84 kg·ha^{-1} reduced sesame plant populations. Plant selectivity by herbicide placement is influenced greatly by the movement of the herbicide in soils [45]. If the dinitroaniline herbicides move, they may come in contact with the absorptive sites of sesame and cause sesame injury [6].

3.2.2. 2015 Results

(1) Sesame Injury. Early-season sesame injury with trifluralin was noted at Hale Center but no other locations (Table 4). At the 0.85 kg·ha^{-1} dose, sesame injury occurred with trifluralin applied 2 and 3 WAP, while at the 1.7 kg·ha^{-1} dose of trifluralin, sesame injury was noted at all application timings. When evaluated late season, sesame injury at Knippa and College Station was noted with both trifluralin doses applied 4 WAP, while at Hale Center, both doses and all application timings with the exception of trifluralin at 0.85 kg·ha^{-1} applied 3 WAP resulted in significant injury when compared to the untreated check. The late-season injury consisted of the brooming effect. No trifluralin injury was noted at Lane.

Pendimethalin injury early season at Hale Center decreased as the sesame plants aged with >40% injury when pendimethalin was applied 2 WAP and <10% injury when applied 4 WAP (Table 4). No early-season injury was noted at the other locations. When evaluated late season, sesame injury with pendimethalin at Hale Center exhibited similar trends as the early-season rating with greater injury at the early application timing. Pendimethalin applications to sesame have

Table 4: Early- and late-season sesame injury at Knippa, Hale Center, and College Station (Texas) and Lane (Oklahoma) with selected herbicides applied 2, 3, or 4 weeks after planting in 2015.

Herbicide[a]	Dose (kg ai·ha)	Timing WAP[b]	Early season				Late season			
			Knippa	Hale Center	Lane	College Station	Knippa	Hale Center	Lane	College Station
			WAP							
			4	7	4	6	14	18	12	18
			(%)							
		2	0	17	0	2	0	23	0	2
Trifluralin	0.85	3	0	7	0	2	0	8	0	2
		4	0	3	—	2	10	12	—	10
		2	5	33	0	2	0	33	0	2
Trifluralin	1.70	3	0	7	0	2	0	10	0	2
		4	0	12	—	2	18	12	—	25
		2	0	42	0	2	4	37	0	2
Pendimethalin	1.06	3	0	27	0	2	0	18	0	2
		4	0	8	—	2	2	2	—	2
		2	0	45	0	2	0	40	0	2
Pendimethalin	2.12	3	0	23	0	2	0	22	0	2
		4	0	5	—	2	0	10	—	2
		2	0	18	0	—	0	28	0	—
Ethalfluralin	0.84	3	0	13	0	—	0	10	0	—
		4	0	5	—	—	6	8	—	—
		2	2	10	0	—	0	32	0	—
Ethalfluralin	1.68	3	2	17	0	—	0	17	0	—
		4	0	10	—	—	12	30	—	—
		2	12	38	10	—	0	13	0	—
Fluometuron	1.12	3	0	20	0	—	0	8	0	—
		4	2	8	—	—	0	3	—	—
		2	0	13	0	2	0	25	0	2
Pyroxasulfone	0.12	3	0	17	0	—	0	10	0	—
		4	2	8	—	—	0	0	—	—
		2	12	20	10	—	0	5	0	—
Diuron	1.12	3	0	15	0	—	0	2	0	—
		4	0	18	—	—	4	3	—	—
		2	45	97	0	—	0	97	0	—
Trifloxysulfuron	0.008	3	82	67	0	—	9	5	0	—
		4	60	67	—	—	42	42	—	—
Untreated		—	0	0	0	0	0	0	0	0
LSD (0.05)			8	7	6	NS	6	9	NS	3

[a]Agridex at 1.0% v/v added to fluometuron, diuron, and trifloxysulfuron treatments. [b]WAP, weeks after planting.

resulted in less brooming effect than with other of the dinitroaniline herbicides (author's personal observation).

Early-season ethalfluralin injury to sesame was noted only at the Hale Center location (Table 4). Sesame injury with ethalfluralin at 0.84 kg·ha^{-1} decreased from 18 to 5% as herbicide application was delayed, but at 1.68 kg·ha^{-1}, this trend was not seen as injury ranged from 10 to 17%. Late-season injury with ethalfluralin was noted at Knippa with both doses applied 4 WAP, and this injury was in the form of the brooming effect. At the later evaluation at the Hale Center location, similar trends as seen with the early-season evaluation were noted, with injury at the lower dose decreasing as herbicide application was delayed, but this was not true with the higher dose. The dose of a dinitroaniline herbicide can affect sesame stand establishment. The 1/2x dose of ethalfluralin, pendimethalin EC, and trifluralin or the 3/4x dose of pendimethalin H_2O resulted in higher stand counts than the 1 to 2x dose of these herbicides when incorporated with rolling cultivator mixing wheels [46]. Previous research by Grichar et al. [4, 6] reported sesame injury following the use of dinitroaniline herbicides applied PPI using various incorporation methods. Also, Grichar et al. [4] reported that ethalfluralin, pendimethalin, and trifluralin reduced sesame stand numbers when compared with the untreated check. In that study, the dinitroaniline herbicides were incorporated 2.5 cm deep with a tractor-driven power tiller. In another study, Grichar et al. [6] reported that a spring-tooth harrow, with the lack of the ability to adjust incorporation depth, caused similar problems. However, the use of rolling cultivator mixing wheels, set to a depth of less than 2.5 cm, resulted in excellent sesame stands. Therefore, only a shallow incorporation of the dinitroaniline herbicides can be done when used in sesame to ensure a good stand.

Table 5: Sesame yield at Knippa, Hale Center, and College Station (Texas) and Lane (Oklahoma) as influenced by selected herbicides applied 2, 3, or 4 weeks after planting in 2015.

Herbicide[a]	Dose (kg ai·ha)	Appl timing WAP[b]	Knippa	Hale Center	Lane	College Station
				(kg·ha)		
Trifluralin	0.85	2	1786	318	502	716
		3	1537	581	577	846
		4	1568	616	—	977
Trifluralin	1.70	2	1721	297	689	846
		3	1537	470	588	846
		4	1704	587	—	977
Pendimethalin	1.06	2	1772	200	563	911
		3	1620	435	568	977
		4	1601	603	—	1042
Pendimethalin	2.12	2	1512	203	717	1107
		3	1538	464	517	977
		4	1631	861	—	846
Ethalfluralin	0.84	2	1656	277	609	—
		3	1573	393	553	—
		4	1631	534	—	—
Ethalfluralin	1.68	2	1634	316	643	—
		3	1634	612	509	—
		4	1593	621	—	—
Fluometuron	1.12	2	1702	481	624	—
		3	1556	670	604	—
		4	1503	752	—	—
Pyroxasulfone	0.12	2	1679	439	621	911
		3	1469	601	609	—
		4	1560	804	—	—
Diuron	1.12	2	1630	734	619	—
		3	1576	610	572	—
		4	1541	574	—	—
Trifloxysulfuron	0.008	2	1586	0	—	—
		3	1240	387	—	—
		4	1168	251	—	—
Untreated	—	—	1616	585	637	781
LSD (0.05)			177	234	128	195

[a]Agridex at 1.0% v/v added to fluometuron, diuron, and trifloxysulfuron treatments; [b]WAP, weeks after planting.

Early-season fluometuron injury was noted with the 2 WAP application at Knippa and Lane, while at the Hale Center location, sesame injury decreased as application timing was delayed. This trend also was visible at the late-season rating at Hale Center, but no late-season injury was apparent at the other locations (Table 4).

Sesame injury with pyroxasulfone early season and late season was visible at Hale Center but no other locations. Sesame injury early season was less with the 4 WAP application then the 3 WAP application; however, at the late-season evaluation sesame injury decreased as pyroxasulfone application was delayed.

Diuron injury was noted with the 2 WAP application at Knippa, Hale Center, and Lane, but the 3 and 4 WAP applications did not cause any sesame injury at Knippa or Lane. Late-season sesame injury was 5% or less at all locations.

Trifloxysulfuron-sodium injury to early-season sesame ranged from 45 to 82% at Knippa and 67 to 97% at Hale Center, but no injury was noted at Lane (Table 4). No late-season injury at Knippa with trifloxysulfuron-sodium applied 2 WAP was noted; however, the 4 WAP application resulted in >40% injury. Sesame injury at Hale Center was inconsistent and ranged from 5% with the 3 WAP application to 97% with the 2 WAP application. In cotton, trifloxysulfuron-sodium applied POST at the one-, three-, or five-leaf stage resulted in 22, 16, and 6% injury, respectively, when evaluated 21 days after treatment; however, no effect on yield was noted [47]. Tobacco (*Nicotiana tabacum* L.) metobilized ^{14}C-trifloxysulfuron-sodium rapidly, with 60.9% of the absorbed herbicide remaining in the parent herbicide form 4 h after treatment, whereas only 12.1% remained after 72 h [48]. These results show that the limited absorption and translocation, as well as rapid metabolism, are the basis for tobacco tolerance to foliar-applied trifloxysulfuron-sodium.

(2) Sesame Yield. At Knippa, only trifloxysulfuron-sodium applied 3 and 4 WAP reduced sesame yields when compared with the untreated check (Table 5). At Hale Center, the 2

WAP application of either trifluralin at 0.85 and 1.7 $kg{\cdot}ha^{-1}$, pendimethalin at 1.06 and 2.12 $kg{\cdot}ha^{-1}$, or ethalfluralin at 0.84 and 1.68 $kg{\cdot}ha^{-1}$ and trifloxysulfuron-sodium applied 2 and 4 WAP reduced the yield from the untreated check (Table 5). At Lane, trifluralin at 0.85 $kg{\cdot}ha^{-1}$ applied 2 WAP and ethalfluralin at 1.68 $kg{\cdot}ha^{-1}$ applied 3 WAP reduced the sesame yield when compared with the untreated check. No yield difference from the untreated check was noted with trifluralin or pendimethalin at any application timing at the College Station location. At this location, pendimethalin at 1.06 $kg{\cdot}ha^{-1}$ applied 4 WAP or pendimethalin at 2.12 $kg{\cdot}ha^{-1}$ applied 2 WAP produced the highest yields.

4. Conclusion

As these results show, sesame has a great ability to compensate for injury. In these studies where some of the herbicides caused severe sesame injury, sesame yields were good because the plants can compensate for open space and poor growth by additional branches with capsules [7, 15, 49]. However, branching can only compensate for gaps of less than 30 cm. Wider gaps not only lead to lower yields, but also let light through the canopy to encourage late-season weed emergence and growth [49]. A limited number of herbicides are available that can help control weeds during the production of sesame. Increasing the number of effective herbicides without crop injury would be a welcomed addition in sesame production. Annual grasses can be easily controlled in sesame with clethodim and quizalofop-P without sesame injury; however, only clethodim is approved for use on sesame in the US. Also, the label states that clethodim should not be applied during sesame flowering as an inhabitation of blooming and/or capsule formation may result [50]. The use of herbicides such as diuron or fluometuron is not without issues. These herbicides can effectively control weeds but can also affect sesame growth and yield as seen in these studies [5, 7]. Also, the dinitroaniline herbicides can extend weed control when used POST but can result in sesame injury and yield reductions in some instances.

Another option that may be available to growers is the use of cultivation to control unwanted or hard-to-kill weeds. However, cultivation cannot reliably control weeds within the seed row that emerge while the sesame is emerging. Since sesame grows slowly in the first three to four weeks, many growers have waited three to four weeks to cultivate. Sesame roots follow moisture, and with rain or irrigation in the first few weeks after planting, the roots may grow laterally and stay near the surface. Cultivating too close to the plant can cut roots, and plants will wilt quickly. In times of a dry season, roots grow more vertically allowing for closer cultivation. The cultivation process can throw soil up on the base of the plant covering any small weed after sesame plants are 10 to 15 cm in height.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request. Readers may gain access to the references by using View at Publisher, View at Google Scholar, or View at Scopus.

Conflicts of Interest

The authors declare there are no conflicts of interest regarding the publication of this manuscript.

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