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Control of Volunteer Glyphosate-Resistant Corn in Soybean With Clethodim Plus Adjuvants

Nader Soltani[1], Christy Shropshire[1] & Peter H. Sikkema[1]

[1] Department of Plant Agriculture, University of Guelph Ridgetown Campus, ON, Canada

Correspondence: Nader Soltani, Department of Plant Agriculture, University of Guelph Ridgetown Campus, 120 Main St. East, Ridgetown, ON, N0P 2C0, Canada. E-mail: soltanin@uoguelph.ca

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Abstract

In Ontario, volunteer glyphosate-resistant (GR) corn is one the most common annual grass escapes in GR soybean sprayed with glyphosate. Six field experiments were established in southwestern Ontario during 2021 and 2022 to determine volunteer GR corn control in soybean with glyphosate (900 g ae ha^{-1}) + clethodim (45 g ai ha^{-1}) plus three adjuvants. At 1, 2, and 4 WAA, there was no visible soybean injury from the herbicide treatments evaluated. At 1 WAA, glyphosate + clethodim controlled volunteer GR corn 23%; the addition of the adjuvants Amigo®, Journey HSOC®, and StrikeLock® at 0.5% v/v improved control to 45 to 49%; there was no statistical difference in volunteer corn control among the adjuvants evaluated. At 2 WAA, glyphosate + clethodim controlled volunteer GR corn 23%; the addition of the adjuvants Amigo®, Journey HSOC®, and StrikeLock® at 0.5% v/v improved the control to 73 to 79%; there was no statistical difference in volunteer corn control among the adjuvants evaluated. At 4 WAA, glyphosate + clethodim controlled volunteer GR corn 16%; the addition of the adjuvants Amigo®, Journey HSOC®, and StrikeLock® at 0.5% v/v improved the control to 91 to 95%; there was no statistical difference in volunteer corn control among the adjuvants evaluated. Volunteer corn interference reduced soybean yield by up to 23% in this trial (highest yielding treatment compared to the non-treated control). Reduced volunteer corn interference with clethodim increased soybean yield 13%. Reduced volunteer corn interference with clethodim plus an adjuvant increased soybean yield 27 to 31%. This study concludes that the addition of Amigo®, Journey HSOC®, or StrikeLock® to clethodim improves volunteer GR corn control resulting in a concomitant increase in soybean yield.

Key words: cyclohexanedione, ACCase inhibitor, GR corn, glyphosate-resistant, soybean, visible injury, yield

1. Introduction

Soybean is a major field crop grown in Ontario, Canada. It is grown on about 1.2 million hectares with a farm-gate value of approximately 1.7 billion (Soltani et al., 2022). Weed management is critical for profitable soybean production; a meta-analysis concluded that weed interference would reduce soybean yield 52% across North America if producers did not implement any weed management tactics (Soltani et al., 2017). In recent years, volunteer glyphosate-resistant (GR) corn has become the number one annual grass escape in GR soybean sprayed with glyphosate when it follows GR corn in the crop rotation. Volunteer corn seeds within the soybean field mostly come from stalk lodging or breakage, dropped ears, kernel losses, and combine head shatter losses of corn grown in the previous year and are generally more abundant in fields that experience greater environmental stresses (*i.e.*, storm damage, diseases, and/or insects) (Marquardt & Johnson, 2013; Stahl et al., 2013). A recent study estimated that GR volunteer corn is present on 50% of soybean hectares in the province of Ontario and causes 20% soybean yield loss with a potential monetary loss of approximately $170 million (Soltani et al., 2022).

Soybean yield losses of 51% have been reported due to volunteer GR corn interference (Deen et al. 2006; Soltani et al. 2006). Reduction in soybean yield has been attributed to volunteer corn's ability to outcompete soybeans for water, moisture, nutrients, and light (Anderson, 1976; Anderson & Geadelmann, 1982; Marquardt & Johnson, 2013; Wilson et al., 2010). Volunteer corn can also decrease harvesting efficiency and reduce soybean grain quality by seed contamination (Anderson & Geadelmann, 1982; Marquardt & Johnson, 2013). Beckett and Stoller (1988) reported that soybean yield can be reduced by 25% when volunteer corn is present at a density of 5-6 plants m^{-2} in the field. In another study, soybean yield was reduced by 14 to 49% (average of 31%) when volunteer corn was present at a uniform density of 0.4 plants m^{-2} and 31 to 78% when volunteer corn was present at a uniform density of 0.8 plants m^{-2} (Andersen et al., 1982). Studies conducted in Nebraska have shown a 10, 27, and 97% reduction in soybean yield when volunteer GR corn was present at a density of 8,750, 17,500, and 35,000 plants ha^{-1}, respectively (Chahal et al., 2015; Chahal & Jhala, 2016; Wilson et al., 2010).

Earlier studies have shown that soybean yield losses from GR corn interference can be decreased to less than 6% with a postemergence (POST) application of a Group 1 herbicide such as clethodim and sethoxydim (Deen et al., 2006; Soltani et al., 2006). Clethodim and sethoxydim are from the cyclohexanedione family and inhibit acetyl-CoA carboxylase (ACCase), the enzyme that catalyzes the first elongation step in fatty acid biosynthesis in the chloroplast. Fatty acids are needed for the synthesis of phospholipids which are an essential component of cell membranes (Burton et al., 1989; Focke & Lichtenthaler, 1987). In addition to volunteer GR corn, clethodim and sethoxydim can control many other annual and perennial grass species in soybean (OMAFRA, 2023).

Control of volunteer GR corn with glyphosate + clethodim in GR soybean is poor when an adjuvant is not included in the spray solution (Deen et al., 2006; Soltani et al., 2006). The addition of Amigo® or Crop oil concentrate surfactants to glyphosate + clethodim has been shown to increase the efficacy and the consistency of GR volunteer corn control in GR soybean (Deen et al., 2006; Soltani et al., 2006).

Amigo® is a 30% phosphate ester solvent/surfactant registered for use with clethodim. Amigo improves the spreading of spray droplets on the leaf surface and increases the contact area. Amigo increases the speed of clethodim absorption through the cuticle resulting in reduced photo-degradation of the herbicide on the leaf surface thereby increasing weed control efficacy.

Journey HSOC® is a high surfactant oil concentrate (HSOC) that has been introduced into the Canadian market by Winfield United, LLC (Winfield Solutions, LLC, St. Paul, MN, USA). Journey® adjuvant is a methylated seed oil (MSO) based surfactant blend that is marketed by the manufacturer for increased pesticide uptake and effectiveness. Journey® is designed to be compatible with glyphosate tankmixtures requiring an oil adjuvant and can help increase herbicide efficacy against target grass weed species with waxy leaf surfaces (Winfield United, 2023a).

StrikeLock® is a HSOC-MSO plus drift and deposition technology that has been introduced into the Canadian market by Winfield United, LLC (Winfield Solutions, LLC, St. Paul, MN, USA). StrikeLock® is marketed for use with oil-based herbicides to improve spray pattern, reduce herbicide spray drift, and increase herbicide deposition which results in increased herbicide uptake (Winfield United, 2023b). According to the manufacturer, StrikeLock® offers better-flowing oil vs. traditional high surfactant MSO (Winfield United, 2023b).

To our knowledge, there has been no study that evaluated volunteer GR corn control with clethodim applied postemergence (POST) in GR soybean with the following three adjuvants: Amigo®, Journey®, and StrikeLock®. This data is essential so that Ontario soybean producers can make science-based decisions to maximize volunteer GR corn control, minimize weed management costs, maximize soybean yield, and maximize net returns.

The aim of this study was to determine the efficacy of clethodim applied alone or in combination with Amigo®, Journey® or StrikeLock® adjuvants for the control of volunteer GR corn in GR soybean and to determine the effect of volunteer GR corn interference on GR soybean yield.

2. Materials and Methods

Six field experiments were conducted, four near Exeter, Ontario in 2021 and two near Ridgetown, Ontario in 2022. The site description including soil characteristics is presented in Table 1. Seedbed preparation consisted of fall moldboard plowing followed by three passes with a field cultivator with rolling basket harrows in the spring.

Table 1. Year, location, soil characteristics, soybean seeding and emergence dates, herbicide application dates, and weather conditions at application for six experiments conducted in Ontario, Canada in 2021 and 2022

	Year	Location	Texture	Soil characteristics[a]					Seeding date	Emergence date	Application date	Application weather conditions		
				Sand	Silt	Clay	Organic matter	pH				Air temperature	Relative humidity	Wind speed
				------------------ % --------------								C	%	km h^{-1}
E1	2021	Exeter A	Clay Loam	35	43	22	4.4	8.0	May 14	May 21	June 11	29.5	43.8	4.8
E2	2021	Exeter B	Clay Loam	35	43	22	4.4	8.0	May 14	May 21	June 11	29.2	41.7	5.5
E3	2021	Exeter C	Clay Loam	35	43	22	4.4	8.0	May 14	May 21	June 14	23.3	55.4	4.2
E4	2021	Exeter D	Clay Loam	35	43	22	4.4	8.0	May 14	May 21	June 14	25.6	49.6	3.3
E5	2022	Ridgetown A	Loam	36	29	35	3.3	7.2	May 31	June 9	June 21	21.6	68.5	12.4
E6	2022	Ridgetown B	Loam	36	29	35	3.3	7.2	May 31	June 9	June 29	26.2	52.6	6.6

Note. [a] Soil cores were extracted to a depth of 15 cm and analyzed by A&L Canada Laboratories Inc. (2136 Jetstream Road, London, ON) to determine soil characteristics.

The experimental design was a randomized complete block design (RCBD) with four replications. Treatments consisted of POST glyphosate at 900 g ae ha^{-1} alone (control) and in a mixture with clethodim at 45 g ai ha^{-1} alone or plus Amigo® at 0.5% v/v, Journey® at 0.5% v/v or StrikeLock® at 0.5% v/v as listed in Table 2.

Table 2. Control of volunteer GR corn in soybean and soybean yield with clethodim plus various adjuvants at Exeter, ON in 2021 (n = 4) and Ridgetown, ON in 2022 (n=2). Means followed by the same letter within a column do not differ according to a Tukey-Kramer multiple range test at P < 0.05 [a]

Treatment[b]	Rate	Volunteer GR corn control			Soybean yield
		1 WAA	2 WAA	4 WAA	
	g ai ha^{-1}	--------------------- % --------------------			T ha^{-1}
Non-treated control		0 c	0 c	0 c	3.39 c
Clethodim	45	23 b	23 b	16 b	3.82 b
Clethodim + Amigo®	45 + 0.5% v/v	47 a	73 a	91 a	4.32 a
Clethodim + Journey®	45 + 0.5% v/v	45 a	76 a	94 a	4.43 a
Clethodim + StrikeLock®	45 + 0.5% v/v	49 a	79 a	95 a	4.41 a

Note. [1] Abbreviations: WAA, weeks after herbicide application.

[b] All treatments included glyphosate (900 g a.e. ha^{-1}).

Plots were 3 m wide and 8 m long and consisted of four rows of 'DKB 10-16/DKB 10-20' soybeans (glufosinate/glyphosate/dicamba-resistant) spaced 0.75 m apart. Soybean was planted at a rate of approximately 400,000 seeds ha^{-1}. The volunteer GR corn seed (saved from the previous year's crop) was spread at approximately 80,000 seeds ha^{-1} using a broadcast fertilizer spreader and tilled into the soil with two passes of a cultivator with rolling basket harrows, prior to seeding the soybean.

Herbicides were applied using a CO_2-pressurized backpack sprayer, calibrated to deliver 200 L ha^{-1} of liquid at 210 kPa. The boom length was 1.5 m wide with four ULD 120-02 ultra-low drift nozzles (Hypro, New Brighton, MN, United States) spaced 50 cm apart producing a spray width of 2.0 m. Treatments were applied postemergence up to 4 weeks after planting (WAP) soybean when the volunteer GR corn was approximately 10 to 15 cm in height.

Volunteer GR corn control was evaluated at 1, 2, and 4 weeks after herbicide application (WAA) on a scale of 0 to 100% where 0 was no control and 100 was total control. Soybean in middle 2 rows of each plot was harvested at harvest maturity using a small plot combine. The soybean weight and seed moisture content were recorded. All yields were adjusted to 13% seed moisture content.

The GLIMMIX procedure in SAS (Ver. 9.4, SAS Institute Inc., Cary, NC) was utilized for data analysis. For the generalized linear mixed model, the fixed effect was herbicide treatment and random effects were environment, the environment by treatment interaction, and the replicate nested within environment. The assumptions of analysis were met using the Gaussian distribution to analyze volunteer corn control and soybean yield, and the level of significance was set at $P < 0.05$. The non-treated control was excluded from the analysis of volunteer corn control because it did not have any variance; treatment least square means were compared to the value zero using the P-value in the output LSMEANS table.

3. Results and Discussion

The random effects of experiments, years, years by location, and their interactions with herbicide treatments were not significant for any of the variables analyzed. Thus, it was possible to pool the means for each variable analyzed.

At 1, 2, and 4 WAA, there was no visible GR soybean injury from glyphosate at 900 g ae ha^{-1} alone and tankmixed with clethodim at 45 g ai ha^{-1} alone or plus Amigo® (0.5% v/v), Journey® (0.5% v/v) or StrikeLock® (0.5% v/v) applied POST for the control of volunteer GR corn (data not shown). These results are similar to other studies that have shown minimal GR soybean injury with the POST application of glyphosate + clethodim applied alone or in combination with various adjuvants (Dean et al., 2006; Duenk et al., 2023; Kniss et al., 2012; Striegel et al., 2020; Underwood et al., 2016).

At 1 WAA, glyphosate (900 g ae ha^{-1}) + clethodim (45 g ai ha^{-1}) controlled volunteer GR corn 23%; the addition of the adjuvants Amigo®, Journey®, or StrikeLock® at 0.5% v/v improved the control to 45 to 49%; there was no statistical difference in volunteer corn control among the adjuvants evaluated (Table 2).

At 2 WAA, glyphosate + clethodim controlled volunteer GR corn 23%; the addition of the adjuvants Amigo®, Journey®, or StrikeLock® at 0.5% v/v improved the control to 73 to 79%; there was no statistical difference in volunteer corn control among the adjuvants evaluated (Table 2).

At 4 WAA, glyphosate + clethodim controlled volunteer GR corn 16%; the addition of the adjuvants Amigo®, Journey®, or StrikeLock® at 0.5% v/v improved the control to 91 to 95%; there was no statistical difference in volunteer corn control among the adjuvants evaluated (Table 2).

Volunteer GR corn control levels observed in this study are similar to other studies in which glyphosate + clethodim + Amigo® (0.5% v/v) controlled of volunteer GR corn up to 88% at 4 and 8 WAA (Soltani et al., 2006). The same study reported that clethodim at 15, 22.5, and 30 g ai ha^{-1} caused a 73, 88, and 92% reduction in volunteer GR corn density and an 89, 98, and 99% reduction in volunteer GR corn dry weight, respectively (Soltani et al., 2006). In other studies, glyphosate + clethodim + Crop Oil Concentrate (0.5% v/v) applied POST controlled volunteer Enlist™ corn 75 to 84, 88 to 95, 92 to 97, and 90 to 98% at 1, 2, 4, and 8 WAA, respectively (Soltani et al., 2015). In addition, clethodim at 30 and 60 g ai ha^{-1} reduced volunteer Enlist™ corn density 95 to 97% and volunteer Enlist™ corn dry weight 97 to 99%, relative to the weedy control (Soltani et al., 2015).

Adding Crop Oil Concentrate to clethodim applied POST improved volunteer GR corn control by 15% in studies conducted in Nebraska and Wyoming, USA (Kniss et al., 2012). Zollinger and Ries (2004) in North Dakota reported up to 80% control of volunteer GR corn with clethodim applied POST in soybean. Similarly, Duenk et al. (2023) reported 81% control of volunteer glyphosate/glufosinate resistant corn with glyphosate + clethodim (30 g ai ha^{-1}) + Amigo® (0.5% v/v) in glyphosate/glufosinate/2,4-D choline-resistant soybean. Underwood et al. (2016) observed 85 to 95% control of volunteer GR corn with glyphosate + clethodim (30 to 45 g ai ha^{-1}) + Amigo® (0.5% v/v) in dicamba-resistant soybean. Alms et al. (2016) reported that volunteer corn was controlled 90% when clethodim + Crop Oil Concentrate (1% v/v) was applied POST to V4 soybean at 51 g ai ha^{-1} rate but, the volunteer corn control was only 15% when clethodim was applied POST at 12.7 g ai ha^{-1} rate.

Soybean yields generally reflected the level of GR volunteer corn control with glyphosate + clethodim alone or in combination with Amigo®, Journey®, or StrikeLock® adjuvants. Volunteer GR corn interference reduced soybean yield up to 23% in this trial (highest yielding treatment compared to the control) (Table 2). Reduced volunteer corn interference with clethodim resulted in an increase in soybean yield of 13% (Table 2). Reduced volunteer corn interference with clethodim plus Amigo®, Journey®, or StrikeLock® resulted in an increase in soybean yield of 27 to 31% (Table 2). In other studies, Soltani et al. (2006) reported that soybean yields were nearly doubled in the glyphosate + clethodim + Amigo® (0.5% v/v) treated plots compared to the glyphosate control (Soltani et al., 2006). In another study, soybean yield was comparable to weed-free control and as much as 20-26% greater with glyphosate (900 g ai ha^{-1}) + clethodim (30 or 60 g ai ha^{-1}) + Crop oil concentrate (0.5% v/v) compared the glyphosate (900 g ai ha^{-1}) alone applied POST for the control of volunteer Enlist™ corn in soybean (Soltani et al., 2015). Alms et al. (2016) reported that interference from volunteer corn in soybean yield caused only 5% yield loss when clethodim + Crop Oil Concentrate (1% v/v) was applied POST to V4 soybean at 51 g ai ha^{-1} rate but, the soybean yield loss was 50% when clethodim + Crop Oil Concentrate (1% v/v) was applied at 12.7 g ai ha^{-1} rate.

4. Conclusions

Glyphosate + clethodim applied POST alone or in combination with Amigo®, Journey®, or StrikeLock® adjuvants caused no visible injury in soybean. Glyphosate + clethodim applied POST alone provided minimal (16-23%) control of volunteer GR corn at 1, 2, and 4 WAA in soybean. The addition of the Amigo®, Journey®, or StrikeLock® adjuvants enhanced volunteer GR corn as much as 26% at 1 WAA, 56% at 2 WAA, and 79% at 4 WAA compared to glyphosate + clethodim without adjuvants. There was no statistical difference in volunteer GR corn control among Amigo®, Journey®, and StrikeLock® adjuvants when added to glyphosate + clethodim. Soybean yield reflected the level of weed control. The yield was reduced as much as 23% from volunteer GR corn interference in soybean. Lower volunteer corn interference with glyphosate + clethodim alone or in combination with Amigo®, Journey®, and StrikeLock® adjuvants enhanced soybean yield. Based on these results, glyphosate + clethodim applied POST in combination with Amigo®, Journey®, or StrikeLock® adjuvants provides adequate control of volunteer GR corn in GR soybean. However, glyphosate + clethodim applied POST alone does not provide adequate control of volunteer GR corn in soybean.

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Authors Contributions

Drs. Nader Soltani and Peter Sikkema were responsible for the study design and writing of this manuscript. MS. Christy Shropshire conducted the statistical analysis of the data collected.

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Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Obtained.

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The Publication Ethics Committee of the Canadian Center of Science and Education.

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The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data Sharing Statement

No additional data are available.