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## Research Article

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Flumioxazin; fomesafen; halosulfuron; napropamide; oxyfluorfen; pendimethalin; rimsulfuron; *S*-metolachlor; sulfentrazone; cucumber, *Cucumis sativus* L.; summer squash, *Cucurbita pepo* L.

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# Weed control using preemergence herbicides in cucumber and summer squash cultivars

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## Abstract

There is limited information on the crop safety and weed control potential of commercially available PRE herbicides when applied under plastic mulch on various cucumber and summer squash cultivars grown in Florida. Two cucumber field trials were conducted at the Gulf Coast Research and Education Center in Wimauma, FL, in fall 2021 and spring 2022 to determine the effects of halosulfuron, pendimethalin, *S*-metolachlor, sulfentrazone, fomesafen, napropamide, oxyfluorfen, and flumioxazin on crop growth and development, yield, and the control of various weed species in the fields. We conducted this trial using three cucumber cultivars: 'Speedway', 'Dominator', and 'Mongoose'. Two summer squash field trials were conducted simultaneously, evaluating all the mentioned herbicides, except flumioxazin, in addition to rimsulfuron on three summer squash cultivars: 'Spineless Beauty', 'Payload', and 'Everglade'. In the cucumber trials, crop damage varied with cultivar and ranged from 3% to 16% in fall 2021. All herbicides caused ≥10% crop injury, except oxyfluorfen and flumioxazin, at 28 d after transplanting (DATr) in spring 2022. In the summer squash trial, halosulfuron, *S*-metolachor, and flumioxazin were the three most injurious PRE herbicides, causing more than 10% crop injury in seed-grown summer squash, with no effect of PRE herbicides on crop injury in transplant-grown summer squash in fall 2021. In spring 2022, crop injury with PRE herbicides varied with cultivar, where pendimethalin and *S*-metolachlor were consistently the most injurious PRE herbicides, causing 14% to 25% injury at 28 DATr. All PRE herbicides caused some damage to cucumber and summer squash, with limited differences between cultivars and no effect on overall crop yield.

## Introduction

Cucumber is one of the important vegetable crops in Florida, with a harvest area of 8,300 ha and an economic value of US$102 million. Florida also grows 3,885 ha of squash, including both summer and winter varieties, with an economic value of US$45 million (USDA-NASS 2023). Field cucumbers and squash are typically cultivated in Florida on raised beds covered with plastic mulch. They can be grown multiple times a year, excluding the extremely hot months, such as July and August, and the cold months, when there is a risk of frost. Although cucumber can be grown as a primary crop, most field cucumbers are cultivated as a second crop following the termination of tomato, bell pepper, or eggplant on the same plastic mulch. Despite its economic significance, cucumber production in Florida has declined over the past two decades owing to increased imports from Mexico (Huang et al. 2022). Florida grows primarily summer squash (*Cucurbita pepo* L.), including yellow squash (*Cucurbita pepo* L. var. *recticollis*), crookneck (*Cucurbita pepo* L. subsp. *torticollia*), zucchni (*Cucurbita pepo* L. var. *cylindrica*), and scallop types (*Cucurbita pepo* L. var. *clypeata*).

Weeds are one of the major production problems faced by Florida cucurbit growers. Although plastic mulch effectively suppresses weeds on the bed, nutsedge species (*Cyperus* spp.) penetrate the plastic mulch, and broadleaf and grassy weed species emerge and grow in the planting holes, where they compete directly with the crop. Even at low densities (1 to 3 weeds $m^{-2}$), common Florida broadleaf weeds, such as smooth pigweed (*Amaranthus hybridus* L.) and livid amaranth (*Amaranthus lividus* L.), can cause yield reductions of up to 10% in cucumber crops (Berry et al. 2006). Gianessi and Reigner (2007) reported that weeds could lead to yield losses of up to 66% in cucumber fields across the United States, and Samuel (2021) reported yield reductions ranging from 45% to 90% due to weed interference. Even though there is no published information on yield loss due to weeds in summer squash, the foregoing data indicate that cucurbits tend to be susceptible to competition.

Weed management in Florida cucumber and squash fields has traditionally relied on soil fumigation with methyl bromide and hand weeding. After the ban on methyl bromide, alternative fumigants have struggled to provide consistent and effective control (Gilreath et al. 2004; McMillan and Bryan 2001; VanSickle and NaLampang 2002). Herbicides traditionally served as a supplemental weed control tool with soil fumigation in plasticulture production. However, they become the primary weed control method when cucurbits are grown on bare soil, where soil fumigation is not feasible, or when cucurbits are double-cropped with another vegetable in plasticulture production. Approximately 66% of U.S. cucurbit production fields are treated with herbicides, underscoring the role of herbicides in weed control (Gianessi and Reigner 2007).

Almost no PRE herbicides are registered for use under plastic mulch in cucumber and summer squash. Clomazone and clomazone + ethalfluralin are registered for bare ground production but are not typically recommended for sandy soil with low organic matter, which is typical of Florida. Halosulfuron is the only PRE herbicide registered for use under plastic mulch for cucumber but cannot be used with summer squash. A limited number of registered posttransplant or postemergence herbicide options can be sprayed over the top of both crops, with more options available between the rows (Samuel Daramola 2021).

Various published field trials have examined different commercially available PRE herbicides in cucumber (Al-Khatib et al. 1995; Besançon et al. 2020; Derr and Monaco 1982; Trader et al. 2007) and squash (Peachey et al. 2012; Walters and Young 2008). However, these studies did not specifically test the herbicides under plasticulture systems, where they would serve as supplemental weed control tools alongside soil fumigation during bed formation. Many published evaluations of PRE herbicide use in vegetables occurred under low-density polyethylene mluch and not under totally impermeable films (TIFs). There is some evidence that crop injury following the use of PRE herbicides may increase under high-barrier films versus under low-density mulches (Wallace et al. 2012).

It is hypothesized that using PRE herbicides under plastic mulch, alongside standard soil fumigation, could efficiently manage weeds in Florida's cucumber and summer squash cultivation without inducing notable crop injury or yield reduction. Examining the influence of PRE herbicides on diverse, commercially cultivated cucumber and summer squash cultivars could provide Florida growers with alternative tools. Hence this research aimed to evaluate the effect of various PRE herbicides on weed suppression, crop tolerance, growth, and yield across three cucumber and three summer squash cultivars commonly grown in Florida.

## Materials and Method

### *Experimental Design and Treatment Application*

Four field experiments were conducted at the Gulf Coast Research and Education Center in Wimauma, FL (coordinates 27.76°N, 82.22°W), during fall 2021 and spring 2022. Two experiments evaluated PRE herbicides for each of cucumber and summer squash. Fumigation, transplant, and data collection dates were similar for both crops in each season. The experimental site had a Myakka fine sand soil texture, characterized as sandy, siliceous hyperthermic Oxyaqui Alorthod. In fall 2021, the soil had 1.26% organic matter with 92%, 3%, and 5% sand, silt, and clay, respectively. In spring 2022, the soil had 0.7% organic matter with the same sand, silt, and clay ratio as in fall 2021.

Fields were prepared by disking, followed by shaping and compressing the soil to form the raised beds using bed-pressing equipment (Kennco Manufacturing, Ruskin, FL, USA). The beds were spaced 1.5 m apart (center to center), 30.5 cm tall, and 66 cm wide at the top. Each experimental plot consisted of a single raised bed with a linear length of 7.62 m. The beds were fumigated using 1,3-dichloropropene + chloropicrin (Pic-Clor 60, Cardinal Professional Products, Hollister, CA, USA) at 225 kg ha$^{-1}$ with a standard fumigation rig. Dates for fumigation were the same for cucumber and summer squash trials and were July 26 and January 12 for fall 2021 and spring 2022, respectively.

**Table 1.** Trade name, common name, rate used, and manufacturer information of herbicides used in the cucumber and summer squash field experiment.

| Trade name | Common name | Rate | Manufacturer and location |
|---|---|---|---|
| | | g ai ha$^{-1}$ | |
| Sandea® | Halosulfuron | 52 | Canyon Group, Yuma, AZ, USA |
| Prowl® | Pendimethalin | 1,062 | BASF, Research Triangle Park, NC, USA |
| Dual Magnum® | *S*-metolachlor | 1,058 | Syngenta Crop Protection, Greensboro, NC, USA |
| Spartan® | Sulfentrazone | 104 | FMC, Philadelphia, PA, USA |
| Reflex® | Fomesafen | 269 | Syngenta Crop Protection |
| Devrinol® 2-XT | Napropamide | 1,076 | UPL NA, King of Prussia, PA, USA |
| Goal® 2XL | Oxyfluorfen | 269 | Dow AgroSciences, Indianapolis, IN, USA |
| Chateau® | Flumioxazin[a] | 212 | Valent USA, Walnut Creek, CA, USA |
| Solida® | Rimsulfuron[b] | 35 | FMC |

[a]Flumioxazin was used only for cucumber.
[b]Rimsulfuron was used only for summer squash.

The experimental design employed a randomized complete-block design with four replicates and separate experiments for the cucumber and summer squash trials. The treatments were arranged in a 3 × 10 factorial design, with crop cultivar as the first factor and PRE herbicide as the second factor. PRE herbicides were applied at the recommended rates (Table 1) on the bed top using a $CO_2$-pressurized backpack sprayer (Bellspray, Opelousa, LA, USA). The herbicides evaluated in this experiment were selected based on known efficacy on problem weeds in the area and preliminary information suggesting the possibility of crop tolerance. The sprayer was equipped with a single 8002 EVS nozzle (TeeJet® Technologies, Wheaton, IL, USA) at a pressure of 240 kPa and a spray volume of 189 L ha$^{-1}$. Immediately after treatment application, two drip tapes were buried 2.5 cm beneath the soil surface, and the beds were covered with a TIF (1.25 mm thickness, Berry Plastics, Evansville, IN, USA). Three cultivars of slicing cucumber ('Speedway', 'Dominator', and 'Mongoose') and summer squash ('Spineless Beauty', 'Payload', and 'Everglade') were transplanted in a single row with 30-cm plant spacing. Both crops were transplanted on September 2, 2021, and February 23, 2022. Each experimental unit consisted of ten plants. For the summer squash trial in fall 2021, owing to a plant shortage, five plants were directly seeded in the field, and five plants were transplanted following growth in a greenhouse.

### *Data Collection*

Crop injury on cucumber and summer squash plants was visibly assessed on a scale of 0% to 100%, where 0% indicated no crop injury and 100% represented complete crop death. Injury was evaluated based on yellowing, wilting, and plant tissue death or deformation. The evaluations were conducted 7, 14, and 28 d after transplant (DATr). Additionally, vine length for cucumber and crop height for summer squash were measured using a meter stick

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(cm) at 14 and 28 DATr. Crop mortality data were also recorded at the first harvest and collected only in spring 2022 for cucumber. Crop mortality data were collected for both seasons for summer squash. Mortality data are the percentage of plants that did not survive from planting to harvest; however, mortality data for summer squash in fall 2021 were the combination of seedling mortality and lack of seed emergence. In fall 2021, crop injury and plant height were recorded separately for seed-grown and transplant-grown summer squash.

For weed control evaluations, nutsedge species penetrating the plastic mulch were counted across the entire experimental plot at three time points: transplant, mid-season, and first harvest. Yellow nutsedge (*Cyperus esculentus* L.) and purple nutsedge (*Cyperus rotundus* L.) were two nutsedge species recorded in this study. In the fall 2021 trial, the corresponding dates for transplant, mid-season, and first harvest were September 2, September 13, and October 11, respectively. In spring 2022, those dates were February 23, March 28, and April 21, respectively. Additionally, the number of broadleaf and grassy weeds growing in the planting holes was noted at the first harvest.

Cucumber and summer squash were harvested manually, with ten plants harvested per experimental plot. In fall 2021, cucumbers and summer squash were harvested on four different dates: October 1, October 4, October 7, and October 15. In spring 2022, there were six harvesting dates for both crops: April 4, April 7, April 11, April 14, April 18, and April 21. Yields from seed- and transplant-grown summer squash were reported separately in fall 2021.

### Data Analysis

Data were analyzed using the PROC GLIMMIX procedure in SAS (version 9.4; SAS Institute, Cary, NC, USA). PRE herbicide type, cucumber or summer squash cultivar, dates for data collection (for repeated-measures variables), and all interactions containing these three factors were fixed effects in the analysis, whereas block was considered a random effect. The LSMEAN statement was used to determine significant differences between treatment means at the significance level of $P \leq 0.05$. The data from the fall and spring seasons were analyzed separately because they were conducted as separate experiments with different weather conditions (Table 2).

**Table 2.** Monthly weather data for the experimental site (Wimauma, FL) during the trial period, collected from the Florida Automatic Weather Network[a].

| | Fall 2021 | | | Spring 2022 | | |
|---|---|---|---|---|---|---|
| | Aug | Sep | Oct | Feb | Mar | Apr |
| Average air temperature (C) | 27 | 26 | 24 | 18 | 21 | 22 |
| Minimum air temperature (C) | 21 | 19 | 15 | 6 | 3 | 8 |
| Maximum air temperature (C) | 34 | 33 | 34 | 30 | 31 | 31 |
| Average soil temperature (C) | 29 | 28 | 26 | 20 | 23 | 25 |
| Average rainfall (mm) | 117 | 172 | 53 | 17 | 70 | 78 |

[a]Air temperature data were collected 10 m above and soil temperature data were collected 10 cm below the soil surface.

## Results and Discussion

### Cucumber

### Vine Length

In fall 2021, vine length varied among cultivars, with 'Dominator' and 'Mongoose' having significantly longer vine lengths than 'Speedway' (Table 3). None of the PRE herbicides had a significant effect on vine length. These results align with Webster et al. (2003), who evaluated the effect of halosulfuron on cucumber and squash cultivars and found that cucumber cultivars were more tolerant to halosulfuron than squash and that halosulfuron had no effect on cucumber plant biomass or vine length based on the greenhouse studies.

In spring 2022, vine length did not differ between cultivars, whereas the effect of PRE herbicide was significant. Herbicides such as flumioxazin, *S*-metolachlor, sulfentrazone, and fomesafen resulted in a 13% to 28% reduction in vine length compared to the nontreated control (Table 3). The differences between seasons cannot be adequately explained, but increased susceptibility to PRE herbicides has been observed in other crops when the herbicides were applied during the cooler spring temperatures (unpublished data). There was no significant interaction between cultivar and PRE herbicide in both seasons, and as a result, the data are presented for cultivars and PRE herbicides separately. Furthermore, the interaction between the date of vine length measurement, cultivar, and PRE herbicide was insignificant in fall 2021 and spring 2022; therefore injury data were averaged across the two measurement dates (Table 3).

### Crop Injury

In fall 2021, cultivar and PRE herbicide had a significant effect on crop injury. There was a significant PRE Herbicide × Cultivar interaction; thus injury data were presented across all PRE herbicide and cultivar combinations (Table 4). Injury data with all combinations ranged between 5% and 16%, where the highest crop injury was caused by sulfentrazone in cultivar 'Mongoose' and the lowest was caused by oxyfluorfen in cultivar 'Dominator'. Injury data were averaged across three measurement dates because there was no significant interaction between the date of injury measurement, cultivar, and PRE herbicide. This indicates that plants did not recover from herbicide injuries over time.

In spring 2022, there was a significant effect of PRE herbicide, whereas the effect cultivar was not significant at 7 DATr (Table 4). There was a significant PRE Herbicide × Cultivar interaction, and thus injury data were presented across all PRE herbicide and cultivar combinations. Injuries from all cultivar and PRE herbicide combinations were less than 14%. The highest crop injury resulted from flumioxazin in 'Dominator' and *S*-metolachlor in 'Mongoose'. The lowest crop injury resulted from flumioxazin in 'Speedway' and napropamide in 'Dominator' (Table 4). At 14 DATr, cultivars and PRE herbicides had significant effects on crop injury. Cultivar 'Speedway' had a lower injury of 8% compared to 10% injury with 'Dominator' and 'Mongoose' (Table 3). This indicates that cucumber cultivars differ in their susceptibility to the PRE herbicide application. *S*-metolachlor, sulfentrazone, fomesafen, and flumioxazin were the most injurious herbicides, causing 12% to 14% injury. It is noteworthy that flumioxazin is the only herbicide registered for use in cucumber to control row-middle weeds out of all the herbicides used in this experiment. At 28 DATr, there was a significant effect of PRE herbicide, whereas the effect of cultivar was not significant. Pendimethalin and *S*-metolachlor were the two most injurious PRE herbicides, causing 32% and 24% injury, respectively (Table 3). *S*-metolachlor, which had previously been shown to induce 13% and 36% crop stunting in the cucumber cultivar 'Python' when applied as a PRE herbicide at 700 g ai $ha^{-1}$ and 1,400 g ai $ha^{-1}$, respectively, consistently caused the highest crop stunting across all measurement dates,

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**Table 3.** Effect of cultivar and PRE herbicide on cucumber growth and yield in the field trial at Gulf Coast Research and Education Center in Wimauma, FL, in fall 2021 and spring 2022[a,b,c].

| | Vine length | | Injury, spring 2022 | | | Yield | |
|---|---|---|---|---|---|---|---|
| | Fall 2021 | Spring 2022 | 14 DATr | 28 DATr | Mortality, spring 2022 | Fall 2021[d] | Spring 2022[e] |
| Cultivar | cm | | % | | % | $kg\ ha^{-1}$ | |
| Speedway | 47 a | 26 | 8 a | 14 | 8 a | 19,627 b | 14,547 b |
| Dominator | 53 b | 25 | 10 b | 14 | 24 b | 15,087 a | 15,866 a |
| Mongoose | 53 b | 28 | 10 b | 13 | 34 c | 14,910 a | 21,973 a |
| PRE herbicide | | | | | | | |
| Nontreated control | 51 | 29 b | 0 a | 0 a | 22 | 17,776 | 23,249 |
| Halosulfuron | 51 | 28 b | 8 b | 10 b | 23 | 14,999 | 18,571 |
| Pendimethalin | 55 | 31 b | 7 b | 32 c | 34 | 17,014 | 21,415 |
| *S*-metolachlor | 47 | 24 a | 13 c | 24 c | 20 | 15,343 | 12,639 |
| Sulfentrazone | 51 | 24 a | 12 c | 18 bc | 18 | 17,055 | 14,595 |
| Fomesafen | 51 | 25 a | 12 c | 15 bc | 23 | 16,593 | 20,673 |
| Napropamide | 50 | 27 b | 9 b | 12 b | 13 | 15,927 | 14,758 |
| Oxyfluorfen | 54 | 30 b | 8 b | 7 b | 21 | 17,598 | 16,095 |
| Flumioxazin | 51 | 21 a | 14 c | 7 b | 23 | 16,566 | 15,165 |
| Cultivar | 0.003 | 0.083 | 0.035 | 0.830 | <0.001 | <0.001 | 0.005 |
| PRE herbicide | 0.481 | <0.001 | <0.001 | <0.001 | 0.407 | 0.763 | 0.129 |
| Cultivar × PRE Herbicide | 0.951 | 0.497 | 0.688 | 0.188 | 0.870 | 0.595 | 0.827 |

[a]Abbreviation: DATr, days after transplant.
[b]Means within the same column followed by the same letter are statistically similar at the 0.05 significance level based on a least square means multiple comparison test.
[c]Vine length is the average of vine length at two measurement dates because there was no significant interaction ($P > 0.05$) between cultivar, PRE herbicide, and date of vine length measurement. Mortality refers to the number of plants that did not survive from planting to harvesting. Mortality data were collected once at the first harvest and only in spring 2022.
[d]Sum of four harvests.
[e]Sum of six harvests.

(Besançon et al. 2020). In contrast, Peachey et al. (2012) reported less than 5% crop injury in cucumber cultivar 'Speedway', even with the high-rate (2,100 g ai $ha^{-1}$) application of *S*-metolachlor. Besançon et al. (2020) speculated that the high clay (20%) and organic matter (2.4%) contents may have increased *S*-metolachlor adsorption to the soil particles, resulting in reduced herbicide uptake by plants and reduced crop injury in the study by Peachey et al. (2012). The field sites used in our experiment and in Besançon et al. (2020) were similar, with high sand (>90%) and low organic matter (<2%) contents. Furthermore, Peachey et al. (2012) found that cucumber lacks tolerance to other PRE herbicides, with injury ranging from 18% to 39% at 14 DATr and from 6% to 25% at 28 DATr with fomesafen at 350 g ai $ha^{-1}$. These injury percentages increased from 24% to 44% at 14 DATr and from 40% to 59% at 28 DATr with a higher rate of fomesafen at 700 g ai $ha^{-1}$. Fomesafen applied at 269 g ai $ha^{-1}$ caused only 15% injury at 28 DATr in our studies. Because there was no significant ($P < 0.05$) interaction between cultivar and PRE herbicide with injury data at 14 DATr and 28 DATr, data were separately averaged for cultivars and PRE herbicides. Furthermore, owing to significant interaction between cultivars, PRE herbicides, and date of injury measurements, injury data were presented by date of injury measurement for spring 2022 (Table 3).

### Mortality

In spring 2022, there was a significant effect of cultivar, whereas the effect of PRE herbicide was not significant (Table 3). No significant interaction was observed between herbicide and cucumber cultivar; therefore mortality data were separately averaged across the cultivar and PRE herbicide. Cultivar 'Speedway' had the lowest mortality (8%) among other cultivars 'Dominator' and 'Mongoose'. The herbicide had no significant effect on mortality, but it is worth noting that plots, where pendimethalin was applied, had a numerically higher mortality rate, at 34%.

### Yield

In both seasons, cultivars had a significant effect, whereas the effect of PRE herbicide was not significant. No significant interaction was observed between PRE herbicide and cucumber cultivar, so the yield data were averaged across the cultivars and herbicides (Table 3). Even though there was a significant cultivar effect, the yield from each cultivar was inconsistent. For example, 'Speedway' had the highest yields in fall 2021 but the lowest in spring 2022. This suggests that overall yield likely varies with environmental conditions. Most important, the use of a PRE herbicide in the absence of weed pressure had no effect on yield, despite herbicide damage early in the season. Therefore the use of a PRE herbicide may be beneficial in fields with a history of high weed density. Previous field trials have shown a significant increase in cucumber fruit yield and count with the use of PRE herbicides like *S*-metolachlor and bensulide (Besançon et al. 2020). However, herbicide selection is critical, as Peachey et al. (2012) found that fomesafen at 280 g ai $ha^{-1}$ resulted in little fruit in two out of three experiments with the 'Speedway' cultivar. Further research is needed to evaluate the herbicides that caused the least damage in this trial in fields with high weed densities. This would enable us to determine if yield increases associated with weed control are adequate to compensate for the added management costs.

## Summer Squash

### Plant Height

None of the PRE herbicides appears to adversely affect the growth of seed-grown summer squash (Table 5), although, in fall 2021, there was a significant effect of cultivar, PRE herbicide, and interaction between cultivar and PRE herbicide on plant height of seed-grown summer squash (Table 5). Because there was a significant interaction between cultivar and PRE herbicide, plant height data were presented with all cultivar and PRE herbicide combinations. There was no significant effect of cultivar, PRE

**Table 4.** Effect of cultivar and PRE herbicide on cucumber injury in the field trial at Gulf Coast Research and Education in Wimuama, FL, in fall 2021 and spring 2022[a,b,c].

| Cultivar | PRE herbicide | Injury | |
|---|---|---|---|
| | | Fall 2021, average | Spring 2022, 7 DATr |
| | | % | |
| Speedway | Nontreated control | 0 a | 0 a |
| | Halosulfuron | 5 a | 4 ab |
| | Pendimethalin | 6 a | 5 ab |
| | *S*-metolachlor | 10 b | 6 ab |
| | Sulfentrazone | 5 a | 5 ab |
| | Fomesafen | 9 a | 9 ab |
| | Napropamide | 10 b | 8 ab |
| | Oxyfluorfen | 6 a | 5 ab |
| | Flumioxazin | 8 a | 3 ab |
| Dominator | Nontreated control | 0 a | 0 ab |
| | Halosulfuron | 11 b | 5 ab |
| | Pendimethalin | 7 a | 3 ab |
| | *S*-metolachlor | 7 a | 8 ab |
| | Sulfentrazone | 6 a | 10 b |
| | Fomesafen | 6 a | 8 ab |
| | Napropamide | 10 a | 3 ab |
| | Oxyfluorfen | 3 a | 8 ab |
| | Flumioxazin | 13 b | 13 b |
| Mongoose | Nontreated control | 0 a | 0 a |
| | Halosulfuron | 11 b | 8 ab |
| | Pendimethalin | 11 b | 11 b |
| | *S*-metolachlor | 9 b | 13 b |
| | Sulfentrazone | 16 b | 0 ab |
| | Fomesafen | 8 a | 10 b |
| | Napropamide | 12 b | 5 ab |
| | Oxyfluorfen | 11 b | 10 b |
| | Flumioxazin | 10 a | 8 ab |
| Cultivar | | 0.005 | 0.120 |
| PRE herbicide | | <0.001 | 0.003 |
| Cultivar × PRE Herbicide | | 0.045 | 0.014 |

[a]Abbreviation: DATr, days after transplant.
[b]Means within the same column followed by the same letter are statistically similar at the 0.05 significance level based on a least square means multiple comparison test.
[c]Average injury is the mean of injury data collected at three measurement dates because there was no significant interaction (P > 0.05) between cultivar, PRE herbicide, and date of injury measurement.

**Table 5.** Effect of cultivar and PRE herbicides on summer squash growth in the field trial at Gulf Coast Research and Education Center in Wimauma, FL, in fall 2021 and spring 2022[a,b,c].

| Cultivar | PRE herbicide | Plant height, fall 2021 (seed) | Injury, spring 2022, 28 DATr |
|---|---|---|---|
| | | cm | % |
| Spineless Beauty | Nontreated control | 28 b | 0 a |
| | Halosulfuron | 25 ab | 0 a |
| | Pendimethalin | 24 ab | 18 c |
| | *S*-metolachlor | 26 ab | 14 c |
| | Sulfentrazone | 27 b | 0 a |
| | Fomesafen | 30 b | 0 a |
| | Napropamide | 28 b | 8 ab |
| | Oxyfluorfen | 33 b | 0 a |
| | Flumioxazin | 31 b | 8 ab |
| Payload | Nontreated control | 30 b | 0 a |
| | Halosulfuron | 22 ab | 0 a |
| | Pendimethalin | 26 ab | 21 c |
| | *S*-metolachlor | 28 ab | 25 c |
| | Sulfentrazone | 33 b | 0 a |
| | Fomesafen | 29 b | 0 a |
| | Napropamide | 30 b | 8 ab |
| | Oxyfluorfen | 29 ab | 0 a |
| | Flumioxazin | 27 b | 0 a |
| Everglade | Nontreated control | 27 ab | 0 a |
| | Halosulfuron | 20 a | 0 a |
| | Pendimethalin | 30 b | 24 c |
| | *S*-metolachlor | 28 b | 25 c |
| | Sulfentrazone | 26 ab | 0 a |
| | Fomesafen | 27 ab | 0 a |
| | Napropamide | 27 ab | 10 b |
| | Oxyfluorfen | 29 b | 0 a |
| | Flumioxazin | 23 ab | 5 ab |
| Cultivar | | 0.028 | 0.097 |
| PRE herbicide | | <0.001 | <0.001 |
| Cultivar × PRE Herbicide | | 0.044 | 0.016 |

[a]Abbreviation: DATr, days after transplant.
[b]Means within the same column followed by the same letter are statistically similar at the 0.05 significance level based on a least square means multiple comparison test.
[c]Plant height is the average of two plant heights at two measurement dates because there was no significant interaction (P > 0.05) between cultivar, PRE herbicide, and date of plant height measurement.

herbicide, and interaction between cultivar and PRE herbicide on plant height for transplant-grown summer squash (Table 6). Plant height data were averaged separately for cultivar and PRE herbicide due to the lack of significant interaction (Table 6). Because no significant interaction (P > 0.05) was observed between the cultivar, PRE herbicide, and date of plant height measurement, plant height data were averaged across two measurement dates for both seed- and transplant-grown summer squash.

In spring 2022, there were significant effects of cultivar and PRE herbicide on plant height. Cultivar 'Payload' was the tallest cultivar out of the three cultivars evaluated. Flumioxazin and halosulfuron significantly reduced plant height to 40% and 20%, respectively, compared to the nontreated control (Table 6). Plant height data were averaged separately for cultivar and PRE herbicide due to lack of significant interaction between cultivar and PRE herbicide. Because no significant interaction was observed between the cultivar, PRE herbicide, and date of plant height measurement, plant height data were averaged across two measurement dates.

### Crop Injury

In fall 2021, there was a significant effect of PRE herbicide on crop injury of seed-grown summer squash, whereas the PRE herbicide effect was nonsignificant for crop injury of transplant-grown summer squash. Halosulfuron, *S*-metolachor, and flumioxazin were the three most injurious PRE herbicides, causing more than 10% crop injury in seed-grown summer squash (Table 6). Our results are different from those of Randell et al. (2020), in which halosulfuron at 80 g ai $ha^{-1}$ resulted in 2% to 3% crop injury in summer squash cultivar 'Enterprise' when applied 14 to 21 d before planting (DBP). However, the injury increased to 40% if halosulfuron was applied 1 DBP. PRE herbicides in our study were applied 40 DBP, along with soil fumigants. In transplant-grown summer squash, all injuries were <4% with all PRE herbicides. Cultivar did not have an effect on crop injury. There was no significant (P > 0.05) interaction between cultivar and PRE herbicide; therefore data were averaged across cultivar and PRE herbicide separately for both seed- and transplant-grown summer squash. In addition, injury data were averaged for two injury data measurement dates because of no significant interaction between cultivar, PRE herbicide, and date of injury measurement.

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**Table 6.** Effect of cultivar and PRE herbicide on summer squash growth and yield in the field trial at Gulf Coast Research and Education Center in Wimauma, FL, in fall 2021 and spring 2022[a,b,c].

| | Plant height | | Injury | | | | | | Yield | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fall 2021 | Spring 2022 | Fall 2021 | | Spring 2022 | | Mortality | | Fall 2021[d] | Spring 2022[e] | |
| | Transpl. | | Seed | Transpl. | 7 DATr | 14 DATr | Fall 2021 | Spring 2022 | Seed | Transpl. | |
| | cm | | % | | | | | | kg ha$^{-1}$ | | |
| Cultivar | | | | | | | | | | | |
| Spineless Beauty | 40 | 18 a | 7 | 2 | 2 | 12 b | 25 | 6 | 15,519 | 16,011 | 17,885 |
| Payload | 40 | 20 b | 7 | 1 | 0 | 8 a | 30 | 2 | 17,308 | 14,380 | 14,054 |
| Everglade | 40 | 19 ab | 9 | 1 | 1 | 10 b | 27 | 4 | 17,841 | 14,991 | 14,226 |
| PRE herbicide | | | | | | | | | | | |
| Nontreated control | 41 | 21 b | 2 a | 0 | 0 | 0 a | 33 | 5 | 22,789 | 16,369 | 18,573 |
| Halosulfuron | 38 | 17 a | 13 b | 2 | 1 | 9 b | 20 | 8 | 16,414 | 12,683 | 13,649 |
| Pendimethalin | 40 | 22 b | 7 b | 1 | 1 | 10 b | 24 | 3 | 14,098 | 12,831 | 19,676 |
| *S*-metolachlor | 41 | 19 b | 12 b | 1 | 1 | 10 b | 39 | 3 | 10,169 | 15,031 | 18,951 |
| Sulfentrazone | 40 | 19 b | 7 b | 3 | 1 | 11 b | 33 | 3 | 18,395 | 13,393 | 13,609 |
| Fomesafen | 41 | 19 b | 4 a | 0 | 1 | 12 b | 29 | 1 | 17,198 | 14,870 | 12,357 |
| Napropamide | 40 | 18 b | 7 b | 3 | 1 | 9 b | 19 | 2 | 19,065 | 15,552 | 12,053 |
| Oxyfluorfen | 42 | 20 b | 6 a | 2 | 2 | 12 b | 24 | 2 | 10,622 | 17,256 | 18,959 |
| Flumioxazin | 41 | 15 a | 11 b | 1 | 2 | 18 c | 25 | 8 | 13,254 | 18,161 | 10,667 |
| Cultivar | 0.895 | <0.001 | 0.427 | 0.926 | 0.005 | <0.001 | 0.794 | 0.244 | 0.391 | 0.578 | 0.321 |
| PRE herbicide | 0.382 | <0.001 | <0.001 | 0.188 | 0.873 | <0.001 | 0.749 | 0.427 | 0.784 | 0.555 | 0.055 |
| Cultivar × PRE Herbicide | 0.108 | 0.438 | 0.076 | 0.834 | 0.958 | 0.198 | 0.946 | 0.500 | 0.571 | 0.377 | 0.940 |

[a]Abbreviations: DATr, days after transplant; transpl., transplant.
[b]Means within the same column followed by the same letter are statistically similar at the 0.05 significance level based on a least square means multiple comparison test.
[c]Plant height is the average of two plant heights at two measurement dates because there was no significant interaction ($P > 0.05$) between cultivar, PRE herbicide, and date of plant height measurement. Mortality refers to the number of plants that did not survive from planting to harvesting in spring 2022; however, mortality data in fall 2021 were the combination of seedling mortality and lack of seed emergence.
[d]Sum of four harvests.
[e]Sum of six harvests.

In spring 2022, a significant interaction was observed between the cultivar, PRE herbicide, and date of injury measurement; therefore the injury data were presented by the date of injury measurement (Table 6). There was no significant effect of cultivar and herbicide on crop injury at 7 DATr. At 14 DATr, PRE herbicide caused significant injury ranging from 9% to 12%, except flumioxazin, which caused 18% crop injury. Cultivar 'Payload' was significantly more tolerant to PRE herbicide, with an average of 8% injury, compared to 'Spineless Beauty' and 'Everglade'. As there was no significant interaction between cultivar and PRE herbicide, injury data were separately averaged for the cultivar and PRE herbicide. There was a significant effect of cultivar and PRE herbicide on crop injury at 28 DATr. Injury data were presented in all cultivar and PRE herbicide combinations because of significant interactions between these two factors. Pendimethalin and *S*-metolachlor consistently had the highest crop injury, from 18% to 14% and from 14% to 25%, respectively, in all three cultivars; similar results were observed in the cucumber trial in spring 2022 (Table 6). Besançon et al. (2020) reported *S*-metolachlor as a suitable PRE herbicide for summer squash 'Gold Prize', in which it caused 1% to 4% crop injury when applied at 1,400 g ai ha$^{-1}$, which might be an acceptable level of crop injury for cucumber growers, unlike the 14% to 25% crop injury in our studies. Besançon et al. also reported less than 17% crop stunting 4 wk after planting when *S*-metolachlor was applied at 1,400 g ai ha$^{-1}$. In addition, Grey et al. (2000) observed severe stunting of 31% and 68% in squash varieties like 'Dixie' and 'Senator' when pendimethalin was applied at a rate of 80 g ai ha$^{-1}$ and 560 g ai ha$^{-1}$, respectively, as a PRE herbicide in one of the two seasons studied.

Halosulfuron, sulfentrazone, fomesafen, and oxyfluorfen were four herbicides that caused no crop injury by 28 DATr (Table 5). This agrees with the results of Randell et al. (2020), in which halosulfuron appeared to be a safe herbicide for summer squash, in disagreement with our results from fall 2021. This result also supports that halosulfuron is the only tested herbicide registered for summer squash.

### Crop Mortality

There was no significant effect of cultivar and PRE herbicide on crop mortality in either season. Additionally, there was no interaction between cultivar and PRE herbicide; therefore crop mortality data were averaged across cultivar and PRE herbicide separately in both seasons. There was relatively higher crop mortality, in the range of 19% to 39%, in fall 2021, whereas all treatments had a crop mortality of <10% for all treatments in spring 2022 (Table 4). The high mortality rate in the fall season might be attributed to higher temperatures at the time of planting compared to the spring season (Table 6).

### Yield

There was no significant effect of cultivar and PRE herbicide on crop yield in either season. Additionally, there was no interaction between cultivar and PRE herbicide; therefore yield data were separately averaged across cultivar and PRE herbicide in both seasons (Table 6). Studies by Randell et al. (2020) reported 0% and 10% to 40% yield loss with the use of halosulfuron at 80 g ai ha$^{-1}$ when applied 21 DBP and 1 to 14 DBP, respectively. Furthermore, Randell et al. reported a 4% yield loss with halosulfuron at

**Table 7.** Effect of cultivar and PRE herbicide on nutsedge count in the cucumber and summer squash field trial at Gulf Coast Research and Education Center in Wimauma, FL, in fall 2021[a].

| | Average nutsedge | |
|---|---|---|
| | Cucumber trial | Summer squash trial |
| | ——— nutsedge m$^{-2}$ ——— | |
| Cucumber cultivar | | |
| Speedway | 1 | — |
| Dominator | 2 | — |
| Mongoose | 2 | — |
| Summer squash cultivar | | |
| Spineless Beauty | — | 3 |
| Payload | — | 4 |
| Everglade | — | 4 |
| PRE herbicide | | |
| Nontreated control | 4 | 6 |
| Halosulfuron | 2 | 1 |
| Pendimethalin | 1 | 5 |
| *S*-metolachlor | 1 | 4 |
| Sulfentrazone | 1 | 3 |
| Fomesafen | 1 | 3 |
| Napropamide | 2 | 4 |
| Oxyfluorfen | 2 | 3 |
| Flumioxazin | 1 | 3 |
| Cultivar | 0.311 | 0.376 |
| PRE herbicide | 0.158 | 0.263 |
| Cultivar × PRE Herbicide | 0.662 | 0.448 |

[a]Average nutsedge is the mean of nutsedge data collected at three nutsedge measurement dates because there was no significant interaction (P > 0.05) between cultivar, PRE herbicide, and date of nutsedge measurement. Yellow nutsedge and purple nutsedge were two nutsedge species recorded in this study.

**Table 8.** Effect of cultivar and PRE herbicide on nutsedge count in the cucumber field trial at the Gulf Coast Research and Education Center in Wimauma, FL, in spring 2022[a,b].

| Cultivar | PRE herbicide | Nutsedge |
|---|---|---|
| | | nutsedge m$^{-2}$ |
| Speedway | Nontreated control | 1 b |
| | Halosulfuron | 0 b |
| | Pendimethalin | 0 b |
| | *S*-metolachlor | 0 b |
| | Sulfentrazone | 0 b |
| | Fomesafen | 0 b |
| | Napropamide | 2 b |
| | Oxyfluorfen | 1 b |
| | Flumioxazin | 0 b |
| Dominator | Nontreated control | 0 b |
| | Halosulfuron | 0 b |
| | Pendimethalin | 2 b |
| | *S*-metolachlor | 0 b |
| | Sulfentrazone | 1 b |
| | Fomesafen | 0 b |
| | Napropamide | 0 b |
| | Oxyfluorfen | 1 b |
| | Flumioxazin | 0 b |
| Mongoose | Nontreated control | 0 b |
| | Halosulfuron | 4 a |
| | Pendimethalin | 1 b |
| | *S*-metolachlor | 0 b |
| | Sulfentrazone | 1 b |
| | Fomesafen | 0 b |
| | Napropamide | 3 a |
| | Oxyfluorfen | 1 b |
| | Flumioxazin | 0 b |
| Cultivar | | 0.008 |
| PRE herbicide | | 0.027 |
| Cultivar × PRE Herbicide | | 0.014 |

[a]Means within the same column followed by the same letter are statistically similar at the 0.05 significance level based on a least square means multiple comparison test.
[b]Average nutsedge is the mean of nutsedge data collected at three nutsedge measurement dates because there was no significant interaction (P > 0.05) between cultivar, PRE herbicide, and date of nutsedge measurement. Yellow nutsedge and purple nutsedge were two nutsedge species recorded in this study.

160 g ai ha$^{-1}$ when applied 21 DBP. Halosulfuron caused a 25% to 27% yield reduction in our studies, even though it was not statistically significant.

### Nutsedge Control

In the cucumber trial of fall 2021, there was no significant effect of cultivar and PRE herbicide on nutsedge density (Table 7). There was no significant interaction between cultivar, PRE herbicide, and date of nutsedge data collection; therefore nutsedge data were averaged across the three measurement dates. Furthermore, nutsedge data were separately averaged for cultivar and PRE herbicide because of no significant interaction. It is worth noting that although PRE herbicides did not significantly reduce nutsedge density, all PRE herbicides tended to suppress the nutsedge population by 25% to 40% compared to the nontreated control (Table 7).

In the cucumber trial of spring 2022, there was a significant effect of cultivar and PRE herbicide on nutsedge density (Table 8). There was no significant interaction between cultivar, PRE herbicide, and date of nutsedge data collection; therefore nutsedge data were averaged across the three measurement dates. Furthermore, nutsedge data were presented across all cultivar and PRE herbicide combinations because of a significant interaction between cultivar and PRE herbicide. In spring 2022, the overall weed population was lower compared to fall 2021. The highest nutsedge population was of 4 nutsedge m$^{-2}$ in the plots where halosulfuron was applied to the 'Mongoose' cultivar (Table 8).

In the squash trials, there was no significant effect of cultivar and PRE herbicide on the nutsedge population (Table 7). The interaction between cultivar, PRE herbicide, and date of nutsedge data collection was not significant; therefore nutsedge populations were averaged across the three measurement dates. Nutsedge data were averaged for cultivar and PRE herbicide separately because of no significant interaction between cultivar and PRE herbicide. Halosulfuron was the most effective PRE herbicide, causing 83% suppression of nutsedge, even though it was not statistically significant (Table 7). In spring 2022, nutsedge counts were minimal; therefore these data were excluded from the analysis.

Previous field trials have evaluated the herbicidal efficacy of PRE herbicides used in our study. *S*-metolachlor at 225 g ai ha$^{-1}$ was able to provide up to 72% nutsedge control when applied as PRE herbicide in a bell pepper–cucumber double-cropping system in Florida (Gilreath et al. 2004). The efficacies of *S*-metolachlor against broadleaf and grassy weeds at 700 g ai ha$^{-1}$ and against purple nutsedge at 1,366 g ai ha$^{-1}$ have been demonstrated in various field trials (Besançon et al. 2020; Yu et al. 2020). *S*-metolachlor at 2,250 g ai ha$^{-1}$ can provide nutsedge control as high as 60% with no interaction with fumigants applied at the time of bed formation (Gilreath et al. 2004). Fomesafen at 710 or 1,070 g ai ha$^{-1}$ is another effective herbicide that has shown similar herbicidal efficacy as *S*-metolachlor at 280 or 420 g ai ha$^{-1}$ for nutsedge control in Florida plasticulture fields (Miller and Dittmar 2014). However, Boyd (2015) reported that *S*-metolachlor applied at 1,070 g ai ha$^{-1}$ or fomesafen applied at 420 g ai ha$^{-1}$ on the bed top before laying the plastic was not an effective herbicide for reducing nutsedge populations compared to the nontreated

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control. In contrast, other herbicides, such as oxyfluorfen and halosulfuron, provided consistently better nutsedge control than the nontreated control. Flumioxazin has shown up to 85% yellow nutsedge control when applied as PRE herbicide at 108 g ai ha$^{-1}$ in sweet potato [*Ipomoea batatas* (L.) Lam.], which is half the rate used in our experiment (Kelly et al. 2006). Further studies are needed to clarify these varying results.

### Weed Control at Planting Hole

The presence of broadleaf and grassy weeds at the planting holes was minimal in all trials in all experimental plots, with most of the weed count being zero. Therefore the weed data at the planting hole were excluded from the data analysis.

## Practical Implications

All PRE herbicides tested caused varying levels of crop injury, but there were no adverse effects on crop yield. None of the PRE herbicides controlled nutsedge. Some of the PRE herbicides appeared to suppress nutsedge, but the differences were not significant in this study. There were cultivar effects and significant interactions between cultivar and PRE herbicide in some instances, but overall, the differences in cultivar susceptibility to PRE herbicides tended to be small. Therefore crop cultivar selection cannot be used as a method to avoid herbicide injury. Given that none of the PRE herbicides negatively impacted crop yield, we recommend further evaluations in locations with high weed densities to determine if weed control could lead to improved yields even if early-season crop damage occurs.

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