Weed Technology

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Row spacing and layered residual herbicides influence weed control and profitability in herbicide-resistant soybean

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Research Article

Cite this article: Lammers C, Roozeboom K, Ibendahl G, Lancaster S (2025) Row spacing and layered residual herbicides influence weed control and profitability in herbicide-resistant soybean. Weed Technol. **39**(e45), 1–7. doi: 10.1017/wet.2025.10

Received: 30 April 2024
Revised: 13 January 2025
Accepted: 3 February 2025

Associate Editor:
Michael Flessner, Virginia Tech

Nomenclature:
Common waterhemp, *Amaranthus tuberculatus* (Moq.) Sauer; Palmer amaranth, *Amaranthus palmeri* S. Watson; Venice mallow, *Hibiscus trionum* L.; yellow foxtail, *Setaria pumila* (Poir.) Roem. & Schult.; soybean, *Glycine max* (L.) Merr.

Keywords:
Integrated weed management; Enlist; LLGT27

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Abstract

Narrow row spacing and layered residual herbicides are recommended for season-long control of herbicide-resistant weeds, but limited research is available to describe interactions between the two practices. The integration of narrow row spacing with layered residual herbicides in herbicide-resistant soybean was evaluated in 4 site-years with a split-split-plot treatment arrangement where the whole plot was soybean trait (LibertyLink® GT27 or Enlist® E3), the subplot was row spacing (38 or 76 cm), and the sub-subplot factor was herbicide program with five treatments: nontreated, preemergence herbicide only (PRE), PRE followed by postemergence (PRE fb POST), PRE fb POST with overlapping residual herbicide (POR), and weed-free. Weed control was evaluated through R7 soybean, and weed biomass was collected before POST applications and at R7 soybean. Soybean yield was recorded. Data were subjected to analysis of variance (ANOVA) and means separation ($\alpha = 0.05$). Row spacing had minimal effects on weed control and mixed effects on yield. Waterhemp and Venice mallow control ranged from 83% to 100% 4 wk after treatment (WAT). POST and POR treatments provided ≥94% control of Palmer amaranth 4 WAT; however, PRE resulted in 33% Palmer amaranth control. All treatments resulted in ≥95% Palmer amaranth and yellow foxtail control at Scandia during 2021. The greatest income in rainfed site-years was with Enlist® E3 soybean planted in 76-cm rows with PRE herbicide treatment. The greatest income in the irrigated site-year was with Enlist® E3 soybean planted in 38-cm rows with PRE herbicide treatment. Both POST and POR increase weed control compared to PRE, regardless of row spacing, in the soybean varieties evaluated, although POR resulted in less income than POST treatments. However, this research did not evaluate weed seed production, which is crucial for long-term weed management and profitability.

Introduction

Palmer amaranth and common waterhemp are commonly found in Kansas soybean fields and have the potential to decrease yields by 79% and 63%, respectively (Bensch et al. 2003). Many populations of these weeds are resistant to acetolactate synthase–, photosystem II–, protoporphyrinogen oxidase–, or 4-hydroxyphenylpyruvate dioxygenase–inhibiting herbicides; auxin mimic herbicides; or glyphosate, including populations with resistance to up to six herbicides (Heap 2024). The best way to control herbicide-resistant weeds is to use an integrated approach that includes nonchemical tactics to complement herbicides (Norsworthy et al. 2012). Cultural practices like narrow row spacing can be adopted as part of an integrated weed management system. A meta-analysis of 35 previously published papers suggests that soybean row spacings <76 cm are associated with reductions in weed density and weed biomass (Singh et al. 2023). Specifically, McDonald et al. (2021) and Bell et al. (2015) reported reduced Palmer amaranth densities. Hay et al. (2019) investigated row spacings as part of an integrated weed management program and reported that Palmer amaranth biomass 8 wk after planting (WAP) was reduced in 19-cm rows compared to 76-cm rows, with 38-cm rows resulting in biomass similar to both 19- and 76-cm rows at one of two locations. At a third location, waterhemp density was reduced in 19-cm rows compared to 76-cm rows. Palmer amaranth and waterhemp densities were similar for all three row spacings at each location. Yadav et al. (2023) also evaluated the effect of row spacings in combination with other integrated weed management tactics and suggested that waterhemp control was greater in 38-cm rows compared to 76-cm rows. Greater weed control in narrow rows is associated with reduced weed seed germination resulting from a reduction in solar radiation reaching the soil surface (Yelverton and Coble 1991). Previous research has reported that 38-cm row spacing promoted canopy closure 1 to 2 wk sooner than 76-cm rows (Harder et al. 2007). In fact, during dry years, 76-cm rows may never fully canopy (Bell et al. 2015).

Yields for narrow- and wide-row soybean vary, but soybean yield is greater in narrow rows when planted late in the season and adequate moisture is available (Andrade et al. 2019). De Bruin and Pedersen (2008) and Hanna et al. (2008) reported >5% yield increases when soybean was planted in 19- or 38-cm rows compared to 76-cm rows. Bell et al. (2015) reported a 44% increase in 45-cm-row soybean yield compared to 90-cm rows. During dry years or when heavy rainfall occurs shortly after planting, yields tend to be similar for narrow and wide rows (Hanna et al. 2008; McDonald et al. 2021). Andrade et al. (2019) regularly observed a 5% to 35% yield increase with narrow rows in small-plot research but did not detect yield differences between narrow and wide rows in producers' fields in Wisconsin, Minnesota, and the Dakotas. The authors reported similar results for Ohio, Illinois, Iowa, and Kansas, where they observed a 5% loss to a 15% gain in yield for narrow-row soybean compared to wide-row soybean in small-plot research trials, but they reported no yield response to row spacing from farmers' fields.

Chemical weed control methods are commonly implemented by soybean producers. Incorporating multiple, effective herbicide modes of action is a management strategy that helps slow the selection for herbicide-resistant weeds (Norsworthy et al. 2012). Two soybean traits genetically engineered to allow the application of different herbicide modes of action are Enlist® E3 (Corteva Agriscience, Indianapolis, IN, USA) and LibertyLink® GT27 (LLGT27) (BASF, Florham Park, NJ, USA). Enlist® E3 soybean is resistant to glyphosate, glufosinate, and 2,4-D, while LLGT27 soybean is resistant to glyphosate, glufosinate, and isoxaflutole. Applying glufosinate and 2,4-D POST or isoxaflutole PRE will improve weed control in these soybean systems (Craigmyle et al. 2013; Hay et al. 2019; Merchant et al. 2013; Smith et al. 2019). Co-applications of 2,4-D and glufosinate resulted in 98% control of common waterhemp compared to 75% to 78% control for a single active ingredient (Craigmyle et al. 2013). Similarly, Merchant et al. (2013) reported 90% to 97% control of Palmer amaranth with the same co-application compared to 68% to 80% control with 2,4-D alone. Isoxaflutole + metribuzin followed by (fb) glyphosate has been shown to control grass and broadleaf weeds >98% (Smith et al. 2019). However, glyphosate resistance is widespread (Heap 2024). Therefore glyphosate alone should not be relied on for weed control.

POST applications that include glyphosate, glufosinate, or 2,4-D alone or in combination will control weeds that have emerged at the time of application. However, summer annual weeds, such as waterhemp and Palmer amaranth, can emerge throughout the growing season after POST herbicide applications have been made. Including residual herbicides in POST applications can help provide season-long control of such species. Sarangi and Jhala (2019) reported that PRE fb POST with overlapping residual herbicide (POR) programs resulted in 98% control of Palmer amaranth compared to 84% without overlapping residual. Similarly, co-applications of *S*-metolachlor with glufosinate increased common waterhemp control 23% at harvest compared to glufosinate alone (Aulakh and Jhala 2015). However, including an additional residual herbicide in dicamba-resistant soybean resulted in similar Palmer amaranth control compared to treatments that did not include residual herbicides (McDonald et al. 2021).

Weed management strategies influence farm profitability. Harder et al. (2007) and Nelson and Renner (1999) reported that narrow-row soybean had greater gross profit margins compared to wide-row soybean. Sarangi and Jhala (2019) reported a greater gross profit margin when a residual herbicide was included with POST applications to soybean compared to POST applications with no residual herbicide. Economic partial budgets have been calculated to compare soybean resistant to glyphosate or glufosinate (Rosenbaum et al. 2013), dicamba and glyphosate or glufosinate (Striegel et al. 2020), and overlapping residual herbicide programs in non–genetically engineered soybean (Sarangi and Jhala 2019). However, weed control and profitability of Enlist® E3 or LLGT27 soybean grown in 38- or 76-cm row spacings with corresponding herbicide programs is unknown. The objectives of this study were to evaluate the effects of row spacing (38 or 76 cm), herbicide resistance trait, and herbicide on weed control, soybean yield, and profitability.

Materials and Methods

Trial Management

The experiment was conducted at Kansas State University Agronomy Experiment Fields at Ottawa, KS (38.539°N, 95.243°W), during 2020 (OT20) and 2021 (OT21); at Ashland Bottoms, KS (39.118°N, 96.636°W), in 2021 (AB21); and at Scandia, KS (39.834°N, 97.839°W), in 2021 (SC21). Soils at the Ottawa, Ashland Bottoms, and Scandia locations were Woodson silt loam, Reading silt loam, and Crete silt loam, respectively (USDA-SSS 2022). OT20, OT21, and AB21 were under rainfed conditions, whereas SC21 was irrigated. Field sites were tilled with a Great Plains Turbo-Max (Salina, KS, USA) vertical cultivator at OT20 and OT21 or a John Deere field cultivator (Moline, IL, USA) at AB21 and SC21 within 1 d prior to planting. Soybean was planted with a Kinze (Williamsburg, IA, USA) 3000 planter in 2020 and a custom-built split-row planter in 2021. The split-row vacuum planter was made with John Deere XP row units with double-disk openers. It is capable of planting four 76-cm rows or seven 38-cm rows. Target seeding rates, as well as soybean varieties, seed treatments, crop rotations, and the availability of irrigation, are provided in Table 1.

The experimental design was a randomized complete block with a split-split-plot treatment arrangement and four replicates. The whole plot was soybean trait (LLGT27 or Enlist® E3), and the subplot was row spacing (38 or 76 cm). The sub-subplot factor was herbicide program with five treatments—nontreated check, PRE, PRE fb POST, POR, and weed-free check—for a total of 20 treatment combinations evaluated in 3×9.1 m experimental units (field plots).

All herbicide applications were made with a CO_2-pressurized backpack sprayer and a 2-m boom with 51-cm nozzle spacing. PRE herbicides were applied immediately after planting, and POST applications were made when weeds were 7 to 10 cm tall. Herbicides and application parameters are presented in Table 2. In OT21 and SC21, POST and POR applications also included clethodim (803 g ha^{-1}) and non-ionic surfactant (NIS) (0.25% v/v).

Weed control was evaluated between the third and fifth rows for plots with 38-cm rows and between the second and third rows for plots with 76-cm rows using a 0% (no control) to 100% (complete control) scale recorded every 2 wk after treatment (WAT) until the soybean reached R7. Weed biomass was sampled from a 0.25-m^2 quadrat randomly placed between the center rows of each plot immediately before POST and POR applications and at R7 soybean. Biomass was dried at 50 C to constant weight. Soybean stand counts in two 3-m lengths of the middle three or two rows were recorded prior to POST applications. Canopeo (Patrignani and Ochsner 2015) readings were used to quantify canopy cover. Images were captured from 140 cm above the ground 8 WAP. The Canopeo app is not able to distinguish between weeds and the crop; therefore only weed-free plots were analyzed and reported. The second through sixth rows were harvested from plots with 38-cm

https://doi.org/10.1017/wet.2025.10

Table 1. Locations, crop histories, irrigation availability, soybean variety, seed treatment, and seeding rates used to evaluate interactions of row spacing and layered residual herbicides.[a,b]

			Variety			
Location	Previous crop	Irrigation	LLGT27	Enlist® E3	Seed treatment	Target seeding rate
						seeds ha^{-1}
OT20	Soybean	No	38GB20	38EB03	None	345,000
OT21	Soybean	No	37GB02	38EB03	Servo DPI, Saltro	395,000
AB21	Corn	No	37GB02	38EB03	Servo DPI, Saltro	387,700
SC21	Corn	Yes	37GB02	38EB03	Servo DPI, Saltro	395,000

[a]All soybean varieties used were from Stine Seed Company (Adel, IA, USA).
[b]Abbreviations: AB21, Ashland Bottoms, KS, 2021; OT20, Ottawa, KS, 2020; OT21, Ottawa, KS, 2021; SC21, Scandia, KS, 2021.

Table 2. Herbicide treatment timings, active ingredients, and rates used to evaluate interactions of row spacing and layered residual herbicides in soybean.[a,b,c]

		Enlist® E3		LLGT27	
Treatment	Timing	Active ingredients	Rate	Active ingredients	Rate
			g ai/ae ha^{-1}		g ai/ae ha^{-1}
PRE	At planting	Pyroxasulfone[d] + sulfentrazone[e]	146 + 280	Pyroxasulfone + isoxaflutole[f]	146 + 105
POST	At planting	Pyroxasulfone + sulfentrazone	146 + 280	Pyroxasulfone + sulfentrazone	146 + 105
	7- to 10-cm weeds	Glufosinate[g] + 2,4-D[h]	655 + 1,064	Glufosinate	655
POR	At planting	Pyroxasulfone + sulfentrazone	146 + 280	Pyroxasulfone + sulfentrazone	146 + 105
	7- to 10-cm weeds	Glufosinate + 2,4-D + *S*-metolachlor[i]	655 + 1,064 + 1,419	Glufosinate + *S*-metolachlor	6,551 + 419
Weed-free	At planting	Pyroxasulfone + sulfentrazone	146 + 280	Pyroxasulfone + sulfentrazone	146 + 105
	7- to 10-cm weeds	Glufosinate + 2,4-D + *S*-metolachlor[g]	655 + 1,064 + 1,419	Glufosinate + *S*-metolachlor	655 + 1,419
	As needed	Hand weeded	—	Hand weeded	—

[a]At planting applications were applied at 140 L ha^{-1} with TT110015 nozzles and 245 kPa.
[b]POST applications contained ammonium sulfate (3,351 g ai ha^{-1}; N-Pak® ammonium sulfate, WinField, St. Paul, MN, USA) and were applied at 187 L ha^{-1} and 262 kPa with TeeJet® TT110002 and AIXR11002 nozzles (TeeJet® Technologies, Glendale Heights, IL, USA) for the LLGT27 and Enlist® E3 soybean, respectively.
[c]Abbreviation: POR, POST with overlapping residual herbicide.
[d]Zidua® SC.
[e]Spartan® FL 4F.
[f]Alite® 27.
[g]Liberty® 280 SL.
[h]Enlist One®.
[i]Dual Magnum®.

rows and the second and third rows were harvested from plots with 76-cm rows using a plot combine with a platform head equipped with a grain-weighing system. Yield was adjusted to 13% moisture, and 100-seed weights were recorded.

Economic Analysis

A partial budget economic analysis was conducted to estimate profit for the different management strategies at all 4 site-years. Enlist® E3 78-cm rows were used as the baseline. This treatment was chosen due to greater use of Enlist® E3 soybean compared to LLGT27 and wider rows considered to be the standard practice. Factors like the tillage cost, taxes, and insurance were not considered in the partial budget analysis because these expenses are fixed. Planting costs were estimated using values for typical farm equipment determined by the K-State machinery cost calculator (Ibendahl and Griffin 2020). A 12.2-m planter requiring a 200-hp tractor using US\$0.87 L^{-1} diesel was used in the calculator. Estimated costs were US\$47.88 ha^{-1} for the 38-cm-row planter and \$27.06 ha^{-1} for the 76-cm-row planter. The 37GB02 and 38EB03 seed prices were obtained from Tarwater Farm and Home Supply (Topeka, KS, USA). Herbicide prices for Zidua® SC (BASF), Liberty® 280 SL (BASF), Dual Magnum® (Syngenta Crop Protection, Basal, Switzerland), Enlist One® (Corteva Agriscience), ammonium sulfate, and NIS were based on the approximate cost published in the K-State Research and Extension 2022 chemical weed control guide (Lancaster et al. 2022) with prices from November 1, 2021. The price for Alite® 27 (BASF) was estimated based on the 2021 suggested retail price. MKC Coop (Manhattan, KS, USA) provided the price of Spartan® (FMC, Philadelphia, PA, USA) and custom herbicide application.

Data Analysis

Normality and homogeneity assumptions were checked with *Shapiro.test* (R Core Team 2021) and *levene.test* (Fox et al. 2021) functions, and transformations did not improve the model fit (Hebbali 2021). Data were subjected to ANOVA ($\alpha = 0.05$), and means were separated with Tukey's honestly significant difference (HSD) ($\alpha = 0.05$). Fixed factors were herbicide program, row spacing, and soybean herbicide resistance trait and their interactions. Replication, replication within row spacing, and soybean trait were considered random factors. The R packages employed and their uses were as follows: LMERTEST to fit mixed effect models; CARI as a companion to applied regression; EMMEANS to estimate marginal means; MULTCOMPVIEW to summarize multiple paired comparisons; MULTCOMP to compare groups of data; and the tidyverse to organize data (Fox et al. 2021; Graves and Dorai-Raj 2019; Hothorn et al. 2022; Kuznetsova et al. 2017; Lenth 2020; R Core Team 2020; Wickham et al. 2019). Nontreated and weed-free checks were removed from the weed control analyses because these treatments had 0% and 100% control, respectively. Weed biomass was adjusted to a percentage of the nontreated check prior to analysis.

https://doi.org/10.1017/wet.2025.10

Results and Discussion

Growing conditions varied for OT20, OT21, AB21, and SC21. The 30-yr average for rainfall in Ottawa, KS, from May 1 to October 31 was 629 mm. However, during 2020, only 355 mm was received during that time frame. OT21 received more rain (767 mm), but 312 mm of that occurred before the soybean was planted. OT20 was warmer than normal in June, and OT21 was warmer than normal from August through October. AB21 received 142 mm less precipitation from May 1 to harvest and had a warmer fall than the 30-yr averages. Scandia was irrigated, receiving a similar amount of water as the 30-yr average, and had a cooler June with a warmer fall compared to normal. Deviations from the 30-yr average weather likely had little effect on weed control results, but it is likely that deviations in precipitation explain variability in yield response to row spacing among the site-years.

ANOVA of soybean plant counts indicated a significant main effect of row spacing for OT20, OT21, and SC21. At OT20 and OT21, 76-cm rows had greater density (286,202 and 141,625 plants ha^{-1}, respectively) than 38-cm rows (225,874 and 99,659 plants ha^{-1}, respectively). Stand reductions were likely associated with crusting that resulted from rainfall shortly after planting. Planting conditions at SC21 were ideal, and greater stands were observed in 38-cm rows (355,368 plants ha^{-1}) compared to 76-cm rows (295,872 plants ha^{-1}). Soybean populations in both row spacings were similar at AB21.

Weed Control 4 wk after POST

Ratings of visible weed control were analyzed separately for each location because weed species were different at each location. Common waterhemp and Venice mallow control 4 WAT in OT20 was similar for both soybean traits and showed the importance of a PRE fb POST program. POST and POR treatments resulted in similar control (98% to 100%) of both weeds and provided greater control than the PRE treatment (Table 3). Craigmyle et al. (2013) reported a 23% increase in common waterhemp control when 0.45 kg ha^{-1} 2,4-D was added to 0.56 kg ha^{-1} glufosinate. Greater rates of glufosinate (0.65 kg ha^{-1}) were utilized in the current experiment, resulting in weed control ≥98% for POST herbicide treatments when pooled across soybean trait.

At OT21, common waterhemp control was similar for all treatments 4 WAT and ranged from 91% to 99%. There was a three-way interaction between soybean trait, row spacing, and herbicide treatment for Venice mallow control. Venice mallow control was 88% to 99% for all treatments, except Enlist® E3 soybean grown in 38-cm rows with the PRE herbicide treatment, which had 35% control (data not shown). Four weeks after treatment at AB21, POST and POR resulted in similar Palmer amaranth control and greater control than the PRE treatment. Sarangi and Jhala (2019) reported excellent control with both POST and POR treatments, although POR improved season-long Palmer amaranth control from 92% to 99%.

There was an interaction between herbicide timing and soybean trait for ivyleaf morningglory (*Ipomoea hederacea* Jacq.) control. Once again, control by POST and POR treatments was similar (83% to 93%) for both the LLGT27 and Enlist® E3 soybean varieties. However, control of ivyleaf morningglory by the PRE herbicide treatment was 71% in Enlist® E3 compared to 1% in LLGT27. The Enlist® E3 PRE herbicide treatment contained pyroxasulfone + sulfentrazone, whereas the LLGT27 treatment contained pyroxasulfone + isoxaflutole. Sulfentrazone is known to provide greater morningglory control than isoxaflutole (Lancaster et al. 2022).

At SC21, ANOVA indicated no differences in control of yellow foxtail. All treatments averaged 95% control 4 WAT. Relatively low weed density combined with greater soybean density likely contributed to this result (Liebert and Ryan 2017).

Weed Control 10 wk after POST

At OT20 10 WAT, common waterhemp control was influenced by herbicide treatment, with the POST and POR treatments having similar control, both greater than the PRE alone (Table 3). No differences in common waterhemp or Venice mallow control 10 WAT were detected at OT21. Control of both weeds ranged from 88% to 98%. Similarly, at SC21, yellow foxtail control had a significant interaction between herbicide treatment, trait, and row spacing; however, control was ≥99% for all treatments.

At AB21 10 WAT, POST and POR treatments had similar and greater control than the PRE treatment (Table 3). Control of Palmer amaranth was similar between soybean traits. However, Merchant et al. (2013) reported that Palmer amaranth control increased 10% to 29% when 2,4-D and glufosinate were co-applied, compared to being applied separately. For ivyleaf morningglory, there was an interaction between the herbicide treatment and row spacing. Ivyleaf morningglory control by all POST and POR herbicide treatments was similar and ranged from 93% to 99%. However, ivyleaf morningglory control with PRE was 86% and 95% for 76- and 38-cm rows, respectively, in Enlist® E3 soybean but 40% or less in LLGT27 soybean (data not shown).

Weed Biomass

At OT20, OT21, and SC21, there were negligible differences in weed biomass when the soybean was at R7. AB21 was the only location with differences in weed biomass among soybean trait, row spacing, and herbicide timing. The 38-cm-row LLGT27 soybean with PRE herbicide had greater weed biomass than any other treatment combination (data not shown). This was likely due to the abundance of ivyleaf morningglory as well as lower than expected Palmer amaranth control associated with low amounts of rainfall in-season.

Canopy Cover

Canopy cover in 38- and 76-cm rows was similar at both OT20 (86% to 92%) and OT21 8 WAP (41% to 53%; data not shown). Less cover at OT21 was likely due to low soybean population density and limited rainfall after planting until mid-July. Canopy cover in 38-cm rows was greater than in 76-cm rows at AB21 (94% and 91%, respectively) and SC21 (90% and 79%, respectively). The differences in canopy cover among locations highlight the influence of environment on soybean canopy development and potential for weed suppression.

100-Seed Weight

There was a significant main effect of row spacing in OT20 and OT21 and trait in OT20 on 100-seed weight. No differences were detected in AB21 or SC21. Seeds were 0.3 to 0.4 g heavier when grown in 76-cm rows in OT20 and OT21 compared to 38-cm rows (data not shown). De Bruin and Pedersen (2008) also reported mixed results for 100-seed weight of soybean grown in 38- or 76-cm rows. They reported no difference at two locations; however, at the third location, seeds from soybean grown in 76-cm rows were 0.5 g heavier than seeds from 38-cm rows. Additionally, in the current study, at OT20, Enlist® E3 100-seed weights were 0.9 g greater than 100-seed weights for LLGT27; however, it is not possible to determine if this was the result of differences in the herbicide

Table 3. Percent visible control of common waterhemp and Venice mallow in Ottawa, KS, in 2020 and Palmer amaranth in Manhattan, KS, in 2021, 4 and 10 wk after POST treatment.[a,b,c]

Herbicide treatment	Common waterhemp		Venice mallow		Palmer amaranth	
	4 WAT	10 WAT	4 WAT	10 WAT	4 WAT	10 WAT
	%					
PRE	83 b	49 b	86 b	89 a	33 b	49 b
POST	100 a	100 a	98 a	100 a	99 a	94 a
POR	100 a	100 a	100 a	100 a	99 a	99 a

[a]Herbicide treatments with LLGT27 were as follows: PRE, pyroxasulfone + isoxaflutole; POST, PRE followed by (fb) glufosinate + ammonium sulfate; POR, PRE fb glufosinate + ammonium sulfate + *S*-metolachlor. Herbicide treatments with Enlist® E3 were as follows: PRE, pyroxasulfone + sulfentrazone; POST, PRE fb glufosinate + ammonium sulfate + 2,4-D choline; POR, PRE fb glufosinate + ammonium sulfate + 2,4-D choline + *S*-metolachlor.
[b]Abbreviations: POR, POST with overlapping residual herbicide; WAT, weeks after treatment.
[c]Means within a column followed by the same letters are similar according to Tukey's HSD ($P \leq 0.05$).

Table 4. Soybean yield at Ottawa, KS, in 2020 and 2021, Ashland Bottoms, KS, in 2021, and Scandia, KS, in 2021, pooled across herbicide treatments.[a,b]

Trait	Row spacing	Yield			
		OT20	OT21	AB21	SC21
	cm	kg ha^{-1}			
LLGT27	38	2,463 a	2,597 ab	1,099 c	3,957 ab
	76	2,806 a	2,702 ab	1,934 b	3,862 bc
Enlist® E3	38	2,800 a	2,258 b	2,588 a	4,085 a
	76	2,681 a	2,837 a	2,427 a	3,681 c
SE		144	180	134	61.5

[a]Abbreviations: AB21, Ashland Bottoms, KS, 2021; LLGT27, LibertyLink® GT27; OT20, Ottawa, KS, 2020; OT21, Ottawa, KS, 2021; SC21, Scandia, KS, 2021; SE, standard error.
[b]Means within a column followed by the same letters are similar according to Tukey's HSD ($P \leq 0.05$).

systems or a difference between soybean varieties. Anda et al. (2020) also reported differences in seed weight between varieties.

Yield

There was an interaction between site-year, trait, and row spacing; therefore yield data are presented separately for each site-year. In OT20, no differences in yield were observed, with all treatments averaging 2,688 kg ha^{-1}, compared to the county average of 2,488 kg ha^{-1} (Table 4) (USDA-NASS 2021). There was a two-way interaction between soybean trait and row spacing at OT21. At this location, Enlist® E3 soybean yield was 25% more when grown in 76-cm rows compared to 38-cm rows, whereas the LLGT27 soybean yielded similarly in both soybean row spacings. Heavy rains after planting and poorer emergence in the narrow-row soybean could have contributed to the 76-cm Enlist® E3 soybean yielding more. Hanna et al. (2008) also reported that one location received heavy rains after planting, reducing plant population. However, in that instance, wide rows yielded similarly to narrow rows.

At AB21, yields were below the county average of 2,953 kg ha^{-1} (USDA-NASS 2022). POST and POR were similar to weed-free plots (2,328 to 2,525 kg ha^{-1}) and greater than PRE (1,850 kg ha^{-1}), which yielded more than nontreated plots (990 kg ha^{-1}). The Row Spacing × Trait interaction was also significant for AB21. Yields from Enlist® E3 soybean grown in 38- and 76-cm rows were similar to each other and greater than yields from LLGT27 soybean. The 38-cm Enlist® E3 soybean yielded 34% and 135% more than the 76- and 38-cm LLGT27 soybean, respectively. The 76-cm LLGT27 soybean yielded 76% more than the 38-cm LLGT27 soybean. Greater yields for Enlist® E3 soybean were likely due to poor morningglory control in LLGT27 soybean. Howe and Oliver (1987) reported 62% and 81% soybean yield reductions by pitted morningglory at a density of 40 plants m^{-2} for 20-cm and 100-cm rows, respectively. Data are likely confounded by a Dectes stem borer (*Dectes texanus* LeConte) infestation that started in September and affected all treatments.

In SC21, an interaction between soybean trait and row spacing was detected. Yield ranged from 3,681 to 4,085 kg ha^{-1}, compared to the county average of 3,392 kg ha^{-1} (USDA-NASS 2022). The order of the greatest to least yield was 38-cm Enlist® E3, 38-cm LLGT27, 76-cm LLGT27, and 76-cm Enlist® E3 soybean. The 38-cm Enlist® E3 soybean yielded 11% more than the 76-cm Enlist® E3 soybean. Andrade et al. (2019) reported similar results, where narrow-row soybean tended to have a yield advantage when planted late.

Economic Analysis

Partial budget analyses are useful for comparing the profitability of different practices. Table 5 presents the results from the partial budget analysis for OT20, OT21, and AB21 (rainfed locations) and SC21 (irrigated location) using nontreated Enlist® E3 soybean grown in 76-cm rows as a baseline. Averaged over the rainfed locations, the greatest net income was observed when Enlist® E3 soybean was grown in 76-cm rows and a PRE herbicide treatment was applied. However, weed control was reduced in the PRE herbicide treatment compared to the POST and POR treatments for many of the weed species evaluated at these rainfed locations. Reduced weed control in one year could translate into increased weed seeds in the soil seedbank and increased difficulty in controlling weeds the next year. PRE treatments were more profitable for the Enlist® E3 soybean because the added input cost of POST and POR herbicide applications did not offset the yield gained by controlling low-density weed populations.

Among the rainfed locations, POST treatments resulted in higher net income than POR treatments in seven scenarios, while POR treatments resulted in higher net income in five scenarios. POR treatments resulted in greater net income in wide rows than in

https://doi.org/10.1017/wet.2025.10

Table 5. Partial budget comparing soybean trait, row spacing, and herbicide treatment to the nontreated control in the Enlist® E3 trait in 76-cm rows.[a,b]

Trait	Row spacing	Treatment	OT20 AI	OT20 AC	OT20 NIC	OT21 AI	OT21 AC	OT21 NIC	AB21 AI	AB21 AC	AB21 NIC	Average NIC for rainfed[c]	SC21 AI	SC21 AC	SC21 NIC
	cm		US$												
LLGT27	38	NT	−37	25	−61	−370	25	−395	−219	25	−244	−233	193	25	168
		PRE	−34	132	−166	574	133	441	−174	132	−307	−10	238	133	105
		POST	154	183	−29	357	212	145	292	211	81	66	159	212	−53
		POR	227	211	17	244	240	4	375	211	164	62	133	240	−107
	76	NT	43	4	40	−83	4	−87	73	4	69	7	145	4	140
		PRE	248	111	137	374	112	262	522	112	410	270	174	112	63
		POST	395	162	233	522	191	331	606	162	443	336	145	191	−46
		POR	291	190	101	520	219	301	766	190	576	326	58	219	−161
Enlist® E3	38	NT	27	21	6	−317	21	−338	297	21	276	−19	272	21	251
		PRE	316	126	190	249	126	123	860	126	734	349	287	126	161
		POST	319	209	111	134	237	−103	1,133	209	924	311	211	237	−26
		POR	300	237	64	277	265	12	1,138	237	901	326	259	265	−6
	76	NT	0	0	0	0	0	0	0	0	0	0	0	0	0
		PRE	482	105	377	438	105	333	765	105	660	457	122	105	17
		POST	105	188	−83	647	221	426	1,033	188	845	396	6	217	−211
		POR	51	216	−165	465	217	249	1,121	216	906	330	30	244	−215

[a]Abbreviations: AB21, Ashland Bottoms, KS, 2021; AC, added costs; AI, added income; LLGT27, LibertyLink® GT27; NIC, net income change; NT, nontreated; OT20, Ottawa, KS, 2020; OT21, Ottawa, KS, 2021; POR, POST with overlapping residual herbicide; SC21, Scandia, KS, 2021.
[b]Herbicide treatments were as follows: PRE (LLGT27), pyroxasulfone + isoxaflutole; POST (LLGT27), PRE fb glufosinate + ammonium sulfate; POR (LLGT27), PRE fb glufosinate + ammonium sulfate + *S*-metolachlor; PRE (Enlist® E3), pyroxasulfone + sulfentrazone; POST (Enlist® E3), PRE fb glufosinate + ammonium sulfate +2,4-D choline; POR (Enlist® E3), PRE fb glufosinate + ammonium sulfate + 2,4-D choline + *S*-metolachlor.
[c]OT20, OT21, and AB21 were rainfed; SC21 was irrigated.

narrow rows in five of six scenarios at dryland locations. Differing outcomes can be attributed to differences in weed density and soybean canopy cover, which were both greatest at AB21, where POR treatments led to the greatest net income in three of four scenarios. Outcomes can also be attributed to differences in soybean yield, which were greatest at OT21, where POST treatments resulted in greater yield than did POR treatments in three of four scenarios. When herbicide treatments were averaged across rainfed locations and ranked according to profitability, the three most profitable treatments were Enlist® E3 in 76-cm rows with PRE herbicide, Enlist® E3 in 76-cm rows with POST herbicide, and Enlist® E3 in 38-cm rows with PRE herbicide.

At the irrigated location, SC21, Enlist® E3 soybean grown in 38-cm rows with no herbicide application resulted in the greatest profit, with LLGT27 soybean in 38-cm rows with no herbicide applications being the second most profitable. These results are due to the low weed density, faster canopy development in 38-cm rows, and greater yields at this location.

Practical Implications

From a weed control standpoint, either POST or POR herbicide treatments are needed, regardless of soybean trait or row spacing. POST treatments tended to be more profitable compared to POR treatments, as both controlled weeds similarly, but POR treatments were costlier. However, even slight numerical differences in weed control may be important when the long-term effects of escaped weeds are considered. Norsworthy et al. (2014) reported that a single Palmer amaranth plant left uncontrolled can result in plants spreading across an entire field in two years.

Both LLGT27 and Enlist® E3 soybean have their advantages, such as including multiple effective modes of action during a growing season. Knowing the weed species present, and herbicide resistances present in weed populations, will help one decide which soybean trait to use. For example, in Ashland Bottoms, KS, during 2021, the primary weeds were morningglory and glyphosate-resistant Palmer amaranth. At this location, the PRE herbicide for Enlist® E3 soybean included sulfentrazone, which prevented morningglory emergence, while the PRE for LLGT27 did not include a product that effectively controlled morningglory.

Soybean grown in narrow rows has been documented to canopy sooner, increase weed control, and have greater yields compared to soybean grown in wide rows (Andrade et al. 2019; Bell et al. 2015; Dalley et al. 2004). In the current study, 38-cm rows resulted in faster canopy closure at two locations (both soybean varieties at AB21 and SC21) and greater yield at two locations (Enlist® E3 soybean at OT21 and SC21), with mixed results for weed control. However, soybean grown in 38-cm rows was more profitable than soybean grown in 76-cm rows only at the irrigated location (SC21).

The best weed management strategies for Kansas soybean will vary from field to field as precipitation, soil properties, and weed populations change. This research indicates that each herbicide treatment, row spacing, and soybean trait has its place. In general, using a two-pass system provided the greatest weed control, regardless of the soybean trait and row spacing. If a dryland producer is considering purchasing a narrow-row planter, it will be important to remember that yield is influenced by moisture availability. When the results of this study are considered in the context of previous research, it can be concluded that a yield advantage is unlikely during dry years, but in years with timely rain or in irrigated environments, narrow rows are likely to yield more than wide rows. In general, farmers growing dryland soybean can expect greater profitability planting in 76-cm rows. However, the benefits of layered residual herbicides are more variable.

Acknowledgments. Excellent technical assistance was provided by Malynda Smith, Scott Dooley, and Jim Kimball.

Funding. Funding for this research was provided by the Kansas Soybean Association. This publication is contribution no. 25-031-J from the Kansas Agricultural Experiment Station, Manhattan.

Competing interests. The authors declare no conflicts of interest.

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