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Efficacy of Pre-Emergence and Post-Emergence Soybean Herbicides for Control of Glufosinate-, Glyphosate-, and Imidazolinone-Resistant Volunteer Corn

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Abstract

Glyphosate-resistant corn and soybean are grown in rotations in the Midwest, including Nebraska. Volunteer corn is a problematic weed in soybean fields because it causes harvest problems, reduces yield and seed quality, and potentially harbors insects, pests, and diseases. Several pre-packaged herbicides have been registered in soybean in recent years, but response of volunteer corn to these herbicides has not yet been documented. Greenhouse experiments were conducted to evaluate the response of glufosinate-, glyphosate-, and imidazolinone-resistant volunteer corn to 20 pre-emergence (PRE) and 17 post-emergence (POST) soybean herbicides. Cumulative emergence of volunteer corn was not affected by PRE soybean herbicides compared with the nontreated control regardless of herbicide-resistant trait at 21 days after treatment (DAT). Although comparable with several other treatments, clomazone provided ≥ 90% control of glufosinate- and imidazolinone-resistant volunteer corn at 21 DAT. The POST soybean herbicides were applied when volunteer corn plants were at the 2 to 3 or 5 to 6 leaf stage. The ACCase-inhibiting herbicides, including clethodim, fenoxaprop plus fluazifop, fluazifop, quizalofop, and sethoxydim, provided ≥ 96 and ≥ 85% control of the 2 to 3 or 5 to 6 leaf stage volunteer corn, respectively, regardless of the herbicide-resistance trait at 28 DAT. Glyphosate tank mixed with acifluorfen, chlorimuron-ethyl, or imidazolinones usually provided > 83% control of glufosinate-and imidazolinone-resistant volunteer corn when sprayed at the 2 to 3 leaf stage at 28 DAT, but control was ≤ 71% for the 5 to 6 leaf stage volunteer corn. Similar results were usually reflected in volunteer corn biomass. It is concluded that PRE soybean herbicides partially controlled volunteer corn; therefore, ACCase inhibiting herbicides are the only highly effective option for soybean growers.

Keywords: herbicide efficacy, pre-packaged herbicides, volunteer corn biomass, volunteer corn leaf stage

1. Introduction

The United States is the largest producer of corn in the world (USDA, 2013). In 2013, the estimated area planted to corn in the United States was about 35.39 million ha (USDA, 2013), and by 2016, this number is expected to increase to 38 million ha (Malcolm & Aillery, 2009). Corn-soybean is the most prominent crop rotation in the Corn Belt. Glyphosate-resistant volunteer corn is a problem weed not only in soybean, but also in continuous corn rotations (Marquardt et al., 2012a). Storm damage, harvesting problems, poor stalk quality, and insect damage, among other factors, can lead to kernel and ear losses that result in volunteer corn the following year. Volunteer corn results from the overwintering of the hybrid corn used the previous year or from a failed corn stand in corn replant situation (Steckel et al., 2009; Shauck & Smeda, 2012).

Volunteer corn was documented as a weed even before the commercialization of herbicide-resistant corn (Andersen et al., 1982; Beckett & Stroller, 1988), with glyphosate used in rope-wick applications to control volunteer corn (Andersen et al., 1982; Beckett & Stroller, 1988; Dale, 1981). With the commercialization of glyphosate-resistant corn and soybean in the late 1990s, growers rapidly adopted them in the Americas (Castle et al., 2006). In 2010, more than 70% of corn and 93% of soybean planted were herbicide-resistant, primarily glyphosate-resistant (USDA-NASS, 2010). Increased adoption of glyphosate-resistant corn resulted in increasing issues of volunteer corn. Volunteer corn also plays a role in the survival and dispersal of corn rootworm and grey leaf spot disease; therefore, it limits the benefits of corn-soybean rotation and creates challenges for insect-resistance manage/ment (Marquardt et al., 2012b; Krupke et al., 2009; Shaw et al., 1978).

Volunteer corn is a competitive weed, as it grows taller than soybean, and like many other weeds, causes yield reduction by competing for light, space, nutrients, and moisture (Beckett & Stoller, 1988; Marquardt et al., 2012b). In addition, if corn volunteers remain in the field until maturity, corn seeds would contaminate the harvested soybean and reduce the market quality (Deen et al., 2006). Beckett and Stroller (1988) reported 25% soybean yield reduction at a volunteer corn density of 5,380 plants ha^{-1}. In Minnesota, a uniform corn density of 0.4 plants m^{-1} of soybean row caused a 14 to 49% yield reduction depending on the location and year (Andersen et al., 1982). A recent study by Marquardt et al. (2012b) also reported a 10 to 14% soybean yield reduction. Wilson et al. (2010) reported that a volunteer corn density of 8,750 and 17,500 plants ha^{-1} reduced soybean yields by 10 and 27%, respectively in Nebraska.

The ACCase (acetyl-coenzyme A carboxylase) inhibiting-herbicides, also known as graminicides, are often used in soybean to control grass weeds, including volunteer corn. Several studies reported that diclofop, fluazifop, quizalofop, and sethoxydim were effective for controlling volunteer corn in soybean (Andersen, 1976; Andersen et al., 1982; Andersen & Geadelmann, 1982; Beckett & Stroller, 1988; Beckett et al., 1992); however, the efficacy of an ACCase inhibitors can be affected by a number of factors, including the growth stage of the volunteer corn, the environmental conditions at the time of application, and the efficacy of the individual herbicide (Wilson et al., 2010). Several pre-packaged herbicide tank-mixtures have been registered in recent years and are widely used by soybean growers specifically for the control of glyphosate- and ALS inhibitor-resistant weeds.

Several PRE herbicides exist for residual grass weed control in soybean; however, none of them list volunteer corn on their labels. Information is not available, to our knowledge, in scientific literature about the response of volunteer corn to PRE soybean herbicides. In addition, several new pre-packaged herbicide tank-mixtures, such as sulfentrazone plus chloransulam-methyl (Authority™ First), sulfentrazone plus metribuzin (Authority™ MTZ), etc., have been registered for PRE weed control in soybean. These new residual herbicides may expand the weed control spectrum, though the response of herbicide-resistant volunteer corn to these herbicides is unknown. Therefore, the objectives of study were to (1) evaluate the efficacy of PRE soybean herbicides for control of glufosinate-, glyphosate-, and imidazolinone-resistant volunteer corn, and (2) evaluate the efficacy of POST soybean herbicides registered for grass weed control applied at two growth stages (2-to 3- or 4-to 5-leaf stage) for control of glufosinate-, glyphosate-, and imidazolinone-resistant volunteer corn.

2. Materials and Methods

2.1 Greenhouse Experiment and Data Collection

Greenhouse studies were conducted at the University of Nebraska-Lincoln in 2013. All PRE- and POST-applied soybean herbicides registered for grass weed control were evaluated for the control of glufosinate-, glyphosate-, and imidazolinone-resistant volunteer corn. The herbicide application rates were selected based on the recommended labeled rates. The hybrids of glufosinate-, glyphosate-, and imidazolinone-resistant corn were planted in 2012 at the South Central Agriculture Laboratory, University of Nebraska-Lincoln near Clay Center, Nebraska. Seeds were harvested in October 2012 and kept at room temperature until they were used for this study. A preliminary study was conducted to determine the germination percentage of volunteer corn seeds. The results suggested ≥ 98% germination for each herbicide-resistant trait (data not shown).

2.1.1 PRE Herbicide Study

The soil used in this study was collected from a field near Lincoln, Nebraska (24% sand, 25% clay, 51% silt, and 2.7% organic matter) with known history of no herbicide usage for at least the last eight years. Ten seeds each of glufosinate-, glyphosate-, and imidazolinone-resistant volunteer corn were planted at 2- to 3-cm depth in plastic pots (15 cm diameter and 15 cm height) filled with the soil. The pots were watered at field capacity. Herbicides were applied on the soil surface 1 d after planting the seeds using a chamber track bench sprayer fitted with a 8001-E nozzle (Teejet Technologies, Wheaton, IL). The experiment was laid out in a 20 × 3 factorial randomized complete block design with four replications. The two factors were 20 herbicide treatments (including nontreated control) and 3 herbicide-resistant volunteer corn traits (glufosinate-, glyphosate-, and imidazolinone-resistant). The day/night temperature and photoperiod of the greenhouse were 28/24 ^{o}C and 14 h, respectively, and the pots were watered as required. The PRE soybean herbicides used in this study are listed in Table 1. Herbicide rates were selected based on the recommended labeled rates for soybean.

A cumulative number of emergences of glufosinate-, glyphosate-, and imidazolinone-resistant volunteer corn were recorded at 7, 14, and 21 d after treatment (DAT). Visual estimates of control of emerged volunteer corn plants were recorded at 7, 14, and 21 d after treatment (DAT) based on a 0 to 100% scale, with 0% meaning no injury or control (healthy plant) and 100% meaning complete control or severe injury with no chance of plant survival. Volunteer corn plants were harvested at the base of the plant at 21 DAT and the fresh weight was recorded. The plants were kept in a paper bag, oven dried at 60 ^{o}C for 96 h, and dry biomass weight was recorded. The experiment was repeated again for the consistency of results.

2.1.2 POST Herbicide Study

Three seeds each of glufosinate-, glyphosate-, and imidazolinone-resistant volunteer corn were seeded at a depth of 2 to 3 cm in separate plastic pots (15 cm diameter and 15 cm height), filled with 75% commercial potting mix (Berger BM1 potting mix, Berger Peat Moss Ltd., Quebec, Canada) and 25% soil. Plants were thinned to two plants per pot at 7 days after emergence. The experiment was laid out in a 2 × 18 × 3 factorial randomized complete block design with four replications. The three factors included two heights of volunteer corn [2- to 3-leaf stage (12 to 15 cm tall) and 5- to 6-leaf stage (30 to 33 cm tall)], 18 herbicide treatments (including a nontreated control), and three herbicide-resistant volunteer corn traits (glufosinate-, glyphosate-, and imidazolinone-resistant). Plants were watered every other day and were supplied with nutrients using fertilizer solution (Scotts Miracle-Gro Products, Inc. Marysville, OH) before 5 d of herbicide treatment. Herbicide treatments were applied when volunteer corn plants were at the 2- to 3-leaf stage (12- to 15-cm tall) or the 5- to 6-leaf stage (30- to 33-cm tall). Details of POST soybean herbicides used in this study are provided in Table 2. Herbicide rates used were based on recommended labeled rates for soybean. Recommended adjuvants were added to the herbicide solutions (Table 2). Treatments were applied using the same chamber track bench sprayer noted in the PRE herbicide study.

Visual estimates of control of glufosinate-, glyphosate-, and imidazolinone-resistant volunteer corn were recorded at 7, 14, 21, and 28 DAT based on a 0 to 100% scale as explained in the PRE herbicide study. Volunteer corn plants were harvested at the base of the plant at 28 DAT and the fresh weight was recorded. The plants were kept in paper bags, oven dried at 60 ^{o}C for 96 h and biomass weight was recorded. The experiment was repeated again for the consistency of results.

2.2 Statistical Analysis

Data from PRE and POST soybean herbicide studies were subjected to ANOVA using the PROC GLIMMIX procedure in SAS version 9.3 (SAS Institute Inc, Cary, NC). Before analysis, data were tested for normality with the use of PROC UNIVARIATE. Visual estimates of volunteer control, volunteer corn emergence, and biomass data were arcsine square-root transformed before analysis; however, back-transformed data are presented with mean separation based on transformed data. For PRE herbicide study, herbicide treatments and corn types were the fixed effects, while replications and experimental repeats (nested within replication) were considered random effects. For POST herbicide study, herbicide treatments, volunteer corn type, and plant heights were the fixed effects, while replications and experimental repeats (nested within replication) were considered random effects. Where the ANOVA indicated treatment effects were significant, means were separated at $P \leq 0.05$ with Tukey-Kramer's pairwise comparison test.

Table 1. Details of pre-emergence (PRE) soybean herbicides used in this study

Herbicide	Trade name	Formulation	Rate (g ai ha^{-1})	Manufacturer
Sulfentrazone + Imazethapyr	Authority Assist	480 g L^{-1}	422	FMC Corporation, Philadelphia, PA 19103
Sulfentrazone + Chloransulam methyl	Authority First	621 g kg^{-1}	315	Monsanto Company, 800 North Lindberg Ave., St. Louis, Mo
Sulfentrazone + Metribuzin	Authority MTZ	450 g kg^{-1}	567	FMC Corporation
Sulfentrazone + Chlorimuron ethyl	Authority XL	700 g kg^{-1}	343	FMC Corporation
Clomazone	Command 3ME	360 g L^{-1}	840	FMC Corporation
Chlorimuron methyl + Flumioxazin + Thifensulfuron	Enlite	479 g kg^{-1}	94	DuPont Crop Protection, P. Box 80705 CRP 705/L1S11, Wilmington, DE 19880-0705.
Flumioxazin + Cloransulam	Gangster co pack	510 g kg^{-1} + 840 g kg^{-1}	107 + 35.3	Valent USA Corporation, Walnut Creeks, CA 94596
Alachlor	Intrro	480 g L^{-1}	2,800	Monsanto Company
Saflufenacil + Imazethapyr	Optill	680 g kg^{-1}	95	BASF Corporation, 26 Davis Drive, Research Triangle Park, NC 27709
S-metolachlor + Fomesafen	Prefix	566 g kg^{-1}	1,490	Syngenta Crop Protection, Inc. Greensboro, NC 27419
Pendimethalin	Prowl H_2o	456 g L^{-1}	1,070	BASF Ag Products
Pendimethalin + Metribuzin	Prowl H_2o + Sencor DF/Dimetric	456 g L^{-1} + 750 g kg^{-1}	1,070 + 420	BASF Ag Products + AgriSolutions 31832 Delhi Road Brighton, IL 62012
Imazethapyr	Pursuit	240 g L^{-1}	70	BASF Corporation
Imazethapyr + S-metolachlor	Pursuit + Dual II Magnum	240 g L^{-1} + 824 g kg^{-1}	137 + 1,600	BASF Corporation + Syngenta Crop Protection
Imazaquin +S-metolachlor	Scepter + Dual II Magnum	700 g kg^{-1} + 824 g kg^{-1}	137 + 1,247	BASF Corporation + Syngenta Crop Protection
Metribuzin + S-metolachlor	Sencor + Dual II Magnum	750 g kg^{-1} + 824 g kg^{-1}	420 + 1,070	Bayer Crop Science, Research Triangle Park, NC 27709 + Syngenta Crop Protection
Trifluralin	Treflan	480 g L^{-1}	840	Dow AgroSciences, LLC 9330 Zionsville Road Indianapolis, IN 46268
Flumioxazin	Valor SX	510 g kg^{-1}	89	Valent U.S.A. Corporation Agricultural Products
Flumioxazin + Chlorimuron-ethyl	Valor XLT	597 g kg^{-1}	113	Valent U.S.A. Corporation + BASF Corporation

Table 2. Details of post-emergence (POST) soybean herbicides used in this study

Herbicide	Trade name	Rate g ai ha^{-1}	Manufacturer	Adjuvant[a]
Quizalofop	Assure II	38.6	DuPont Crop Protection, P.O.Box 80705 Wilmington, DE 19880	COC 1% v/v
Fluthiacet-ethyl	Cadet	7.2	FMC Corporation, Philadelphia, PA 19103	NIS 0.25% v/v + UAN-28% 2.34 L ha^{-1}
Imazethapyr + Glyphosate	Extreme	910	Syngenta Crop Protection, Inc. Greensboro, NC 27419	NIS 0.125% v/v + AMS 2% w/w
Fomesafen + Glyphosate	Flexstar GT	1,380	Syngenta Crop Protection	NIS 0.25% v/v + AMS 2% w/w
Fluazifop	Fusilade DX	210	Syngenta Crop Protection	NIS 0.25% v/v + UAN-28% 9.4 L ha^{-1}
Glyphosate + Imazamox	Roundup PowerMAX + Raptor	1,120 + 44	Monsanto Company, 800 North Lindberg Ave., St. Louis, Mo	NIS 0.25% v/v + AMS 1.8% wt/wt
Glyphosate + Imazaquin	Roundup PowerMAX + Scepter	1,120 + 76	Monsanto Company + BASF Corporation, 26 Davis Drive, Research Triangle Park, NC 27709	NIS 0.25% v/v
Glyphosate + Acifluorfen	Roundup PowerMAX + Ultra Blazer	1,120 + 340	Monsanto Company + United Phosphorus, Inc. 630 Freedom Business Center, PA 19406	NIS 0.25% v/v + AMS 2% wt/wt
Glufosinate	Liberty 280 SL	595	Bayer Crop Science, Research Triangle Park, NC 27709	AMS 2% wt/wt
Sethoxydim	Poast Plus	350	BASF Corporation	COC 2% v/v + AMS 2.8% wt/wt
Imazamox	Raptor	44	BASF Corporation	NIS 0.25% v/v + AMS 1.8% wt/wt
Clethodim	Select Max	136	Valent USA Corporation, Walnut Creek, CA 94596	NIS 0.25% v/v + AMS 1.8% wt/wt
Fenoxaprop + Fluazifop	Fusion	135	Syngenta Crop Protection	COC 0.25% v/v + AMS 4.5% wt/wt
Glyphosate + Chlorimuron-ethyl	Roundup PowerMAX + Classic	1,120 + 5.8	Monsanto Company + DuPont Crop Protection, P. Box 80705 CRP 705/L1S11, Wilmington, DE	NIS 0.25% v/v + AMS 2% wt/wt
Imazethapyr	Pursuit	70	BASF Corporation	NIS 0.25% v/v + AMS 1.8% wt/wt
Acifluorfen	Ultra Blazer	170	United Phosphorous Inc.	NIS 0.25% v/v + AMS 2% wt/wt
Imazamox + Acifluorfen	Raptor + Ultra Blazer	35 + 280	BASF Corporation + United Phosphorous Inc. + United phosphorous Inc.	NIS 0.25% v/v + AMS 2% wt/wt

Note. AMS = ammonium sulfate (DSM chemicals North America Inc., Augusta, GA), COC = crop oil concentrate (Agridex, Helena Chemical Co., Collierville, TN), NIS = nonionic surfactant (Induce, Helena Chemical Co., Collierville, TN), UAN-28 = Urea ammonia nitrate solution 28% (Sylvite Agri-Services, Ontario, Canada).

3. Results and Discussion

3.1 PRE Herbicide Study

The two-way interaction of herbicide treatments and volunteer corn type was significant; therefore, data are presented separately. Control of volunteer corn varied among herbicide treatments at 7 d after treatment (DAT) (Table 3). Control of glufosinate-, glyphosate-, and imidazolinone-resistant volunteer corn was in the range of 9 to 69%, 6 to 58%, and 25 to 69%, respectively, at 7 DAT. However, control was improved in a few herbicide treatments at 21 DAT. For example, although comparable with several other treatments, clomazone provided ≥ 90% control of glufosinate- and imidazolinone-resistant volunteer corn at 21 DAT. Surprisingly, clomazone was not very effective (< 50% control) on glyphosate-resistant volunteer corn. Cumulative emergence of volunteer corn at 21 DAT was comparable with the nontreated control without difference among herbicide treatments, indicating the failure of PRE soybean herbicides to prevent volunteer corn emergence.

Sulfentrazone tank mixes usually resulted in 47 to 75% control of volunteer corn and was comparable with few other treatments, including clomazone at 21 DAT (Table 3). Volunteer corn biomass reflected similar results with several treatments comparable with the nontreated control that indicated control failure of PRE soybean herbicides. The overall results of the PRE soybean herbicides suggest that with the exception of clomazone for glufosinate- and imidazolinone-resistant volunteer corn, no other herbicide provided economically acceptable control. Based on these greenhouse studies, it is concluded that PRE herbicide is not available for acceptable control of glyphosate-resistant volunteer corn in soybean.

3.2 POST Herbicide Study

The three-way interaction of herbicide treatments, volunteer corn type (glufosinate-, glyphosate-, and imidazolinone-resistant), and volunteer corn height was significant. Control of volunteer corn was affected by growth stage and POST soybean herbicides (Table 4). The ACCase-inhibiting herbicides, including clethodim, fenoxaprop plus fluazifop, fluazifop, quizalofop, and sethoxydim, resulted in 48 to 75% control of glufosinate- and glyphosate-resistant volunteer corn at 7 DAT when sprayed at the 2- to 3-leaf stage, and usually were comparable with glyphosate tank-mix treatments. The ACCase inhibitors resulted in 28 to 45% control of imidazolinone-resistant volunteer corn at 7 DAT; however, control was improved at 28 DAT and resulted in ≥ 96 % control, regardless of the resistant trait. Similarly, several studies have reported > 90% control of volunteer corn with ACCase (Andersen, 1976; Andersen et al., 1982; Andersen & Geadelmann, 1982; Beckett & Stroller 1988; Beckett et al., 1992; Marquardt & Johnson, 2013).

Glyphosate tank mixed with acifluorfen, chlorimuron, imazamox, imazaquin, or imazethapyr usually provided 83 to 91% and 87 to 98% control of glufosinate-and imidazolinone-resistant volunteer corn, respectively, and was comparable with an ACCase inhibitor at 28 DAT. Acifluorfen, fluthiacet-ethyl, imazamox, imazethapyr, and imazethapyr plus acifluorfen resulted in poor control (≤ 57%) of volunteer corn. Results of volunteer corn control were reflected in biomass. For example, the lowest biomass (≤ 1.2 g pot^{-1}) was recorded with ACCase-inhibitor herbicides and was comparable with glyphosate tank-mix treatments. Fluthiacet-ethyl, imazethapyr, or acifluorfen resulted in the highest biomass that was comparable with the nontreated control and confirmed poor control of volunteer corn in soybean.

The POST soybean herbicides applied at the 5- to 6-leaf stage of volunteer corn resulted in variable response compared with the 2- to 3-leaf stage (Tables 4 and 5). Similarly, Marquardt and Johnson (2013) reported that clethodim applied to ≤ 30 cm-tall volunteer corn provided higher and more consistent control compared to 90 cm-tall plants at 14 DAT at all volunteer corn densities. All herbicide treatments resulted in < 40% control of volunteer corn at 7 DAT. However, ACCase inhibitors resulted in 85 to 97% control at 28 DAT. Similarly, several studies demonstrated effective control of volunteer corn with ACCase inhibitors. For example, Andersen et al. (1982) reported > 90% control of volunteer corn with diclofop. Young and Hart (1997) reported > 90% control with sethoxydim or quizalofop. Deen et al. (2006) reported that use of a recommended adjuvant significantly improved the effectiveness of ACCase inhibitors, specifically when reduced rates were applied. Glyphosate tank mixed with acifluorfen, chlorimuron, fomesafen, imazamox, imazaquin, and imazethapyr resulted in ≤ 71% control of volunteer corn, regardless of resistant trait. The lowest volunteer corn biomass was usually recorded with ACCase inhibitors confirming results of visual control estimates at 28 DAT.

Results of the PRE soybean herbicide study revealed that clomazone resulted in > 90% control of glufosinate- and imidazolinone-resistant volunteer corn, but < 50% control of glyphosate-resistant volunteer corn. A predominant number of corn hybrids planted in the Midwestern United States are glyphosate-resistant, and the occurrence of glyphosate-resistant volunteer corn is more widely distributed compared to glufosinate- and imidazolinone-resistant volunteer corn. In this study, PRE or POST application of imidazolinones resulted in poor control of volunteer corn. In contrast, Young and Hart (1997) reported 70 and 83% control of volunteer corn with imazaquin and imazethapyr plus imazaquin in soybean. More research is required to identify a PRE herbicide with excellent efficacy for volunteer corn control, soybean selectivity as well as to better understand the natural range in tolerance of volunteer corn lines to herbicides.

Overall results suggest that volunteer corn can be effectively controlled with ACCase inhibitors regardless of herbicide-resistant trait. The ACCase-inhibiting herbicides were more effective and consistent (≥ 96% control) when applied to 2- to 3-leaf stage volunteer corn compared with the 5- to 6-leaf stage (≥ 85% control). Therefore, it is advisable to control volunteer corn with ACCase inhibitors when they are at the 2- to 3-leaf stage to avoid competition with soybean during the early growth stage. In addition, early season control is recommended from an insect resistance management standpoint, if volunteer corn plants also express transgenic Bt traits (Krupke et al., 2009). Repeated application of ACCase inhibitors for the last several years has resulted in the evolution of 44 grass weed species resistant to this herbicide chemistry (Heap, 2014). In fact, resistance to ACCase inhibitors has become the third most frequent type of weed resistance (Kukorelli et al., 2013). Therefore, in the fields with ACCase inhibiting herbicide-resistant weed(s), ACCase inhibitors should be tank-mixed with other herbicides that can effectively control resistant weeds without antagonism. Therefore, growers should adopt an integrated volunteer corn management program that may include tillage, crop rotation, and improved cultural agronomic practices to maximize control and reduce the potential for evolution of herbicide-resistant weeds.

Table 3. Effect of PRE soybean herbicides for the control of glufosinate-, glyphosate-, and imidazolinone-resistant volunteer corn at 7 and 21 DAT, cumulative emergence at 21 DAT, and volunteer corn biomass

Herbicide	Rate	Control at 7 DAT[a,b]			Control at 21 DAT[a,b]			Cumulative emergence 21 DAT[b]			Volunteer corn biomass[b]		
		Glufo	Glypho	Imida	Glufo	Glypho	Imida	Glufo	Glypho	Imida	Glufo	Glypho	Imida
	g ai ha^{-1}	%						%			g pot^{-1}		
Nontreated Control[c]	-	0	0	0	0	0	0	90a	100a	100a	3.3a	3.5a	3a
Sulfentrazone + Imazethapyr	422	66ab	39ab	68a	64a-f	50abc	72abc	80a	100a	90a	1bc	1.6bc	0.4bc
Sulfentrazone + Chloransulam	315	58ab	36ab	68a	65a-f	48a-d	64a-d	90a	90a	80a	0.7bc	1bc	0.5bc
Sulfentrazone + Metribuzin	567	69a	26ab	69a	70a-d	31b-f	75abc	90a	90a	80a	0.7bc	1.1bc	0.5bc
Sulfentrazone + Chlorimuron	343	55ab	35ab	66abc	68a-e	52abc	64a-d	90a	100a	70ab	0.5bc	1bc	0.3c
Clomazone	840	50ab	16ab	68a	92a	47a-e	90a	90a	90a	60ab	0.8bc	1.1bc	0.4bc
Chlorimuron + Flumioxazin + Thifensulfuron	94	32ab	3b	29a-e	4j	6f	3f	90a	100a	60ab	2.5abc	2.3abc	1.2abc
Flumioxazin + Cloransulam	107 + 35.3	43ab	6ab	58a-e	61a-g	23c-f	67a-d	90a	100a	70ab	0.6bc	1.7abc	0.5bc
Alachlor	2,800	44ab	8ab	39a-e	22g-j	4f	4f	80a	90a	60ab	1.9abc	2.6abc	1.2abc
Saflufenacil + Imazethapyr	95	9ab	1b	29a-e	26f-j	1f	12ef	90a	100a	60ab	1.6abc	2.7abc	1.4abc
S-metolachlor + Fomesafen	1,490	51ab	29ab	75a	41c-j	13c-f	81abc	80a	100a	60ab	1.3abc	2.1abc	0.3c
Pendimethalin	1,070	24ab	14ab	5cde	19h-j	2f	1f	80a	70a	70ab	2.5abc	1.9abc	1.9abc
Pendimethalin + Metribuzin	1,070 + 420	38ab	16ab	21a-e	58a-h	14c-f	30def	90a	90a	70ab	1.5abc	1.5abc	0.8bc
Imazethapyr	70	13ab	4b	4cde	29e-j	8def	1f	90a	100a	80a	2.1abc	2.1abc	2.2abc
Imazethapyr + S-metolachlor	137 + 1,600	4b	0.5b	6b-e	8ij	8ef	1f	90a	80a	60ab	2abc	2.2abc	1.3abc
Imazaquin + S-metolachlor	137 + 1,247	36ab	18ab	3de	74abc	70ab	3f	70a	90a	70ab	0.6bc	0.6c	1.4abc
Metribuzin + S-metolachlor	420 + 1,070	6b	0.5b	25a-e	47b-i	6f	32def	90a	90a	60ab	1bc	2abc	0.5bc
Trifluralin	840	5b	0.5b	3e	1j	6f	1f	80a	100a	80a	2.6ab	3ab	2.5ab
Flumioxazin	89	45ab	16ab	39a-e	40c-j	14c-f	49b-e	90a	90a	70ab	1.6abc	2.2abc	1.3abc
Flumioxazin + Chlorimuron	113	28ab	11ab	29a-e	31d-j	21c-f	44cde	90a	80a	60ab	1.3abc	1.7abc	0.6bc

Glufo = glufosinate-resistant, Glypho = glyphosate-resistant, Imida = imidazolione-resistant.

[a] The data of visual control estimates were arc-sine square-root transformed before analysis; however, data presented are the means of actual values for comparison based on interpretation from the transformed data.

[b] Means within columns with no common letter(s) are significantly different according to Tukey-Kramer's pairwise comparison test at $P \leq 0.05$.

[c] Visual estimates of nontreated control (0%) are not included in analysis.

Table 4. Effect of POST soybean herbicides for the control of 2- to 3-leaf stage glufosinate-, glyphosate-, and imidazolinone-resistant volunteer corn at 7 and 28 DAT and volunteer corn biomass

Herbicide	Rate	Control at 7 DAT[a,b]			Control at 28 DAT[a,b]			Volunteer corn biomass[b]		
		Glufo	Glypho	Imida	Glufo	Glypho	Imida	Glufo	Glypho	Imida
	g ae or ai ha^{-1}	——%						——g pot^{-1}——		
Nontreated Control[c]	-	0	0	0	0	0	0	4a	4a	4a
Quizalofop	38.6	63abc	64abc	39bcd	99a	99a	99a	1b	1b	1d
Fluthiacet-ethyl	7.2	33def	32def	28cde	12d	11ef	11ef	4a	4a	4a
Imazethapyr + Glyphosate	910	47b-e	47b-e	68a	85ab	53c	94ab	2b	2b	0.7d
Fomesafen + Glyphosate	1,380	57a-d	57a-d	57ab	70b	56c	80b	2b	2b	1.2cd
Fluazifop	210	75a	75a	45ab	99a	99a	99a	1b	1b	1d
Glyphosate + Imazamox	1,120 + 44	72ab	71ab	65a	91ab	65b	95ab	1b	1b	1d
Glyphosate + Imazaquin	1,120 + 76	49a-e	48a-e	55ab	85ab	59c	91ab	1b	1b	1d
Glyphosate + Acifluorfen	1,120 + 340	58a-d	57a-d	60ab	83ab	53c	87ab	1.5b	1b	1d
Glufosinate	595	23ef	25ef	17def	12d	65b	21cde	4a	2b	3ab
Sethoxydim	350	70ab	69ab	37bcd	97a	97a	96ab	1b	1b	1.2cd
Imazamox	44	31def	30def	9ef	57c	57c	31c	2b	2b	2bc
Clethodim	136	74ab	72ab	45abc	99a	99a	99a	1b	1b	1d
Fenoxaprop + Fluazifop	135	48a-e	50a-e	28cde	98a	98a	99a	1b	1b	1d
Glyphosate + Chlorimuron-ethyl	1,120 + 5.8	51a-d	52a-d	58ab	64b	64b	98a	1b	2b	2bc
Imazethapyr	70	5f	7f	2f	1d	1d	1f	4a	4a	3ab
Acifluorfen	170	32def	30def	28cde	10d	10d	13def	4a	4a	4a
Imazamox + Acifluorfen	35 + 280	38cde	36cd	36bcd	50c	51c	30cd	2b	2b	3ab

Note. DAT = days after treatment; Glufo = glufosinate-resistant, Glypho = glyphosate-resistant, Imida = imidazolione-resistant.

[a] The data of visual control estimates were arc-sine square-root transformed before analysis; however, data presented are the means of actual values for comparison based on interpretation from the transformed data.

[b] Means within columns with no common letter(s) are significantly different according to Tukey-Kramer's pairwise comparison test at P ≤ 0.05.

Table 5. Effect of POST soybean herbicides for control of 5- to 6-leaf stage glufosinate-, glyphosate-, and imidazolinone-resistant volunteer corn at 7 and 28 DAT and volunteer corn biomass

Herbicide	Rate	Control at 7 DAT[a,b]			Control at 28 DAT[a,b]			Volunteer corn biomass[b]		
		Glufo	Glypho	Imida	Glufo	Glypho	Imida	Glufo	Glypho	Imida
	g ae or ai ha^{-1}	%						g pot^{-1}		
Nontreated control[c]	-	0	0	0	0	0	0	6ab	6ab	6ab
Quizalofop	38.6	8de	8de	6g	97a	97a	97a	2f	2f	3ef
Fluthiacet-ethyl	7.2	3e	3e	3g	3f	3f	4e	6ab	6ab	7a
Imazerthapyr + Glyphosate	910	19b-e	19b-e	23b-f	34cde	34cde	60cd	4.5b-e	4.5b-e	4def
Fomesafen + Glyphosate	1,380	24a-d	24a-d	30a-d	44cd	45cd	55d	4b-f	4b-f	4.8b-e
Fluazifop	210	12cde	12cde	13efg	98a	97a	95a	2f	2f	2.8f
Glyphosate + Imazamox	1,120 + 44	38a	38a	42a	69bc	63bc	71a-d	2.5f	3ef	2.8f
Glyphosate + Imazaquin	1120 + 76	24a-d	24a-d	27a-e	58cd	43cd	66bcd	4b-f	4c-f	3.3def
Glyphosate + Acifluorfen	1,120 + 340	28abc	28abc	36ab	55cd	38cd	59cd	4.5b-e	4.5b-e	4c-f
Glufosinate	595	3e	3e	9fg	8ef	8ef	17e	5a-d	5a-d	5a-e
Sethoxydim	350	16b-e	16b-e	14d-g	87ab	85ab	87ab	2.7ef	2.6ef	3ef
Imazamox	44	3e	3e	3g	21def	21def	15e	5.5abc	5.5abc	6abc
Clethodim	136	18b-e	18b-e	17c-g	89a	88a	88ab	3def	3def	3ef
Fenoxaprop + Fluazifop	135	16b-e	16b-e	13efg	87ab	86ab	86ab	3def	3def	2.7f
Glyphosate + Chlorimuron-ethyl	1,120 + 5.8	33ab	33ab	33abc	50cd	44cd	65bcd	4.5b-e	4.5b-e	3ef
Imazethapyr	70	2e	2e	1g	3f	3f	1e	6ab	6ab	5.8abc
Acifluorfen	170	4e	4e	2g	4f	3f	4e	6ab	6ab	5.8abc
Imazamox + Acifluorfen	35 + 280	8de	8de	7fg	9ef	8f	10e	6ab	6ab	5a-d

Note. DAT = days after treatment; Glufo = glufosinate-resistant, Glypho = glyphosate-resistant, Imida = imidazolione-resistant.

[a] The data of visual control estimates were arc-sine square-root transformed before analysis; however, data presented are the means of actual values for comparison based on interpretation from the transformed data.

[b] Means within columns with no common letter(s) are significantly different according to Tukey-Kramer's pairwise comparison test at $P \leq 0.05$.

[c] Visual estimates of nontreated control (0%) are not included in analysis.

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