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Influence of Water Quality, Formulation, Adjuvant, Rainfastness, and Nozzle Type on Efficacy of Fomesafen on Palmer Amaranth (*Amaranthus palmeri*) Control

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Abstract

Protoporphyrinogen oxidase (PPO) inhibitors are one of the few remaining postemergence herbicide options for controlling Palmer amaranth in soybean growing areas of Mississippi, USA. Most Palmer amaranth populations in Mississippi are resistant to both glyphosate and acetolactate synthase inhibitors. Resistance to PPO inhibiting herbicides in Palmer amaranth has very recently been reported in Arkansas, Tennessee, and isolated pockets of Mississippi. A significant proportion of reports of PPO inhibitor failures in Mississippi are not considered to be resistance-related at this time. Therefore, the objective of this research was to evaluate factors affecting the efficacy of fomesafen on Palmer amaranth including: quality of spray carrier (water), formulations, adjuvant, rainfastness, and nozzle type. All water samples and formulation combinations provided >95% control of Palmer amaranth 3 WAT. Some combinations of water samples and formulations did not result in complete control of the treated plants, with one or two individuals surviving 3 WAT. Formulation 1 provided 99% control compared to 95% from formulation 2. Irrespective of combinations of herbicide, adjuvant and height, control of Palmer amaranth was ≥91%. Formulation 1 provided 94% control compared to 88% from formulation 2. The adjuvant x height interaction was significant, owing to a 10% reduction in control of larger plants (86%) compared to smaller plants (96%) in presence of COC. COC provided better control (93%) than NIS (88%). Simulated rainfall applied ≥60 min after herbicide application did not adversely affect efficacy on Palmer amaranth when formulation 1 was applied in combination with NIS, with control ranging from 94% to 100%. Formulation 1 with COC provided ≥93% control at all rainfall application times, except 30 min after herbicide treatment, which resulted in 79% control. Formulation 2 provided better control with COC (79% to 100%) than NIS (71% to 90%), in general, across the rainfall treatments applied at various times following herbicide application. All nozzle and weed height combinations resulted in 89% or better control of Palmer amaranth. In summary, water quality, formulation, adjuvant, rainfastness, or nozzle type did not affect the activity of fomesafen under optimal application conditions in the greenhouse.

Keywords

Adjuvant, Fomesafen, Formulation, Nozzle, Palmer Amaranth, Rainfastness, Soybean, Water Quality

1. Introduction

Widespread distribution of glyphosate-resistant (GR) weeds in soybean [*Glycine max* (L.) Merr.]-growing areas across Mississippi has economically affected soybean planting and follow-up crop management operations. Several of the GR weeds, especially pigweeds (*Amaranthus* spp.), are also resistant to acetolactate synthase (ALS)-inhibiting herbicides [1] thereby, limiting the number of herbicide choices for post weed control. Protoporphyrinogen oxidase (PPO) inhibitors are one of the few remaining postemergence (POST) weed control herbicide options, another being glufosinate in LibertyLink® (glufosinate-resistant) soybean, for soybean growers in Mississippi, USA.

New multiple herbicide-resistant crop technologies, involving dicamba and 2,4-D resistance, with associated formulations have been deregulated (transgenic traits by USDA)/registered (herbicide formulations by EPA), but their performance on large production fields is not clear. In 2016, several growers across the states of Arkansas, Missouri, Tennessee, and to a lesser extent in Mississippi treated fields planted to dicamba-resistant cotton (*Gossypium hirsutum* L.) and soybean with unauthorized/off-label/unregistered dicamba formulations, thereby, injuring large swaths of non dicamba-resistant soybean fields in the midsouthern US [2]. Injury to soybean from dicamba applications took a new turn in 2017. Labeled applications of registered dicamba formulations on dicamba-resistant soybean drifted (volatile/vapor drift and/or physical drift due to droplet movement owing to temperature inversion and other factors) off-target and injured an alarmingly large area, 1 million ha across the midwestern and southern U.S. [3] and 1.5 million ha across the U.S. (https://ipm.missouri.edu/IPCM/2017/10/final_report_dicamba_injured_soybean/), of non dicamba-resistant soybean. States like Arkansas are in the process of legislatively limiting the window of application of dicamba on dicamba-resistant soybean in the 2018 growing season [4]. Similar issues will most likely be encountered with 2,4-D-resistant crop technologies when commercialized. In addition, effectiveness of these technologies could be short-lived as it has been shown that Palmer amaranth can become less susceptible under conditions of continuous exposure to sub-lethal doses of dicamba [5].

Resistance to PPO-inhibiting herbicides in Palmer amaranth [*Amaranthus palmeri* (S.) Wats.] has recently been documented in Arkansas and Tennessee [6]. To date, resistance to PPO inhibitors in Mississippi has been isolated [7]. Recent research reported less than acceptable levels of control of Palmer amaranth from PPO inhibitors such as fomesafen [7], which indicates a developing issue of resistance to PPO inhibitors in Mississippi. It is not clear if field failures of PPO inhibitors are due to resistance or misapplication/adverse application conditions. Under the uncertain conditions of the utility of auxin (2,4-D and dicamba)-resistant crop technologies and the potential for wide spread development of PPO-resistant weed populations in Mississippi, prolonging the sustainability of PPO herbicides for MS soybean producers is of paramount importance.

Adjuvants improve an herbicide's efficacy [8] [9] by increasing its absorption [10] [11]. Adequate absorption across the leaf cuticle is key to the performance of contact type herbicides such as PPO inhibitors. The performance of adjuvants is influenced by the herbicide with which they are used, the weed species, water quality, and prevailing weather conditions [8] [10] [12]. Rainfastness is the property of an herbicide to be effective, via adequate drying on the applied plant or absorption by plant tissues, before the first rain after application. It can influence effectiveness of herbicides, particularly, contact type.

Therefore, the objective of this research was to evaluate the effect of water quality, formulation, adjuvant, rainfastness, and nozzle type on efficacy of fomesafen, a PPO inhibitor, on susceptible/wild type Palmer amaranth.

2. Materials and Methods

2.1. Seeding, Plant Growth, and Herbicide Treatment Conditions

All experiments were conducted in a greenhouse at the Jamie Whitten Delta States Research Center of USDA-ARS in Stoneville, Mississippi set to 25/20˚C ± 3˚C day/night temperature under ambient conditions. Wild type/susceptible (to all major families of herbicides, data not shown) Palmer amaranth seed was sown at a depth of 0.5 cm in plastic trays (50 cm × 20 cm× 6 cm) containing a commercial potting mix [formulated Canadian sphagnum peat moss, coarse perlite, bark ash, starter nutrient charge (with gypsum) and slow release nitrogen and dolomitic limestone] (Metro-Mix 360, Sun Gro Horticulture, Bellevue, WA) and watered. Two weeks after germination, 2.5-cm tall seedlings were transplanted into 8 cm × 8 cm × 7 cm pots containing the same potting mix. Thereafter, plants were watered as needed and fertilized once two weeks after transplanting with a water-soluble fertilizer (Miracle-Gro, Scotts Miracle-Gro Products, Inc., Marysville, OH). All herbicide treatment were applied using an air-pressurized indoor spray chamber (DeVries Manufacturing Co., Hollandale, MN) equipped with a nozzle mounted with 8002E flat-fan tip (Spraying Systems Co., Wheaton, IL), except additional nozzles being included in the Nozzle study, delivering 190 $L \cdot ha^{-1}$ at 220 kPa. Fomesafen was applied at 0.42 $kg \cdot ai \cdot ha^{-1}$, single highest dose recommended in Mississippi [13], in all experiments. All herbicide treatments were evaluated for efficacy based on percent control ratings (0 = no injury, 100 = dead) recorded 3 wk after treatment (WAT). Percent mortality was recorded 3 WAT only in the Water Quality and Formulation study. A plant was considered a survivor when there was evidence of green tissue in the axillary and/or terminal growing points. An individual plant represented one replication. There were 10 replications per treatment in the Water Quality and Formulation study, and 4 replications per treatments in all the other studies.

2.2. Water Quality and Formulation

All water samples were collected in 2016 in clean 3.8-L plastic containers and stored at 2 to 8 C until further use. Water sources included city or well at mixing facilities of participating members (commercial applicators) of the Mississippi Agricultural Aviation Association, county agents, and industry representatives (**Table 1**, **Figure 1**). Detailed information on water sources was provided only by few cooperators. Sources of water samples collected from the same county were at least 25 km apart to maintain randomness and uniqueness of location. Global Positioning System (GPS) coordinates were available for only a few of the samples, hence not shown. These water sources draw from deep groundwater aquifers, opposed to shallow groundwater aquifers which are primarily used for irrigation purposes. Aircraft applicators made up a bulk of the chosen sources since they apply herbicides on the largest crop area based on unit water source. An aliquot of each water sample was analyzed for selected properties by a commercial agricultural analytical laboratory (Waypoint Analytical, Memphis, TN, USA). A representative analytical report is shown in **Figure 2**. Palmer amaranth plants, 5- to 10-cm tall, three to six true leaves, were treated with three formulations: Flexstar® (formulation 1, 22.1% a.i., Syngenta Crop Protection, Greensboro, NC), Reflex® (formulation 2, 22.8% a.i., Syngenta Crop Protection), and Top Gun® (formulation 3, 22.8% a.i., Loveland Products, Inc., Greeley, CO), all at 0.42 kg ai/ha, using city or well water samples as spray carrier. All treatments included had crop oil concentrate (COC, Agridex®, Helena Chemical Co., Collierville, TN) at 1% v/v.

2.3. Formulation and Adjuvant

Both formulations 1 (Flexstar®) and 2 (Reflex®), described previously, were applied with a nonionic surfactant (NIS, Induce®, Helena Chemical Co.) at 0.25% v/v and a COC at 1% v/v to plants at four different growth stages, 2.9 to 3.8 cm, 5.6 to 7 cm, 9.1 to 9.6 cm, and 11.6 to 13.5 cm.

2.4. Adjuvant Rate

Both formulations 1 (Flexstar®) and 2 (Reflex®) were applied with an NIS at 0.25 and 0.5% v/v and a COC at 1 and 2% v/v to plants at two different growth stages, 11.5 to 15.5 and 24.8 to 26.8 cm.

Table 1. Details of water sampling locations and summary of water quality analyses.[a]

Sample#	County	Source	pH	Hardness	Fe	CO_3	HCO_3	Na	Cl
						mg·L^{-1}			
1	Bolivar	City	8.3	2.09	0.06	22	333	171	45
2	Bolivar	City	8.3	8.08	0.36	24	478	418	242
3	Bolivar	Well	8.1	449	0.8	39	384	18	37
4	Bolivar	City	8.4	18.2	0.35	36	323	166	39
5	Bolivar		8.7	1.33	0.05	39	101	100	30
6	Bolivar	City	8.5	4.46	0.05	29	483	231	35
7	Bolivar	City	8.6	2.07	0.06	34	434	189	20
8	Bolivar	City	8.3	22.4	0.05	39	338	163	37
9	Coahoma	Well	8.0	277	0.53	39	197	12	42
10	DeSoto	Well	7.7	266	13.7	0	278	14	14
11	DeSoto	City	8.0	12.2	0.16	10	145	65	11
12	Humphreys		8.2	5.34	0.09	24	163	78	18
13	Humphreys		8.3	1.95	0.05	22	163	90	12
14	Issaquena		8.6	3.06	0.05	49	483	282	81
15	Issaquena		8.4	3.04	0.05	29	471	281	75
16	Leflore		8.0	240	1.48	32	249	11	17
17	Leflore		8.4	3.89	0.05	49	259	136	7
18	Leflore		8.4	12.6	0.06	44	293	138	12
19	Leflore		8.5	3.98	0.05	39	269	126	12
20	Leflore		8.5	2.73	0.05	19	259	127	7
21	Madison		8.2	6.6	0.05	39	212	172	41
22	Sharkey	Well	7.9	419	2.22	27	419	15	11
23	Sharkey		9.0	1.78	0.05	87	392	223	30
24	Sharkey		8.7	2.43	0.05	36	394	201	33
25	Sharkey		8.5	2.42	0.05	44	382	199	36
26	Tallahatchie	City	8.4	8.81	0.05	10	328	408	289
27	Tallahatchie	City	8.3	3.81	0.12	24	274	147	27
28	Tallahatchie		7.9	18.4	0.05	19	163	72	21
29	Tallahatchie		8.5	4.37	0.14	51	234	121	28
30	Tallahatchie		8.0	7.23	0.2	27	269	148	41
31	Washington		8.1	76.5	0.05	32	338	116	22
32	Washington	Well	8.7	2.61	0.05	61	407	231	20
33	Washington		8.7	2.56	0.07	63	490	314	100
34	Washington		8.0	384	1.21	36	421	47	30
35	Washington		8.5	6.39	0.05	58	333	177	30
36	Washington		8.0	76	0.68	34	446	226	65
37	Washington	City	8.4	3.09	0.05	32	224	151	38
38	Washington	Well	9.1	2.36	0.05	95	352	241	81
39		Distilled Water	6.1	1.05	0.05	0	10	0	5

[a]The levels for each of the water quality parameters indicating severe, slight to moderate, and no problems/issues, respectively, were established as follows: pH: >7.9, <5.8 and 7.1 - 7.9, 5.8 - 7; hardness: >180, 60 - 180, <60; Fe: >1.5, 0.3 - 1.5, <0.3; CO_3: >510, 120-510, <120; HCO_3: >519, 122 - 519, <122; Na: >138, 69 - 138, <69; Cl: >179, 107 - 179, <107.

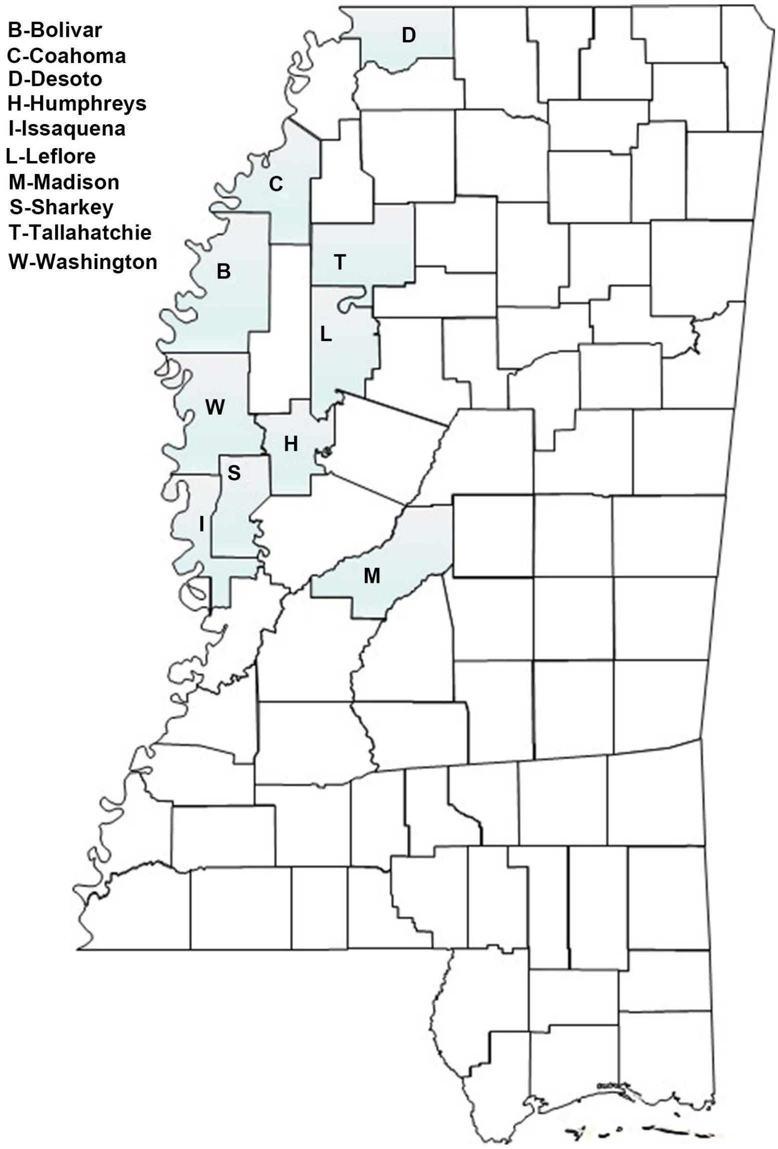

Figure 1. Map of counties in Mississippi where water samples were collected.

2.5. Rainfastness

Both formulations 1 (Flexstar®) and 2 (Reflex®) were applied with an NIS at 0.25% v/v and a COC at 1% v/v to 10-cm-tall plants. Treated plants were sprayed with simulated rainfall equivalent to 0.5 cm [14] for a duration of 0, 10, 30, 60, 120, and 240 min. After each rainfall timing, plants were returned to the greenhouse.

2.6. Nozzle

In this experiment, nine different nozzles, 8002, Airmix 110-02 (agrotop, Obertraubling, Germany), TT360, AITT36011002, AI11002VS, TTI02, DG11002VS, AIXR11002, 11002, were evaluated using the indoor spray chamber mentioned before. All nozzles, except Airmix 11-02, were acquired from Spraying Systems Co., Wheaton, IL, USA. Formulation 2 (Reflex®) was applied with a COC at 1%

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IRRIGATION WATER

Send to :	Project :	Report No :	**16-159-0299**
USFA-ARS	Analytical Testing	Cust No :	20048
Mr. Earl Gordon		Date Printed :	06/09/2016
PO Box 350		Date Received :	06/07/2016
Stoneville , MS 38776		Page :	
		Lab Number :	**90496**

Sample Id : **1**

CATIONS		mg/L	meq/L
Sodium	Na	14	0.61
Calcium	Ca	77	3.84
Magnesium	Mg	18	1.48
Potassium	K	3	0.08
Ammonium	NH_4	1	0.07
	NH_4 - N	1	
SUM OF CATIONS			**6.08**

ANIONS		mg/L	meq/L
Chloride	Cl	14	0.39
Sulfate	SO_4	21	0.44
	S	7	
Bicarbonate	HCO_3	278	4.56
Carbonate	CO_3	0	0.00
Nitrate	NO_3	0	0.00
	NO_3 - N	0	
Phosphate	PO_4	2	0.06
	P	1	
SUM OF ANIONS			**5.45**

Hydrogen Ion Activity	pH	7.7	
Equilibrium Reaction	pHc	6.17	
Electrical Conductivity	ECw	0.53	dS/m
Total Dissolved Solids	TDS	339	mg/L
Adj Na Adsorption Ratio	SARadj	0.48	
Sodium Adsorption Ratio	SAR	0.37	
Hardness		266	ppm

Copper	Cu	0.01	mg/L
Zinc	Zn	0.06	mg/L
Manganese	Mn	0.85	mg/L
Iron	Fe	13.70	mg/L
Boron	B	0.05	mg/L
Fluoride	F		
Aluminum	Al	0.40	mg/L
Molybdenum	Mo	0.02	mg/L

mg/L = parts per million parts water meq/L - milliequivalents per liter
Hardness is determined from calculations using the calcium and magnesium concentrations in the water.
TDS calculated by ECw * 640

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(a)

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IRRIGATION WATER

Send to :	Project :	
USFA-ARS Mr. Earl Gordon PO Box 350 Stoneville , MS 38776	Analytical Testing	Report No : **16-159-0299** Cust No : 20048 Date Printed : 06/09/2016 Date Received : 06/07/2016 Page : Lab Number : **90496**

Sample Id : **1**

WATER ANALYSIS INTERPRETATION, AGRICULTURAL

Potential Problem	Units	Test Result	Degree of Restriction on Use: Criteria None	Criteria Slight to Moderate	Criteria Severe	Graphical Results (None / Slight to Moderate / Severe)
Salinity						
ECw[1]	dS/m	0.53	< 0.7	0.7 - 3	> 3	
Specific Ion Toxicity						
Sodium (Na)[1]						
Surface irrigation	SARadj	0.48	< 3	3 - 9	> 9	
Sprinkler irrigation[2]	meq/L	0.61	< 3	3 - 6	> 6	
Chloride (Cl)[1]						
Surface irrigation	meq/L	0.39	< 4	4 - 10	> 10	
Sprinkler irrigation[2]	meq/L	0.39	< 3	3 - 5	> 5	
Boron (B)[1]	mg/L	0.05	< 0.7	0.7 - 3	> 3	
Fluoride (F)[1]			< 1	1 - 5	> 5	
Clogging of Drip Systems or Unsightly Residues						
Iron (Fe)[3]	mg/L	13.70	< 0.3	0.3 - 1.5	> 1.5	
Manganese (Mn)[3]	mg/L	0.85	< 0.2	0.2 - 1.5	> 1.5	
pH - pHc[4]		1.53	<= 0	> 0		
Reduced Water Infiltration[5] **(Ratio based on adjSAR / ECw)**		0.91	< 4	4 - 10	> 10	
Alkalinity						
Bicarbonate (HCO_3) + Carbonate (CO_3)[6]	meq/L	4.56	< 2	2 - 8.5	> 8.5	
Potential Low Nutrient Issues (Soilless media)[7]						
Sulfate	mg/L	21	> 48	48 - 20	< 20	
Magnesium	mg/L	18	> 10	10 - 4	< 4	
Boron	mg/L	0.05	> 0.3	0.3 - 0.05	< 0.05	

1. Crop tolerance to salinity, sodium, chloride, boron and fluoride varies widely. Most tree crops are sensitive to sodium and chloride while many annual crops are not. Soil conditions, irrigation method and climate must be considered.
2. Leaf burn from foliar and root absorption will be enhanced under conditions of : low humidity, high temperature and high air movement .
3. Elevated iron in combination with sulfides or tannins can result in bacterial slimes that can clog drip systems. Removal of iron and manganese often involves oxidation (aeration or chlorination) followed by filtering.
4. Positive pH - pHc (saturation index) values indicate the potential for calcium and magnesium carbonate precipitates that might impair efficiency of irrigation systems with small orificed parts and/or may leave unsightly lime deposits on leaves. Problems can be reduced by mineral acid addition.
5. Infiltration problems are most likely when water with low ECw and/or high SAR adj. is used on mineral soils containing some silt and clay. Evaluation of infiltration problems should include analysis of both irrigation water and soil-water extracts. Treatment may involve injecting gypsum into the water or applying gypsum to the soil surface.
6. Bicarbonate when excessive may result in difficulty in controlling soil pH and may impair root assimilation of minor elements.
7. Sulfur, magnesium and /or boron may become limiting if not supplied by soil or fertilizer. Use soil and leaf analysis to confirm need.

Comments :

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(b)

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IRRIGATION WATER

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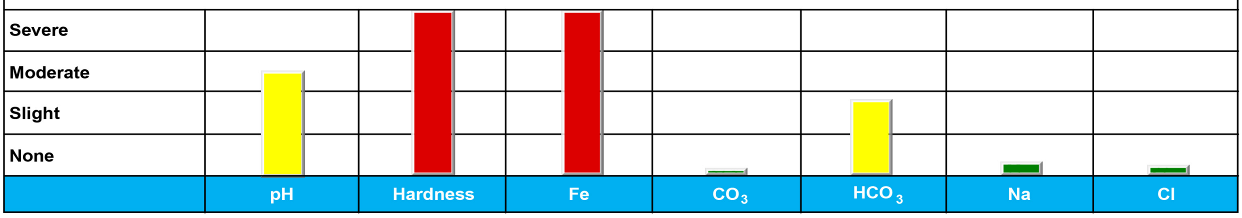
USFA-ARS	Analytical Testing	Cust No : 20048
Mr. Earl Gordon		Date Printed : 06/09/2016
PO Box 350		Date Received : 06/07/2016
Stoneville , MS 38776		Page :
		Lab Number : **90496**

Sample Id : **1**

SPRAY WATER ANALYSIS INTERPRETATION

Potential Problem	pH	Hardness	Iron	Carbonate	Bicarbonate	Sodium	Chloride
Test Result	7.7	266	13.70	0	278	14	14
Units	s.u	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Severe	> 7.9	> 180	> 1.5	> 510	> 519	> 138	> 179
Slight to Moderate	< 5.8 ; 7.1 - 7.9	60 - 180	0.3 - 1.5	120 - 510	122 - 519	69 - 138	107 - 179
None	5.8 - 7	< 60	< 0.3	< 120	< 122	< 69	< 107



One or more potential problems are moderate to severe. Consider the use of a water conditioner or a different water source.
Water Hardness indicates water conditioning recommended.
For weak acid herbicides (which includes most of those applied post), buffering is recommended when pH exceeds 7.5. Optimum range for pH is between 3.0 and 6.0.
For insecticide/fungicide active ingredients that are subject to decomposition by alkaline hydrolysis, buffer addition is recommended when pH exceeds 7.0. Optimum range is pH between 3.0 and 5.0 depending on active ingredient.
For glyphosate, buffering is recommended when pH exceeds 5.0. Optimum range is pH between 3.0 and 4.5.
Iron at this level may antagonize glyphosate.

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(c)

Figure 2. A representative water analysis report. of counties in Mississippi where water samples were collected.

v/v to plants at 3 growth stages, 4.25 to 6, 6.13 to 8, and 10.4 to 13.8 cm. formulations 1 (Flexstar®) and 2 (Reflex®) were applied with an NIS at 0.25 and 0.5% v/v and a COC at 1 and 2% v/v to plants at two different growth stages, 11.5 to 15.5 and 24.8 to 26.8 cm.

2.7. Statistical Analyses

All experiments were conducted using a completely randomized design and repeated. Data from all experiments were subjected to ANOVA using the PROC GLM statement in SAS (version 9.2, SAS Institute, Inc., Cary, NC, USA). Data from repeated experiments were pooled due to a non-significant experimental effect. Treatment means were separated using Fisher's Protected LSD test at P = 0.05.

3. Results and Discussion

3.1. Water Quality and Formulation

Analytical report for each water sample included individual estimates of cations such as Na^+, Ca^{2+}, Mg^{2+}, K^+, and NH_4^+, anions such as Cl^-, SO_4^{2-}, S^{2-}, HCO_3^-, CO_3^{2-}, NO_3^-, PO_4^{3-}, and P^{3-}, minerals such as Cu, Zn, Mn, Fe, B, F, Al, and Mo, and other parameters such as pH, electrical conductivity, and hardness (Figure 2). The levels for each of the water quality parameters indicating severe, slight to moderate, and no problems/issues, respectively, were established as follows: pH: >7.9, <5.8 and 7.1 - 7.9, 5.8 - 7; hardness: >180, 60 - 180, <60; Fe: >1.5, 0.3 - 1.5, <0.3; CO_3: >510, 120 - 510, <120; HCO_3: >519, 122 - 519, <122; Na: >138, 69 - 138, <69; Cl: >179, 107 - 179, <107 (Table 1). Herbicide applicators will, no doubt, add buffering and conditioning agents to the water before large-scale treatment of fields. However, we added no amendments to the water samples before testing for efficacy of fomesafen on Palmer amaranth. All results including analytical reports and efficacy results have been shared with cooperating aircraft applicators, county agents and growers.

There was no impact of water quality, formulation or water quality x formulation interaction on Palmer amaranth control and mortality (data not shown). All water samples and formulation combinations provided >95% control of Palmer amaranth 3 WAT (data not shown). Some combinations of water samples and formulations did not result in complete control of the treated plants, with one or two individuals surviving 3 WAT (Table 2). Overall, water quality did not adversely affect the efficacy of any of the three fomesafen formulations evaluated despite the marked variation (Table 1) observed in the levels of various parameters measured across different locations.

In Tables 3-6, treatment means for significant main and interaction effects are provided followed by p-values for all sources included in the ANOVA model. The last set of values in any given table represent treatment means of all factors in the interaction containing all main effects, except where such an interaction was significant and whose values have already been reported in the table prior to the p-values.

Table 2. Effect of water quality and fomesafen formulation on Palmer amaranth mortality, 3 wk after treatment.

Fomesafen	Sample#	Mortality
		%
Formulation 1	1	90
	2	95
	4	90
Formulation 2	1	95
	2	95
	3	90
	4	90
	5	95
	7	95
	31	95
	37	95
	39	95
Formulation 3	1	95
	4	95
	6	95
	7	95
	36	95
	38	95
	39	95

3.2. Formulation and Adjuvant

Among main and interaction effects, only the formulation main effect impacted control of Palmer amaranth (Table 3). Formulation 1 provided 99% control compared to 95% from formulation 2. Irrespective of combinations of herbicide, adjuvant and height, control of Palmer amaranth was ≥91% (Table 3).

3.3. Adjuvant Rate

Among main effects, formulation impacted control of Palmer amaranth (Table 4). Formulation 1 provided 94% control compared to 88% from formulation 2. The adjuvant x height interaction was significant, owing to a 10% reduction in control of larger plants (86%) compared to smaller plants (96%) in presence of COC (Table 4).

3.4. Rainfastness

Adjuvant type had a significant impact on Palmer amaranth control (Table 5). COC provided better control (93%) than NIS (88%). The three-way interaction

Table 3. Effect of fomesafen formulation and adjuvant on Palmer amaranth control, 3 wk after treatment.[a]

Main/Interaction factor			P value	Control
				%
Formulation 1				99
Formulation 2				95
LSD (0.05)				3
Formulation			0.0116	
Adjuvant			0.9391	
Height			0.1927	
Formulation × adjuvant			0.7599	
Formulation × height			0.5037	
Adjuvant × height			0.6252	
Formulation × adjuvant × height			0.9470	
Main factor				
Formulation 1	NIS	Height 1		100
		Height 2		100
		Height 3		100
		Height 4		98
	COC	Height 1		100
		Height 2		96
		Height 3		99
		Height 4		100
Formulation 2	NIS	Height 1		100
		Height 2		94
		Height 3		91
		Height 4		93
	COC	Height 1		100
		Height 2		91
		Height 3		94
		Height 4		95

[a]Abbreviations: COC, crop oil concentrate; NIS nonionic surfactant.

between formulation adjuvant and rainfall timing after herbicide treatment was significant for Palmer amaranth control. Simulated rainfall applied ≥60 min after herbicide application did not adversely affect efficacy on Palmer amaranth when formulation 1 was applied in combination with NIS, with control ranging from 94% to 100%. Formulation 1 with COC provided ≥93% control at all rainfall application times, except 30 min after herbicide treatment, which resulted in 79% control. Formulation 2 provided better control with COC (79% to 100%) than NIS (71% to 90%), in general, across the rainfall treatments applied at various times following herbicide application.

Table 4. Effect of fomesafen formulation, adjuvant and adjuvant rate on Palmer amaranth control, 3 wk after treatment.[a]

Main/Interaction factor				P value	Control
					%
Formulation 1					94
Formulation 2					88
LSD (0.05)					5
	NIS		Height 1		88
			Height 2		93
	COC		Height 1		97
			Height 2		86
LSD (0.05)					7
Formulation				0.0111	
Adjuvant				0.6864	
Adjuvant rate				0.1658	
Height				0.2182	
Formulation × adjuvant				0.6180	
Formulation × adjuvant rate				0.4449	
Formulation × height				0.8866	
Adjuvant × height				0.0049	
Formulation × adjuvant × adjuvant rate				0.1822	
Formulation× adjuvant × height				0.0548	
Formulation × adjuvant × adjuvant rate × height				0.1281	
Main factor					
Formulation 1	NIS	0.25	Height 1		94
			Height 2		97
		0.5	Height 1		95
			Height 2		92
	COC	1	Height 1		96
			Height 2		96
		2	Height 1		98
			Height 2		88
Formulation 2	NIS	0.25	Height 1		87
			Height 2		84
		0.5	Height 1		77
			Height 2		98
	COC	1	Height 1		100
			Height 2		89
		2	Height 1		94
			Height 2		73

[a]Abbreviations: COC, crop oil concentrate; NIS nonionic surfactant.

3.5. Nozzle

Neither of the main effects, nozzle type nor height of Palmer amaranth, nor the interaction significantly influenced Palmer amaranth control when treated with

Table 5. Effect of rainfastness on efficacy of fomesafen on Palmer amaranth, 3 wk after treatment.[a]

Main/Interaction factor			P value	Control
				%
NIS				93
COC				88
LSD (0.05)				5
Formulation 1	NIS	MAT 0		86
		MAT 10		85
		MAT 30		85
		MAT 60		100
		MAT 120		94
		MAT 240		100
	COC	MAT 0		100
		MAT 10		95
		MAT 30		79
		MAT 60		100
		MAT 120		98
		MAT 240		93
Formulation 2	NIS	MAT 0		90
		MAT 10		89
		MAT 30		89
		MAT 60		83
		MAT 120		88
		MAT 240		71
	COC	MAT 0		79
		MAT 10		90
		MAT 30		87
		MAT 60		100
		MAT 120		96
		MAT 240		100
LSD (0.05)				3
Formulation			0.0556	
Adjuvant			0.0407	
MAT			0.1159	
Formulation × adjuvant			0.3040	
Formulation × MAT			0.2892	
Adjuvant × MAT			0.4768	
Formulation × adjuvant × MAT			0.0063	

[a]Abbreviations: COC, crop oil concentrate; MAT, min after treatment; NIS nonionic surfactant.

Table 6. Effect of nozzle type on efficacy of fomesafen on Palmer amaranth, 3 wk after treatment.

Main/Interaction factor		P value	Control
			%
Nozzle type		0.3755	
Height		0.2051	
Nozzle type × Height		0.9204	
8002	Height 1		100
	Height 2		95
	Height 3		100
Airmix 110-02	Height 1		100
	Height 2		100
	Height 3		100
TT360	Height 1		100
	Height 2		100
	Height 3		95
AITT36011002	Height 1		100
	Height 2		98
	Height 3		90
AI11002V	Height 1		94
	Height 2		100
	Height 3		89
TTI02	Height 1		94
	Height 2		100
	Height 3		89
DG11002VS	Height 1		100
	Height 2		100
	Height 3		100
AIXR11002	Height 1		100
	Height 2		100
	Height 3		100
11002	Height 1		100
	Height 2		100
	Height 3		100

formulation 2 in combination with COC (**Table 6**). All nozzle and weed height combinations resulted in 89% or better control of Palmer amaranth (**Table 6**).

In summary, water quality, formulation, adjuvant, rainfastness, or nozzle type did not affect efficacy of fomesafen on Palmer amaranth. Of course, activity of other PPO inhibitors could be influenced by one or more of the above parameters. Reports of PPO inhibitor failures in the field must be taken seriously after considering the role of these factors on each individual reported case.

4. Conclusions

This research, especially, with water quality analysis, is an "out-of-the-box" approach to eliminate factors that may result in the mis-diagnosis of non-performance of a PPO inhibitor as a case of resistance. An aircraft applicator from DeSoto County, Mississippi has indicated his readiness to switch from a city water supply to a well at his mixing facility to save on costs, based on results on water quality provided to him from this research.

Uncertainties in commercialization of auxin-resistant crop technologies, coupled with related escalating rhetoric and lack of postemergence herbicide alternatives in soybean with no major herbicide mode of action commercialized in about 20 years [15], have severely limited weed management strategies for soybean growers of Mississippi. Additionally, sporadic development of resistance to PPO inhibiting herbicides in pigweed populations of Mississippi has been documented and there exists a potential for the spread of resistance on a broader scale due to repeated selection pressure and other non-mitigating factors. Hence, the research reported here is very relevant in that application parameters evaluated here can be modified to prolong the sustainability of PPO inhibitors as well as slow the spread of resistance to PPO inhibitors such as fomesafen, which is clearly the preferred treatment in glyphosate-resistant soybean. The research described above can be applicable to several post emergence applied herbicides such as other PPO inhibitors (e.g., acifluorfen, lactofen, saflufenacil), ALS inhibitors (e.g., chlorimuron, imazamox, pyrithiobac, penoxsulam), ACCase inhibitors (e.g., fenoxaprop, clethodim, pinoxaden), photosystem II inhibitors (e.g., atrazine), photosystem I inhibitors (ex. paraquat), glyphosate, glufosinate, 2,4-D, and dicamba labeled for use in various crops including soybean, corn, and cotton grown in the southeastern US.

Fomesafen can be an effective weed management tool for growers in Mississippi and other parts of the US and the world, provided, other control strategies such as cultural and mechanical practices are incorporated in to an integrated weed management program. The results from this research indicate that while some Palmer amaranth populations exhibit trending resistance to fomesafen, fomesafen and other PPO inhibitors still have a role in broad leaf weed management programs. Nevertheless, non performance of all herbicides should be evaluated by taking both biotic (weed growth stage, etc.) and abiotic (weather, application parameters such as water quality, formulation, adjuvant, rainfastness, nozzles, etc.) factors into account.

Disclaimer

Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the US Department of Agriculture.

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