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Herbicide programs for control of a five-way herbicide resistant waterhemp population in Xtendflex or Enlist E3 soybean

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Abstract

Waterhemp [*Amaranthus tuberculatus* (Moq.) J.D. Sauer] is one of the most problematic weeds in soybean [*Glycine max* (L.) Merr.] production in the Midwestern United States. In recent years, the adoption of soybean resistant to dicamba, 2,4-D, and/or glufosinate have enabled the use of these herbicides to improve control of problematic weeds. Field experiments were conducted in Indiana in 2021 and 2022 to determine effective herbicide programs for controlling a waterhemp population resistant to herbicides in Weed Science Society of America (WSSA) Groups 2, 4, 5, 9, and 14. Two soybean varieties, one resistant to dicamba, glufosinate, and glyphosate, and the other resistant to 2,4-D, glufosinate, and glyphosate were evaluated. Preemergence applications included an auxin herbicide, either 2,4-D or dicamba, applied with pyroxasulfone and flumioxazin. Postemergence applications included combinations of 2,4-D or dicamba, glyphosate, and glufosinate. No more than 6% soybean injury from all postemergence applications was observed in 2021 and no injury was observed in 2022. By 21 days after the second postemergence application, two-pass herbicide programs increased waterhemp control by at least 30% compared to one-pass systems. Comparatively, two pass postemergence programs were more effective in 2021 and preemergence followed by postemergence programs were more effective in 2022. Control of waterhemp with 2,4-D and dicamba was similar in 2021; however, 2,4-D was more effective than dicamba in 2022, indicating the diminishing utility of dicamba in this field. Results from this study suggest that effective control of multiple-resistant waterhemp population is most likely achieved with two-pass herbicide programs that include 2,4-D tank-mixed with other effective herbicides, such as glufosinate.

Abbreviations: DASP, days after second POST; DAT, days after treatment; EPSPS, 5-enolpyruvylshiki-mate-4-phosphate synthase; POST, postemergence; POST-POST, postemergence followed by postemergence; PRE, preemergence; PRE-POST, preemergence followed by postemergence; ROS, reactive oxygen species; WAT, weeks after treatment; WSSA, Weed Science Society of America.

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Plain Language Summary

Waterhemp is one of the most problematic weed species in soybean production in the Midwestern United States. The introduction of soybean varieties resistant to 2,4-D, dicamba, and/or glufosinate has enabled the use of these herbicides to improve control of weeds like waterhemp. This study evaluated the control of a multiple-resistant waterhemp population by looking at different herbicide active ingredients and application timings. The results indicated that the use of preemergence followed by postemergence programs were most consistent at reducing waterhemp density. Additionally, with this multiple-resistant population, the use of effective herbicides, such as glufosinate, is important to achieve good control of waterhemp and not allow for seeds to return to the seedbank.

1 | INTRODUCTION

Waterhemp [*Amaranthus tuberculatus* (Moq.) J.D. Sauer] is a competitive summer annual broadleaf weed that has been identified as one of the most problematic weeds in US soybean [*Glycine max* (L.) Merr.] production (Sauer, 1955; Van Wychen, 2022). In Indiana, waterhemp germination extends from mid-April through August (Heneghan, 2016), with season-long waterhemp interference capable of causing up to a 56% yield loss in soybean (Bensch et al., 2003; Steckel, 2007). Therefore, effective waterhemp management is necessary to minimize competition and maximize soybean yield. Waterhemp possesses a dioecious reproductive system, which facilitates high genetic diversity (Steckel, 2007) and long-distance pollen movement increases the spread of favorable alleles, such as herbicide resistance traits (Liu et al., 2012).

Across the Midwestern United States, resistance to seven different mode of action groups has been documented in waterhemp, including Weed Science Society of America (WSSA) Group 2 acetolactate synthase (ALS) inhibitors (Patzoldt & Tranel, 2007), Group 4 synthetic auxins (Bernards et al., 2012), Group 5 photosystem II (PSII) inhibitors (Foes et al., 1998), Group 9 5-enolpyruvyl shikimate-3-phosphate synthase (EPSPS) inhibitors (Legleiter & Bradley, 2008), Group 14 protoporphyrinogen oxidase (PPO) inhibitors (Shoup et al., 2003), Group 15 very long chain fatty acid (VLCFA) inhibitors (Strom et al., 2019), and Group 27 4-hydroxyphenyl pyruvate dioxygenase (HPPD) inhibitors (Hausman et al., 2011). While a single plant may only express one of these herbicide resistance traits, many waterhemp populations possess multiple herbicide-resistance traits. Foes et al. (1998) documented the first multiple-herbicide-resistant waterhemp population with resistance to Group 2 and 5 herbicides. Since 1998, waterhemp populations have been documented with resistance to three, four, five, and sometimes, six herbicide mode of action groups (Bell et al. 2013; Evans et al., 2019; Legleiter & Bradley, 2008; Shergill et al., 2018). Due to the rapid development of herbicide resistance in waterhemp, alternative control options are necessary to control these problematic populations.

Glufosinate, a WSSA Group 10 herbicide, inhibits the glutamine synthetase enzyme, resulting in the accumulation of glutamate and ammonia and the formation of reactive oxygen species (ROS), thereby, disrupting cell membranes (Hack et al., 1994; Takano & Dayan, 2020). Because glufosinate is non-selective, it has historically been used in non-crop areas or in preplant burndown applications. However, the commercialization of glufosinate-resistant soybeans in 2009 allowed for postemergence use of the herbicide for broad-spectrum weed control, including many glyphosate-resistant weed populations (Ross et al., 2015). The recent spread of glyphosate-resistance in many weed species has resulted in a rapid increase in glufosinate use for broad-spectrum weed control, largely in soybean (Duke, 2018). Although glufosinate is generally effective for controlling waterhemp, the potency of the herbicide appears to be diminishing, especially in populations with multiple-herbicide resistance. For example, in the early 2000's, 4- to 5-inch tall waterhemp was completely controlled with 0.36 lb ai acre^{-1} of glufosinate (Beyers et al., 2002). However, Sarangi et al. (2015) applied 0.53 lb ai acre^{-1} of glufosinate but only reported 84% control of glyphosate-resistant waterhemp at 21 days after treatment (DAT). More recently, Shergill et al. (2018) applied 2.04 lb ai acre^{-1} of glufosinate, about three times the labelled rate, but did not achieve greater than 90% control of a waterhemp population exhibiting resistance to six herbicide modes of action at 28 DAT.

Glufosinate activity is highly dependent on environmental conditions (Anderson et al., 1993; Carlson & Burnside, 1984), and weed control is generally greater in conditions of high light intensity, high humidity, and warm temperatures (Coetzer et al., 2002; Wendler et al., 1990). For example, Takano et al. (2019) reported 82% and 4% injury on Palmer amaranth (*Amaranthus Palmeri* S. Watson) following glufosinate applications in light and dark conditions, respectively,

because ROS production occurred only in plants exposed to light. With glufosinate efficacy being variable due to weather, tank-mixing with other chemistries, such as 2,4-D or dicamba, has been shown to improve the consistency of control on glyphosate-resistant waterhemp (Bobadilla et al., 2022; Craigmyle et al., 2013).

Dicamba and 2,4-D are synthetic auxin herbicides that imitate the naturally occurring plant hormone indole-3-acetic acid (IAA) which regulates plant growth and development (Fu et al., 2015; Todd et al., 2020). Preplant and postemergence broadleaf weed control using 2,4-D has been prevalent in grass crops since its widespread commercialization in the 1950's (Munro et al., 1992; Peterson et al., 2016). In a field experiment conducted in Indiana, over 90% control of waterhemp was documented with a 1 lb ae acre rate of 2,4-D at 28 DAT (Robinson et al., 2012). However, in 2012, plants from a waterhemp population in Nebraska were less than 50% controlled with a 32 lb ae acre^{-1} rate of 2,4-D in a field experiment at 28 DAT, confirming 2,4-D resistance (Bernards et al., 2012). More recently, additional populations have been confirmed resistant to 2,4-D across the Midwest (Evans et al., 2019; Shergill et al., 2018). Dicamba use has also been prevalent for the control of broadleaf weeds in grass crops (Johnson et al., 2010). Effective waterhemp control of >85% has been documented with the use of dicamba at 28 DAT (Anderson et al., 1996; Vyn et al., 2006). However, instances of control failure with dicamba have been documented, where less than 30% control was reported with 0.5 lb ae acre^{-1} rate of dicamba (Spaunhorst & Bradley, 2013). In 2022, a waterhemp population from Illinois had a 10-fold higher level of resistance to dicamba than known sensitive populations (Bobadilla et al., 2022).

Maintaining weed-free fields is critical for the protection of soybean yield potential, and the use of two-pass herbicide programs have previously provided more consistent control of herbicide-resistant waterhemp. Hedges et al. (2018) documented a 24% increase in glyphosate-resistant waterhemp control at 8 weeks after postemergence (POST) application with the use of a two-pass herbicide program compared to a PRE-only program. Duenk et al. (2023) documented a 29% and 38% reduction in multiple-resistant waterhemp control with one-pass PRE and one-pass POST programs, respectively, compared to PRE followed by POST programs. Reductions in waterhemp density of 4.5X and 31X were reported when PRE and POST only programs, respectively, were compared to PRE-POST programs at 4 weeks after POST application (Schryver et al., 2017).

In addition to using two-pass herbicide programs, another best management practice (BMP) for controlling troublesome weeds, like waterhemp, while also mitigating the risk of herbicide resistance is the use of herbicides from multiple effective mode of action groups (Norsworthy et al., 2012). Prior to crop emergence, many growers will apply a premix or tank-mix containing multiple herbicide active ingredients that have residual activity for broad spectrum weed control. Previous research has documented >90% control of broadleaf weeds, such as waterhemp, in soybean when two or more chemistries are used in a preemergence (PRE) application at 4 weeks after treatment (WAT) (Hedges et al., 2019; Meyer et al., 2016). The addition of a residual herbicide in tank-mixture with a POST herbicide application has also shown to be effective for controlling waterhemp populations. The inclusion of acetochlor in an early POST application of glufosinate made 21 days after planting increased waterhemp control by 6% in comparison to glufosinate alone 14 days after application (Jhala et al., 2017). Striegel et al. (2021) documented a reduction in waterhemp density when acetochlor at 1.1 lb ae acre^{-1} was added to a POST application of dicamba plus glyphosate compared to dicamba plus glyphosate applied alone at 28 days after the POST application at V6.

The development of soybean technologies that allow for POST over-the-top applications of dicamba and 2,4-D, as well as glufosinate and glyphosate, facilitate the use of tank-mixes with multiple active ingredients to control glyphosate-resistant waterhemp. Craigmyle et al. (2013) reported a 22% increase in control of 4- to 5-inch waterhemp in 2,4-D resistant soybean when 2,4-D and glufosinate were applied together compared to glufosinate alone. Underwood et al. (2017) reported that the addition of glyphosate to a POST application of dicamba increases control of redroot pigweed by as much as 33% 2 weeks after application compared to dicamba alone. These herbicide resistance traits in soybean allow for herbicide options and combinations to control waterhemp population with resistance to multiple herbicide mode of action groups.

Failure to control waterhemp using dicamba in dicamba-resistant soybeans has been observed by Indiana growers since 2019 (William G. Johnson, personal communication, 2020). Seeds collected from Francesville, IN (40.91°N, −86.89°W), were used in a series of preliminary experiments to determine potential herbicide-resistance characteristics in this population. Molecular assay confirmed resistance to WSSA Group 2 herbicides via the Trp574 mutation, to glyphosate via an increase in EPSPS copy number, and to WSSA Group 14 herbicides via the ΔG210 mutation (Bland, 2024). This population also exhibited resistance to foliar applications of atrazine and dicamba, but the mechanism is unknown (Bland, 2024). Applications of a synthetic auxin herbicide (dicamba or 2,4-D) in tank-mixture with glyphosate, and/or glufosinate have been shown to control problematic weeds, including multiple-resistant waterhemp (Riar et al., 2013). Control of glyphosate-resistant Palmer amaranth with different herbicide programs containing glyphosate, glufosinate, and 2,4-D has been recently documented (Shyam et al., 2021). This research was conducted to evaluate the use of different herbicide programs containing dicamba or 2,4-D plus glyphosate

and/or glufosinate, with or without a preceding soil residual herbicide application, in dicamba or 2,4-D resistant soybean systems to control a five-way resistant waterhemp population.

2 | MATERIALS AND METHODS

2.1 | Site description and field plot design

Field experiments were conducted in 2021 and 2022 at a no-till field site near Francesville, IN (40.91°N, −86.89°W), on a waterhemp population resistant to herbicides from WSSA mode of action groups 2, 4, 5, 9, and 14 (Bland, 2024). The soil type was a sandy loam (75% sand, 14% silt, and 11% clay) with 2.4% organic matter and a pH of 7.5. One day prior to planting, a burndown application of paraquat (Gramoxone, Syngenta Crop Protection LLC) at 0.5 lb ai acre^{-1} plus a nonionic surfactant at 0.25% v/v was made to remove winter annual and early emerged summer annual weeds. The experimental design was a 2 × 16 factorial design with four replications. One factor was soybean variety (Enlist E3 Stine 32EA12 or Xtendflex Asgrow AG29XF1) and the experiment was blocked by this factor. The second factor was herbicide program, PRE only, PRE followed by POST (PRE-POST), POST only, and two-pass POST (POST-POST), which were randomized within each soybean variety block. Each herbicide program included the corresponding auxin herbicide in every program, except the nontreated check, which was 2,4-D for the Enlist variety and dicamba for the Xtendflex variety. Additional herbicides used and rates in herbicide programs can be viewed in Table 1.

Soybeans were planted on May 15, 2021, and May 12, 2022, at 140,000 seeds acre^{-1} in rows 30 inches apart. Each plot was 10-ft wide by 30-ft long. PRE herbicide applications were made within 24 h of planting in both years using a 6.67-ft-wide boom CO_2-pressurized backpack sprayer fitted with four TTI 110015 nozzles (TeeJet Technologies) calibrated to deliver 15 gal per acre at 40 PSI. The first POST application was made 29 and 28 days after planting in 2021 and 2022, respectively, when waterhemp was 3- to 6-inches tall in plots that had not received a PRE application. Waterhemp plants from plots that did receive a PRE application were, on average, 0- to 6-inches tall at the first POST application timing. POST applications were made using a CO_2-pressurized backpack sprayer fitted with four TTI 110015 or AIXR 110015 nozzles for dicamba or 2,4-D, respectively, and applied as described above. A second POST application was made on 47 and 43 days after planting in 2021 and 2022, respectively, to POST-POST treatments when waterhemp regrowth was observed. Throughout the duration of the season, a Watchdog Weather Station (Spectrum Technologies) was used to measure daily rainfall accumulation.

2.2 | Data collection and statistical analysis

Visual assessments of crop injury and weed control were taken for the entire plot at the time of the second POST application (0 days), and at 7 and 21 days after the second POST (DASP) application. Crop injury and weed control were rated on a scale of 0 to 100%, where 0% indicates no injury and 100% indicates complete death. In addition to visual evaluations, waterhemp density was assessed at the same time by counting waterhemp plants in two, 2.7-ft^2 quadrats, one positioned near the front of the plot and one near the back, which were combined for analysis. At the end of the growing season, soybeans were harvested with a plot combine, seed weight was corrected to 13% moisture content, and yield was calculated in lb per acre^{-1}. Data were subjected to an ANOVA using the PROC GLIMMIX procedure of SAS v. 9.4 (SAS Institute Inc.). Herbicide programs and soybean variety were the main factors and were treated as fixed effects along with year and replication was treated as a random effect. When ANOVA indicated significant treatment effects, means were separated using Tukey's Honest Significant Difference test at an alpha of 0.05. Additionally, contrast statements were conducted to compare the influence of application timing strategies and differences grouped over POST herbicide actives. Statements included types of herbicide programs, one- vs two-pass programs, PRE-only vs POST-only one-pass programs, and PRE-POST vs POST-POST programs. Additional contrast statements were used to compare dicamba programs to 2,4-D programs and the efficacy of glyphosate and glufosinate when included the tank-mixture of the first POST application, and pyroxasulfone applied PRE vs pyroxasulfone applied with the first POST application. Due to substantial differences in precipitation patterns between 2021 and 2022 (Table 2) and its effect on waterhemp emergence and herbicide performance, the ANOVA indicated to separate waterhemp control data and soybean yield by year. Additionally, there was no interaction between soybean variety and herbicide treatment on soybean yield in either year, so data were pooled across soybean varieties.

3 | RESULTS AND DISCUSSION

3.1 | Rainfall discussion

Rainfall timing and accumulation were different between the two site years for this experiment, which can be viewed in Table 2. In May in 2021, there were no rainfall events until the last week of May, a full week after planting and PRE herbicide application, while in May of 2022 there were rainfall events within 3 days of planting and PRE herbicide application. Rainfall is important for PRE herbicide activation and movement in the soil profile; therefore these differences

TABLE 1 Herbicide treatments tested at Francesville, IN, location in 2021 and 2022.

Treatment	Active ingredients	Application timing	Rate
1	nontreated check	—	—
2	glyphosate + [auxin] [a]	PRE	0.948 lb ae acre + [auxin]
3	pyroxasulfone + flumioxazin + [auxin]+ glyphosate	PRE	0.1 lb ai acre + 0.080 lb ai acre + [auxin] + 0.948 lb ae acre
4	pyroxasulfone + flumioxazin + [auxin] + glyphosate fb [auxin]+ glyphosate	PRE fb POST	0.1 lb ai acre + 0.080 lb ai acre + [auxin] + 0.948 lb ae acre fb [auxin] + 0.948 lb ae acre
5	pyroxasulfone + flumioxazin + [auxin] + glyphosate fb [auxin]+ glufosinate	PRE fb POST	0.1 lb ai acre + 0.080 lb ai acre + [auxin] + 0.948 lb ae acre fb [auxin] + 0.58 lb ai acre
6	pyroxasulfone + flumioxazin + [auxin] + glyphosate fb [auxin]+ glufosinate + glyphosate	PRE fb POST	0.1 lb ai acre + 0.080 lb ai acre + [auxin] + 0.948 lb ae acre fb [auxin] + 0.58 lb ai acre + 0.948 lb ae acre
7	pyroxasulfone + flumioxazin + [auxin]+ glyphosate fb [auxin]+ glufosinate + pyroxasulfone	PRE fb POST	0.1 lb ai acre + 0.080 lb ai acre + [auxin] + 0.948 lb ae acre fb [auxin] + 0.58 lb ai acre + 0.081 lb ai acre
8	[auxin] + glyphosate	POST	[auxin] + 0.948 lb ae acre
9	[auxin] + glufosinate [b]	POST	[auxin] + 0.58 lb ai acre
10	[auxin] + glufosinate + glyphosate	POST	[auxin] + 0.58 lb ai acre + 0.948 lb ae acre
11	[auxin] + glyphosate fb [auxin] + glyphosate	POST fb POST	[auxin] + 0.948 lb ae acre fb [auxin] + 0.948 lb ae acre
12	[auxin] + glyphosate fb [auxin] + glufosinate	POST fb POST	[auxin] + 0.948 lb ae acre fb [auxin] + 0.58 lb ai acre
13	[auxin] + glufosinate fb [auxin] + glufosinate	POST fb POST	[auxin] + 0.58 lb ai acre fb [auxin] + 0.58 lb ai acre
14	[auxin] + glufosinate fb [auxin] + glyphosate	POST fb POST	[auxin] + 0.58 lb ai acre fb [auxin] + 0.948 lb ae acre
15	[auxin] + glufosinate + glyphosate fb [auxin] + glufosinate + glyphosate	POST fb POST	[auxin] + 0.58 lb ai acre + 0.948 lb ae acre fb [auxin] + 0.58 lb ai acre + 0.948 lb ae acre
16	[auxin] + glufosinate + pyroxasulfone fb [auxin] + glufosinate	POST fb POST	[auxin] + 0.58 lb ai acre + 0.081 lb ai acre fb [auxin] + 0.58 lb ai acre

Note: Products were sourced from the following companies: Valent U.S.A. Corporation, Walnut Creek, CA, Corteva Agriscience LLC, Indianapolis, IN, Bayer Crop Science LP, St. Louis, MO, BASF Corporation, Research Triangle Park, NC.

Abbreviations: fb, followed by; PRE, preemergence; POST, postemergence.

[a][auxin] indicates either dicamba at 0.498 lb ae acre with Voliminate at 20 fl oz/acre, Intact at 0.5% v/v, and Class Act Ridion at 1% v/v **OR** 2,4-D at 1.37 lb ae acre with AMS at 2.5% v/v, dependent on soybean variety.

[b]Combination of glufosinate + dicamba is not currently registered for commercial use in dicamba-resistant soybean.

may have affected the study results. In June of 2021, rainfall events were consistent throughout the entire month, therefore plants were growing normally. However, in 2022, very little rainfall accumulated in the last 2 weeks, causing plants to be drought stressed and may have affected herbicide performance. By July in both years, rainfall events were consistent, alleviated drought stress, and plants were growing normally.

3.2 | Soybean injury

No crop injury was observed for either soybean variety for any herbicide or application timing in 2022. Crop injury symptomology observed in 2021 included chlorotic speckling, caused by foliar herbicides, and leaf malformation, caused by pyroxasulfone. There was no more than 6% crop injury for any

TABLE 2 Weekly precipitation distribution for the months of May, June, and July at Francesville, IN, in 2021 and 2022.

Month	Dates	2021	2022
		inches	
May	1–7	0.0	0.0
	8–14	0.0	0.0
	15–21	0.0	0.5
	22–31	2.4	0.3
Total for May	1–31	2.4	0.8
June	1–7	0.4	0.7
	8–14	0.6	0.5
	15–21	1.2	0.0
	22–30	4.3	0.01
Total for June	1–30	6.5	1.21
July	1–7	0.01	1.0
	8–14	1.9	0.5
	15–21	0.8	0.9
	22–31	0.6	3.1
Total for July	1–31	3.31	5.5
Total for May–July		12.21	7.51

treatment in either system. Injury at the time of the second POST application (0 DASP) was <2% and <5% for all PRE and single POST treatments in the Enlist and Xtendflex programs, respectively (data not shown). At 7 DASP, only Xtendflex and Enlist treatments that received a second POST application displayed crop injury, which ranged from 0% to 6% (data not shown). There were no differences in crop injury between herbicide programs and soybean varieties at 21 DASP in 2021 (data not shown). Even though some injury was observed, research has shown no significant yield loss when herbicides are applied in accordance with the label (Kapusta et al., 1986; Priess et al., 2020a; Young et al., 2003).

3.3 | Waterhemp control

Fifteen different herbicide programs, plus a nontreated check, were included for both the Enlist and Xtendflex systems (Table 1). Most of the discussion that follows focuses on the general trends identified by the contrast statements. At 7 and 21 DASP, one-pass programs (PRE-only and POST-only) resulted in less waterhemp control than two-pass programs for both the Enlist and Xtendflex systems in both 2021 and 2022 (Contrast 1, Table 3). In 2021, PRE-only resulted in a 2%–6% increase in waterhemp control compared to POST-only programs at 7 and 21 DASP, but in 2022, PRE-only resulted in a larger increase, 41%, compared to POST-only programs at both evaluation timings (Contrast 2, Table 3). No one-pass POST-only program provided >60% waterhemp control in either year for both systems at 7 and 21 DASP. Previous research has documented inadequate waterhemp control, less than 60% at 4 WAT, with only a POST herbicide application (Schryver et al., 2017) and greater waterhemp control when herbicide programs included a PRE application compared to those without (Sarangi et al., 2017).

In 2021, the effect of PRE-POST vs POST-POST were not consistent across ratings: at 7 DASP, PRE-POST program waterhemp control was on average 7% higher (82%–96%) than POST-POST programs (53%–97%) (Contrast 3, Table 3). However, at 21 DASP, PRE-POST programs ranged 69%–93% and POST-POST programs ranged 70%–98%, and POST-POST provided 5% greater control than PRE-POST on average (Contrast 3, Table 3). In contrast, in 2022, PRE-POST provided greater control at both 7 DASP, on average, 24% greater control (88%–99%) than POST-POST (48%–91%), and 21 DASP, on average, 14% greater control where PRE-POST ranged 90%–96% and POST-POST ranged 50%–98% (Contrast 3, Table 3). The increase in control observed from PRE herbicides in 2022 may be due to drought conditions throughout the month of June (Table 2) which reduced weed seed germination (Singh et al., 2022). Levels of control with two-pass programs (Treatments 4–7 and 11–16) at 21 DASP varied from 69% to 98% in 2021 and 50% to 98% in 2022 for both the Enlist and Xtendflex soybean systems (Table 3). For PRE-POST programs, the inclusion of glufosinate and either glyphosate or pyroxasulfone in the POST application resulted in greater than 90% control in all soybean systems except Enlist in 2021. For POST-POST programs, greater than 85% control was achieved in all soybean systems except Xtendflex in 2022 with programs that either (1) included both glufosinate and glyphosate in tank-mix with the corresponding auxin or (2) included pyroxasulfone in the first POST application. Greater than 90% control of glyphosate-resistant Palmer amaranth has been previously documented at 6 weeks after POST application with two-pass herbicide programs, both PRE followed by POST and two POST applications, that included combinations of herbicides from groups 4 and 9 (Kumar et al., 2019). Similarly, greater than 90% control of glyphosate-resistant waterhemp with a PRE followed by POST programs that included combinations of herbicides from WSSA Groups 4, 9, 14, and 15 was documented by Hedges et al. (2018) at 12 WAT.

In both years and at both evaluation timings, the inclusion of glufosinate in tank-mixture with a synthetic auxin increased waterhemp control from 4% to 12% compared to tank-mixtures with glyphosate (Contrast 5, Table 3). This was expected because the waterhemp population at Francesville was glyphosate-resistant. Previous research has documented more effective control of waterhemp when glufosinate or

TABLE 3 Waterhemp control at all evaluation timings as influenced by the interaction of herbicide treatment and soybean herbicide system at the Francesville, IN, location in 2021 and 2022.

		7 DASP				21 DASP			
		2021		2022		2021		2022	
Treatment	Application timing	Enlist	Xtendflex	Enlist	Xtendflex	Enlist	Xtendflex	Enlist	Xtendflex
		%							
1	NONTREATED	0 i	0 i	0 m	0 m	0 j	0 j	0 j	0 j
2	PRE-ONLY	0 i	0 i	0 m	0 m	0 j	0 j	0 j	0 j
3	PRE-ONLY	23 h	65 c	80 c-h	94 a-c	16 i	66 f	80 cd	90 a-c
4	PRE-POST	84 ab	90 ab	88 a-e	94 a-c	81 b-f	81 b-f	90 a-c	94 a-c
5	PRE-POST	88 ab	86 ab	99 a	96 ab	82 b-e	73 d-f	95 ab	95 ab
6	PRE-POST	82 b	90 ab	95 ab	98 a	69 ef	91 a-c	93 a-c	96 a
7	PRE-POST	95 ab	96 ab	98 a	95 ab	78 c-f	93 ab	96 a	93 a-c
8	POST-ONLY	43 fg	30 gh	58 ij	35 kl	35 gh	26 hi	58 fg	33 i
9	POST-ONLY	40 fg	39 fg	60 ij	30 L	35 gh	30 g-i	48 gh	30 i
10	POST-ONLY	50 d-f	48 ef	58 ij	33 L	43 g	40 gh	43 hi	30 i
11	POST-POST	59 c-e	53 c-f	68 hi	48 jk	83 a-e	70 ef	86 a-d	50 gh
12	POST-POST	94 ab	65 c	83 b-g	71 f-i	91 a-c	73 d-f	96 a	65 ef
13	POST-POST	95 ab	90 ab	91 a-d	75 e-h	93 ab	87 a-d	98 a	80 cd
14	POST-POST	89 ab	63 cd	70 g-i	60 ij	87 a-d	74 d-f	81 b-d	53 f-h
15	POST-POST	97 a	92 ab	85 a-f	78 d-h	92 a-c	90 a-c	96 a	73 de
16	POST-POST	96 ab	94 ab	91 a-d	76 e-h	98 a	94 ab	98 a	81 b-d
Contrasts									
1	ONE PASS VS TWO PASS	42% VS 85%*		56% VS 79%*		36% VS 84%*		52% VS 85%*	
2	PRE-ONLY VS POST-ONLY	44% VS 42%*		87% VS 46%*		41% VS 35%*		85% VS 44%*	
3	PRE-POST VS POST-POST	89% VS 82%*		95% VS 71%		81% VS 86%*		94% VS 80%*	
4	2,4-D VS DICAMBA	74% VS 72%*		80% VS 70%*		69 VS 70%		83% VS 69%*	
5	GLYPHOSATE VS GLUFOSINATE	61% VS 73%*		65% VS 69%*		63% VS 67%*		69% VS 76%*	
6	PYROXASULFONE PRE VS POST	87% VS 95%*		95% VS 84%*		80% VS 96%*		94% VS 90%*	

Note: Means in both soybean varieties at the same evaluation timing with like letters are not statistically different based on Tukey's Honest Significant Difference ($\alpha \leq 0.05$).

Abbreviations: DASP, days after second postemergence application; PRE, preemergence; POST, postemergence.

*Significance at $P \leq 0.05$.

glyphosate was included in tank-mixtures with synthetic auxins, either 2,4-D or dicamba (Duenk et al., 2023; Jhala et al., 2017).

In this study, the effect of the residual herbicide timing on waterhemp control was different between the 2 years. In 2021, pyroxasulfone applied POST resulted in greater waterhemp control than pyroxasulfone applied PRE. In 2022, the opposite effect was observed, pyroxasulfone applied PRE resulted in greater control (Contrast 6, Table 3). This variation was likely due to a lack of precipitation for 2 weeks after pyroxasulfone was applied POST in 2022 (Table 2). A previous study documented poor control of *Amaranthus* species when no rainfall accumulation occurred within 7 days of PRE herbicide application (Priess et al., 2020b). However, the addition of a residual herbicide, specifically a Group 15 herbicide like pyroxasulfone, to a POST application has been shown to increase waterhemp control compared to POST applications without a residual herbicide (Aulakh & Jhala, 2015).

In 2021, programs with 2,4-D provided slightly greater waterhemp control than programs with dicamba at 7 DASP (74% vs 72%), but there was no difference at 21 DASP (69% vs 70%) (Contrast 4, Table 3). However, in 2022, 2,4-D based programs provided 10% or greater waterhemp control than dicamba-based programs at both timings (Contrast

TABLE 4 Waterhemp density at 7 days after second postemergence application as influenced by soybean herbicide program at Francesville, IN, in both years.

Variety	Waterhemp density[a]
	——plants per 5.4 ft^2——
Xtendflex (dicamba)	24 A
Enlist (2,4-D)	12 B

Note: Means with like letters are not statistically different based on Tukey's Honest Significant Difference ($\alpha \geq 0.05$).

[a]Waterhemp counts are a combined total of the two quadrats.

4, Table 3). The continual use of the same herbicide places selection pressure on a weed population to evolve resistance (Montgomery, 2020), so the continued use of dicamba at this location with a population already segregating for resistance may continue to diminish the utility of dicamba.

3.4 | Waterhemp density

At 7 DASP, there was no interaction between year and other variables. When data were pooled across all herbicide treatments, waterhemp density was higher in the dicamba based system (24 per 5.4 ft^2) than 2,4-D based system (12 per 5.4 ft^2) (Table 4), likely due to the presence of dicamba and glyphosate resistance in this population (Bland, 2024). Density data for the Enlist and Xtendflex soybean systems were combined due to a non-significant interaction between them (data not shown). Contrast analysis revealed that two-pass programs resulted in 4X reduction waterhemp density than one-pass programs at 7 DASP (Contrast 1, Table 5), similar to observations of greater reduction in density from PRE-POST programs compared to one-pass programs (Soltani et al., 2009). In addition, PRE-POST programs had fewer waterhemp plants than POST-POST programs

TABLE 5 Waterhemp density at 7 days after second postemergence application as influenced by herbicide treatment across both soybean varieties at Francesville, IN, in 2021 and 2022.

Treatment	Application timing	Waterhemp density[a]
		————plants per 5.4 ft^2————
1	NONTREATED	39 ab
2	PRE-ONLY	29 ab
3	PRE-ONLY	4 b
4	PRE-POST	1 b
5	PRE-POST	1 b
6	PRE-POST	1 b
7	PRE-POST	0.3 b
8	POST-ONLY	41 ab
9	POST-ONLY	24 ab
10	POST-ONLY	72 a
11	POST-POST	28 ab
12	POST-POST	12 ab
13	POST-POST	8 b
14	POST-POST	14 ab
15	POST-POST	9 b
16	POST-POST	6 b
Contrasts		
1	ONE PASS VS TWO PASS	35 VS 8*
2	PRE-ONLY VS POST-ONLY	4 VS 46 NS[†]
3	PRE-POST VS POST-POST	1 VS 13*
4	GLYPHOSATE VS GLUFOSINATE	23 VS 11 NS
5	PYROXASULFONE PRE VS POST	1 VS 6*

Note: Means with like letters are not statistically different based on Tukey's Honest Significant Difference ($\alpha \geq 0.05$).

Abbreviations: PRE, preemergence; POST, postemergence.

[a]Waterhemp counts are a combined total of the two quadrats.

*Significance at $P \leq 0.05$.

[†]NS, non-significant difference.

TABLE 6 Waterhemp density at 21 days after second postemergence application as influenced by the interaction of herbicide treatment and soybean herbicide system at Francesville, IN, in 2021 and 2022[2].

Treatment	Application timing	Enlist	Xtendflex
		plants per 5.4 ft^2	
1	NONTREATED	31 ab	26 abc
2	PRE-ONLY	31 ab	11 cdefg
3	PRE-ONLY	2 efg	2 efg
4	PRE-POST	1 fg	0.125 g
5	PRE-POST	1 fg	1 fg
6	PRE-POST	1 fg	0.125 g
7	PRE-POST	0.40 g	0.25 g
8	POST-ONLY	18 bcdefg	44 a
9	POST-ONLY	17 bcdefg	19 bcdef
10	POST-ONLY	21 bcde	20 bcde
11	POST-POST	2 efg	19 bcdef
12	POST-POST	0.25 g	10 cdefg
13	POST-POST	0.125 g	4 defg
14	POST-POST	1.6 fg	15 bcdefg
15	POST-POST	0.40 g	7 defg
16	POST-POST	0 g	3 defg
Contrasts			
1	ONE PASS VS TWO PASS	18 VS 3*	
2	PRE-ONLY VS POST-ONLY	2 VS 23 NS†	
3	PRE-POST VS POST-POST	1 VS 5*	
4	GLYPHOSATE VS GLUFOSINATE	14 VS 7*	
5	PYROXASULFONE PRE VS POST	1 VS 2*	
6	2,4-D VS DICAMBA	5 VS 10*	

Note: Means with like letters are not statistically different based on Tukey's Honest Significant Difference ($\alpha \geq 0.05$).
*Significance at $P \leq 0.05$.
†Non-significant difference.

(Contrast 3, Table 5), similar to visual control estimates (Table 3). At 7 DASP, the addition of pyroxasulfone in the PRE application reduced waterhemp density more than its inclusion in a POST application (Contrast 5, Table 5).

At 21 DASP, there was no interaction with year, but there was an interaction between herbicide program and soybean system (Table 6). However, the conclusions drawn from contrast statements were similar to those made for 7 DASP data. Two-pass herbicide programs reduced waterhemp density compared to one-pass programs, 3 and 18 plants per 5.4 ft^2, respectively (Contrast 1, Table 6). PRE-POST herbicide programs had fewer waterhemp plants (1 per 5.4 ft^2) than two-pass POST programs (5 per 5.4 ft^2) (Contrast 3, Table 6), and this observation has been previously documented (Schryver et al., 2017). POST applications that included pyroxasulfone did not reduce waterhemp density as much as the addition of a PRE application (Contrast 5, Table 6). The addition of glufosinate instead of glyphosate in tank-mixture across all herbicide programs in both systems reduced waterhemp density by 50% and the use of 2,4-D reduced waterhemp density by 50% in comparison to treatments that used dicamba (Contrasts 4 and 6, Table 6).

3.5 | Soybean yield

In 2021, soybean yield, pooled across all herbicide treatments, was higher with the 2,4-D based system (4500 lb acre^{-1}) than the dicamba based system (4020 lb acre^{-1}) (Table 7). POST-only treatments had a higher yield than the PRE-only treatments (Table 8). Also in 2021, an average yield reduction of roughly 240 lb per acre^{-1} was observed in one-pass compared to two-pass programs (Contrast 1, Table 8). However, there were no yield differences between PRE-POST and POST-POST systems (Contrast 3, Table 8). Yields were lower in 2022, likely due to 4.7 inches less precipitation through the

TABLE 7 Soybean yield as affected by soybean herbicide system at Francesville, IN, in 2021. Data for all herbicide treatments were pooled for this average.

Variety	Yield
	lb acre^{-1}
Xtendflex	4020 b
Enlist	4500 a

Note: Means with like letters are not statistically different based on Tukey's Honest Significant Difference ($\alpha \geq 0.05$).

summer months compared to 2021, and many herbicide treatments were not different from the nontreated check (Table 8). However, two pass POST treatments that included glufosinate in the second application (treatments 13, 15, and 16) had yields 2376–2472 lb acre^{-1} higher than the nontreated check (Table 8). Higher yields have been documented where a two-pass herbicide program was used, either PRE followed by POST or two timely POST applications, in comparison to one-pass herbicide programs (Duenk et al., 2023; Legleiter et al., 2009).

3.6 | Practical implications

Waterhemp is a challenging weed to control in the Midwestern United States because of its propensity to develop resistance to multiple herbicide mode of action groups due to its dioecious nature and high genetic diversity (Liu et al., 2012; Steckel, 2007). Acceptable control of multiple-resistant waterhemp in the Enlist or Xtendflex soybean system is not consistently achievable with a one-pass herbicide program, even if it includes multiple effective modes of action. PRE-POST and POST-POST programs can both be

TABLE 8 Soybean yield pooled across both soybean varieties affected by herbicide treatment at Francesville, IN, in 2021 and 2022.

		Yield	
Treatment	Application timing	2021	2022
		lb acre^{-1}	
1	NONTREATED	3378 c	1380 c
2	PRE-ONLY	3192 c	1644 bc
3	PRE-ONLY	3792 bc	3048 abc
4	PRE-POST	4512 a	4938 a
5	PRE-POST	4314 ab	3588 abc
6	PRE-POST	4494 ab	2520 abc
7	PRE-POST	4326 ab	2472 bc
8	POST-ONLY	4548 a	3078 abc
9	POST-ONLY	4206 ab	3288 abc
10	POST-ONLY	4326 ab	2850 abc
11	POST-POST	4470 ab	3120 abc
12	POST-POST	4476 ab	3624 ab
13	POST-POST	4500 ab	3852 ab
14	POST-POST	4578 a	2628 abc
15	POST-POST	4596 a	3804 ab
16	POST-POST	4314 ab	3756 ab
Contrasts			
1	ONE PASS VS TWO PASS	4218 VS 4458*	3066 VS 3430 NS
2	PRE-ONLY VS POST-ONLY	3792 VS 4360*	3048 VS 3071 NS
3	PRE-POST VS POST-POST	4412 VS 4489 NS†	3380 VS 3463 NS
4	GLYPHOSATE VS GLUFOSINATE	4510 VS 4313 NS	3711 VS 3576 NS
5	PYROXASULFONE PRE VS POST	4412 VS 4314 NS	3380 VS 3756 NS

Note: Means with like letters are not statistically different based on Tukey's Honest Significant Difference ($\alpha \geq 0.05$).

Abbreviations: PRE, preemergence; POST, postemergence.

*Significance at $P \leq 0.05$.

†NS, non-significant difference.

effective, dependent upon weather conditions and the inclusion of multiple effective modes of action. However, PRE-POST programs were more consistent at reducing waterhemp density than POST-POST programs. Understanding the resistance profile of waterhemp in a field will aid in making effective soybean trait package and herbicide choices to control waterhemp and slow the evolution of herbicide resistance. For example, at the Francesville location where this research was conducted, the repeated use of dicamba in a population segregating for dicamba resistance may have diminished its utility in the second year. With this population being five-way resistant, the use of effective modes of action, like glufosinate, as well as PRE herbicides is critical for control of waterhemp and protection of potential soybean yield at this location.

AUTHOR CONTRIBUTIONS

Claudia R. Bland: Conceptualization; data curation; formal analysis; investigation; methodology; writing—original draft; writing—review and editing. **Stephen L. Meyers**: Conceptualization; writing—review and editing. **Mark L. Bernards**: Conceptualization; writing—review and editing. **William G. Johnson**: Conceptualization; methodology; supervision; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

CRB is currently employed by Syngenta.

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REFERENCES

Anderson, D., Roeth, F., & Martin, A. (1996). Occurrence and control of triazine-resistant common waterhemp (*Amaranthus rudis*) in field corn (*Zea mays*). *Weed Technology*, *10*(3), 570–575. https://doi.org/10.1017/S0890037X00040458

Anderson, D. M., Swanton, C. J., Hall, J. C., & Mersey, B. G. (1993). The influence of soil moisture, simulated rainfall, and time of application on the efficacy of glufosinate ammonia. *Weed research*, *33*, 139–147. https://doi.org/10.1111/j.1365-3180.1993.tb01927.x

Aulakh, J. S., & Jhala, A. J. (2015). Comparison of glufosinate-based herbicide programs for broad-spectrum weed control in glufosinate-resistant soybean. *Weed Technology*, *29*(3), 419–430. https://doi.org/10.1614/WT-D-15-00014.1

Bell, M., Hager, A., & Tranel, P. (2013). Multiple resistance to herbicides from four site-of-action groups in waterhemp (*Amaranthus tuberculatus*). *Weed Science*, *61*(3), 460–468. https://doi.org/10.1614/WS-D-12-00166.1

Bensch, C., Horak, M., & Peterson, D. (2003). Interference of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. Palmeri*), and common waterhemp (*A. rudis*) in soybean. *Weed Science*, *51*(1), 37–43. https://doi.org/10.1614/0043-1745(2003)051[0037:IORPAR]2.0.CO;2

Bernards, M. L., Crespo, R. J., Kruger, G. R., Gaussoin, R., & Tranel, P. J. (2012). A waterhemp (*Amaranthus tuberculatus*) population resistant to 2,4-D. *Weed Science*, *60*(3), 379–384. https://doi.org/10.1614/WS-D-11-00170.1

Beyers, J., Smeda, R., & Johnson, W. (2002). Weed management programs in glufosinate-resistant soybean (*Glycine max*). *Weed Technology*, *16*(2), 267–273. https://doi.org/10.1614/0890-037X(2002)016[0267:WMPIGR]2.0.CO;2

Bland, C. R. (2024). *Efficacy of synthetic auxin herbicides on segregating populations of waterhemp (*Amaranthus tuberculatus) [Master's thesis, Purdue University].

Bobadilla, L. K., Giacomini, D. A., Hager, A. G., & Tranel, P. J. (2022). Characterization and inheritance of dicamba resistance in a multiple-resistant waterhemp (*Amaranthus tuberculatus*) population from Illinois. *Weed Science*, *70*(1), 4–13. https://doi.org/10.1017/wsc.2021.76

Carlson, K., & Burnside, O. C. (1984). Comparative phytotoxicity of glyphosate, SC-0345 and HOE-0061. *Weed Science*, *32*, 841–844. https://doi.org/10.1017/S0043174500060094

Coetzer, E., Al-Khatib, K., & Peterson, D. (2002). Glufosinate efficacy on Amaranthus species in glufosinate-resistant soybean (*Glycine max*). *Weed Technology*, *16*(2), 326–331. https://doi.org/10.1614/0890-037X(2002)016[0326:GEOASI]2.0.CO;2

Craigmyle, B., Ellis, J., & Bradley, K. (2013). Influence of herbicide programs on weed management in soybean with resistance to glufosinate and 2,4-D. *Weed Technology*, *27*(1), 78–84. https://doi.org/10.1614/WT-D-12-00099.1

Duenk, E., Soltani, N., Miller, R. T., Hooker, D. C., Robinson, D. E., & Sikkema, P. H. (2023). Multiple-herbicide-resistant waterhemp control in glyphosate/glufosinate/2,4-D-resistant soybean with one- and two-pass weed control programs. *Weed Technology*, *37*(1), 34–39. https://doi.org/10.1017/wet.2023.6

Duke, S. O. (2018). The history and current status of glyphosate. *Pest Management Science*, *74*(5), 1027–1034. https://doi.org/10.1002/ps.4652

Evans, C., Strom, S., Riechers, D., Davis, A., Tranel, P., & Hager, A. (2019). Characterization of a waterhemp (*Amaranthus tuberculatus*) population from Illinois resistant to herbicides from five site-of-action groups. *Weed Technology*, *33*, 400–410. https://doi.org/10.1017/wet.2019.19

Foes, M. J., Liu, L., Tranel, P. J., Wax, L. M., & Stoller, E. W. (1998). A biotype of common waterhemp (*Amaranthus rudis*) resistant to

triazine and ALS herbicides. *Weed Science*, *46*(5), 514–520. https://doi.org/10.1017/S0043174500091013

Fu, S. F., Wei, J. Y., Chen, H. W., Liu, Y. Y., Lu, H. Y., & Chou, J. Y. (2015). Indole-3-acetic acid: A widespread physiological code in interactions of fungi with other organisms. *Plant Signal Behavior*, *10*(8), e1048052. https://doi.org/10.1080/15592324.2015.1048052

Hack, R., Ebert, E., Ehling, G., & Leist, K. H. (1994). Glufosinate ammonium—Some aspects of its mode of action in mammals. *Food and Chemical Toxicology*, *32*(5), 461–470. https://doi.org/10.1016/0278-6915(94)90043-4

Hausman, N. E., Singh, S., Tranel, P. J., Riechers, D. E., Kaundun, S. S., Polge, N. D., Thomas, D. A., & Hager, A. G. (2011). Resistance to HPPD-inhibiting herbicides in a population of waterhemp (*Amaranthus tuberculatus*) from Illinois, United States. *Pest Management Science*, *67*, 258–261. https://doi.org/10.1002/ps.2100

Hedges, B., Soltani, N., Hooker, D., Robinson, D., & Sikkema, P. (2018). Control of glyphosate-resistant waterhemp with two-pass weed control strategies in glyphosate/dicamba-resistant soybean. *American Journal of Plant Sciences*, *9*, 1424–1432. https://doi.org/10.4236/ajps.2018.97104

Hedges, B., Soltani, N., Hooker, D., Robinson, D., & Sikkema, P. (2019). Control of glyphosate-resistant waterhemp with preemergence herbicides in glyphosate- and dicamba-resistant soybean. *Canadian Journal of Plant Science*, *99*(1), 34–39. https://doi.org/10.1139/cjps-2018-0046

Heneghan, J. M. (2016). *The biology and management of waterhemp in Indiana* [Master's thesis, Purdue University].

Jhala, A. J., Sandell, L. D., Sarangi, D., Kruger, G. R., & Knezevic, S. Z. (2017). Control of glyphosate-resistant common waterhemp (*Amaranthus rudis*) in glufosinate-resistant soybean. *Weed Technology*, *31*(1), 32–45. https://doi.org/10.1017/wet.2016.8

Johnson, B., Young, B., Matthews, J., Marquardt, P., Slack, C., Bradley, K., York, A., Culpepper, S., Hager, A., Al-Khatib, K., Steckel, L., Moechnig, M., Loux, M., Bernards, M., & Smeda, R. (2010). Weed control in dicamba-resistant soybeans. *Crop Management*, *9*, 1–23. https://doi.org/10.1094/CM-2010-0920-01-RS

Kapusta, G., Jackson, L., & Mason, D. (1986). Yield response of weed-free soybeans (*Glycine max*) to injury from postemergence broadleaf herbicides. *Weed Science*, *34*(2), 304–307. https://doi.org/10.1017/S0043174500066868

Kumar, V., Liu, R., Lambert, T., Peterson, D. E., Minihan, C. L., & Stahlman, P. W. (2019). Effective herbicide options for controlling glyphosate-resistant Palmer amaranth in Roundup Ready 2 Xtend soybean. *Kansas Agricultural Experiment Station Research Reports*, *5*, 6.

Legleiter, T., & Bradley, K. (2008). Glyphosate and multiple herbicide resistance in common waterhemp (*Amaranthus rudis*) populations from Missouri. *Weed Science*, *56*(4), 582–587. https://doi.org/10.1614/WS-07-204.1

Legleiter, T., Bradley, K., & Massey, R. (2009). Glyphosate-resistant waterhemp (*Amaranthus rudis*) control and economic returns with herbicide programs in soybean. *Weed Technology*, *23*(1), 54–61. https://doi.org/10.1614/WT-08-069.1

Liu, J., Davis, A., & Tranel, P. (2012). Pollen biology and dispersal dynamics in waterhemp (*Amaranthus tuberculatus*). *Weed Science*, *60*(3), 416–422. https://doi.org/10.1614/WS-D-11-00201.1

Meyer, C., Norsworthy, J., Young, B., Steckel, L., Bradley, K., Johnson, W., Loux, M., Davis, V., Kruger, G., Bararpour, M., Ikley, J., Spaunhorst, D., & Butts, T. (2016). Early-season Palmer amaranth and waterhemp control from preemergence programs utilizing 4-hydroxyphenylpyruvate dioxygenase–inhibiting and auxinic herbicides in soybean. *Weed Technology*, *30*(1), 67–75. https://doi.org/10.1614/WT-D-15-00100.1

Montgomery, J. S. (2020). *Understanding the genetic basis of dioecy in waterhemp (*Amaranthus tuberculatus*) and Palmer amaranth (*Amaranthus Palmeri) [Master's thesis, University of Illinois].

Munro, I. C., Carlo, G. L., Orr, J. C., Sund, K. G., & Wilson, R. M. (1992). A comprehensive integrated review and evaluation of the scientific evidence relating to the safety of the herbicide 2,4-D. *Journal of the American College of Toxicology*, *11*(5), 559–664. https://doi.org/10.3109/10915819209141893

Norsworthy, J., Ward, S., Shaw, D., Llewellyn, R., Nichols, R., Webster, T., Bradley, K., Frisvold, G., Powles, S., Burgos, N., Witt, W., & Barrett, M. (2012). Reducing the risks of herbicide resistance: Best management practices and recommendations. *Weed Science*, *60*, 31–62. https://doi.org/10.1614/WS-D-11-00155.1

Patzoldt, W., & Tranel, P. (2007). Multiple ALS mutations confer herbicide resistance in waterhemp (*Amaranthus tuberculatus*). *Weed Science*, *55*(5), 421–428. https://doi.org/10.1614/WS-06-213.1

Peterson, M., McMaster, S., Riechers, D., Skelton, J., & Stahlman, P. (2016). 2,4-D Past, present, and future: A review. *Weed Technology*, *30*(2), 303–345. https://doi.org/10.1614/WT-D-15-00131.1

Priess, G. L., Norsworthy, J. K., Roberts, T. L., & Gbur, E. E. (2020a). Impact of postemergence herbicides on soybean injury and canopy formation. *Weed Technology*, *34*(5), 727–734. https://doi.org/10.1017/wet.2020.55

Priess, G. L., Norsworthy, J. K., Roberts, T. L., & Gbur, E. E. (2020b). Weed control and soybean injury from preplant vs. preemergence herbicide applications. *Weed Technology*, *34*(5), 718–726. https://doi.org/10.1017/wet.2020.47

Riar, D., Norsworthy, J., Steckel, L., Stephenson, D., Eubank, T., & Scott, R. (2013). Assessment of weed management practices and problematic weeds in the Midsouth United States – Soybean: A consultant's perspective. *Weed Technology*, *27*, 612–622. https://doi.org/10.1614/WT-D-12-00167.1

Robinson, A., Simpson, D., & Johnson, W. (2012). Summer annual weed control with 2,4-D and glyphosate. *Weed Technology*, *26*(4), 657–660. https://doi.org/10.1614/WT-D-12-00081.1

Ross, W. J., Bokker, C. D., & Pearrow, N. (2015). Liberty Link, Roundup Ready comparison study. *Arkansas Soybean Research Studies*, 2015, *637*, 32–34.

Sarangi, D., Sandell, L., Knezevic, S., Aulakh, J., Lindquist, J., Irmak, S., & Jhala, A. (2015). Confirmation and control of glyphosate-resistant common waterhemp (*Amaranthus rudis*) in Nebraska. *Weed Technology*, *29*(1), 82–92. https://doi.org/10.1614/WT-D-14-00090.1

Sarangi, D., Sandell, L., Kruger, G., Knezevic, S., Irmak, S., & Jhala, A. (2017). Comparison of herbicide programs for season-long control of glyphosate-resistant common waterhemp (*Amaranthus rudis*) in soybean. *Weed Technology*, *31*(1), 53–66. https://doi.org/10.1017/wet.2016.1

Sauer, J. (1955). Revision of the dioecious amaranths. *Madrono*, *13*, 5–46.

Schryver, M. G., Soltani, N., Hooker, D. C., Robinson, D. E., Tranel, P. J., & Sikkema, P. H. (2017). Control of glyphosate-resistant common waterhemp (*Amaranthus rudis*) in three new herbicide-resistant soybean varieties in Ontario. *Weed Technology*, *31*(6), 828–837. https://doi.org/10.1017/wet.2017.81

Shergill, L., Barlow, B., Bish, M., & Bradley, K. (2018). Investigations of 2,4-D and multiple herbicide resistance in a Missouri waterhemp (*Amaranthus tuberculatus*) population. *Weed Science*, *66*(3), 386–394. https://doi.org/10.1017/wsc.2017.82

Shoup, D., Al-Khatib, K., & Peterson, D. (2003). Common waterhemp (*Amaranthus rudis*) resistance to protoporphyrinogen oxidase-inhibiting herbicides. *Weed Science*, *51*(2), 145–150. https://doi.org/10.1614/0043-1745(2003)051[0145:CWARRT]2.0.CO;2

Shyam, C., Chahal, P., Jhala, A., & Jugulam, M. (2021). Management of glyphosate-resistant Palmer amaranth (*Amaranthus Palmeri*) in 2,4-D-, glufosinate-, and glyphosate-resistant soybean. *Weed Technology*, *35*(1), 136–143. https://doi.org/10.1017/wet.2020.91

Singh, M., Thapa, R., Kukal, M. S., Irmak, S., Mirsky, S., & Jhala, A. J. (2022). Effect of water stress on weed germination, growth characteristics, and seed production: A global meta-analysis. *Weed Science*, *70*(6), 621–640. https://doi.org/10.1017/wsc.2022.59

Soltani, N., Vyn, J. D., & Sikkema, P. H. (2009). Control of common waterhemp (*Amaranthus tuberculatus* var. rudis) in corn and soybean with sequential herbicide applications. *Canadian Journal of Plant Science*, *89*(1), 127–132. https://doi.org/10.4141/CJPS08051

Spaunhorst, D., & Bradley, K. (2013). Influence of dicamba and dicamba plus glyphosate combinations on the control of glyphosate-resistant waterhemp (*Amaranthus rudis*). *Weed Technology*, *27*(4), 675–681. https://doi.org/10.1614/WT-D-13-00081.1

Steckel, L. (2007). The dioecious amaranthus spp.: Here to stay. *Weed Technology*, *21*(2), 567–570. https://doi.org/10.1614/WT-06-045.1

Striegel, S., Oliveira, M. C., DeWerff, R. P., Stoltenberg, D. E., Conley, S. P., & Werle, R. (2021). Influence of postemergence dicamba/glyphosate timing and inclusion of acetochlor as a layered residual on weed control and soybean yield front. *Frontiers in Agronomy*, *3*, 788251.

Strom, S., Gonzini, L., Mitsdarfer, C., Davis, A., Riechers, D., & Hager, A. (2019). Characterization of multiple herbicide–resistant waterhemp (*Amaranthus tuberculatus*) populations from Illinois to VLCFA-inhibiting herbicides. *Weed Science*, *67*(4), 369–379. https://doi.org/10.1017/wsc.2019.13

Takano, H. K., Beffa, R., Preston, C., Westra, P., & Dayan, F. E. (2019). Reactive oxygen species trigger the fast action of glufosinate. *Planta*, *249*, 1837–1849. https://doi.org/10.1007/s00425-019-03124-3

Takano, H. K., & Dayan, F. E. (2020). Glufosinate-ammonium: A review of the current state of knowledge. *Pest Management Science*, *76*, 3911–3925. https://doi.org/10.1002/ps.5965

Todd, O. E., Figueiredo, M. R. A., Morran, S., Soni, N., Preston, C., Kubeš, M. F., Napier, R., & Gaines, T. (2020). Synthetic auxin herbicides: Finding the lock and key to weed resistance. *Plant Science*, *300*, 110631. https://doi.org/10.1016/j.plantsci.2020.110631

Underwood, M., Soltani, N., Hooker, D., Robinson, D., Vink, J., Swanton, C., & Sikkema, P. (2017). Benefit of tank mixing dicamba with glyphosate applied after emergence for weed control in dicamba- and glyphosate-resistant soybean. *Canadian Journal of Plant Science*, *97*(5), 891–901.

Van Wychen, L. (2022). *2022 Survey of the most common and troublesome weeds in broadleaf crops, fruits, & vegetables in the United States and Canada* [Dataset]. Weed Science Society of America. https://wssa.net/wp-content/uploads/2022-Weed-Survey-Broadleaf-crops.xlsx

Vyn, J. D., Swanton, C. J., Weaver, S. E., & Sikkema, P. H. (2006). Control of *Amaranthus tuberculatus* var. rudis (common waterhemp) with PRE and POST-emergence herbicides in *Zea mays* L. (maize). *Crop Protection*, *25*(9), 1051–1056. https://doi.org/10.1016/j.cropro.2006.01.016

Wendler, C., Barniske, M., & Wild, A. (1990). Effect of phosphinothricin (glufosinate) on photosynthesis and photorespiration of C3 and C4 plants. *Photosynthesis Research*, *24*, 55–61. https://doi.org/10.1007/BF00032644

Young, B. G., Young, J. M., Matthews, J. L., Owen, M. D. K., Zelaya, I. A., Hartzler, R. G., Wax, L. M., Rorem, K. W., & Bollero, G. A. (2003). Soybean development and yield as affected by three postemergence herbicides. *Agronomy Journal*, *95*, 1152–1156. https://doi.org/10.2134/agronj2003.1152

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