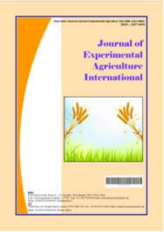

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Sesame (*Sesamum indicum* L.) Response to Delayed Applications of Preemergence Herbicides Applied 3 or 6 Day after Emergence

W. James Grichar[1*], Jack J. Rose[2], Peter A. Dotray[3], Joyce A. Tredaway[4], Muthukumar Bagavathiannan[5], Mark W. Shankle[6] and D. Ray Langham[7]

[1]Texas A&M Agri Life Research and Extension Center, Corpus Christi, TX 78406, United States.
[2]Sesaco Corporation, Austin, TX 78741, United States.
[3]Texas A&M Agri Life Research and Extension Center, Lubbock, TX 79403, United States.
[4]Department of Agronomy and Soils, Auburn University, Auburn, AL 36849, United States.
[5]Texas A&M Agri Life Research, College Station, TX 77843, United States.
[6]North Mississippi Research and Extension Center, Pontotoc, MS 38863, United States.
[7]Sesame Research, LLC, San Antonio, TX 78217, United States.

Authors' contributions

This work was carried out in collaboration among all authors. Each author was responsible for the design of the study at their respective location. Author WJG prepared the manuscript and each author provided the statistical analysis for their respective locations. All authors read and provided input into the manuscript and approved the final version.

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ABSTRACT

Aims: Field studies were conducted to determine sesame response to the pre-emergence herbicides (acetochlor at 1.7 kg ai ha^{-1}; *S*-metolachlor at 0.72, 1.43, and 2.86 kg ai ha^{-1}; dimethenamid-P at 0.84 kg ai ha^{-1}; pethoxamid at 0.22 kg ai ha^{-1}; pyroxasulfone at 0.09 kg ai ha^{-1} and bicyclopyrone at 0.12 and 0.24 kg ai ha^{-1}) applied 3 or 6 days after 50% emergence.
Study Design: Randomized complete block design with 3-4 reps depending on location.
Place and Duration of Study: Sesame growing areas of Alabama, Mississippi, and Texas during the 2016 through 2018 growing seasons.

**Corresponding author: E-mail: James.Grichar@ag.tamu.edu, James.Grichar@ag.tamu.ed;*

Methodology: Treatments consisted of a factorial arrangement of herbicide treatments at two early POST application timings. A non-treated control was included for comparison. Crop oil concentrate (Agridex®, Helena, Collierville, TN 38017) at 1.0% v/v was added to all herbicide treatments. Plot size was either five rows (76 cm apart) by 9.1 m or four rows (101 cm apart) by 7.3 m depending on location. Only the two middle rows were sprayed and the other rows were untreated and served as buffers. Sesame cultivars were seeded approximately 1.0 to 2.0 cm deep at 9 kg/ha at all locations. Injury was evaluated early-season, 7 to 27 days after herbicide application (DAA), and later, 28 to 147 DAA, based on a scale of 0 (no sesame injury) to 100 (complete sesame death). Injury consisted of stuntingand leaf chlorosis and/or necrosis.

Results: All herbicides tested resulted in significant injury to sesame at some location and application timing. None of the herbicides evaluated are safe to use early POST on sesame without causing significant injury.

Conclusion: The ability of sesame to recover from significant injury and compensate for injury led to no yield loss in many instances. However, levels of injury observed are not acceptable by growers and will not allow the use of these herbicides soon after sesame emergence.

Keywords: Application timing; herbicide injury; delayed preemergence; residual herbicides; yield.

1. INTRODUCTION

The greatest challenge for sesame production is weed control. For millennia, sesame has been grown with manual planting, manual weed control, and manual harvest. In the 2020s in many countries early weed control is done with hand-weeding followed by using implements such as hoes. The problem is that manual labor is becoming expensive and scarce, as the young move to the cities for more opportunities. In countries where there is some mechanization the practice is to use a combination of cultivators and hand hoeing. Again, hoe crews are becoming expensive and scarce. The alternative is using herbicides. There is no company that has a goal of developing sesame herbicides since the market is so small. Most herbicides were initially developed for other crops with clearance for use on sesame later.

Sesame has several unique features that contribute to challenges in weed management [1-4]. First, sesame grows very slow especially during the first 4 weeks after planting and the slow growth allows weeds to become established during the early part of the growing season [1-3]. In the first 30 days, sesame plants reach approximately 28 cm in height; however, sesame will double to 60 cm in the next 11 days, triple to 90 cm in the following 8 days, and quadruple to 120 cm in the following 9 days [1,4]. In many cases, weeds such as *Amaranthus* spp. can destroy a sesame stand as they grow over the sesame and crowd it out. This feature affects both manual and mechanical agronomic practices.

The second feature affects mechanized harvest where the plants are left standing in the field to dry down to 6% moisture before combining. Most sesame cultivars grown in the U S require a fairly long growing season of 130 to 150 d depending on cultivar and geographical region when left to dry naturally [1-3]. When using harvest aids, the crop can be sprayed 97-107 d at harvest maturity with an additional 10-14 d of drying [5]. Varieties do not start to dry down before the plants are physiologically mature. Because of this long growing season, soil-applied herbicides may not provide season-long control, resulting in mid to late season weed problems [6-9]. The problems are exacerbated when the sesame starts self-defoliation at about 70 d allowing light to strike the ground and promote weed growth. Weeds in mechanized harvest can increase the moisture in the combine bin, and small seeds of grasses and other weeds are difficult to clean out of the sesame. In manual harvest the plants are cut at harvest maturity, with most countries having varieties that mature at 80-90 d, often before self-defoliation. In some countries the sesame needs to be cut as early as 70 d before the first capsules dry and lose their seed. In manual cutting, only the sesame plants are cut, leaving the weeds in the field eliminating moisture and mixture problems.

The third feature is sesame seeds are small and need to be placed precisely in the soil [1,2,4]. The size of the sesame seed is similar to the size of many weed seeds and cannot be planted too deep that the cotyledons cannot reach the surface, and yet they cannot be planted too shallow that the moisture around the seed is lost to evaporation. The emerged sesame cotyledons are small compared to that of many other crops and grows very slowly. This slow development is compounded by the drought resistance of sesame, which leads to partition of a large portion of photosynthetic resources to create more root mass, particularly root elongation to follow the moisture. Many of the preplant and preemergence herbicides attack small weed seeds letting the large-seeded crops emerge.

The presence of weeds is a major obstacle in sesame production [6-10] and can negatively influence yield. Kropff and Spitters [10] reported that the major factor influencing sesame yield loss in a competitive situation between the crop and weed was 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 [11], Gurnah [12], Ibrahim et al. [13] and Singh et al. [14] reported weed-induced reductions of sesame yield up to 75% and a need for a critical weed-free period of up to 50 days after planting. Babiker et al. [15] 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. [16] found that insufficient weed control during the early growth period of sesame growth caused 35 to 70% yield reductions and they also concluded that the critical period of weed control in sesame is 2 to 3 weeks after crop emergence while Langham et al. [17] reported that in 19 sesame publications the critical weed free period was 20 to 65 d after emergence (DAE).

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 are essential for commercial mechanized sesame production, especially in the U S [6-9]. Also, the long growing season for sesame requires a weed management program that provides season-long weed control [6,8,18]. Currently, *S*-metolachlor is the only herbicide registered for PRE use in the U S and sesame injury has been observed with this treatment under certain conditions [18]. In Texas, *S*-metolachlor resulted in 9 to 29% sesame stand reduction at one location and $\leq$ 8% at a different location [18]. Also, *S*-metolachlor has provided 99% weed control and no injury at other locations [18]. Regardless of early season injury issues, sesame yield with *S*-metolachlor applied PRE was often the greatest of all herbicides evaluated [18]. In earlier work, the application of *S*-metolachlor at 28 d after planting had no effect on sesame growth (Grichar, unpublished data). The major problem of PRE's is a reduction in the percentage of sesame emergence. In many countries, sesame is overplanted and then thinned after emergence resulting in normal stands. In the U S there is no thinning and PRE herbicides may reduce the stands enough to require replanting.

Herbicide tolerance of crops may be affected by many factors including application timing [19]. With cotton (*Gossypium hirsutum* L.), *S*-metolachlor applied PRE can cause up to 47% injury on sandy soils; however, applications made after cotton emergence did not affect cotton stand [20]. Kendig et al. [20] also reported that POST applications of *S*-metolachlor to cotton at the four-leaf stage caused less reduction in cotton biomass than an application at the cotyledon stage. Jefferies et al. [21] reported 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.

There are several different strategies for using herbicides to control weeds in sesame: a) burndown (BURN) is the concept to kill existing weeds without disturbing the soil with the assumption that all the weeds that are in the upper layers of the seed bank will have germinated [9]; b) preplant (PP), there are 2 functions of PP herbicides including to act as a PRE herbicide to keep a field clean before planting without affecting the emergence of the sesame and to kill existing weeds and act as a PRE [9]; c) preplant incorporated (PPI) involves applying a herbicide before planting and incorporating into the soil [9,22]. Incorporation saves the herbicide from photodegradation on the surface and moves the herbicide into the soil [22]. With the development of PRE herbicides, the use of PPI systems has been reduced, but this practice is still used in the U S and some foreign countries. Extensive PPI testing at the research and farmer levels was done with the dinitroanilines in the US, and the conclusion was that when they were not in the seed line, they provided effective weed control, but in the seed line the sesame could be damaged and reduce seed viability [9,22]; d) preemergence (PRE) is the application of a herbicide after the sesame has been planted and before it has emerged. The concept is to prevent any weeds from emerging while the sesame seeds emerge [6,8,9,18]; e) postemergence over the top (POST) is the most used form of weed control in the U S [7,9,23]. Once the crop is tall, one of the disadvantages of a POST is that the herbicides do not penetrate the canopy and thus will not kill weeds in or near the seed line. There are 2 issues: (1) most will not control grasses and broadleaf weeds over a certain height and (2) d weeds tend to have multiple emergence cycles. Generally, after an initial spraying, the sesame will canopy over the weeds and keep them lower than the sesame plants. On the other hand, the fibrous roots of weeds are very efficient in using existing moisture; f) postemergence directed (PDIR) herbicide application can either be sprayed between the sesame rows without spraying the sesame plants or spraying between the rows and spraying the lower stems of the sesame plant thus controlling weeds in the seed row [24]. Once the sesame is taller, it will reach weeds in between the lines of sesame that are under the canopy. Although the canopy controls many weeds by denying sunlight, there are weeds such as *Ipomoea* that can come through the canopy and cover the sesame plants; and g) the use of harvest aids (HAID) [5]. In the U S, all standing sesame is mechanically harvested with a combine, and the use of a harvest aid can help facilitate harvest in most cases because the herbicides will accelerate drydown, kill weeds, even up fields with different maturities, stop regrowth, stop vivipary, and prepare to plant a new crop. Killing weeds is important because they may add moisture to the seed in the combine and some weed seed is difficult to separate from sesame in the cleaning process [5].

Several herbicides that are new to the market were evaluated in this study including bicyclopyrone, pethoxamid, and pyroxasulfone. Bicyclopyrone, a 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitor (WSSA Group 27), is a herbicide that is currently registered in corn (*Zea mays* L.) for PRE control of annual grasses and broadleaf weed species [25,26]. In red beets (*Beta vulgaris* L.), bicyclopyrone applied PRE at 0.48 kg ai ha^{-1} provided excellent ($\geq$ 92%) residual control of common lambsquarters (*Chenopodium album* L.), common purslane (*Portulaca oleracea* L.), redroot pigweed (*Amaranthus retroflexus* L.), common ragweed (*Ambrosia artemisiifolia* L.), and yellow foxtail [*Setaria pumila* (Poir.) Roem. & Schult.] [27]. Bicyclopyrone has demonstrated effective control for several glyphosate-resistant weed species including Palmer amaranth (*Amaranthus palmeri* S. Wats), horseweed [*Conyza canadensis* (L.) Cronquist], and Russian thistle (*Salsola tragus* L.) [26,28,29].

Pethoxamid, a very-long-chain fatty acid (VLCFA) root and shoot inhibitor [30] belonging to the chloroacetamide family and is under development in the U S for use in rice (*Oryza sativa* L.) with registration anticipated in 2021 [31]. Pethoxamid is currently used as a PRE herbicide in Europe in corn and soybean (*Glycine max* L.) production [32] and is a soil-applied herbicide with activity on many annual grasses and small-seeded broadleaf weeds [33].

Pyroxasulfone is a newly registered herbicide in the U S for either preplant, preplant incorporated, PRE, or early postemergence (EPOST) use in corn, cotton, soybean, and wheat (*Triticum aestivum* L.) and application timing is crop specific [34-36]. 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 [37]. Pyroxasulfone inhibits VLCFA synthesis similar to chloroacetamide, oxyacetamide, and tetrazolinone herbicides [38].

All POST herbicides that control broadleaf weeds in sesame have caused some sesame injury or yield reduction [7,9,23]. For broadleaf weed control in sesame, the use of soil-applied herbicides still appears to be the best option [6,8,9,18]. However, with sesame hectares increasing in the U S, there is a critical need to identify more herbicide options for extended weed control especially during the early portion of the growing season [9,23]. Since there is a potential for injury to sesame with all the PRE herbicides previously evaluated, studies were undertaken to determine sesame tolerance to various PRE herbicides that could be applied soon after sesame emergence (i.e., delayed PRE timing), to extend weed control while ensuring crop safety.

2. MATERIALS AND METHODS

2.1 Research Sites

Field studies were conducted from 2016 through the 2018 growing seasons in Alabama, Mississippi, and Texas to evaluate sesame response to PRE herbicides applied 3 or 6 days after 50% sesame emergence (DAE). Emergence was defined as having approximately 50% of the sesame seedlings emerged. This varied from 3 days after planting up to 11 days after planting depending on location Table 1.

Soil type near Castroville, TX (29.3664° N, 98.8748° W) in 2016 was a Atco loam (coarse-loamy, carbonatic, hyperthermic Typic Haplustepts) with less than 1.0% organic matter and pH 7.9; near Knippa, TX (29.4026° N, 99.6163° W) in 2017 and 2018 was a Winterhaven silty clay loam (fine-silty, carbonatic, hyperthermic Fluventic Ustochrepts) with less than 1.0% organic matter and pH 7.8; near New Deal, TX (33.6939° N, 101.8272° W) in 2016, 2017, and 2018 was a Amarillo sandy clay loam (fine-loamy, mixed, thermic Aridic Paleustalf) with 0.8% organic matter and pH 7.8; near College Station, TX (30.4481° N, 96.4747° W) in 2017 the soil type was a Westwood silty clay loam (thermic Udifluventic Haplustepts) with 2.0% organic matter and pH 8.0; near Pontotoc, MS (34.2442° N, 88.9618° W) in 2017 was a Atwood silt loam (fine-silty, mixed, thermic Typic Paleudalfs); and near Shorter, AL (32.3721° N, 85.9099° W) in 2016 and 2017 was a Marvyn sandy loam (fine-loamy, siliceous, thermic Typic Hapludults) with 0.5% organic matter and pH 6.3.

2.2 Herbicides, Plots and Application.

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 either eight (2016) or nine (2017,2018) herbicide treatments including: acetochlor at 1.7 kg ai ha^{-1}; *S*-metolachlor at 0.72, 1.43, and 2.86 kg ai ha^{-1}; dimethenamid-P at 0.84 kg ai ha^{-1}; pethoxamid at 0.22 kg ai ha^{-1}; pyroxasulfone at 0.09 kg ai ha^{-1} (2017, 2018); and bicyclopyrone at 0.12 and 0.24 kg ai ha^{-1} at two early POST application timings (approximately 3 and 6 days after 50% sesame emergence). A non-treated control was included for comparison at all locations. A crop oil concentrate (Agridex®, Helena, Collierville, TN 38017) at 1.0% v/v was added to all herbicide treatments at all locations with the exception of the New Deal locations which did not include an adjuvant. Details of herbicide application are given in Table 1.

Plot size was five rows (76 cm apart) by 9.1 m at Castroville and Knippa and four rows (101 cm apart) by 7.3 m at all other locations. Only the two middle rows were sprayed and the other rows were untreated and served as buffers.

2.3 Sesame Plantings, Observations and Harvest

Sesame varieties were seeded approximately 1.0 to 2.0 cm deep at 9 kg ha^{-1} at all locations. All locations were conventionally tilled with the exception of the Pontotoc location which was planted no-till. Volunteer weeds were controlled either by hand hoeing or with a POST application of diuron at 1.12 kg ai ha^{-1} approximately 8 wks after sesame emergence with the exception of Shorter. AL in 2017 which received no weed control. At maturity, sesame was either hand-harvested, dried, and threshed with a stationary harvester or harvested with a small-plot combine. Yield data were not collected at College Station or Pontotoc in 2017 or Knippa in 2018.

Sesame injury was evaluated early-season, 7 to 27 days after herbicide application (DAA), and later, 28 to 147 DAA, based on a scale of 0 (no sesame injury) to 100 (complete sesame death). At Knippa, in 2018, due to accidental overspraying with glyphosate of the entire test area, the latest evaluation was 33 DAA. Injury consisted of plant stunting and leaf chlorosis and/or necrosis.

2.4 Data Analysis

An analysis of variance was performed using the PROC ANOVA procedure for SAS [39] to evaluate the significance of herbicides and application timing on sesame injury response and yield. Fishers Protected LSD at the 0.05 level of 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. Since evaluation dates and weather varied across locations no attempt was made to combine treatments over locations.

3. RESULTS AND DISCUSSION

3.1 Sesame Injury

Injury consisted of symptoms mentioned above.

3.1.1 Castroville, TX. 2016

When evaluated 14 DAA, bicyclopyrone at either rate and the high rate of *S*-metolachlor resulted in the most injury while *S*-metolachlor at the 0.72

kg ai ha^{-1} rate applied 3 DAE caused the least (Table 2). With acetochlor and bicyclopyrone at 0.12 kg ha^{-1}, the 6 DAE application resulted in greater injury than the initial application while more injury was noted with *S*-metolachlor at 2.86 kg ha^{-1} applied at the initial application (3 DAE) than the 6 DAE application. When evaluated 147 DAA, some of the injury had dissipated with the exception of bicyclopyrone at 0.24 kg ha^{-1} which still showed greater than 40% injury at either application timing. Also, at this evaluation, acetochlor applied 6 DAE, *S*-metolachlor at 1.43 or 2.86 applied 3 DAE, and pethoxamid applied 3 DAE resulted in at least 27% sesame injury. With the exception of pethoxamid applied 3 DAE, all the injury ratings decreased from 14 to 147 DAA.

3.1.2 Knippa, TX. 2017, 2018

In 2017, *S*-metolachlor at 0.72 kg ha^{-1} applied 3 DAE, *S*-metolachlor at 2.86 kg ha^{-1} applied 6 DAE, and bicyclopyrone at 0.24 kg ha^{-1} applied either 3 or 6 DAE resulted in 50% or greater injury when evaluated 14 DAA (Table 3). All other herbicides, with the exception of acetochlor and pyroxasulfone applied 3 and 6 DAE, S-metolachlor at 0.72 kg ha^{-1} applied 6 DAE or pethoxamid applied 3 DAE resulted in at least 20% injury to sesame. However, when evaluated prior to harvest (147 DAA), only bicyclopyrone at 0.24 kg ha^{-1} applied 6 DAE resulted in greater than 20% injury. With the exception of acetochlor and pyroxasulfone applied 3 DAE, injury decreased from early to late evaluation.

In 2018, when evaluated 20 DAA, only acetochlor at 1.7 kg ha^{-1} and bicyclopyrone at 0.24 kg ha^{-1} applied 6 DAE resulted in greater than 10% sesame injury (Table 4). When evaluated 33 DAA, sesame injury with acetochlor or *S*-metolachlor at 2.86 kg ha^{-1} applied 6 DAE or *S*-metolachlor at 1.43 kg ha^{-1} applied 3 DAE were the only treatments that resulted in injury (13 to 18%) that was greater than the untreated check.

3.1.3 College Station, TX. 2017

When evaluated 12 DAA, bicyclopyrone at either 0.12 or 0.24 kg ha^{-1} applied 6 DAE resulted in the greatest injury (71 and 90%, respectively) to sesame (Table 3). Herbicide treatments that included acetochlor applied 3 DAE, *S*-metolachlor at 1.43 kg ha^{-1} applied 3 and 6 DAE, *S*-metolachlor at 2.86 kg $ha^{-1}$and dimethenamid-P or pyroxasulfone applied 6 DAE, and bicyclopyrone at 0.12 or 0.24 kg ha^{-1} applied 3 DAE caused 18 to 31% injury (Table 3). Acetochlor and *S*-metolachlor at 0.72 kg ha^{-1} applied 6 DAE, pethoxamid applied 3 and 6 DAE, and pyroxasulfone applied 3 DAE resulted in $\leq$ 10% injury. At 28 DAA, only bicyclopyrone at either 0.12 or 0.24 kg ha^{-1} applied 6 DAE caused $\geq$ 49% injury. Also, acetochlor, S-metolachlor at 0.72, 1.43, and 2.86 kg ha^{-1}, and bicyclopyrone at 0.24 kg ha^{-1} applied 3 DAE, and pyroxasulfone applied 6 DAE caused sesame injury greater than the untreated check (Table 3).

3.1.4 New Deal, TX. 2016, 2017, 2018

In 2016 at the 9 DAA evaluation, dimethenamid or bicyclopyrone at 0.12 kg ha^{-1} caused greater sesame injury when applied 3 DAE than 6 DAE (Table 2). *S*-metolachlor and bicyclopyrone injury increased as the rate increased. Only acetochlor resulted in $\leq$ 17% injury at either application timing. At the 59 DAA evaluation, sesame injury was $\leq$ 7% with all herbicides regardless of application timing (Table 2). *S*-metolachlor at 2.86 kg ha^{-1} and either rate of bicyclopyrone applied 3 DAE had the greatest injury. Injury with all herbicide treatments decreased from the earlier evaluation.

In 2017, similar injury trends as seen in 2016 were observed at this location with the 9 DAA evaluation. Herbicide injury with bicyclopyrone ranged from 25 to 95% with the 6 DAE application resulting in $\geq$ 85% injury. In contrast to 2016, acetochlor injury ranged from 37 to 40% (Table 3). At the 73 DAA evaluation, only *S*-metolachlor at 2.86 kg ha^{-1} applied either 3 or 6 DAE resulted in injury that was greater than the untreated check.

In 2018, when evaluated 27 DAA, *S*-metolachlor at 0.72 kg ha^{-1} and dimethenamid-P at 0.84 kg ha^{-1} applied 6 DAE resulted in $\leq$ 7% sesame injury while all other herbicide treatments resulted in 10 to 68% injury (Table 4). The greatest injury ($\geq$50%) was observed following *S*-metolachlor at 2.86 kg ha^{-1} applied 3 and 6 DAE, dimethenamid-P applied 3 DAE, and bicyclopyrone at either rate applied 6 DAE. At the 69 DAA evaluation, only *S*-metolachlor at 0.72 kg ha^{-1} or 2.86 kg ha^{-1} and bicyclopyrone at 0.24 kg ha^{-1} applied 6 DAE or pethoxamid applied either 3 or 6 DAE caused sesame injury that was greater than the untreated check.

3.1.5 Pontotoc, MS. 2017

At the 7 DAA evaluation, *S*-metolachlor at 2.86 kg ha^{-1} and pyroxasulfone at 0.09 kg ha^{-1} applied 3 DAE resulted in > 20% injury while acetochlor, *S*-metolachlor at 1.43 kg ha^{-1}, dimethenamid-P, or pethoxamid applied 3 DAE and *S*-metolachlor at 2.86 kg ha^{-1} applied 6 DAE resulted in 13 to 18% injury to sesame (Table 3). At the 34 DAA evaluation, injury increased with all herbicide treatments and application timings with the greatest injury (45 to 48%) following *S*-metolachlor at 2.86 kg ha^{-1} applied either 3 or 6 DAE. None of the herbicide treatments resulted in <23% injury. Contrary to the other locations and years, the injury ratings of all the treatments increased from the early to late rating.

3.1.6 Shorter, AL. 2016, 2017

In 2016 when evaluated 14 DAA, bicyclopyrone at 0.24 kg ha^{-1} applied at 3 and 6 DAE resulted in> 90% injury while *S*-metolachlor at 2.86 kg ha^{-1} resulted in 65 to 69% injury (Table 2). Only *S*-metolachlor at 0.72 kg ha^{-1} and dimethenamid-P applied 3 DAE resulted in < 20% sesame injury. At 28 DAA, sesame injury following bicyclopyrone at 0.24 kg ha^{-1} remained at least 89% while *S*-metolachlor at 2.86 kg ha^{-1} caused 40% injury. Only *S*-metolachlor at 0.72 or 1.43 kg ha^{-1} applied 3 DAE and dimethenamid-P at either application timing resulted in sesame injury not different from the untreated check. With the exception of bicyclopyrone at 0.24 kg ha^{-1} at 6 DAE, all of the injury ratings decreased in the later ratings.

In 2017 at the 8 DAA evaluation, only dimethenamid-P applied 6 DAE resulted in sesame injury (14%) that was not different from the untreated check (Table 3). *S*-metolachlor at 2.86 kg ha^{-1}, pethoxamid, and bicyclopyrone at both rates applied 6 DAE caused >50% injury while acetochlor applied 6 DAE and pyroxasulfone applied at either application timing resulted in 16-17% injury. When evaluated 50 DAA, *S*-metolachlor at 0.72 kg ha^{-1} applied 3 DAE and dimethenamid-P or pyroxasulfone at both application timings injured sesame $\leq$ 3% while acetochlor applied 3 DAE, pethoxamid applied 6 DAE or bicyclopyrone at both rates applied 6 DAE caused $\geq$ 78% injury. Sesame injury increased from first to last rating with acetochlor, S-metolachlor at 1.43 and 2.86 kg ha^{-1} applied 3 DAE, pethoxamid applied 6 DAE, and bicyclopyrone at both rates applied 6 DAE.

Sesame injury was evident with all herbicides at some location or application timing with *S*-metolachlor and bicyclopyrone being the most injurious. *S*-metolachlor has provided mixed results when used on sesame. In one study, metolachlor at 0.6, 1.1, 2.2, and 3.4 kg ha^{-1} resulted in variable sesame plant populations, had no effect on sesame plant height, provided inconsistent weed control, and created higher plot yields than the untreated check [6]. In later work at a south Texas location, *S*-metolachlor caused no sesame stand reduction or injury; however, at the Lubbock location, stand reduction and injury was noted in one of the two years [8]. Also, sesame stand reductions have been noted in Oklahoma where *S*-metolachlor was applied followed by irrigation (C. Medlin & C. Godsey, personal communication). Growers still use *S*-metolachlor in sesame production despite the unpredictable injury potential [40]. Most of the research with *S*-metolachlor in the U S has been with planting in pre-irrigated fields or after a rain. Many of the problems growers have had with *S* metolachlor have occurred when it is applied after sesame is dry planted and irrigation is applied or rainfall occurs to get the sesame up. Then the S metolachlor is moved into the seed zone and results in poor stands (author's personal observations). Application timing interactions with *S*-metolachlor has been observed in other crops as well. In peanut (A*rachis hypogaea* L.), *S*-metolachlor applied preplant or PRE caused more injury than applications made at emergence or POST [41] while *S*-metolachlor applied early POST in cotton resulted in less than 3% injury [42] and PRE applications resulted in 27 to 47% cotton injury [19].

Since acetochlor, pethoxamid and dimethenamid-P are also chloroacetamide herbicides similar to S-metolachlor, it was expected that sesame injury should be similar. Acetochlor injury varied among locations, but was minimal at New Deal location in 2016 and Knippa in 2017. Although the use rate of pethoxamid was lower than that of S-metolachlor, sesame injury was apparent with pethoxamid and varied among application timings and typically was reduced as the growing season progressed. Pethoxamid applied at spiking and one- to two-leaf rice (*Oryza sativa L.*) stages resulted in no more than 5% injury [43]. In a later study, Godwin et al. [31] reported 7% or less injury with pethoxamid on rice when evaluated 2 weeks after treatment (WAT).

Table 1. Variables associated with the study at each location

	Location									
Variables	**College Station**	**Castroville**	**Knippa**		**New Deal**			**Pontotoc**	**Shorter**	
	2017	**2016**	**2017**	**2018**	**2016**	**2017**	**2018**	**2017**	**2016**	**2017**
Planting date	June 19	July 12	June 13	May 23	June 10	June 6	June 19	June 30	June 14	June 15
Application										
3 day	June 30	July 19	June 16	May 26	June 20	June 16	June 29	July 7	June 21	June 20
6 day	July 3	July 22	June 19	May 29	June 23	June 19	July 2	July 10	June 24	June 23
Sprayer	CO_2 backpack									
Operating pressure (kPa)	262	207	207	207	221	221	221	166	262	262
Spray volume (L ha^{-1})	142	190	190	190	142	142	142	142	142	142
Spray nozzles	TT 11002	DG 11002	DG 11002	DG 11002	TT 11002	TT 11002	TT 11002	FFXR 80015	TTI 11015	TDXL 110015
Sesame variety	S-35	S-35	S-40	S-40	S-35	S-40	S-40	S-40	S-39	S-40
Harvest date	-	Dec 27	Oct 27	-	Nov 15	Nov 22	Nov 6	-	Oct 14	Dec 13

Table 2. Sesame injury with selected PRE herbicides applied 3 and 6 days after sesame emergence near Castroville, TX, New Deal, TX, and Shorter, AL in 2016

			Castroville		New Deal		Shorter	
		Appl timing	Days after herbicide application					
	Rate		14	147	9	59	14	28
Herbicide	**Kg ai ha^{-1}**	**DAE**[a]	**%**					
Acetochlor	1.70	3	26	8	12	0	35	14
		6	65	30	17	0	38	13
S-metolachlor	0.72	3	10	0	25	0	10	0
		6	23	0	37	0	21	10
S-metolachlor	1.43	3	40	28	37	0	34	9
		6	33	0	42	0	50	19
S-metolachlor	2.86	3	88	37	72	5	69	40
		6	70	17	68	3	65	40
Dimethenamid-p	0.84	3	37	0	47	3	16	3
		6	42	7	27	0	23	5
Pethoxamid	0.22	3	26	27	35	3	-	-
		6	37	15	33	2	-	-
Bicyclopyrone	0.12	3	58	5	55	5	61	19
		6	78	18	32	0	-	-
Bicyclopyrone	0.24	3	82	42	77	7	95	89
		6	88	77	73	0	94	95
Untreated	-	-	0	0	0	0	0	0
LSD (0.05)			16	34	12	4	11	10

[a] *DAE, days after sesame emergence*

Table 3. Sesame injury with selected pre herbicides applied 3 and 6 days after sesame emergence near Knippa, TX, College Station, TX, New Deal, TX, Pontotoc, Mississippi, and Shorter, AL, in 2017

			Knippa		**College Station**		**New Deal**		**Pontotoc**		**Shorter**	
		Appl timing	**Days after herbicide application**									
	Rate		**14**	**147**	**12**	**28**	**9**	**73**	**7**	**34**	**8**	**50**
Herbicide	**Kg ai ha^{-1}**	**DAE[a]**	%									
Acetochlor	1.70	3	6	8	18	25	40	3	18	49	26	78
		6	14	7	10	14	37	0	2	36	16	32
S-metolachlor	0.72	3	51	17	13	25	37	8	8	24	24	3
		6	13	5	9	10	43	2	3	23	24	18
S-metolachlor	1.43	3	20	17	23	18	47	13	13	31	28	37
		6	21	15	24	13	58	3	2	25	26	18
S-metolachlor	2.86	3	46	13	14	20	73	27	23	48	30	35
		6	63	18	31	16	70	27	15	45	56	53
Dimethenamid-p	0.84	3	25	10	13	11	28	2	13	24	26	2
		6	43	17	31	11	55	3	0	23	14	0
Pethoxamid	0.22	3	15	10	8	13	65	5	18	26	38	30
		6	33	7	10	10	63	5	8	34	55	82
Bicyclopyrone	0.12	3	33	10	25	16	25	2	-	-	34	27
		6	48	5	71	49	85	0	-	-	62	82
Bicyclopyrone	0.24	3	50	10	20	20	65	0	-	-	41	10
		6	61	23	90	84	95	2	-	-	64	97
Pyroxasulfone	0.09	3	6	7	4	8	38	12	23	30	17	2
		6	8	0	29	19	43	4	2	25	16	2
Untreated	-	-	0	0	0	0	0	0	0	0	0	0
LSD (0.05)			15	20	14	17	13	15	8	8	15	39

[a] *DAE, days after sesame emergence*

Table 4. Sesame injury with selected PRE herbicides applied 3and 6 days after sesame emergence near Knippa and New Deal, TX in 2018

			Knippa		**New Deal**	
		Appl timing	**Days after herbicide application (DAA)**			
	Rate		**20**	**33**	**27**	**69**
Herbicide	**Kg ai ha^{-1}**	**DAE**[a]	**%**			
Acetochlor	1.70	3	2	5	15	0
		6	12	13	17	0
S-metolachlor	0.72	3	0	10	13	3
		6	3	2	7	7
S-metolachlor	1.43	3	0	18	27	3
		6	7	5	13	3
S-metolachlor	2.86	3	8	10	65	3
		6	7	13	50	17
Dimethenamid-P	0.84	3	0	0	59	2
		6	2	3	3	0
Pethoxamid	0.22	3	2	3	37	10
		6	8	5	10	8
Pyroxasulfone	0.09	3	5	3	15	0
		6	7	10	15	0
Bicyclopyrone	0.12	3	3	0	17	0
		6	0	7	53	3
Bicyclopyrone	0.24	3	5	8	22	0
		6	22	10	68	6
Untreated	-	-	0	0	0	0
LSD (0.05)			10	13	9	6

[a] *DAE, days after sesame emergence*

Table 5. Sesame yield as influenced by selected PRE herbicides applied 3 and 6 days after sesame emergence in 2016, 2017 and 2018

	Rate	Appl timing	Castroville Knippa TX		New Deal, TX			Shorter, AL	
			2016	2017	2016	2017	2018	2016	2017
Herbicide	**Kg ai ha^{-1}**	**DAE[a]**	**Kg ha^{-1}**						
Acetochlor	1.7	3	1035	559	1300	686	996	543	86
		6	693	637	1216	706	933	490	124
S-metolachlor	0.72	3	1107	588	1271	686	975	643	110
		6	1066	625	1245	735	1019	612	189
S-metolachlor	1.43	3	928	565	1335	541	860	456	193
		6	1090	741	1257	744	1102	494	230
S-metolachlor	2.86	3	649	788	1227	461	881	588	220
		6	874	726	1163	414	823	572	130
Dimethenamid-p	0.84	3	843	562	1241	725	743	649	200
		6	1064	761	1244	667	1098	646	170
Pethoxamid	0.22	3	1012	844	1279	600	784	-	145
		6	1067	757	1265	690	924	-	110
Pyroxasulfone	0.09	3	-	716	-	526	1047	-	260
		6	-	870	-	674	1081	-	208
Bicyclopyrone	0.12	3	931	678	1292	707	857	548	84
		6	747	843	1268	556	1011	827	194
Bicyclopyrone	0.24	3	428	739	1221	722	1078	293	119
		6	306	569	1181	456	784	93	175
Untreated	-	-	1444	508	1208	688	936	510	83
LSD (0.05)			373	257	165	204	242	210	132

[a] *DAE, days after sesame emergence*

Dimethenamid-P injury to sesame also varied across locations and application timings.

Several studies indicate that many vegetable crops have some tolerance to bicyclopyrone. Cucumber (*Cucumis sativas* L. 'Thunder') and zucchini (*Cucurbita pepo* L. 'Noche") tolerated bicyclopyrone applied PRE at 0.056 kg ai ha^{-1} in a low-organic matter (2.23%) and low-cation exchange capacity (11.52 mEq/100 g) soil [44]. Chen et al. [45] reported that bicyclopyrone applied POST severely injured carrot (*Daucus carota* L. subsp. *sativus*), onion (*Allium cepa* L.), radish (*Raphanus sativus* L.) and dill (*Anethum graveolens* L.), but onion showed greater tolerance than the other crops. Bertucci et al. [46] found that bicyclopyrone applied POST at 0.0375 and 0.5 kg ha^{-1} to watermelon (*Citrullus lanatus* L.) resulted in stunting at 3 and 4 WAT, but no injury was observed 6 WAT.

3.2 Sesame Yield.

3.2.1 2016

At Castroville, only *S*-metolachlor at 0.72 kg ai ha^{-1} applied 3 DAE or *S*-metolachlor at 1.43 kg ai ha^{-1} applied 6 DAE did not reduce yield when compared with the untreated check (Table 5). These two treatments caused 10% and 33% early-season sesame injury; however, prior to harvest no injury was noted (Table 2). Bicyclopyrone at 0.24 kg ai ha^{-1} applied either 3 or 6 DAE resulted in 59 to 71% yield reduction when compared with the untreated check. Injury with bicyclopyrone at 0.24 kg ha^{-1} ranged from 82 to 88% early-season and injury was still visible and ranged from 42 (3 DAE) to 77% (6 DAE) when evaluated prior to harvest.

At New Deal, none of the herbicides reduced yield when compared with the untreated check (Table 5) even though early-season sesame injury ranged from 12 to 77% (Table 2). This may be due to optimum watering with subsurface irrigation that was available at this site. At Shorter, only bicyclopyrone at 0.24 kg ai ha^{-1} applied either 3 or 6 DAE resulted in a yield reduction when compared with the untreated check. Sesame injury with bicyclopyrone at this rate remained at least 89% throughout the growing season (Table 2).

3.2.2 2017

At Knippa, none of the herbicides reduced yield when compared with the untreated check (Table 5). In fact, either *S*-metolachlor at 2.86 kg ha^{-1} or pethoxamid at 0.22 kg ha^{-1} applied 3 DAE or pyroxasulfone at 0.09 kg ha^{-1}, and bicyclopyrone at 0.12 kg ha^{-1} applied 6 DAE increased yield 55 to 71% when compared with the untreated check. The *S*-metolachlor and bicyclopyrone rates resulted in at least 46% early-season injury while pethoxamid and pyroxasulfone rates caused 15% or less injury early-season (Table 3).

At New Deal, *S*-metolachlor at 2.86 kg ai ha^{-1} applied either 3 or 6 DAE and bicyclopyrone at 0.24 kg ai ha^{-1} applied 6 DAE resulted in a yield reduction (Table 5). Early-season injury with *S*-metolachlor at 2.86 kg ha^{-1} was at least 70% regardless of application timing and was 27% when evaluated 73 DAA while bicyclopyrone injury with the 6 DAE application was 95% early-season and only 2% at the 73 DAA evaluation (Table 3).

At the Shorter location, yields were extremely low due to severe weed pressure and harvest being delayed until December. The untreated check yielded just 83 kg ha^{-1}. *S*-metolachlor at 1.43 kg ha^{-1} applied 6 DAE, *S*-metolachlor at 2.86 kg ha^{-1} applied 3 DAE, and pyroxasulfone at 0.09 kg ha^{-1} applied 3 DAE produced yields that were over 260% greater than the untreated check (Table 5). *S*-metolachlor at 2.86 kgha^{-1} applied 3 DAE still exhibited 35% injury at the 50 DAA evaluation (Table 3).

3.2.3 2018

At New Deal, no herbicides reduced yield when compared with the untreated check (Table 5). Early-season sesame injury with all herbicides ranged from 3 to 68% with a reduction in injury noted at the 69 DAA evaluation (Table 4).

4. CONCLUSION

Results from this study indicate all the PRE herbicides tested resulted in significant injury to sesame at some location and application timing when applied during the critical time of early sesame plant emergence and none of these herbicides are safe to use at this growth stage on sesame. However, the ability of sesame to recover from significant injury and compensate for injury led to no yield loss with many of these herbicides. With some of the herbicides which caused severe sesame injury, sesame yields were comparable to the untreated check because the plants can compensate for open space and poor growth by adding branches with capsules [1,9,15,16]. 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 [1]. The levels of sesame injury observed are not acceptable by growers and will not allow the use of these herbicides soon after sesame emergence.

Sesame has shown tolerance to many of these PRE herbicides in previous studies. In Ethiopia, metolachlor (1.7 kg ai ha^{-1}) provided good grass and broadleaf control and resulted in a significant yield increase [47]; however, in Australia, Martin [48] reported that metolachlor adequately controlled weeds but caused unacceptable crop injury. Sperry et al. [40] reported no reduction in sesame yield with *S*-metolachlor at 0.69 to 2.78 kg ai ha^{-1} when applied 3 and 6 days after planting (DAP).

Grichar et al. [49] reported that acetochlor applied postemergence-directed did not cause a reduction in sesame yield when compared with the untreated check. In 2010, Monsanto Company launched an encapsulated formulation of acetochlor (Warrant®) [50]. This encapsulated formulation of acetochlor provides greater crop safety in several crops, including soybean, and was designed to give PRE control of weeds as well as assist in POST weed control in acetolactate synthase (ALS) and glyphosate-resistant weeds [51]. The encapsulated formulation requires limited moisture for activation, helps minimize a negative crop response, and also can extend weed control for up to 40 d [51,52].

Godwin et al. [31] reported that pethoxamid caused little or no yield reduction in rice while Bertucci et al. [46] found that bicyclopyrone did not reduce watermelon yield when applied preplant, POST, or postemergence-directed. Studies in other crops have reported some yield reductions when using PRE applications of pyroxasulfone and results can vary by crop [35,53-57]. Potato (*Solanum tuberosum* L.) also showed tolerance to pyroxasulfone at doses up to 0.15 kg ai ha^{-1} with minor yield reduction and quality losses [53]. Pyroxasulfone at 0.125 kg ai ha^{-1} caused unacceptable yield losses in barley (*Hordeum vulgare* L.) as well as durum wheat and oats (*Avena sativa* L.) [58]. Sunflower (*Helianthus annus* L.) has shown acceptable tolerance to pyroxasulfone up to 0.33 kg ai ha^{-1} although injury but not yield loss did occur at locations with heavy precipitation events shortly after application [56]. Eure et al. [54] reported that in peanuts (*Arachis hypogaea* L.) treatments which included pyroxasulfone at 0.12 kg ai ha^{-1} yielded similar to treatments without pyroxasulfone; however, pyroxasulfone applied at 0.24 kg/ha reduced peanut yield by 6%. Neither Prostko et al. [59] or Grichar et al. [60] observed a yield loss following pyroxasulfone applied PRE in peanut.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the esearch was not funded by the producing company rather it was funded by personal efforts of the authors.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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