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Response of Palmer amaranth accessions in South Carolina to selected herbicides

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Abstract

Palmer amaranth with resistance to dicamba, glufosinate, and protoporphyrinogen oxidase inhibitors has been documented in several southern states. With extensive use of these and other herbicides in South Carolina, a survey was initiated in fall 2020 and repeated in fall 2021 and 2022 to determine the relative response of Palmer amaranth accessions to selected preemergence and postemergence herbicides. A greenhouse screening experiment was conducted in which accessions were treated with three preemergence (atrazine, *S*-metolachlor, and isoxaflutole) and six postemergence (glyphosate, thifensulfuron-methyl, fomesafen, glufosinate, dicamba, and 2,4-D) herbicides at the 1× and 2× use rates. Herbicides were applied shortly after planting (preemergence) or at the 2- to 4-leaf growth stage (postemergence). Percent survival was evaluated 5 to 14 d after application depending on herbicide activity. Sensitivity to atrazine preemergence was lower for 49 and 33 accessions out of 115 to atrazine applied preemergence at the 1× and 2× rate, respectively. Most of the accessions (90%) were controlled by isoxaflutole applied preemergence at the 1× rate. Response to *S*-metolachlor applied preemergence indicated that 34% of the Palmer amaranth accessions survived the 1× rate (>60% survival). Eleven accessions exhibited reduced sensitivity to fomesafen applied postemergence; however, these percentages were not different from the 0% survivor group. Glyphosate applied postemergence at the 1× rate did not control most accessions (79%). Palmer amaranth response to thifensulfuron-methyl applied postemergence varied across the accessions, with only 36% and 28% controlled at the 1× rate and 2× rate, respectively. All accessions were controlled by 2,4-D, dicamba, or glufosinate when they were applied postemergence. Palmer amaranth accessions from this survey exhibited reduced susceptibility to several herbicides commonly used in agronomic crops in South Carolina. Therefore, growers should use multiple management tactics to minimize the evolution of herbicide resistance in Palmer amaranth in South Carolina.

Introduction

Palmer amaranth is a summer annual broadleaf weed that has been a consistent threat to a crop production in the United States. With its high production of seeds from one female plant, Palmer amaranth can quickly alter the soil seedbank (Webster and Grey 2015). Studies have shown the potential for one female plant to produce more than 600,000 seeds if left untreated for an entire growing season (Keeley et al. 1987). The rapid and vigorous vegetative growth habit of this weed allows it to preferentially accumulate water and nutrients and intercept light that is necessary for optimum crop productivity (Berger et al. 2015b, Meyers et al. 2010). Yield reductions up to 91%, 68%, and 59% have been observed in corn, soybean, and cotton, respectively, from season-long competition (Bensch et al. 2003; Massinga et al. 2001; Morgan et al. 2001). Research has also shown that Palmer amaranth control can increase yield by 14% for every 0.3-m increase away from a Palmer amaranth plant (Berger et al. 2015b). Palmer amaranth can also interfere with harvest operations from control failure during the growing season. Morgan et al. (2001) reported mechanical impediments in harvesting cotton with Palmer amaranth densities of greater than six plants per 9.1 m.

Herbicides are a chemical management tactic used by growers throughout the United States. The insertion of glyphosate tolerance into corn, cotton, and soybeans has provided growers with a broad-spectrum herbicide for the management of weeds, including Palmer amaranth. Glyphosate-resistant crops have simplified weed management strategies and reduced labor costs, thereby allowing growers to make fewer applications to a field and reduce soil erosion from tillage (Triplett and Dick 2008). Producers have rapidly adopted varieties of crops that are tolerant to glyphosate (USDA-ERS 2024). Soon after this, glyphosate was used as the sole weed management tool. This glyphosate-only weed management tactic resulted in heavy selection pressure, which resulted in glyphosate-resistant Palmer amaranth accessions (Beckie 2011; Diggle et al. 2003; Heap and Duke 2018; Shaner and Beckie 2014). The first documented Palmer amaranth accession found to be resistant to glyphosate was confirmed in Georgia, in 2006 (Culpepper et al. 2006). Many states would later confirm glyphosate resistance in Palmer amaranth in the following years, resulting in the need to diversity herbicide modes of action and to use cultural practices such as tillage and cover crops (Berger et al. 2015a; Butts and Davis 2015; Chahal et al. 2017; Culpepper et al. 2006; Kohrt et al. 2017; Nandula et al. 2012; Norsworthy et al. 2008; Steckel et al. 2008).

The loss of glyphosate as an effective herbicide for the management of Palmer amaranth has resulted in the adoption of strategies such as rotating herbicides with various modes of action, incorporating preemergence soil residual herbicides at planting, and tank-mixing herbicides with multiple modes of action (Norsworthy et al. 2008). Herbicides that inhibit protoporphyrinogen oxidase (PPO) and very-long-chain fatty acid (VLCFA) synthesis were widely adopted as alternatives for controlling weeds in soybean and cotton crops due to their foliar and/or soil residual activity on Palmer amaranth (Hay et al. 2018; Whitaker et al. 2010). Inhibitors of photosystem II (PS II) and hydroxyphenyl pyruvate dioxygenase (HPPD) were often applied to corn because of its natural tolerance to these herbicides (Jachetta and Radosevich 1981). The introduction of glufosinate- and auxinic-resistant traits in cotton, soybean, and corn provided additional over-the-top control options for Palmer amaranth biotypes with multiple resistance (i.e., glyphosate and acetolactate synthase [ALS] inhibitors). However, Palmer amaranth resistance to PPO inhibitors, VLCFA inhibitors, HPPD inhibitors, PS II inhibitors, glufosinate, and auxinic herbicides has been confirmed throughout the southern states (Brabham et al. 2019; Foster and Steckel 2022; Heap 2023; Jhala et al. 2014; Kumar et al. 2019; Nakka et al. 2017; Priess et al. 2022; Salas et al. 2016). Palmer amaranth resistance to the microtubule assembly inhibitors (categorized as a Group 3 herbicide by the Herbicide Resistance Action Network [HRAC] and the Weed Science Society of America [WSSA]), ALS inhibitors (HRAC/WSSA Group 2), and 5-enolpyruvylshikimate-3-phosphate synthase inhibitors (HRAC/WSSA Group 9) has been documented in South Carolina (Gossett et al. 1992, 1998; Heap 2023). South Carolina growers have concerns about the ability to control Palmer amaranth in cotton, corn, soybean, and peanut production. Therefore, the objectives of this study were to 1) collect escaped female Palmer amaranth accessions from key agronomic producing regions of South Carolina, and 2) determine the susceptibility of these accessions to commonly used preemergence and postemergence herbicides in row-crop production in South Carolina.

Materials and Methods

Plant Collection

Palmer amaranth accessions were collected from September to November in 2020, 2021, and 2022 from 27 counties in South Carolina (Figure 1). This study was conducted as a survey to determine the relative susceptibility of Palmer amaranth accessions in South Carolina to commonly used herbicides; therefore, herbicide program history at each field site was not collected. Approximately 30 to 40 female seedheads were collected from each field sampling site and combined into one representative sample. A total of 142 accessions were collected from five corn (*Zea mays* L.), 65 cotton (*Gossypium hirsutum* L.), and 72 soybean (*Glycine max* L.) fields (Supplemental Table S1). The accessions were processed at the greenhouse complex at the Clemson University Edisto Research and Education Center (EREC) located near Blackville, SC (33.36424°N, 81.33155°W; 100 m asl). Seedheads were oven-dried at 30 C for 5 d; hand-threshed; cleaned to remove the chaff from the mature, black seed; and stored in paper bags at 5 C.

Preemergence Susceptibility Bioassay

Soil was collected from a production field at EREC and placed in an electric sterilizer (Pro Grow Supply LLC, Phoenix, AZ) at 93 C for 24 h. The soil used in the preemergence study was a Fuquay sandy loam (Loamy, kaolinitic, thermic Arenic Plinthic Kandiudults) with a sand, silt, and clay content of 88%, 10%, and 2%, respectively. The soil pH was 5.8, and the organic matter content was 1.1%. The soil was then passed through a 4-mm sieve and placed in 48-cell trays (Greenhouse Megastore, Danville, IL). Greenhouse conditions during the study were maintained at 27/21 C day/night temperature with supplemental lighting (450 µmol m^{-2} s^{-1}) on a 16-h day period. Twenty Palmer amaranth seeds from each accession were planted in a 0.64-cm-deep cell. The volume in each cell was 12.86 cm^3. Each 48-cell tray contained eight accessions with six cells per accession, and trays were grouped according to herbicide and rate. To quantify germination ability of each accession, 20 seeds per cell were also planted as a nontreated control (Moore et al. 2021). The experiment was arranged in a randomized complete block design with six replications (cells) per accession, and the study was conducted twice.

The herbicides used in this study were atrazine (Aatrex; Syngenta Crop Protection, Greensboro, NC) at 1,121 and 2,242 g ha^{-1}, *S*-metolachlor (Dual Magnum; Syngenta) at 1,068 and 2,136 g ha^{-1}, and isoxaflutole (Alite 27; BASF, Raleigh, NC) at 105 and 210 g ha^{-1}, which were applied immediately after planting. The rates for each preemergence herbicide were 1× and 2× of the recommended use rate except for atrazine, for which 1× was 1,120 g ha^{-1} (2,240 g ha^{-1} is the 1× rate on the product label), and is the typical single application rate used by growers in South Carolina. Herbicides were applied using a CO_2-pressurized backpack sprayer using a TeeJet 11002 nozzle (Spraying Systems Co., Glendale Heights, IL) calibrated to deliver 140 L ha^{-1} at 207 kPa. Herbicides were activated with 1.3 cm of water within 12 h of herbicide application and watered as needed.

Plants that emerged with no visible herbicide injury symptomology (i.e., green meristems and the emergence of the first and second true leaves) were counted as survivors 14 d after application for each preemergence herbicide. Survival percentage was then calculated by dividing the number of survivors in each cell by the number of untreated control plants in each cell (to account for potential germination differences between accessions). Each preemergence herbicide bioassay was treated as a separate experiment. Percent survivor data were subjected to ANOVA using the MIXED procedure with SAS software (v. 9.4; SAS Institute, Cary, NC) where accession and experimental run were considered fixed variables, while replication was random. Differences between experimental runs were not significant ($P > 0.05$); therefore, percent survivor data were pooled within each accession.

Postemergence Susceptibility Bioassay

For the postemergence greenhouse bioassay experiment, approximately 20 seeds per cell from each accession were planted in

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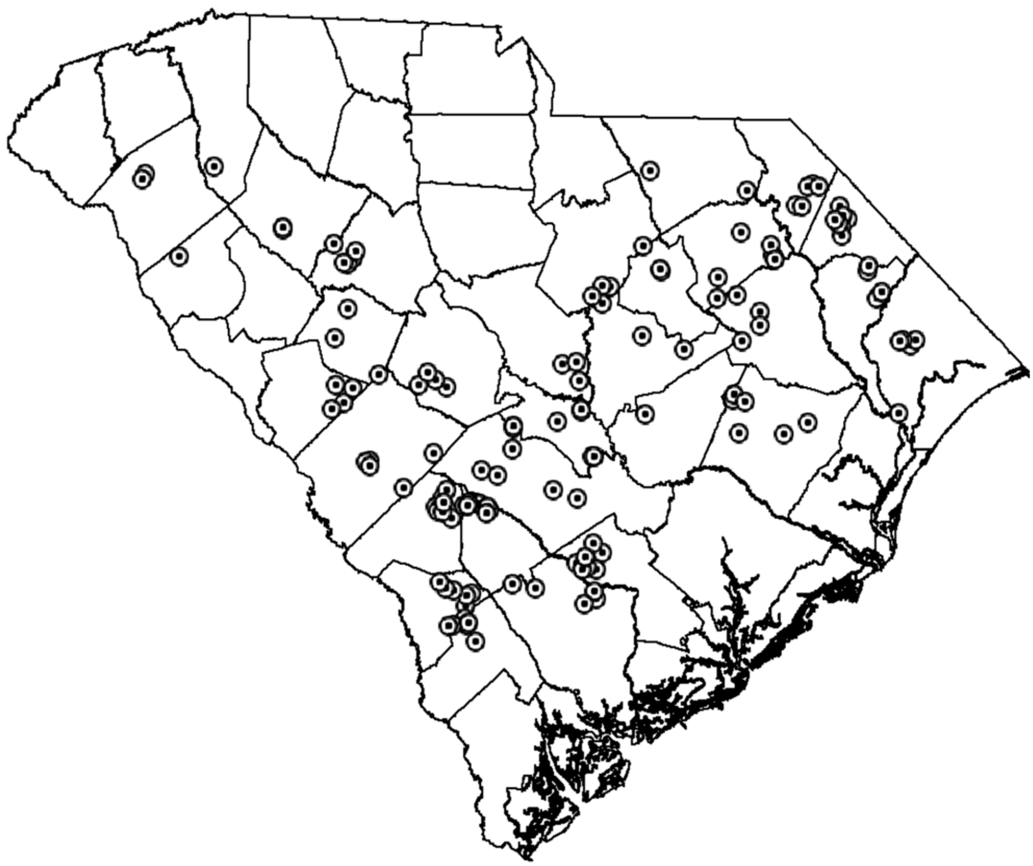

Figure 1. Field locations in South Carolina where Palmer amaranth accessions were collected from 2020 to 2022.

48-cell trays (Greenhouse Megastore, Danville, IL) filled with commercial potting mix (Miracle-Gro; Scotts Company North America, Columbus, OH) at a 0.3-cm depth. Each cell volume was 12.86 cm^3. Each 48-cell tray contained eight accessions with six cells per accession, and trays were grouped according to herbicide and rate. The plants were watered daily using an automated irrigation system. Greenhouse conditions during the study were maintained at 27/21 C day/night temperature with supplemental lighting (450 μmol m^{-2} s^{-1}) on a 16-h day period. At emergence, plants in each cell were thinned to three plants per cell, with eight cells per replication. The experiment was arranged in a randomized complete block design with six replications per accession. The postemergence bioassay experiment was conducted twice.

At the 2- to 4-leaf growth stage (5 to 10 cm height), the following herbicides were applied in separate experiments: glyphosate (Roundup PowerMAX 3; Bayer CropScience, Chesterfield, MO) at 840 and 1,680 g ae ha^{-1}; glufosinate (Liberty 280 SL; BASF) at 656 and 1,312 g ai ha^{-1}; fomesafen (Reflex; Syngenta) at 280 and 560 g ai ha^{-1}; thifensulfuron-methyl (Harmony SG; FMC Corporation, Philadelphia, PA) at 8.75 and 17.5 g ai ha^{-1}; dicamba (Xtendimax; Bayer CropScience) at 560 and 1,120 g ae ha^{-1}; and 2,4-D (Enlist One; Corteva AgriScience, Indianapolis, IN) at 1,065 and 2,130 g ae ha^{-1}. A crop oil concentrate (CropSmart; Carolina Eastern, Inc., Charleston, SC.) at 10 mL L^{-1} was included with fomesafen. A nonionic surfactant (TradeMark; Carolina Eastern) at 2.5 mL L^{-1} and ammonium sulfate (AS-34 Plus; Carolina Eastern) at 25 mL L^{-1} was included with thifensulfuron-methyl. Herbicides were applied using a CO_2-pressurized backpack sprayer with a TeeJet 11002 VS nozzle (Spraying Systems Co.) calibrated to deliver 140 L ha^{-1} at 207 kPa.

Survivor counts were collected 5 to 14 d after application, depending on the relative activity of each of the postemergence herbicides. The foliar symptoms after postemergence herbicide application included chlorosis/necrosis or death. Palmer amaranth survivors had green leaves and active growth at the apical meristems. Survivor counts for each herbicide rate was divided by the total number of plants in each cell to determine the survival percentage for each accession. Each postemergence herbicide bioassay was a separate experiment. Percent survivor data were subjected to ANOVA using the MIXED procedure with SAS software (v. 9.4; SAS Institute) where accession and experimental run were considered fixed variables, while replication was random. Differences between experimental runs was not significant ($P > 0.05$); therefore, percent survivor data were pooled.

Percent Survivor Data Analysis

Survival percentages for each accession ranged from 0% to 100% for each herbicide rate where 0% indicates no survivors and 100% indicates all plants survived the treatment. Accession survival percentages were then assigned to an interval group (0%, 1%–10%, 11%–20%, 21%–30%, 31%–40%, 41%–50%, 51%–60%, 61%–70%, 71%–80%, 81%–90%, and 91%–100%) with 1%–30%, 31%–60%, and 61%–100% representing the low, moderate, and high survivor groups, respectively (Mahoney et al. 2020). Dunnett's procedure ($\alpha = 0.05$) was then used to determine significant differences

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Table 1. Response of Palmer amaranth accessions from South Carolina to selected preemergence and postemergence herbicides.[a]

Herbicide	Rate[b]	% Survivor[c]			
		0	1–30	31–60	61–100
	g ai or ae ha^{-1}	Number of accessions			
Atrazine PRE	1,121	38	28	27	22
Atrazine PRE	2,242	45	37	24	9
Fomesafen POST	280	133	9	0	0
Fomesafen POST	560	140	2	0	0
Glyphosate POST	840	1	11	18	112
Glyphosate POST	1,680	1	11	31	99
Isoxaflutole PRE	105	10	2	0	0
Isoxaflutole PRE	210	0	0	0	0
S-metolachlor PRE	1,068	24	27	25	39
S-metolachlor PRE	2,136	35	41	20	19
Thifensulfuron-methyl POST	8.75	3	44	43	52
Thifensulfuron-methyl POST	17.5	3	56	42	41

[a]Abbreviations: POST, postemergence; PRE, preemergence.
[b]The herbicide rates were 1× and 2× of the recommended use rate except for atrazine, for which the 1× rate was 1,121 g ha^{-1} (2,242 g ha^{-1} is the recommended 1× rate listed on the product label), which is the typical single application rate used by growers in South Carolina. Crop oil concentrate at 10 mL L^{-1} was included with fomesafen POST. Nonionic surfactant at 2.5 mL L^{-1} and ammonium sulfate at 25 mL L^{-1} was included with thifensulfuron-methyl POST.
[c]Palmer amaranth survivors were based on green leaves and active growth at the apical meristems.

between survival percentages across accessions (Mahoney et al. 2020). In addition, accession survival percentages were compared to the 0% (no survivors) group using 95% confidence intervals. Survivor percentage intervals not containing 0% were considered to have reduced herbicide sensitivity. Accessions with 0% survival were not included in the analysis (Moore et al. 2021).

Results and Discussion

Preemergence Susceptibility Bioassay

A total of 115 Palmer amaranth accessions were evaluated for sensitivity to atrazine, isoxaflutole, and *S*-metolachlor applied preemergence. Twenty-seven accessions collected in 2020 were not included in the preemergence bioassay experiment because an insufficient number of seeds was available to conduct both preemergence and postemergence bioassay experiments. The authors prioritized these accessions for the postemergence bioassay because that information would provide the highest benefit for South Carolina growers.

No atrazine resistance in Palmer amaranth has been documented in South Carolina; however, resistant Palmer amaranth accessions have been reported in Georgia, Kansas, Nebraska, North Carolina, and Texas (Heap 2023). Differences were observed in Palmer amaranth survival percentages at the 1× ($P < 0.0001$) and 2× ($P < 0.0001$) rates of atrazine. In South Carolina, following an application of atrazine at the 1× and 2× rates, 38 and 45 out of 115 accessions had zero survivors at the 1× and 2× rates, respectively (Table 1). Based on 95% confidence intervals, the moderate (31%–60%) and high survival (61%–100%) groups were different than the no-survivors group (0%). Twenty-seven and 22 accessions, respectively, had moderate (31%–60%) to high (61%–100%) survival at the 1× rate of atrazine. There were 28 accessions in the low survivor (1%–30%) group at the 1× rate, which was not different from the 0% group according to 95% confidence intervals. Similar to the 1× rate, 24 accessions were in the moderate (31%–60%) survival group for the 2× rate of atrazine. However, only nine survivors were in the high survival (61%–100%) group. The low survivor category had 37 accessions (1%–30%) at the 2× rate of atrazine. No difference in the low survivor versus the no-survivor (0%) groups at the 2× rate of atrazine was observed. In this survey, 49 and 33 accessions out of 115 were less susceptible to atrazine at the 1× and 2× rates, respectively. These results indicate a reduction in Palmer amaranth susceptibility to atrazine; however, the 1× rate of atrazine used in this study was half of the recommended rate listed on the product label (2,242 g ha^{-1}). The 1,121 g ai ha^{-1} rate is the typical atrazine rate used in South Carolina. The number of survivors in the high range (61%–100%) was higher at the 1× rate than the 2× rate of atrazine. A survey in Texas found that 16% of the Palmer amaranth accessions sampled were resistant to atrazine (Garetson et al. 2019). However, the 120 Palmer amaranth accessions from North Carolina were controlled at the recommended field use rate of atrazine (Moore et al. 2021).

Palmer amaranth biotypes with resistance to the HPPD-inhibitor herbicides mesotrione, tembotrione, and topramezone have been documented in Kansas, Nebraska, and North Carolina (Heap 2023; Jhala et al. 2014; Mahoney et al 2020; Nakka et al. 2017). However, there have been no reports of Palmer amaranth resistance to isoxaflutole. Determining the sensitivity or response of Palmer amaranth to isoxaflutole applied preemergence was critical for this study because its use in South Carolina will significantly increase after the introduction of HPPD-tolerant soybean and cotton varieties (M. Marshall, personal observation). Differences were observed in Palmer amaranth survival percentages at the 1× rate of isoxaflutole ($P < 0.0001$) rate but not the 2× rate ($P > 0.05$). At the 1× isoxaflutole rate, 103 Palmer amaranth accessions did not survive (0%) (Table 1). Survivors from five accessions ranged from 1% to 10%. Four accessions had survivors between 11% and 20%, and one accession in each of the 21%–30%, 31%–40%, and 41%–50% interval groups, respectively. Although two accessions exhibited reduced susceptibility (31%–50%) to the 1× rate of isoxaflutole, most of the accessions (112 out of 115) were not different from the 0% (no survivors) group according to 95% confidence intervals. In addition, no (0%) survivors were observed at the 2× rate of isoxaflutole (Table 1). The relative low number of survivors observed from the study in which isoxaflutole was applied preemergence indicate that this will be an effective soil residual herbicide in HPPD-tolerant soybean and cotton crops in

South Carolina; however, additional screening is needed to determine the sensitivity of Palmer amaranth to postemergence-applied HPPD-inhibitor herbicides including mesotrione, tembotrione, and tompramezone.

In the United States, *S*-metolachlor is the fourth most used active ingredient applied to corn crops behind glyphosate, mesotrione, and atrazine (USDA-NASS 2022). It is a widely used preemergence and postemergence residual herbicide in cotton, soybean, and peanut in South Carolina (M. Marshall, personal observation). Palmer amaranth resistance to *S*-metolachlor has been confirmed in Arkansas and Mississippi (Brabham et al. 2019; Heap 2023; Kouame et al. 2022; Rangani et al. 2021). In the South Carolina survey, *S*-metolachlor was applied as a preemergence treatment at the 1× and 2× rates to 115 accessions (Table 1). Differences were observed in Palmer amaranth survival percentages at the 1× ($P < 0.0001$) and 2× ($P < 0.0001$) use rates of *S*-metolachlor. At the 1× and 2× rates of *S*-metolachlor, 24 and 35 accessions, respectively, had no survivors (0%). No differences were observed between the low and no-survivor percentages according to 95% confidence intervals, whereas differences were observed between moderate and high survivor percentages. The low survival (1% to 30%) group had 27 and 41 accessions after the 1× and 2× rates, respectively, of *S*-metolachlor were applied. The moderate survivor group (31% to 60%) had 25 and 20 accessions after the1× and 2× rates, respectively, were applied (Table 1). In the high survivor group (61% to 100%), 39 accessions that survived the 1× rate were observed. This survey showed that 34% of the accessions in the high survivor group were not controlled by *S*-metolachlor at the 1× rate. These results agree with a survey conducted in North Carolina where 18 populations survived *S*-metolachlor at the 1× rate (Moore et al. 2021). Overall, 39 out of 115 accessions survived (>60% threshold) an application of the 1× rate of *S*-metolachlor, indicating a reduction in susceptibility. In addition, 19 accessions survived the 2× rate of *S*-metolachlor (>60% threshold). Additional research is needed to determine whether these survivors in this study are resistant to the herbicide.

Postemergence Susceptibility Bioassay

A total of 142 Palmer amaranth accessions collected in South Carolina were screened to determine the frequency of their ability to survive the 1× and 2× rates of fomesafen, glufosinate, 2,4-D, and dicamba. Fomesafen resistance has been confirmed in Arkansas and Tennessee (Salas et al. 2016; Umphres et al. 2018). No differences were observed in Palmer amaranth survival percentages at the 1× ($P = 0.8422$) and 2× ($P = 0.9872$) rates of fomesafen. Out of 142 accessions, 132 and 140 exhibited 0% survival at the 1× and 2× rates, respectively (Table 1). Nine accessions in the low range (1% to 30%) survived the 1× rate. However, the low survival percentages did not differ from the 0% survival according to 95% confidence intervals. Similarly, two accessions were in the low survival group (1% to 30%) at the 2× rate of fomesafen (Table 1), which was also not different from the 0% group according to 95% confidence intervals. A survey conducted in North Carolina found four accessions with a 1% to 10% survival when fomesafen was applied at the 1× rate (Mahoney et al. 2020). In this study, 10 out of 142 accessions from South Carolina had reduced sensitivity to fomesafen; therefore, these accessions should be monitored for potential resistance in the future.

Glyphosate-resistant Palmer amaranth accessions were first confirmed in 2006 in South Carolina (Heap 2023; Nichols et al. 2009). Differences were observed in Palmer amaranth survival percentages at the 1× ($P < 0.0001$) and 2× ($P < 0.0001$) rates of glyphosate. At the 1× rate, one accession did not have any survivors (0%). Eleven accessions were in the low survival group (1%–30%) at both the 1× and 2× rates (Table 1). No differences were observed between the low survival percentages and the no-survivor group according to the 95% confidence intervals. In the moderate survival range (31%–60%), 18 accessions survived the 1× rate and 31 survived the 2× rate. However, 79% of the accessions from the survey (112 out of 142) survived the 1× rate of glyphosate (high survival range, 61%–100%). At the 2× rate of glyphosate, 99 accessions out of 142 survived the 2× rate of glyphosate (Table 1). Two studies from North Carolina observed high levels of Palmer amaranth resistance to glyphosate (Mahoney et al. 2020; Poirier et al. 2014). Based on these results, most accessions were low in susceptibility, indicating that Palmer amaranth remains resistant to glyphosate in South Carolina.

Palmer amaranth resistance to ALS-inhibiting herbicides was first observed in 1993 in Kansas (Heap 2023; Horak and Peterson 1995). In 1997, Palmer amaranth resistance to imazapic, imazaquin, and imazethapyr was confirmed in South Carolina (Gossett et al. 1998; Heap 2023). In this survey, 142 Palmer amaranth accessions were tested for susceptibility to thifensulfuron-methyl. Differences were observed for Palmer amaranth survival percentages at the 1× ($P = 0.0381$) and 2× ($P = 0.0079$) rates of thifensulfuron-methyl. Three accessions were controlled (0% survival) following application of the 1× and 2× rates of thifensulfuron-methyl (Table 1). No differences were observed between the low survival percentages (1% to 30%) and the no-survivor group according to the 95% confidence intervals. The low survival percentage (1%–30%) group had 44 accessions at the 1× rate. There were 43 accessions in the moderate survival group (31%–60%), and 52 accessions in the high survival group (61%–100%) at the 1× rate. There were 56, 42, and 41 accessions in the low (1%–30%), moderate (31%–60%), and high (61%–100%) survival groups at the 2× rate. Overall, lower survival was observed in the high survival group (37% and 29% for the 1× and 2×rates, respectively) than for glyphosate. Although Palmer amaranth accessions with resistance to ALS inhibitors were confirmed in South Carolina (Gossett et al. 1998), the overall response among the accessions varied (31% and 39% for the 1× and 2× rates, respectively) for the low survival range, indicating genetic heterogeneity. Mahoney et al. (2020) reported that 41 out of 110 North Carolina accessions were sensitive to thifensulfuron-methyl (16% or less) despite the previously documented ALS resistance in the state. However, the 1× rate of thifensufluron was 17.5 g ai ha^{-1}, which was equivalent to the 2× rate in this study. The relatively low to moderate survival observed in this survey may be due to the reduction in the use of ALS-inhibitor herbicides in South Carolina following the adoption of herbicide-tolerant crops in the late 1990s.

There were no Palmer amaranth survivors (0%) following a postemergence application of glufosinate, 2,4-D, or dicamba at the 1× and 2× rates (data not shown). However, other states have confirmed Palmer amaranth resistance to glufosinate (Jones et al. 2022; Priess et al. 2022), 2,4-D (Kumar et al. 2019), and dicamba (Foster and Steckel 2022).

This survey demonstrated the relative response of selected Palmer amaranth accessions to three preemergence and six postemergence herbicides commonly used on agronomic crops in South Carolina. Reduced sensitivity at the normal use rates of atrazine and *S*-metolachlor when applied preemergence was observed in about 40% of the accessions; however, only about 10%

of the accessions demonstrated lower sensitivity to the 1× rate of isoxaflutole applied preemergence. Additional research is needed to determine whether there is potential evolved resistance to these preemergence herbicides. For the postemergence-applied herbicides, moderate to high levels of survivors were observed when glyphosate and thifensulfuron-methyl were applied postemergence. In addition, there was one accession with reduced sensitivity to fomesafen applied postemergence at the 2× rate, which warrants future research on this accession for potential resistance. It should be noted that the higher potency of PPO-inhibitor herbicides applied postemergence in the greenhouse may have increased the sensitivity among the sampled accessions compared to field conditions. Glufosinate, 2,4-D, and dicamba provided 100% control of all Palmer amaranth accessions collected in this survey. The intent of this survey was to evaluate Palmer amaranth accession susceptibility to commonly used preemergence and postemergence herbicides in South Carolina. However, this survey did not sample these accessions at random and does not represent the actual distribution of Palmer amaranth in the state, and conclusions from this study should be drawn with caution. In summary, growers in South Carolina should consider using multiple control tactics when managing Palmer amaranth to minimize selection pressure. This would reduce the likelihood of the evolution of Palmer amaranth resistance to glufosinate, 2,4-D, and dicamba.

Practical Implications

Palmer amaranth is one of the most problematic weeds in corn, soybean, and cotton production. It is well documented that it can reduce crop yield by competing for water, light, and nutrients. In addition, Palmer amaranth has also evolved resistance to multiple herbicides across different modes of action. Therefore, growers see Palmer amaranth as the toughest challenge in their weed management programs. Without the development of new herbicide modes of action, there will be fewer effective products to mitigate Palmer amaranth effect on yield. Palmer amaranth resistance to different modes of action is prevalent throughout the southern United States. The introduction of HPPD-tolerant cotton and soybean will provide additional preemergence and postemergence timing options for isoxaflutole. In the South Carolina accessions, isoxaflutole applied preemergence controlled 90% of the accessions in this survey, indicating a high susceptibility in Palmer amaranth. Atrazine and *S*-metolachlor applied preemergence resulted in 38% and 49% of survivors, respectively, in the high (61% to 100%) survival group, indicating a reduction in susceptibility. However, additional research is needed to confirm whether these accessions with a low response have evolved resistance to atrazine and *S*-metolachlor when they are applied preemergence. Fomesafen applied postemergence controlled most of the accessions in this survey at both rates. However, susceptibility to glyphosate and thifensulfuron-methyl applied postemergence at the 1× and 2× rates was relatively low in the survey accessions. However, several accessions were controlled when thifensulfuron-methyl was applied postemergence. All accessions were effectively controlled when dicamba, 2,4-D, and glufosinate were applied postemergence at both rates. These herbicides are available for use on transgenic corn, cotton, and soybean varieties. Overall, several of the preemergence and postemergence herbicides evaluated in this study effectively controlled Palmer amaranth; however, reduced susceptibility was observed to *S*-metolachlor and atrazine herbicides, which were not known at the time of the survey. This research provides critical information to agronomic producers in developing an effective management plan for Palmer amaranth involving different control tactics, which reduces the potential selection pressure given the widespread use of these herbicides in South Carolina.

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