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Control of dicamba/glufosinate/glyphosate-resistant volunteer soybean in corn with preemergence and postemergence herbicides

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Research Article

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Abstract

The widespread adoption of multiple-herbicide-resistant corn and soybean often causes the problem of volunteers in corn–soybean rotation, which necessitates alternative herbicides for effective management. The objective of this research was to evaluate PRE and POST herbicides labeled in corn for control of dicamba/glufosinate/glyphosate-resistant volunteer soybean. Field experiments were conducted from 2021 to 2023 near Clay Center, NE. Two separate field experiments were conducted to evaluate 12 PRE and 14 POST herbicides to control volunteer soybean in Enlist® corn. Soybean resistant to dicamba/glufosinate/glyphosate was planted perpendicular to corn rows to mimic volunteer soybean. Among the PRE herbicides tested, acetochlor/clopyralid/flumetsulam (1,190; 1,050/106/34 g ai ha^{-1}) and acetochlor/clopyralid/mesotrione (2,304; 1,961/133/210 g ai or ae ha^{-1}) provided 97% and 99% control of volunteer soybean, respectively, in 2021 and 68% and 89% control, respectively, in 2023 at 42 d after PRE. Among POST herbicides tested, 2,4-D choline (1,064 g ae ha^{-1}), acetochlor/clopyralid/mesotrione (2,304; 1,961/133/210 g ai or ae ha^{-1}), atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (2,409; 700/42/168/1,499 g ai ha^{-1}), clopyralid/flumetsulam (192; 146/46 g ai ha^{-1}), nicosulfuron + atrazine (34 + 1,120 g ai ha^{-1}), and thiencarbazone-methyl/tembotrione + atrazine (76; 12/63 + 896 g ai ha^{-1}) provided ≥97% volunteer soybean control, ≥94% density reduction, and ≥97% biomass reduction 28 d after POST herbicide application. Corn yield did not differ from the weed-free control in these treatments. The results of this study suggest that PRE and POST herbicides are available for control of dicamba/glufosinate/glyphosate-resistant volunteer soybean in Enlist® corn and that careful selection of an herbicide is required based on the herbicide-resistant soybean planted in the previous year.

Introduction

The United States is the leading producer and the second-largest exporter of soybean in the world (USDA-ERS 2024). Soybean accounts for more than 90% of oilseed production in the United States (USDA-ERS 2024). In 2023, the United States produced 113.3 billion kg of soybean from 33.3 million ha (USDA-NASS 2024a). Approximately 42% of soybean (i.e., 48 billion kg) worth US$27.7 billion was exported in 2023 (USDA-FAS 2023). Domestically, soybean is used primarily for animal feed, cooking oil, and biodiesel (USDA 2015).

Soybean grain harvests are a major operation for growers each year, covering more than 2 million ha in Nebraska and Indiana, approximately 3 million ha in Minnesota, and exceeding 4 million ha in major soybean-producing states like Illinois and Iowa (USDA-NASS 2024b). Volunteer soybean emerges from soybean seeds lost in the previous season. As per soybean harvest loss estimates, approximately 2% to 4% of potential soybean yield, equating to 67 to 134 kg ha^{-1}, is typically lost under good harvest conditions (Gliem et al. 1990; Huitink 2020; Staton 2023). Soybean harvest loss can exceed 134 kg ha^{-1} in certain situations, such as green stems, lodged plants, harvest delays causing brittle pods, and short plants with low-hanging pods. (Staton 2023). Volunteer soybean is usually not a concern for growers in subsequent cropping seasons, but it may occur as scattered plants or substantial stands during occasional years when seed shattering or harvest losses are high or when soybean is not harvested or only partially harvested due to extreme weather events (Jhala et al. 2013). Though not always a concern for corn growers, season-long interference of volunteer soybean at a density of 3.5 plants m^{-2} (19.4 kg ha^{-1} seed loss, assuming 30% germination/survival and 6,000 seeds kg^{-1}) can reduce 10% of corn yield (Alms et al. 2016); therefore control of volunteer soybean may be warranted, depending on the level of infestation.

Growers can modify herbicide programs that are labeled in corn for control of volunteer soybean; however, multiple-herbicide-resistant soybean has been developed and adopted, which makes it complex for growers to choose an effective herbicide for controlling volunteer soybean.

For example, 2,4-D/glufosinate/glyphosate would not kill soybean volunteers possessing the Enlist® E3 trait (2,4-D/glufosinate/glyphosate-resistant; Corteva Agriscience, Indianapolis, IN, USA), and dicamba/glufosinate/glyphosate would not control volunteer soybean with the XtendFlex® trait (dicamba/glufosinate/glyphosate-resistant; Bayer Crop Science, St. Louis, MO, USA). Similarly, 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibitors, such as isoxaflutole (and glufosinate/glyphosate), would not be an effective option for managing LibertyLink® GT27 soybean (BASF, Research Triangle Park, NC, USA) volunteers resistant to glufosinate/glyphosate/isoxaflutole. Thus the widespread cultivation of soybean traits with resistance to one or more herbicides limits the available herbicide options for controlling multiple-herbicide-resistant soybean volunteers.

Growers use PRE and/or POST herbicides to control weeds in corn. Sometimes precipitation during early spring may wet the soil, delaying PRE herbicide application until after weeds have become established, or excessive rainfall can leach down PRE herbicides that were applied before rain events, depending on the solubility of the herbicides (Jhala 2017). In contrast, a lack of moisture can reduce the efficacy of residual herbicides. In such circumstances, POST herbicides might be the only option to control emerged weeds. Some extension publications (e.g., Cahoon et al. 2019; Currie and Geier 2018) and conference proceedings (e.g., Zollinger and Ries 2004) list PRE and/or POST herbicides for control of volunteer soybean in corn or other crops, such as cotton (*Gossypium hirsutum* L.) (York et al. 2005) and rice (*Oryza sativa* L.) (Bond and Walker 2009). Alms et al. (2016) evaluated five POST herbicides for control of glyphosate-resistant volunteer soybean in corn in South Dakota; however, limited scientific literature is available evaluating both PRE and POST herbicides for the control of multiple-herbicide-resistant volunteer soybean in corn. In addition, several PRE herbicides with multiple active ingredients have been labeled in corn in the last few years. Many fields may contain dicamba-resistant soybean volunteers, as these varieties have been widely adopted in the United States since their commercialization in 2016 (Wechsler et al. 2019). Furthermore, recent commercialization of corn resistant to 2,4-D/aryloxyphenoxypropionates/glufosinate/glyphosate (Enlist® corn) enables the use of 2,4-D choline for controlling broadleaf weeds. The objective of this study was to evaluate PRE and POST herbicides for control of dicamba/glufosinate/glyphosate-resistant volunteer soybean in Enlist® corn and their effects on volunteer soybean density, soybean biomass, and corn yield.

Materials and Methods

Site Description and Experimental Design

Field experiments were conducted at the University of Nebraska–Lincoln's South Central Ag Lab near Clay Center, NE (40.57°N, 98.13°W). The experimental site had silt loam soil (montmorillonitic, mesic, Pachic Argiustolls) with a sand:silt:clay percentage ratio of 17:58:25, pH 6.5, and 3.0% organic matter. The field was irrigated through a center-pivot irrigation system. Two separate field experiments were conducted from 2021 to 2023 to evaluate PRE (2021 and 2023) and POST (2021 to 2022) herbicides for control of dicamba/glyphosate/glufosinate-resistant soybean volunteers in Enlist® corn. Both experiments were conducted using a randomized complete-block design with three replicates. The plot size was 3 × 9 m with four rows of Enlist® corn (Hoegemeyer 8097 SXE™, NK29-Z4E3) planted at 76-cm row spacing. Volunteer soybean (Asgrow®, AG27XF0, NK31-J9XF, Bayer Crop Science) was planted perpendicular to corn in 76-cm-wide rows at approximately 4 cm depth. Dates of planting and the seeding rates of corn and volunteer soybean, along with the timing of the PRE and POST herbicide applications, are given in Table 1.

Table 1. Planting time and seeding rate of corn and volunteer soybean and application timing of PRE and POST herbicides for control of volunteer soybean in Enlist® corn in field experiments conducted near Clay Center, NE, from 2021 to 2023.

	Planting date		Seeding rate		
Year	Enlist® corn	Volunteer soybean	Enlist® corn	Volunteer soybean[a]	Herbicide application date
			——— seeds ha^{-1} ———		
PRE herbicide study					
2021	7 May	5 May	87,500	125,000	7 May
2023	2 May	2 May	87,500	200,000	3 May
POST herbicide study					
2021	7 May	5 May	87,500	125,000	15 Jun
2022	16 Jun	16 Jun	87,500	325,000	12 Jul

[a]Bin-run soybean seeds were planted to mimic volunteer soybean. The seeding rate was increased in 2022 and 2023 due to low germination of bin-run seeds.

The treatments and application rates used in the PRE and POST experiments are listed in Table 2 and Table 3, respectively. Additionally, nontreated and weed-free treatments were included in each experiment for comparison. Volunteer soybean in weed-free plots was killed with hand weeding and POST herbicide application. PRE herbicides were applied within 1 d of planting corn, and POST herbicides were applied when corn and volunteer soybean were around the V4 to V5 and V3 to V4 stage, respectively (Table 1). In 2021, the experimental sites received two additional POST applications of glyphosate (Roundup PowerMAX®, Bayer Crop Science) at 1,260 g ae ha^{-1} on May 26 and June 9 for in-season weed control. Similarly, in 2022, pyroxasulfone (Zidua® SC, BASF) at 128 g ai ha^{-1} plus glufosinate (Liberty® 280 SL, BASF) at 655 g ai ha^{-1} was applied on June 24 to the POST herbicide experimental site. In 2023, pyroxasulfone at 147 g ai ha^{-1} + glyphosate at 1,260 g ae ha^{-1} was applied on May 31 to the PRE herbicide experimental site. These herbicides labeled for use in soybean were applied to control nontarget weeds naturally present in the study area. Weed-free plots received a PRE application of atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (Acuron®, Syngenta Crop Protection, Greensboro, NC, USA) at 2,900 g ai ha^{-1} and a POST application of acetochlor (Warrant®, Bayer Crop Science) at 1,260 g ai ha^{-1} + dicamba (DiFlexx®, Bayer Crop Science) at 420 g ae ha^{-1} for broad-spectrum weed control. Herbicides were applied using a CO_2-pressurized backpack sprayer delivering a spray volume of 140 L ha^{-1} at 276 kPa. The sprayer was equipped with 11015 Turbo TeeJet® induction nozzles for PRE herbicides and 110015 AIXR flat-fan nozzles for POST herbicides (TeeJet® Technologies, Wheaton, IL, USA).

Data Collection and Statistical Analysis

Control of volunteer soybean was recorded at 28, 42, and 63 d after PRE (DAPRE) and at 14 and 28 d after POST (DAPOST) herbicide applications using a scale of 0% to 100%, with 0% meaning no control and 100% meaning that plants were completely dead.

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Table 2. PRE herbicides and their common and trade names, sites of action, application rates, manufacturers, and adjuvants used with application[a].

Common name	Trade name	SOA	Rate	Manufacturer	Adjuvant
			g ai or ae ha^{-1}		
Acetochlor/atrazine	Degree Xtra®	15,5	3,961 (2,647/1,314)	Bayer Crop Science (St. Louis, MO, USA)	—
Acetochlor/clopyralid/flumetsulam	SureStart® II	15,4,2	1,190 (1,050/106/34)	Corteva Agriscience (Indianapolis, IN, USA)	—
Acetochlor/clopyralid/mesotrione	Resicore®	15,4,27	2,304 (1,961/133/210)	Corteva Agriscience	0.25% v/v NIS
Acetochlor/mesotrione	Harness® MAX	15,27	2,696 (2,465/231)	Bayer Crop Science	3.0% v/v AMS
Atrazine/bicyclopyrone/ mesotrione/*S*-metolachlor	Acuron®	5,27,27,15	2,409 (700/42/ 168/1,499)	Syngenta Crop Protection (Greensboro, NC, USA)	1.0% v/v COC
Dimethenamid-*P*/saflufenacil	Verdict®	15,14	731 (656/75)	BASF (Research Triangle Park, NC, USA)	1.0% v/v MSO
Fluthiacet-methyl/pyroxasulfone	Anthem® MAXX	14,15	188 (5/183)	FMC (Philadelphia, PA, USA)	0.25% v/v NIS
Isoxaflutole + atrazine	Balance® Flexx + AAtrex® 4L	27 + 5	88 + 560	Bayer Crop Science, Syngenta Crop Protection	1.0% v/v COC
Isoxaflutole/thiencarbazone-methyl + atrazine	Corvus® + AAtrex® 4L	27,2 + 5	129 (92/37) + 560	Bayer Crop Science, Syngenta Crop Protection	1.0% v/v COC + 3.0% v/v AMS
Pendimethalin + atrazine	Prowl® H2O + AAtrex® 4L	3 + 5	1,916 + 1,120	BASF, Syngenta Crop Protection	—
Pyroxasulfone + atrazine	Zidua® SC + AAtrex® 4L	15 + 5	110 + 1,120	BASF, Syngenta Crop Protection	1.0% v/v COC
Saflufenacil + atrazine	Sharpen® + AAtrex® 4L	14 + 5	62 + 1,120	BASF, Syngenta Crop Protection	1.0% v/v MSO + 3.0% v/v AMS

[a]Abbreviations: AMS, ammonium sulfate (N-Pak® AMS Liquid, Winfield United, St. Paul, MN, USA); COC, crop oil concentrate (KALO, Overland Park, KS, USA); MSO, methylated seed oil (Loveland Products, Greeley, CO, USA); NIS, non-ionic surfactant (Preference®, Winfield United); SOA, site of action as per the classification list by the Weed Science Society of America.

Enlist® corn injury was recorded on a similar scale of 0% to 100% at 14 and 28 DAPRE/POST herbicide application. Volunteer soybean density was recorded by counting the number of plants in a 1-m soybean row distance with three repetitions by randomly placing a 1-m scale in the middle of two corn rows in each plot. After counting volunteer soybean plants, two 0.25-m^2 quadrats were randomly placed in each plot to collect aboveground volunteer soybean biomass, followed by oven drying (70 C) to a constant weight to record dry biomass. Volunteer soybean density and biomass data were taken 63 DAPRE in 2021 and 28 DAPRE in 2023 for the PRE herbicide experiment and 28 DAPOST for both years (2021 and 2022) of the POST herbicide experiment. Percent reductions (relative to the nontreated control) in volunteer soybean density and biomass were calculated using (Singh et al. 2023)

$$Y = \left(\frac{A - B}{A}\right) \times 100 \quad [1]$$

where A is volunteer soybean density/biomass from the nontreated control plot and B is volunteer soybean density/biomass from the herbicide-treated plot. At crop maturity, the grain yield of Enlist® corn was recorded by harvesting the middle two rows of each plot with a small plot combine and adjusting to 15.5% moisture content.

Data were analyzed using R software version 4.2.2 (R Core Team 2024) for analysis. Data were checked for analysis of variance (ANOVA) assumptions of normality and homogeneity of variance using the PERFORMANCE package (Lüdecke et al. 2022). Data for corn grain yield met the ANOVA assumptions. A linear mixed-effects model was built using the LME4 package (Bates et al. 2023) to analyze the normal data, whereas a generalized linear mixed (*glmer*) model with beta error distribution (link = "logit") was built using the GLMMTMB package (Brooks et al. 2023; Stroup 2015) to analyze the nonnormal data. For both models, year, herbicide, and their interaction were considered fixed factors, while replication nested within year was considered a random factor. Data were analyzed separately for each year if a Year × Herbicide interaction was significant. Data from the nontreated and weed-free controls were excluded from the analysis due to a lack of variance among replicates. If the ANOVA showed significant differences, treatment means were separated using Tukey's method for P-value adjustments and Sidak confidence-level adjustments using the EMMEANS and MULTCOMP packages in R (Hothorn et al. 2022; Lenth et al. 2022). For the *glmer* models, data were back-transformed for presentation.

Results and Discussion

Volunteer Soybean Control with PRE Herbicides

Volunteer soybean control with PRE herbicides differed between years (Table 4). Control was relatively lower in 2023 than in 2021, probably because of less rainfall for fully activating the PRE herbicides (Figure 1). Cumulative rainfall during the first 3 wk of May was 56 mm in 2021 compared to 15 mm in 2023 (Figure 1 B). The PRE herbicides used in this study required at least 6 mm (Anonymous 2023, 2024) to 13 mm (Anonymous 2018, 2022) of activating rainfall (or sprinkler irrigation) within the first week of application and before the emergence of weeds. However, for optimal performance of soil-applied herbicides, approximately 51 mm of rainfall, evenly distributed over the 2 wk following application, is beneficial (Johnson and Zimmer 2022). The experimental site was irrigated; however, the first irrigation in 2021 and 2023 was not applied until 41 d (June 17; 38 mm) and 20 d (May 23; 20 mm) after PRE herbicides were applied, respectively (data not shown). The crop was irrigated to meet seasonal water demand, as the growing seasons of 2021, 2022, and 2023 received 95, 118, and 50 mm less precipitation, respectively, than long-term (1990 to 2020) accumulated precipitation (453 mm; Figure 1 B).

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Table 3. POST herbicides and their common and trade names, sites of action, application rates, manufacturers, and adjuvants used with application[a].

Common name	Trade name	SOA	Rate	Manufacturer	Adjuvant
			g ai or ae ha^{-1}		
2,4-D choline	Enlist One®	4	1,064	Corteva Agriscience	—
Acetochlor/clopyralid/mesotrione	Resicore®	15,4,27	2,304 (1,961/133/210)	Corteva Agriscience	0.25% v/v NIS
Acetochlor/mesotrione	Harness® MAX	15,27	2,157 (1,972/185)	Bayer Crop Science	0.25% v/v NIS + 3.0% v/v AMS
Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor	Acuron®	5,27,27,15	2,409 (700/42/168/1,499)	Syngenta Crop Protection	1.0% v/v COC
Carfentrazone-methyl	AIM® EC	14	9	FMC	0.25% v/v NIS
Clopyralid/flumetsulam	Hornet®	4,2	192 (146/46)	AMVAC (Newport Beach, CA, USA)	0.25% v/v NIS
Dicamba/tembotrione	DiFlexx® DUO	4,27	597 (521/76)	Bayer Crop Science	1.0% v/v COC
Dimethenamid-*P*/topramezone	Armezon® PRO	15,27	937 (919/18)	BASF	0.25% v/v NIS + 3.0% v/v AMS
Fluthiacet-methyl	Cadet™	14	6	FMC	0.25% v/v NIS + 3.0% v/v AMS
Fluthiacet-methyl/mesotrione	Solstice®	14,27	98 (5/93)	FMC	0.25% v/v NIS
Glufosinate + atrazine	Liberty® 280 SL + AAtrex® 4L	10 + 5	655 + 896	BASF, Syngenta Crop Protection	3.0% v/v AMS
Nicosulfuron + atrazine	Accent® Q + AAtrex® 4L	2 + 5	34 + 1,120	Corteva Agriscience, Syngenta Crop Protection	1.0% v/v COC
Thiencarbazone-methyl/tembotrione + atrazine	Capreno® + AAtrex® 4L	2 + 5	75 (12/63) + 896	Bayer Crop Science, Syngenta Crop Protection	1.0% v/v COC + 3.0% v/v AMS
Tolpyralate	Shieldex® 400SC	27	35	Summit Agro USA (Durham, NC, USA)	0.25% v/v NIS + 2.5% v/vAMS

[a]Abbreviations: AMS, ammonium sulfate (N-Pak® AMS Liquid); COC, crop oil concentrate (KALO); MSO, methylated seed oil (Loveland Products); NIS, non-ionic surfactant (Preference®); SOA, herbicide site of action as per the classification list by the Weed Science Society of America.

The average temperature during the growing seasons of 2021 to 2023 broadly followed the long-term temperature trend (Figure 1 A).

Treatments containing clopyralid were the most effective, with acetochlor/clopyralid/flumetsulam (1,190; 1,050/106/34 g ai ha^{-1}) and acetochlor/clopyralid/mesotrione (2,304; 1,961/133/210 g ai or ae ha^{-1}) providing 83% and 97% control of volunteer soybean, respectively, 28 DAPRE in 2021 (Figure 2; Table 4). In 2023, acetochlor/clopyralid/flumetsulam and acetochlor/clopyralid/mesotrione provided 42% and 55% control, respectively, 28 DAPRE, which increased to 68% and 89%, respectively, by 42 DAPRE. By 63 DAPRE, control was ≥98% in both years in these treatments, which was greater than all other treatments in 2023. In a multistate field experiment, Courtney (2016) found that acetochlor/clopyralid/flumetsulam (1,193; 1,053/106/34 g ha^{-1}) applied PRE reduced volunteer soybean stand by 56% in Mississippi (45 vs. 20 plants, 62 d after application [DAA]), 72% in South Dakota (70 vs. 20 plants, 42 DAA), and 100% in North Carolina (55 vs. 0 plants, 52 DAA).

Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (2,409; 700/42/168/1,499 g ai ha^{-1}) provided 75% control of volunteer soybean 28 DAPRE and 83% control 42 DAPRE in 2021, with almost half the efficacy in 2023. Other treatments containing HPPD inhibitors, such as acetochlor/mesotrione (2,696; 2,465/231 g ai ha^{-1}), isoxaflutole + atrazine (88 + 560 g ai ha^{-1}), and isoxaflutole/thiencarbazone-methyl + atrazine (129; 92/37 + 560 g ai ha^{-1}) provided similar control of 63% to 70% 28 DAPRE, 70% to 78% 42 DAPRE, and 75% to 89% 63 DAPRE in 2021 (Figure 3). However, in 2023, they provided 18% to 43% control 63 DAPRE. Acetochlor/atrazine (2,647/1,314 g ai ha^{-1}) provided 62% control of volunteer soybean 28 DAPRE and 45% control 42 DAPRE in 2021, whereas in 2023, it provided 48% control 28 DAPRE and 18% control 42 DAPRE. Atrazine (1,120 g ai ha^{-1}) mixed with pendimethalin (1,916 g ai ha^{-1}), pyroxasulfone (110 g ai ha^{-1}), or saflufenacil (62 g ai ha^{-1}) provided ≤27% control in 2021 and ≤32% control in 2023 28 DAPRE. Similarly, Courtney (2016) found that atrazine (1,120 g ha^{-1}) reduced volunteer soybean stand by 45% in South Dakota (70 vs. 39 plants, 42 DAA) and 51% in Mississippi (45 vs. 20 plants, 62 DAA). Dimethenamid-*P*/saflufenacil (731; 656/75 g ai ha^{-1}) and fluthiacet-methyl/pyroxasulfone (188; 5/183 g ai ha^{-1}) did not control volunteer soybean in 2021 (<26% at 28 DAPRE) or 2023 (<11% at 63 DAPRE), as both herbicides are labeled in soybean.

Volunteer Soybean Control with POST Herbicides

2,4-D (1,064 g ae ha^{-1}) provided 99% control of dicamba/glufosinate/glyphosate-resistant V3 to V4 volunteer soybean 28 DAPOST in both years (P = 0.03; Table 5). Dan et al. (2011) also observed 95% to 96% control of V3 volunteer soybean with 2,4-D (1,340 g ha^{-1}) 28 DAA in a greenhouse experiment. However, they observed only 64% to 74% control when 2,4-D was applied at 1,005 g ha^{-1}. Zollinger and Ries (2004) observed 60% control of V4 to V6 volunteer soybean with 2,4-D amine (280 g ha^{-1}) 28 DAPOST, while Theodoro et al. (2018) reported 75% control of V3 volunteer soybean 28 DAA with 2,4-D (806 g ha^{-1}) in a greenhouse experiment. Minor injury symptoms (≤4%) on Enlist® corn were observed 28 DAPOST with some POST herbicides (data not shown); however, the injury was transient and was not visible later in the season. Treatments containing another synthetic auxin, that is, clopyralid, such as acetochlor/clopyralid/mesotrione (2,304; 1,961/133/210 g ai or ae ha^{-1}) and clopyralid/flumetsulam (192; 146/46 g ai ha^{-1}), provided ≥93% control 14 DAPOST and 99% control 28 DAPOST. Similarly, Zollinger et al. (2018) reported 90% to 99% control of V2 to V3 volunteer soybean with clopyralid/flumetsulam (48 to 96 g ha^{-1}) and clopyralid (79 to 105 g ha^{-1}). Zollinger and Ries (2004) also reported 95% and 75% control of V2 to V3 and V4 to V6 glyphosate-resistant volunteer soybean, respectively, 28 DAA with clopyralid/flumetsulam (56; 13/43 g ha^{-1}). In this study, the rate of clopyralid/flumetsulam was more than 3X

Table 4. Control of dicamba/glyphosate/glufosinate-resistant soybean volunteers 28, 42, and 63 d after PRE with PRE herbicides evaluated in field experiments conducted near Clay Center, NE, in 2021 and 2023[a,b,c].

Herbicide	Rate	28 DAPRE		42 DAPRE		63 DAPRE	
		2021	2023	2021	2023	2021	2023
	g ai or ae ha^{-1}	%					
Nontreated control	—	0	0	0	0	0	0
Weed-free control	—	100	100	100	100	100	100
Acetochlor/atrazine	3,961 (2,647/1,314)	62 b–f	48 c–h	45 b–f	18 ef	48 b–d	13 de
Acetochlor/clopyralid/flumetsulam	1,190 (1,050/106/34)	83 ab	42 c–h	97 a	68 a–d	98 a	98 a
Acetochlor/clopyralid/mesotrione	2,304 (1,961/133/210)	97 a	55 b–g	99 a	89 ab	99 a	98 a
Acetochlor/mesotrione	2,696 (2,465/231)	70 a–d	52 b–h	70 a–c	50 c–e	75 a–c	43 b–e
Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor	2,409 (700/42/168/1,499)	75 a–c	40 d–h	83 a–c	42 c–f	87 ab	43 b–e
Dimethenamid-*P*/saflufenacil	731 (656/75)	25 g–i	32 e–i	30 d–f	5 f	32 de	10 de
Fluthiacet-methyl/pyroxasulfone	188 (5/183)	5 i	37 d–i	7 ef	10 f	4 e	10 de
Isoxaflutole + atrazine	88 + 560	63 b–e	30 e–i	75 a–c	23 ef	85 ab	27 de
Isoxaflutole/thiencarbazone-methyl + atrazine	129 (92/37) + 560	70 a–d	42 c–h	78 a–c	23 ef	89 a	18 de
Pendimethalin + atrazine	1,916 + 1,120	27 g–i	32 e–i	25 d–f	41 c–f	20 de	39 c–e
Pyroxasulfone + atrazine	110 + 1,120	18 hi	32 e–i	18 ef	12 ef	18 de	10 de
Saflufenacil + atrazine	62 + 1,120	23 g–i	28 f–i	25 d–f	8 f	22 de	12 de
P-value		0.003		<0.001		<0.001	

[a]Abbreviation: DAPRE, days after preemergence.
[b]Within a given evaluation timing, values with the same letter are not different according to estimated marginal means with Tukey P-value adjustments and Sidak confidence-level adjustments.
[c]Nontreated and weed-free controls were not included in the analysis.

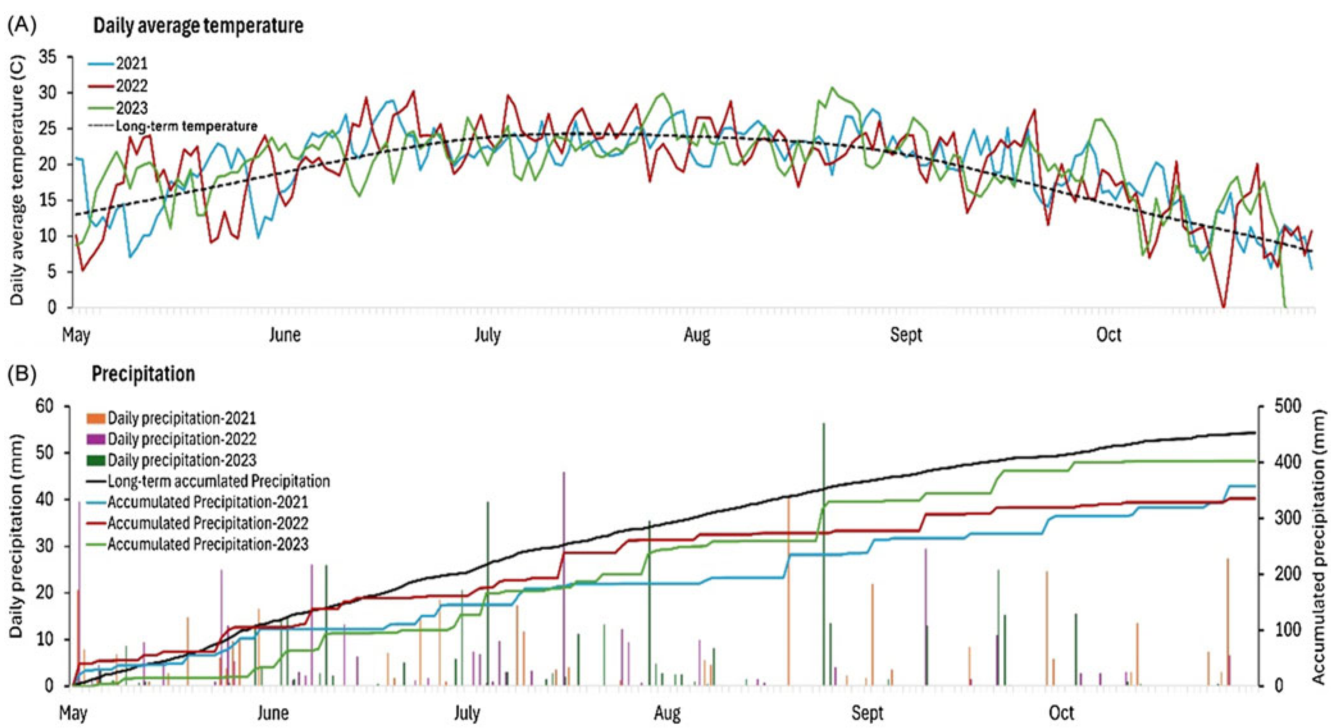

Figure 1. Daily average temperature (A) and precipitation (mm) (B) for the 2021, 2022, and 2023 growing seasons along with long-term (1990 to 2020) temperature and accumulated precipitation for South Central Ag Lab, near Clay Center, NE.

higher (192 vs. 56 g ha^{-1}) than Zollinger and Ries (2004), leading to better control of V3 to V4 volunteer soybean (99%).

Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (2,409; 700/42/168/1,499 g ai ha^{-1}) was equally effective as herbicides containing synthetic auxins, providing similar control of 94% to 98% 14 DAPOST and 98% to 99% 28 DAPOST. Dan et al. (2011) reported 58% to 59% control of volunteer soybean with mesotrione (120 g ha^{-1}) 28 DAA. Theodoro et al. (2018) observed 39% control of V3 volunteer soybean with mesotrione (480 g ha^{-1}) 35 DAA. Dicamba/tembotrione (597; 521/76 g ai ha^{-1}) provided 80% to 95% control 28 DAPOST, similar to 2,4-D atrazine/bicyclopyrone/mesotrione/S-metolachlor, and clopyralid-based treatments. Because the volunteer soybean used in this study was resistant to dicamba, the activity came mostly from the HPPD inhibitor tembotrione. Volunteer soybean has shown a mixed response to tembotrione in the literature, depending on the herbicide rate and growth stage. Dan et al. (2011) observed 64% to 72% control of volunteer soybean with tembotrione (100 g ha^{-1}) 28 DAA, while Alms et al. (2016) observed 87% to 89% control of V3 to V4 volunteer soybean with tembotrione (15 or 31 g ha^{-1}) in corn 28

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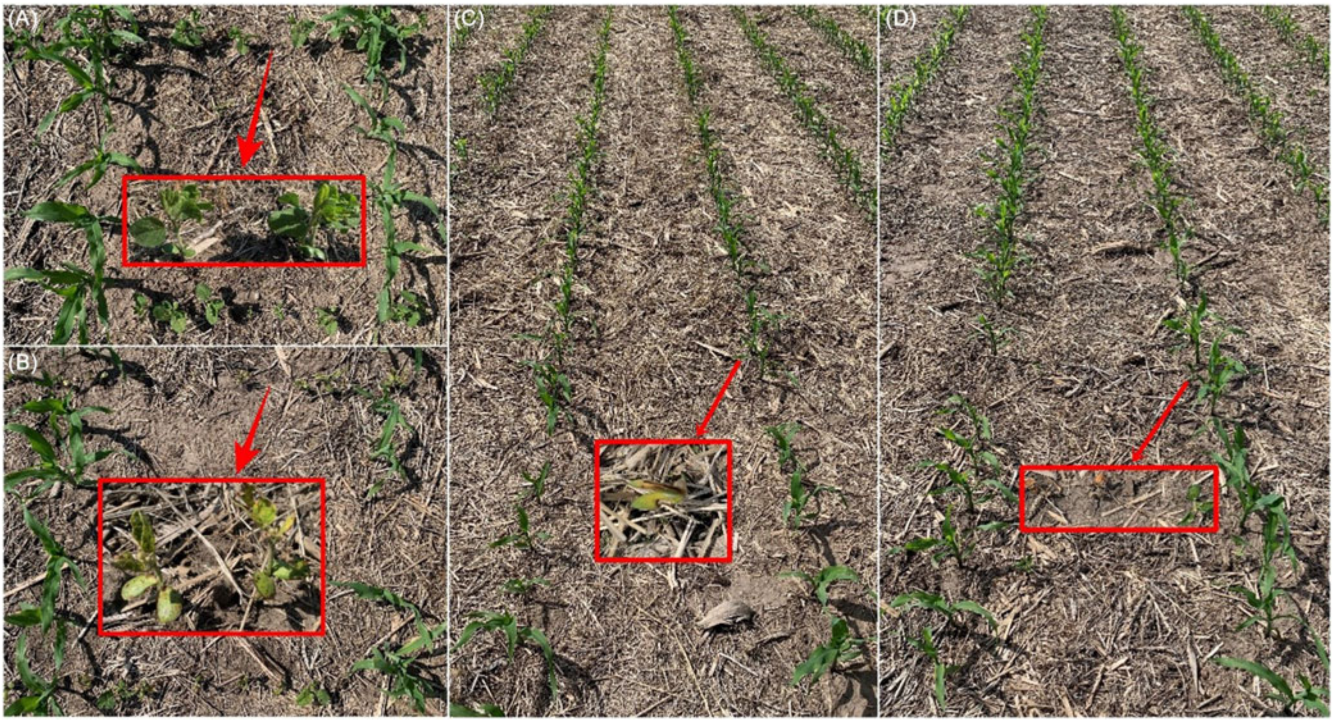

Figure 2. Dicamba/glufosinate/glyphosate-resistant volunteer soybean in nontreated control (A), atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (B), acetochlor/clopyralid/mesotrione (C), and acetochlor/clopyralid/flumetsulam (D) 28 d after preemergence applied in a field experiment conducted near Clay Center, NE in 2021.

Figure 3. Injury symptoms on dicamba/glufosinate/glyphosate-resistant volunteer soybean 34 d after PRE application of isoxaflutole/thiencarbazone-methyl + atrazine (129 + 560 g ai ha^{-1}) in a field experiment conducted near Clay Center, NE, in 2021.

DAA. However, in contrast, Theodoro et al. (2018) reported 46% control of V1 volunteer soybean and 12% control of V3 volunteer soybean with tembotrione (75 g ha^{-1}) 35 DAA. Similarly, Brighenti (2015) noted 5% to 13% control of V3 volunteer soybean in sunflower (*Helianthus annuus* L.) with tembotrione (21 g ha^{-1}) 7 to 21 DAA. Dimethenamid-*P*/topramezone (937; 919/18 g ai ha^{-1}) provided 47% to 50% control of volunteer soybean 14 DAPOST and 85% to 89% control 28 DAPOST. Currie and Geier (2018) noted 95% control of dicamba-resistant soybean 5 DAA and 100% control 82 DAA with dimethenamid-*P*/topramezone (736 g ha^{-1}) +

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Table 5. Control of dicamba/glyphosate/glufosinate-resistant soybean volunteers 14, 28, and 56 d after POST with POST herbicides evaluated in field experiments conducted near Clay Center, NE, in 2021 and 2022[a,b,c].

Herbicide	Rate	14 DAPOST		28 DAPOST	
		2021	2022	2021	2022
	g ai or ae ha^{-1}	%			
Nontreated control	—	0	0	0	0
Weed-free control	—	100	100	100	100
2,4-D choline	1,064	99 a–d	99 a	99 a–c	99 a
Acetochlor/clopyralid/mesotrione	2,304 (1,961/133/210)	99 a	99 a	99 a	99 a
Acetochlor/mesotrione	2,157 (1,972/185)	63 a–f	75 a–e	78 a–c	88 ab
Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor	2,409 (700/42/168/1,499)	98 a	94 a	99 a	98 a
Carfentrazone-methyl	9	0 h	47 c–g	23 d–f	48 b–f
Clopyralid/flumetsulam	192 (146/46)	95 a	93 a	99 a	99 a
Dicamba/tembotrione	597 (521/76)	43 d–g	63 a–f	80 a–c	95 a
Dimethenamid-*P*/topramezone	937 (919/18)	47 c–g	50 b–g	85 ab	89 ab
Fluthiacet-methyl	6	0 h	17 gh	23 d–f	22 ef
Fluthiacet-methyl/mesotrione	98 (5/93)	32 f–h	37 e–h	38 c–f	12 f
Glufosinate + atrazine	655 + 896	66 a–f	87 a–c	69 a–d	97 a
Nicosulfuron + atrazine	34 + 1,120	97 a	92 ab	99 a	97 a
Thiencarbazone-methyl/tembotrione + atrazine	75 (12/63) + 896	98 a	99 a	99 a	99 a
Tolpyralate	35	35 e–h	18 gh	62 a–e	23 d–f
P-value		0.028		0.027	

[a]Abbreviation: DAPOST, days after postemergence.
[b]Within a given evaluation timing, values with the same letter are not different according to estimated marginal means with Tukey P-value adjustments and Sidak confidence-level adjustments.
[c]Nontreated and weed-free controls were not included in the analysis.

atrazine (560 g ha^{-1}) and glyphosate (1,260 g ha^{-1}). Currie and Geier reported higher control of volunteer soybean (95% to 100% vs. 85% to 89%) despite applying a lower dose of dimethenamid-*P*/topramezone (736 vs. 937 g ha^{-1}), probably because atrazine (560 g ha^{-1}) was another effective herbicide in their treatment.

Atrazine (1,120 and 896 g ai ha^{-1}) mixed with nicosulfuron (34 g ai ha^{-1}) and thiencarbazone-methyl/tembotrione (75; 12/63 g ai ha^{-1}) provided ≥97% control of V3 to V4 volunteer soybean 28 DAPOST. Zollinger et al. (2018) reported 80% to 90% control of V2 to V3 and V4 to V6 glyphosate-resistant volunteer soybean with atrazine + thiencarbazone-methyl/tembotrione (420 + 91 g ha^{-1}). The atrazine rate for the atrazine + thiencarbazone-methyl/tembotrione in this study was more than double (896 vs. 420 g ha^{-1}) that used by Zollinger et al., although the thiencarbazone-methyl rate was 16 g ha^{-1} lower in this study (75 vs. 91 g ha^{-1}). With a lower rate of atrazine than this study, Theodoro et al. (2018) reported 100% control of V3 volunteer soybean 35 DAA with atrazine + nicosulfuron (500 + 40 g ha^{-1}) and atrazine + tembotrione (500 + 75 g ha^{-1}) in a greenhouse experiment. Nicosulfuron (40 g ha^{-1}) and tembotrione (75 g ha^{-1}) alone provided 42% and 12% control of volunteer soybean, respectively, in their study. Knezevic et al. (2014) observed that atrazine (560 g ha^{-1}) mixed with tembotrione (92 g ha^{-1}), topramezone (25 g ha^{-1}), or mesotrione (105 g ha^{-1}) provided 90% to 100% control of V2 to V3 glyphosate-resistant volunteer soybean and 66% to 69% control of V4 to V6 glyphosate-resistant volunteer soybean 14 DAA. Volunteer soybean control with glufosinate + atrazine (655 + 896 g ai ha^{-1}) varied by year, with 69% and 97% control 28 DAPOST in 2021 and 2022, respectively. Similarly, Alms et al. (2016) observed varying control with atrazine (1,120 g ha^{-1}): 98% control 56 DAA of V2 volunteer soybean in one year and 59% control 28 DAA of V3 to V4 volunteer soybean in another year. Dan et al. (2011) observed 100% control of volunteer soybean with a higher rate of atrazine (1,500 g ha^{-1}) 28 DAA. Zollinger and Ries (2004) reported 70% control of V4 to V6 glyphosate-resistant volunteer soybean with atrazine (560 g ha^{-1}) 28 DAPOST. Carfentrazone-methyl (9 g ai ha^{-1}), fluthiacet-methyl (6 g ai ha^{-1}), fluthiacet-methyl/mesotrione (98; 5/93 g ai ha^{-1}), and tolpyralate (35 g ai ha^{-1}) provided <50% control of volunteer soybean. Similarly, Brighenti (2015) noted that carfentrazone (4 g ha^{-1}) did not provide effective control (23%; 7 DAA) of V3 volunteer soybean.

Among PRE herbicides, clopyralid-based herbicides (acetochlor/clopyralid/flumetsulam and acetochlor/clopyralid/mesotrione) controlled ≥98% of dicamba/glufosinate/glyphosate-resistant volunteer soybean by 63 DAPRE in both years. Similarly, clopyralid-based POST herbicides (acetochlor/clopyralid/mesotrione and clopyralid/flumetsulam) provided 99% volunteer soybean control by 28 DAPOST in both years. Atrazine-based POST treatments, such as atrazine/bicyclopyrone/mesotrione/*S*-metolachlor, atrazine + nicosulfuron, and atrazine + thiencarbazone-methyl/tembotrione, also controlled ≥97% of dicamba/glufosinate/glyphosate-resistant volunteer soybean by 28 DAPOST. These herbicide options can also be valuable for controlling soybean volunteers with Enlist® E3 (2,4-D/glufosinate/glyphosate-resistance), LibertyLink® GT27 (glufosinate/glyphosate/isoxaflutole-resistance), or Roundup Ready 2 Xtend® (dicamba/glyphosate-resistance) (Bayer Crop Science) traits, as they lack resistance to clopyralid, atrazine, and so on. Factors like soil organic matter, pH, texture, clay content, amount of rainfall, and growth stage of volunteer soybeans are important to consider when determining herbicide rates and assessing carryover potential (Courtney 2016).

Volunteer Soybean Density and Biomass with PRE and POST Herbicides

Clopyralid-based PRE herbicides, that is, acetochlor/clopyralid/flumetsulam (1,190; 1,050/106/34 g ai ha^{-1}) and acetochlor/clopyralid/mesotrione (2,304; 1,961/133/210 g ai or ae ha^{-1}) provided ≥98% control of volunteer soybean that resulted in 100% reduction in density and biomass of volunteer soybean relative to the nontreated control 63 DAPRE in 2021 (Table 6). However, these treatments had only a 52% to 55% reduction of volunteer soybean biomass 28 DAPRE in 2023. Herbicides containing HPPD

Table 6. Density and biomass reduction of volunteer soybean and Enlist® corn yield affected by PRE herbicides evaluated for control of dicamba/glufosinate/glyphosate-resistant volunteer soybean in field experiments conducted near Clay Center, NE, in 2021 and 2023[a,b,c].

Herbicide	Rate	2021, 63 DAPRE		2023, 28 DAPRE		
		Density reduction	Biomass reduction	Density reduction	Biomass reduction	Corn yield[d]
	g ai or ae ha^{-1}	%				kg ha^{-1}
Nontreated control	—	0	0	0	0	15,481
Weed-free control	—	100	100	100	100	16,735
Acetochlor/atrazine	3,961 (2,647/1,314)	50 b–d	66 b–d	8	55	15,637
Acetochlor/clopyralid/flumetsulam	1,190 (1,050/106/34)	100 a	100 a	12	52	16,463
Acetochlor/clopyralid/mesotrione	2,304 (1,961/133/210)	100 a	100 a	14	56	16,862
Acetochlor/mesotrione	2,696 (2,465/231)	44 b–d	86 ab	15	63	17,258
Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor	2,409 (700/42/168/1,499)	69 a–c	89 ab	5	42	15,017
Dimethenamid-*P*/saflufenacil	731 (656/75)	49 b–d	53 cd	11	52	16,141
Fluthiacet-methyl/pyroxasulfone	188 (5/183)	19 d	8 e	7	49	17,328
Isoxaflutole + atrazine	88 + 560	44 b–d	85 a–c	13	38	16,404
Isoxaflutole/thiencarbazone-methyl + atrazine	129 (92/37) + 560	85 ab	95 ab	15	37	16,396
Pendimethalin + atrazine	1,916 + 1,120	30 cd	35 de	11	45	16,080
Pyroxasulfone + atrazine	110 + 1,120	46 b–d	15 e	6	43	17,413
Saflufenacil + atrazine	62 + 1,120	35 cd	36 de	18	43	16,645
P-value		<0.001	<0.001	0.969	0.883	0.294

[a]Abbreviation: DAPRE, days after preemergence.
[b]Within a given evaluation timing, values with the same letter are not different according to estimated marginal means with Tukey P-value adjustments and Sidak confidence-level adjustments.
[c]Nontreated and weed-free controls were not included in the analysis.
[d]Yield data were combined across years (2021 and 2023) as they did not differ between years.

inhibitors, such as acetochlor/mesotrione, atrazine/bicyclopyrone/mesotrione/*S*-metolachlor, isoxaflutole + atrazine, and isozaflutole/thiencarbazone-methyl + atrazine, provided 85% to 95% biomass reduction with 44% to 85% volunteer soybean density reduction 63 DAPRE in 2021. In 2023, these treatments had a 37% to 63% biomass reduction 28 DAPRE. Among POST herbicides, synthetic auxin or HPPD-inhibitor-containing treatments, such as 2,4-D acetochlor/clopyralid/mesotrione, clopyralid/flumetsulam, atrazine/bicyclopyrone/mesotrione/*S*-metolachlor, and thiencarbazone-methyl/temborione + atrazine, provided 98% to 100% biomass reduction and 96% to 100% density reduction of volunteer soybean relative to the nontreated control 28 DAPOST (Table 7). Courtney (2016) observed a 100% stand reduction of V3 to V4 volunteer soybean with acetochlor/clopyralid/flumetsulam (1,193; 1,053/106/34 g ha^{-1}) in corn in North Carolina and a 69% stand reduction in Mississippi (45 vs. 14 plants) and South Dakota (70 vs. 22 plants) 28 DAPOST.

Corn Yield

Averaged across 2021 and 2023, corn yield across PRE herbicides (15,017 to 17,413 kg ha^{-1}) was similar to that for the nontreated control (15,481 kg ha^{-1}; Table 6). Corn yield in the POST herbicide experiment varied by year ($P = 0.026$; Table 7). Corn yield did not differ among POST herbicides, except for the nontreated control in 2022 (7,412 kg ha^{-1}), when the volunteer soybean seeding rate was more than double compared to 2021 (32.5 vs. 12.5 plants m^{-2}). The nontreated control had 36% less yield than atrazine/bicyclopyrone/mesotrione/*S*-metolachlor in 2022. Similarly, Alms et al. (2016) estimated 37% corn yield loss with volunteer soybean at 33 plants m^{-2}. However, as an overall assessment combined across years, volunteer soybean did not cause significant yield loss, even when not controlled with PRE or POST herbicides. It must be noted that in each experiment, other weeds were mostly controlled using PRE and POST herbicides.

Practical Implications

Although volunteer soybean is not always a primary concern for corn growers implementing a corn–soybean rotation, it can become problematic in certain situations. The widespread adoption of multiple-herbicide-resistant soybean traits can complicate the management of volunteer soybean because certain herbicides would not be effective, depending on the herbicide-resistant traits present in the soybean grown in the previous year. In this study, PRE and POST herbicides labeled in corn were evaluated for control of dicamba/glufosinate/glyphosate-resistant soybean volunteers. Among PRE herbicides, treatments containing clopyralid, such as acetochlor/clopyralid/flumetsulam (1,190 g ai ha^{-1}) and acetochlor/clopyralid/mesotrione (2,304 g ai or ae ha^{-1}), provided ≥98% control of volunteer soybean by 63 DAPRE in 2021 and 2023. The activating rainfall (or sprinkler irrigation) is crucial for PRE herbicides, as they provided 83% to 97% control by 28 DAPRE in 2021 and 68% to 89% control by 42 DAPRE in 2023, likely due to more rainfall around the PRE application in 2021 than in 2023. Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (2,409 g ai ha^{-1}) provided 87% control 63 DAPRE in 2021. In this study, volunteer soybean was planted at a depth of approximately 4 cm; however, soybean volunteers emerging from shallow or bare soil surfaces in no-till fields may not be effectively controlled by PRE herbicides, as these require contact with germinating seedlings. Among POST herbicides, 2,4-D (1,064 g ae ha^{-1}) and clopyralid-containing programs, such as acetochlor/clopyralid/mesotrione (2,304 g ai or ae ha^{-1}) and clopyralid/flumetsulam (192 g ai ha^{-1}), provided 99% control of dicamba/glufosinate/glyphosate-resistant volunteer soybean in Enlist® corn 28 DAPOST. Atrazine-based mixtures, such as atrazine + nicosulfuron (1,120 + 34 g ai ha^{-1}) and atrazine + thiencarbazone-methyl/tembotrione (896 + 75 g ai ha^{-1}), provided ≥97% control of volunteer soybean 28 DAPOST. It is concluded that PRE and POST herbicide options are available that can control dicamba/glufosinate/glyphosate-resistant soybean volunteers in Enlist®

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Table 7. Density and biomass reduction of volunteer soybean and Enlist® corn yield influenced by POST herbicides evaluated for control of dicamba/glufosinate/glyphosate-resistant volunteer soybean in field experiments conducted near Clay Center, NE, in 2021 and 2022[a,b,c].

Herbicide	Rate	2021–2022, 28 DAPOST		Corn yield	
		Density reduction	Biomass reduction	2021	2022
	g ai or ae ha^{-1}	%		kg ha^{-1}	
Nontreated control	—	0	0	14,042 a	7,412 b
Weed-free control	—	100	100	14,486 a	9,261 ab
2,4-D choline	1,064	100 ab	100 a	13,982 a	10,633 a
Acetochlor/clopyralid/mesotrione	2,304 (1,961/133/210)	100 a	100 a	14,873 a	10,384 a
Acetochlor/mesotrione	2,157 (1,972/185)	47 b–d	78 ab	14,192 a	9,188 ab
Atrazine/bicyclopyrone/mesotrione/*S*-metolachlor	2,409 (700/42/168/1,499)	99 a	100 a	14,539 a	11,504 a
Carfentrazone-methyl	9	12 d	66 ab	13,314 ab	11,340 a
Clopyralid/flumetsulam	192 (146/46)	97 a	98 a	14,849 a	10,939 a
Dicamba/tembotrione	597 (521/76)	29 d	72 ab	14,538 a	11,263 a
Dimethenamid-*P*/topramezone	937 (919/18)	34 cd	78 ab	15,056 a	11,524 a
Fluthiacet-methyl	6	14 d	43 b	13,543 ab	10,255 ab
Fluthiacet-methyl/mesotrione	98 (5/93)	8 d	50 b	14,516 a	11,269 a
Glufosinate + atrazine	655 + 896	77 a–c	82 ab	14,350 a	10,234 ab
Nicosulfuron + atrazine	34 + 1,120	94 a	99 a	14,259 a	9,554 ab
Thiencarbazone-methyl/tembotrione + atrazine	75 (12/63) + 896	96 a	100 a	14,855 a	10,436 a
Tolpyralate	35	21 d	50 b	14,049 a	10,138 ab
P-value		<0.001	<0.001	0.026	

[a]Abbreviation: DAPOST, days after postemergence.
[b]Within a given evaluation timing, values with the same letter are not different according to estimated marginal means with Tukey P-value adjustments and Sidak confidence-level adjustments.
[c]Nontreated and weed-free controls were not included in the analysis.

corn; however, herbicides should be carefully selected based on the herbicide-resistant soybean planted in the previous year. Owing to the widespread adoption of dicamba/glufosinate/glyphosate-resistant soybean, these herbicides will not control volunteer soybean. Moreover, volunteer soybean should be targeted at an early vegetative stage for better control with POST herbicides (Alms et al. 2016; Knezevic et al. 2014; Zollinger and Ries 2004).

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