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Yellow nutsedge (*Cyperus esculentus*) tuber production and viability in response to postemergence herbicides

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Research Article

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Abstract

Yellow nutsedge (*Cyperus esculentus* L.) is one of the most problematic weeds in turfgrass due to its fast growth rate and high tuber production. Effective long-term control relies on translocation of systemic herbicides to underground tubers. Two identical trials were conducted simultaneously in separate greenhouses to evaluate the effect of several acetolactate synthase (ALS)- and protoporphyrinogen oxidase (PPO)-inhibiting postemergence herbicides on *C. esculentus* tuber production and viability. Seven tubers were planted into 1-L pots, and plants were allowed to mature for 6 wk before trial initiation. Treatments included pyrimisulfan at 73 g ai ha^{-1} once or 49 g ai ha^{-1} twice, imazosulfuron at 736 g ai ha^{-1} once or 420 g ai ha^{-1} twice, carfentrazone-ethyl + sulfentrazone at 22 + 198 g ai ha^{-1} once or 14 + 127 g ai ha^{-1} twice, halosulfuron at 70 g ai ha^{-1} once or 35 g ai ha^{-1} twice, and a nontreated control. Sequential applications were made 3 wk after initial treatment (WAIT) for both trials. Both single and sequential applications of carfentrazone-ethyl + sulfentrazone exhibited the quickest control (80% to 83% 4 WAIT). Two applications of imazosulfuron resulted in the greatest reduction in tuber number (81%) and tuber dry biomass (85%), while one application of carfentrazone-ethyl + sulfentrazone resulted in the greatest reduction in shoot biomass (71%). The viability of tubers that were recovered from each pot was reduced 48% to 70%, with the greatest reduction in response to carfentrazone-ethyl + sulfentrazone. Although two applications of pyrimisulfan only resulted in tuber number and shoot biomass reductions of 66% and 38%, respectively, tuber dry biomass reduction was 80%. Therefore, pyrimisulfan, imazosulfuron, halosulfuron, and carfentrazone-ethyl + sulfentrazone are all viable options for long-term *C. esculentus* control in turfgrass.

Introduction

Yellow nutsedge (*Cyperus esculentus* L.) has been described as one of the most troublesome perennial weeds in numerous crops worldwide (Henry et al. 2021; Holm et al. 1991). While infestations often originate in wet, poorly drained areas, *C. esculentus* displays remarkable adaptability to thrive in many different soil types and environmental conditions (Henry et al. 2021; Lowe et al. 2000). This adaptability, along with the rapid production of rhizomes and tubers, enables it to outcompete desirable turfgrass for resources and lowers the aesthetic quality and playability of golf courses and athletic fields (Lowe et al. 2000). Seed production of *C. esculentus* in managed landscapes, such as golf courses, athletic fields, and residential lawns, is often limited due to the removal of seedheads during mowing practices. Any remaining seeds that are produced often have low viability, rendering population recruitment through germination and emergence of seeds insignificant. Therefore, *C. esculentus* primarily reproduces through the formation of tubers (Lowe et al. 2000; Stoller and Sweet 1987). A single tuber can produce 1,900 plants and 6,900 tubers within a single year, with tubers remaining viable in the soil for more than 3.5 yr depending on burial depth, temperature, and moisture (Tumbleson and Kommedahl 1962). Tuber dormancy prevents them from sprouting at the same time and helps to maintain a reservoir of new plants in the soil for multiple years (Stoller and Sweet 1987).

Long-term *C. esculentus* control traditionally incorporated cultural, mechanical, and chemical methods focused on reducing tuber development and viability. Most importantly, mowing height and frequency have been shown to affect the lateral spread and tuber production of *C. esculentus*. Summerlin et al. (2000) reported that mowing three times a week at 1.3 cm reduced the lateral spread of *C. esculentus* shoots 78% to 84%, while mowing once a week at 3.8 cm reduced lateral spread 62% to 67%. Additionally, both mowing height and frequency combinations inhibited new tuber production. Li et al. (2019) reported that weekly mowing at 7.6 cm reduced *C. esculentus* new tuber production 63% and rhizome dry biomass 55%.

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De Ryck et al. (2023) identified that mowing twice per week at 2 cm effectively reduced *C. esculentus* patches in field margins. Although mowing has been observed to suppress *C. esculentus* growth and spread, elimination of established plants requires additional control methods, likely in the form of herbicides.

Some postemergence contact herbicides effectively suppress or desiccate *C. esculentus* foliage but fail to provide long-term control. For example, postemergence applications of imazaquin and MSMA are often used to control *Cyperus* species; however, regrowth is often observed. Coats et al. (1987) reported up to a 65% reduction in purple nutsedge (*Cyperus rotundus* L.) control efficacy between 5 and 9 wk after a single application of imazaquin plus MSMA. The ability of *C. esculentus* and other sedge species to regenerate from carbohydrate reserves present within tubers following defoliation often requires sequential applications of these herbicides to achieve >90% control (Blum et al. 2000; Kopec et al. 1991). Therefore, this suggests that postemergence herbicide translocation to vegetative reproductive structures is essential to achieve long-term control.

Several systemic postemergence herbicides are labeled for *C. esculentus* control in turfgrass. Imazosulfuron is a member of the sulfonylurea family of acetolactate synthase (ALS)- inhibiting herbicides that controls various sedge and broadleaf weed species both preemergence and postemergence in turfgrass (Anonymous 2020). Felix and Boydston (2010) observed 92% to 99% control of *C. esculentus* with imazosulfuron applied preemergence and postemergence at 0.34 to 0.56 kg ha^{-1} 42 d after initial treatment. Additionally, imazosulfuron applied postemergence has been shown to translocate from leaf tissue to belowground rhizomes and tubers of mother and daughter *C. rotundus* plants (Ikeda et al. 1999). Halosulfuron, another sulfonylurea herbicide, is labeled for postemergence *C. esculentus* control in both warm- and cool-season turfgrasses (Blum et al. 2000). Li et al. (2019) observed >95% control of *C. esculentus* in perennial ryegrass (*Lolium perenne* L.) with sequential applications of halosulfuron at 3-wk intervals. Root and rhizome dry biomass, number of new tubers, and new tuber fresh weight were also reduced (Li et al. 2021). Additionally, Blum et al. (2000) demonstrated that both halosulfuron and sulfentrazone applied postemergence effectively controlled *C. esculentus* (>80% control) in both the presence and absence of bermudagrass [*Cynodon dactylon* (L.) Pers.]. Unfortunately, confirmed cases of resistance to halosulfuron and other ALS-inhibiting herbicides have been reported for *C. esculentus* populations, so alternating herbicides with different modes of action is recommended (Tehranchian et al. 2015). Carfentrazone-ethyl + sulfentrazone is a common premix postemergence herbicide containing two protoporphyinogen oxidase (PPO)-inhibiting compounds marketed to selectively control annual grasses, broadleaf weeds, and sedges (Anonymous 2017). Although an alternative mode of action, PROTOX-inhibiting herbicides generally do not translocate as readily as ALS herbicides and therefore may not be as effective for long-term *C. esculentus* control.

Pyrimisulfan is a relatively new sulfonanilide herbicidal inhibitor of the ALS enzyme currently labeled for postemergence control of broadleaf weeds and sedges in turfgrass (Anonymous 2022; Brosnan and Breeden 2019). Applications of pyrimisulfan at 50 to 75 g ha^{-1} successfully controlled several key weed species in rice production, such as *Echinochloa* spp. and perennial *Cyperus* spp. in greenhouse studies (Asakura et al. 2012). Additionally, pyrimisulfan + penoxsulam applied postemergence provided 99% to 100% control of *C. esculentus* in common bermudagrass and tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort.; syn.: *Festuca arundinacea* Schreb.] with sequential applications (Brosnan and Breeden 2019). Although previous studies demonstrated pyrimisulfan efficacy for *C. esculentus* control, information regarding translocation and subsequent impacts on tuber production and viability is limited. Therefore, the objective of this research was to evaluate the effects of single and sequential applications of common postemergence herbicides, including pyrimisulfan, on *C. esculentus* tuber production and viability.

Materials and Methods

Trials were conducted at the Athens Turfgrass Research and Education Center greenhouse complex from January to March 2022. Two identical trials were conducted simultaneously in separate greenhouses under different environmental conditions. The first trial was conducted in a greenhouse maintained at 30/24 C (day/night) with average midday (1200 and 1300 hours) solar radiation ranging from 636 to 754 μmol m^{-2} s^{-1}. The second trial was conducted in an adjacent greenhouse maintained at 24/18 C (day/night) with similar solar radiation. Supplemental lighting (350 μmol m^{-2} s^{-1}) was provided with metal-halide lamps (1,000 W) to simulate a 16-h daylength for both trials. Irrigation was supplied through an overhead irrigation system calibrated to deliver approximately 3.8 cm water wk^{-1}.

Tubers of *C. esculentus* were purchased from Azlin Seed Service (P.O. Box 914, Leland, MS 38756). Seven pre-germinated *C. esculentus* tubers were planted at a 2.5-cm depth evenly spaced apart from one another in 1-L (181 cm^2 surface area) pots filled with a 2:1 mixture of a native Cecil clay loam (fine, kaolinitic, thermic Typic Kanhapludults) and a Wakulla sand (siliceous, thermic Psammentic Hapludults) with a pH of 5.9 and organic matter content of 1.8%. Pots received a starter fertilizer (20 N-10 P_2O_5-20 K_2O) (Plant Marvel Laboratories, 371 E 16th Street, Chicago Heights, IL 60411) at 1.2 g N m^{-2} at planting. The *C. esculentus* plants were allowed to mature in the greenhouse for 6 wk. All plants were cut to a height of 10.2 cm with scissors just before herbicide application. Pots were arranged in a randomized complete block design with four replications. Blocking assignment was based on the location of the pots on the greenhouse bench to account for any slight changes in temperature, light, and/or irrigation.

Initial herbicide treatments were applied on January 13, 2022, with sequential treatments applied on February 4, 2022, for both trials (Table 1). The same herbicide doses were used for both applications. A nonionic surfactant (Induce®, Helena Chemical, 225 Schilling Boulevard, Suite 300, Collierville, TN 38017) was added to imazosulfuron treatments at 0.25% v/v. Pots receiving pyrimisulfan were treated by evenly spreading granules across the surface of the pot and hand watered with 0.63 cm of water immediately following application. All other postemergence herbicide treatments were applied with a CO_2-powered backpack sprayer equipped with two XR8004VS flat-fan extended-range spray tips (TeeJet® Spraying Systems, North Avenue and Schmale Road, Wheaton, IL 60129) calibrated to deliver 374 L ha^{-1} at 221 kPa.

Percent visual control (0% to 100%, with 0% representing a perfectly healthy plant and 100% being completely dead) was assessed 4, 6, 8, and 11 wk after initial treatment (WAIT). Pots were destructively harvested 8 wk after the last herbicide treatment they received to determine shoot dry biomass (g), tuber dry biomass (g), tuber number, and tuber viability (%). Pots receiving a single

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Table 1. Postemergence herbicide treatments applied to *Cyperus esculentus*.[a]

Herbicide[b]	Active ingredient	Application code[c]	Dose	Manufacturer
			g ai ha^{-1}	
Nontreated check	—	A	—	
Nontreated check	—	AB	—	
Vexis®	Pyrimisulfan	A	73	PBI Gordon Corporation, 22701 W 68th Terrace, Shawnee, KS 66226
Vexis®	Pyrimisulfan	AB	49 fb 49	PBI Gordon Corporation, 22701 W 68th Terrace, Shawnee, KS 66226
Celero®	Imazosulfuron[d]	A	736	Valent Professional Products, 4600 Norris Canyon Rd, San Ramon, CA 94583
Celero®	Imazosulfuron[d]	AB	420 fb 420	Valent Professional Products, 4600 Norris Canyon Rd, San Ramon, CA 94583
Dismiss® NXT	Carfentrazone-ethyl + sulfentrazone	A	22 + 198	FMC Corporation, 2929 Walnut Street Philadelphia, PA 19104
Dismiss® NXT	Carfentrazone-ethyl + sulfentrazone	AB	14 + 127 fb 14 + 127	FMC Corporation, 2929 Walnut Street Philadelphia, PA 19104
Sedgehammer® +	Halosulfuron	A	70	Gowan Company, 370 South Main Street Yuma, AZ 85364
Sedgehammer® +	Halosulfuron	AB	35 fb 35	Gowan Company, 370 South Main Street Yuma, AZ 85364

[a]Abbreviations: fb, followed by WAIT; weeks after initial treatment.
[b]Pots receiving pyrimisulfan were treated by evenly spreading granules across the surface of the pot. All other postemergence herbicide treatments were applied with a CO_2-powered backpack sprayer equipped with two XR8004VS flat-fan extended-range spray tips and calibrated to deliver 374 L ha^{-1} at 221 kPa.
[c]Application A occurred on January 13, 2022; application B occurred on February 4, 2022 (3 WAIT) for both trials. The same dose was applied for both A and B applications.
[d]A nonionic surfactant was added to imazosulfuron treatments at 0.25% v/v.

herbicide application were harvested on March 10, 2022, and pots receiving sequential applications were harvested on March 30, 2022. Nontreated control pots were included for both harvest dates for comparison. Upon harvest, all aboveground biomass for each pot was cut at the soil surface and allowed to air-dry in a laboratory environment for at least 1 wk before analysis. Similarly, tubers were harvested from each pot, washed free of soil, separated from rhizome and root tissue, and allowed to air-dry in a laboratory environment for at least 1 wk before analysis. Following harvest, all tubers from each pot were cut in half longitudinally and soaked in a 0.1% triphenyl tetrazolium chloride (Carolina Biological Supply, 2700 York Road, Burlington, NC 27215) solution for 3 h to determine tuber viability. Tubers were considered viable if the tetrazolium chloride stained any respiring tissue pink, similar to Akin and Shaw (2001).

All data collected were subject to ANOVA ($\alpha = 0.05$) in R v. 4.3.2 (The R Foundation for Statistical Computing, Vienna, Austria). Block and trial effects were considered as fixed effects within the statistical model. Normality testing was conducted on the residuals for each response variable using the Shapiro-Wilk test and deemed acceptable if the P-value was greater than 0.05. All residuals were also assumed independent and having equal variance for each response variable. When the herbicide treatment main effect was significant, means were separated according to Fisher's protected LSD ($\alpha = 0.05$) for all response variables.

Shoot dry biomass, tuber dry biomass, and tuber viability data were normalized as percent reduction compared with the corresponding nontreated pot in each block associated with each harvest date. Non-normalized tuber number and tuber viability data are also presented to provide context for the percent reduction of tubers containing respiring tissue data. Significant trial by treatment interactions were observed for non-normalized tuber number and non-normalized tuber viability data; therefore, trials are presented separately for these responses. For all other response variables, data were pooled across trials.

Results and Discussion

Percent Visual Control

Herbicides differed in their effect on *C. esculentus* as determined by percent visual control (Table 2). Both single and sequential applications of carfentrazone-ethyl + sulfentrazone exhibited the quickest *C. esculentus* control of any herbicide following a single application (80% to 83% at 4 WAIT). All other treatments resulted in ≤35% control at 4 WAIT, regardless of herbicide. Carfentrazone-ethyl + sulfentrazone continued to provide the greatest amount of control (≥94%) at 8 WAIT, regardless of application number. Both single and sequential pyrimisulfan and halosulfuron treatments were not significantly different from each other throughout the experiment, with both achieving 50% to 55% *C. esculentus* control at 8 WAIT. Single and sequential imazosulfuron treatments were not significantly different, except at 6 WAIT; however, both treatments resulted in better *C. esculentus* control (64% to 68%) than single and sequential pyrimisulfan and halosulfuron treatments (50% to 55%) at 8 WAIT. At 11 WAIT, sequential applications of carfentrazone-ethyl + sulfentrazone achieved the highest level of control (98%), followed by imazosulfuron (74%) and pyrimisulfan/halosulfuron (63% each; Table 2).

Shoot and Tuber Biomass

Significant treatment effects were observed for shoot and tuber biomass (Table 3). All herbicide treatments reduced shoot biomass by at least 27%. Single and sequential carfentrazone-ethyl + sulfentrazone treatments exhibited the highest reductions in shoot biomass but were not significantly different from each other (67% and 57%, respectively). However, significant differences were detected between single and sequential treatments of imazosulfuron (41% and 55%, respectively) and halosulfuron (38% and 54%, respectively). Additionally, no significant differences were detected between single and sequential treatments of pyrimisulfan (27% and

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Table 2. Percent visual control of *Cyperus esculentus* at 4, 6, 8, and 11 WAIT.[a]

Herbicide	Application code[b]	Dose	Visual control[c]			
		g ai ha^{-1}	WAIT			
			4	6	8	11[d]
			%			
Nontreated check	A	—	0 e	0 f	0 d	—
Nontreated check	AB	—	0 e	0 f	0 d	0 d
Pyrimisulfan	A	73	23 cd	36 de	52 c	—
Pyrimisulfan	AB	49 fb 49	20 d	32 e	50 c	63 c
Imazosulfuron[e]	A	736	33 b	51 c	64 b	—
Imazosulfuron[e]	AB	420 fb 420	35 b	56 b	68 b	74 b
Sulfentrazone + carfentrazone	A	22 + 198	83 a	94 a	94 a	—
Sulfentrazone + carfentrazone	AB	14 + 127 fb 14 + 127	80 a	99 a	98 a	98 a
Halosulfuron	A	70	25 cd	35 de	51 c	—
Halosulfuron	AB	35 fb 35	28 c	39 d	55 c	63 c
$LSD_{0.05}$	—	—	5.2	4.8	5.8	6

[a]Abbreviations: fb, followed by; WAIT, weeks after initial treatment.
[b]Application A occurred on January 13, 2022; application B occurred on February 4, 2022 (3 WAIT) for both trials.
[c]Percent visual control was rated on a scale of 0–100%, with 0% representing a perfectly healthy plant and 100% being completely dead. Means followed by the same letter within the same column are not significantly different at $\alpha = 0.05$.
[d]Pots that received only application A were destructively harvested at 8 WAIT.
[e]A nonionic surfactant was added to imazosulfuron treatments at 0.25% v/v.

Table 3. Percent reduction in total shoot and tuber biomass of *Cyperus esculentus* per pot compared with the corresponding nontreated pot in each block measured at 8 wk after the last herbicide treatment they received.[a]

Herbicide	Application code[b]	Dose	Reduction in shoot biomass[c]	Reduction in tuber biomass[c]
		g ai ha^{-1}	%	
Nontreated check	A	—	—[d]	—[e]
Nontreated check	AB	—	—	—
Pyrimisulfan	A	73	27 c	67 cd
Pyrimisulfan	AB	49 fb 49	36 c	76 abc
Imazosulfuron[f]	A	736	41 bc	77 ab
Imazosulfuron[f]	AB	420 fb 420	55 ab	83 ab
Sulfentrazone + carfentrazone	A	22 + 198	67 a	78 ab
Sulfentrazone + carfentrazone	AB	14 + 127 fb 14 + 127	57 a	85 a
Halosulfuron	A	70	38 c	62 d
Halosulfuron	AB	35 fb 35	54 ab	74 bc
$LSD_{0.05}$	—	—	15.2	9.1

[a]Abbreviations: fb, followed by; WAIT, weeks after initial treatment.
[b]Application A occurred on January 13, 2022; application B occurred on February 4, 2022 (3 WAIT) for both trials. Pots that received only application A were harvested at 8 WAIT and those that received both A and B applications were harvested at 11 WAIT.
[c]Means with the same letter within the same column are not significantly different at $\alpha = 0.05$.
[d]Nontreated check actual shoot dry biomass means: application A = 8.4 g; application AB = 9.1 g.
[e]Nontreated check actual tuber dry biomass means: application A = 18.88 g; application AB = 24.65 g.
[f]A nonionic surfactant was added to imazosulfuron treatments at 0.25% v/v.

36%, respectively). Both carfentrazone-ethyl + sulfentrazone treatments, the sequential imazosulfuron treatment, and the sequential halosulfuron treatment exhibited the highest reductions in shoot biomass. Conversely, both pyrimisulfan treatments and the single treatment of halosulfuron exhibited the lowest reductions in shoot biomass.

All herbicide treatments reduced tuber biomass by at least 62%. Single and sequential carfentrazone-ethyl + sulfentrazone treatments (78% and 85%, respectively), single and sequential treatments of imazosulfuron (77% and 83%, respectively), and the sequential treatment of pyrimisulfan (76%) exhibited the highest reductions in tuber biomass. Additionally, the lowest reductions in tuber biomass were observed in response to single applications of pyrimisulfan and halosulfuron (67% and 62%, respectively; Table 3).

Tuber Production and Viability

Significant treatment effects were observed for tuber number and viability (Table 4). Nontreated check pots exhibited 83 to 106 and 68 to 77 tubers at the time of harvest in Trials 1 and 2, respectively. All herbicides resulted in significant reductions in tuber numbers compared with the nontreated check for both harvest dates in both trials. Single and sequential treatments of imazosulfuron (24 and 22, respectively) and carfentrazone-ethyl + sulfentrazone (21 and 15, respectively) plus the sequential treatment of halosulfuron (26) had the lowest tuber numbers in Trial 1. Similar trends were observed in Trial 2 with the addition of the single halosulfuron treatment (27) and sequential pyrimisulfan treatment (26; Table 4).

All herbicide treatments significantly reduced tubers containing respiring tissue when compared with the nontreated checks for both harvest dates in both trials (Table 4). However, it is important to note that the simple detection of respiring tissue in *C. esculentus* tubers using the tetrazolium chloride test may not indicate tubers that can germinate and/or sprout (Keeley et al. 1986). Keeley et al. (1986) observed that the basal part of a dead *C. esculentus* tuber may still react to the tetrazolium chloride test indicating respiring tissue while the bud of the tuber is nonviable. This suggests that some of the tubers identified as viable in the current study may in

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Table 4. Total tuber number per pot and viability of *Cyperus esculentus* at 8 wk after the last herbicide treatment they received.[a]

Herbicide	Application code[b]	Dose	Tuber no.[c]		Tuber viability[c,d]		Reduction in viable tubers[c,e]
			Trial 1[f]	Trial 2	Trial 1[f]	Trial 2	
		g ai ha^{-1}	%				
Nontreated check	A	—	83 b	68 a	65 b	52 b	—
Nontreated check	AB	—	106 a	77 a	88 a	66 a	—
Pyrimisulfan	A	73	32 cd	28 b	16 cd	13 c	75 b
Pyrimisulfan	AB	49 fb 49	30 cd	26 bc	20 cd	12 c	80 ab
Imazosulfuron[g]	A	736	24 cde	15 c	13 cd	9 c	80 ab
Imazosulfuron[g]	AB	420 fb 420	22 cde	15 c	15 cd	9 c	84 a
Sulfentrazone + carfentrazone	A	22 + 198	21 de	20 bc	14 cd	15 c	75 b
Sulfentrazone + carfentrazone	AB	14 + 127 fb 14 + 127	15 e	20 bc	8 d	12 c	86 a
Halosulfuron	A	70	35 c	27 bc	24 c	17 c	65 c
Halosulfuron	AB	35 fb 35	26 cde	23 bc	17 cd	12 c	81 ab
$LSD_{0.05}$	—	—	13.5	12.4	11.3	9.8	8.8

[a]Abbreviations: fb, followed by; WAIT, weeks after initial treatment.
[b]Application A occurred on January 13, 2022; application B occurred on February 4, 2022 (3 WAIT) for both trials. Pots that received only application A were harvested at 8 WAIT and those that received both A and B applications were harvested at 11 WAIT.
[c]Means with the same letter within the same column are not significantly different at $\alpha = 0.05$.
[d]Tuber viability was determined via tetrazolium chloride test. Tubers were considered viable if any respiring tissue was detected.
[e]Percent reduction in number of viable tubers compared with the corresponding nontreated pot in each block associated with each harvest date.
[f]A significant treatment × trial interaction was detected for tuber number and viability; therefore, trials are presented separately.
[g]A nonionic surfactant was added to imazosulfuron treatments at 0.25% v/v.

fact be false positives and unable to germinate. Therefore, it is possible that tuber viability was overestimated in the current study. However, single and sequential imazosulfuron treatments along with sequential pyrimisulfan, carfentrazone-ethyl + sulfentrazone, and halosulfuron treatments still reduced tubers containing respiring tissue 80% to 86% compared with the nontreated check. The single halosulfuron treatments exhibited the lowest overall reduction in tubers containing respiring tissue among all herbicide treatments; however, tubers containing respiring tissue were reduced by 65% (Table 4).

Effective long-term control of *C. esculentus* relies on herbicide translocation to belowground reproductive tubers (Blum et al. 2000; Kopec et al. 1991). Of the postemergence herbicides examined in the current study, carfentrazone-ethyl + sulfentrazone most negatively affected the growth and production of *C. esculentus* with respect to above- and belowground structures. These results align with previous reports of sulfentrazone by Blum et al. (2000) and current label claims and recommendations for carfentrazone-ethyl + sulfentrazone (Anonymous 2017). However, pyrimisulfan, halosulfuron, and imazosulfuron failed to achieve the same levels of visual control within our study as observed in previous research (Blum et al. 2000; Brosnan and Breeden 2019; Felix and Boydston 2010; Henry et al. 2012; Li et al. 2021). However, despite the lack of visual control, pyrimisulfan, halosulfuron, and imazosulfuron significantly reduced shoot biomass compared with the nontreated check, with two applications of halosulfuron and imazosulfuron reducing shoot biomass to similar levels as carfentrazone-ethyl + sulfentrazone (Tables 2–4). This suggests that although these herbicides may not cause the same level of visual control, a similar level of canopy reduction is still achieved, further limiting photosynthetic activity and subsequent carbohydrate production.

Additionally, all herbicide treatments significantly reduced tubers containing respiring tissue by at least 65% compared with the nontreated check, and sequential applications reduced tubers containing respiring tissue by at least 80% (Table 4). Sequential applications of pyrimisulfan provided an 80% reduction in tubers containing respiring tissue despite only reducing shoot biomass by 36% and causing 63% visual control (Tables 2–4). This phenomenon may be attributed to the difference in pyrimisulfan formulation and application technique compared with other herbicides examined in our research. Pyrimisulfan was hand applied as a granular evenly across the soil surface, therefore limiting direct shoot exposure. Granular products applied to the soil surface must first enter the soil solution before being absorbed by the plant, thus potentially reducing the efficacy of granular formulations compared with sprayable formulations due to less active ingredient reaching the target site. Despite this potential limiting factor, two applications of pyrimisulfan achieved similar reductions in tubers containing respiring tissue compared with all other herbicide treatments. Tank mixing pyrimisulfan with more expeditious postemergence herbicides may provide greater canopy control and, therefore, greater reductions in tuber viability due to reduced photosynthetic capability.

It is important to note that the results from the current study may differ from similar applications made in the field. Plants used in our research were grown in pots in the greenhouse and lacked competition from surrounding turfgrass. Blum et al. (2000) reported only 5% visual control of *C. esculentus* at 13 WAIT after a single application of halosulfuron in the absence of bermudagrass competition compared with 84% control in the presence of bermudagrass. Turfgrass competition can reduce overall *C. esculentus* shoot production and often increases herbicidal efficacy (Blum et al. 2000; Summerlin 1997). Additionally, plants grown in the greenhouse are not exposed to the same environmental stresses experienced in a field environment (temperature, light intensity, soil moisture, relative humidity, etc.) (Fausey and Renner 2001; Hatterman-Valenti et al. 2011; Hwang et al. 2004; Matzenbacher et al. 2014).Therefore, plants grown in a greenhouse environment are often more susceptible to herbicides, leading to increased levels of control. Henry et al. (2019) observed 81% common carpetgrass [*Axonopus fissifolius* (Raddi) Kuhlm.] control at 8 WAIT in response to nicosulfuron (0.035 kg ha^{-1}) and 75% control in response to trifloxysulfuron (0.028 kg ha^{-1}) in the greenhouse, but only observed 19% control for both chemistries when applied at the same rates in the field. Lingenfelter and Curran (2007) reported 60% to 87% control of wirestem muhly [*Muhlenbergia frondosa* (Poir.) Fernald] at 4 wk after treatment (WAT) in response to glyphosate (0.42 and 0.84 kg ha^{-1}) in the field,

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but reported 98% control in the greenhouse in response to the same treatments. Additionally, Cooper et al. (2016) demonstrated that metamifop (0.3 to 0.5 kg ha^{-1}) completely controlled bermudagrass (100%) at 6 WAIT in the greenhouse, whereas Doroh et al. (2011) only reported 36% control of bermudagrass at 9 WAIT in the field following sequential applications of metamifop (0.4 kg ha^{-1}). Although field and greenhouse studies often yield differing results, the primary objective of the current study was to specifically assess the herbicidal effects on total tuber production of *C. esculentus*, a task that is often difficult to perform in field settings. Additionally, the controlled greenhouse environment facilitated the evaluation of herbicidal effects under two different temperature regimes. However, complementary field studies are necessary to validate the results of the current study.

As with most plants, an overall trend in the data of the current study suggests that temperature affects both above- and belowground growth of *C. esculentus*. This trend aligns with literature describing the effect temperature has on the growth, production, and herbicidal efficacy of *C. esculentus* (Holt and Orcutt 1996; Jansen 1971; Kehler 1991; Matzenbacher et al. 2014; Miles et al. 1996; Webster 2003; Wilen et al. 1996). The decrease in overall growth and tuber production from Trial 2 was likely a result of the lower day/night temperature maintained in the greenhouse and thus fewer growing degree days (GDD) compared with Trial 1. While this reduced tuber number and biomass, herbicides performed similarly with respect to reduction in tubers containing respiring tissue across both trials. Additionally, it is likely that *C. esculentus* may produce even more tubers and rhizomes in a field setting than observed in the current study. The nontreated plants in the current study may have become root-bound, reaching the maximum amount of tuber and rhizome production for the pot space provided and trial duration. Future studies evaluating *C. esculentus* tuber production under similar conditions in greenhouse studies should consider using a larger pot size (>1 L) to limit this possibility. Additionally, although it is impossible to thoroughly simulate field settings in the greenhouse, implementing soil and *C. esculentus* plant material acclimated to field settings into greenhouse studies would reduce the risk of observing conflicting results with field studies. Therefore, using larger pot sizes (>1 L) and harvesting material from the field would likely improve the outcome of the current study.

Results of the current study confirm that several labeled postemergence herbicides (halosulfuron, imazosulfuron, and carfentrazone-ethyl + sulfentrazone) provide *C. esculentus* control through the reduction of tuber production and viability. However, given the rapid growth and reproductive capabilities of *C. esculentus*, annual herbicide programs are necessary to keep populations from spreading. Pyrimisulfan, a relatively new herbicide labeled for use in turfgrass, has also shown potential for the control of *C. esculentus*. Future research should further evaluate the effectiveness of these herbicides to reduce *C. esculentus* tuber production and viability in a field setting. Further investigating the mechanisms responsible for reducing tuber production, whether through canopy desiccation and subsequent photosynthesis reduction or through direct herbicide translocation to belowground structures may also be warranted. The level of soil activity and root absorption exhibited by these chemistries is also intriguing and may necessitate the examination of these herbicides for preemergence sedge control.

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