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Authors: Torbiak, Alysha T., Blackshaw, Robert E., Brandt, Randall N., Hamman, Bill, and Geddes, Charles M.

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ARTICLE

Glyphosate- and acetolactate synthase inhibitor-resistant kochia (*Bassia scoparia*) control in field pea

Alysha T. Torbiak, Robert E. Blackshaw, Randall N. Brandt, Bill Hamman, and Charles M. Geddes

Abstract: Kochia [*Bassia scoparia* (L.) A.J. Scott] is an invasive C_4 tumbleweed in the Great Plains of North America, where it impedes crop harvest and causes significant crop yield losses. Rapid evolution and spread of glyphosate- and acetolactate synthase (ALS) inhibitor-resistant kochia in western Canada limit the herbicide options available for control of these biotypes in field pea (*Pisum sativum* L.); one of the predominant pulse crops grown in this region. Field experiments were conducted near Lethbridge, Alberta, in 2013–2015 and Coalhurst, Alberta, in 2013–2014 to determine which herbicide options effectively control glyphosate- and ALS inhibitor-resistant kochia in field pea. Visible injury of field pea was minor (0%–4%) in all environments except for Lethbridge 2013, where pre-plant (PP) flumioxazin and all treatments containing post-emergence (POST) imazamox/bentazon resulted in unacceptable (14%–23%) visible injury in field pea. Herbicide impacts on field pea yield were minor overall. Carfentrazone + sulfentrazone PP and saflufenacil PP followed by imazamox/bentazon POST resulted in ≥80% visible control of kochia in all environments, while POST imazamox/bentazon alone resulted in ≥80% reduction in kochia biomass in all environments compared with the untreated control (albeit, absent of statistical difference in Coalhurst 2014). These results suggest that layering the protoporhyrinogen oxidase-inhibiting herbicides saflufenacil or carfentrazone + sulfentrazone PP with the ALS- and photosystem II-inhibiting herbicide combination imazamox/bentazon POST can effectively control glyphosate- and ALS inhibitor-resistant kochia in field pea while also mitigating further selection for herbicide resistance through the use of multiple effective herbicide modes-of-action.

Key words: acetolactate synthase, glyphosate, herbicide-resistant, herbicide resistance, herbicide stewardship.

Résumé : Le cyprès d'été ou kochie à balais [*Bassia scoparia* (L.) A.J. Scott] est une amaranthacée en C_4 envahissante des grandes plaines d'Amérique du Nord, où elle nuit à la récolte et suscite de lourdes pertes de rendement. L'évolution rapide et la prolifération de la kochie résistante au glyphosate et aux inhibiteurs de l'acétolactate synthase (ALS) dans l'Ouest canadien restreignent le nombre d'herbicides disponibles pour lutter contre ces biotypes dans les champs de pois (*Pisum sativum* L.), une des principales légumineuses cultivées dans la région. Les auteurs ont effectué des expériences sur le terrain près de Lethbridge (Alberta) de 2013 à 2015 ainsi qu'à Coalhurst (Alberta) en 2013-2014 en vue d'établir quels herbicides permettraient de combattre efficacement la kochie résistante au glyphosate et aux inhibiteurs de l'ALS dans les champs de pois. Ils n'ont observé que peu de dommages à la culture (0 %–4 %) dans toutes les conditions, sauf à Lethbridge, en 2013, où l'application de flumioxazine avant la levée et celle d'imazamox/bentazon après la levée ont entraîné des dommages excessifs (14 %–23 %). En général, l'herbicide n'a qu'une faible incidence sur le rendement. L'application de carfentrazone + sulfentrazone avant la levée et celle de saflufénacil avant la levée puis d'imazamox/bentazon après la levée détruisent au moins 80 % de l'adventice dans tous les environnements, alors que l'application d'imazamox/bentazon seul, après la levée, réduit la biomasse de la kochie d'au moins 80 %, quelles que soient les conditions, comparativement à la parcelle témoin (aucun écart statistique à Coalhurst, en 2014). Ces résultats laissent croire que l'application avant la levée d'herbicides qui inhibent la protoporhyrinogène oxydase comme le saflufénacil ou le mélange carfentrazone + sulfentrazone, puis l'application, après la levée, d'un mélange d'herbicides inhibant l'ALS- et le

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A.T. Torbiak and B. Hamman. Hamman Ag Research Inc., 347 Squamish Court West, Lethbridge, AB T1K 7R8, Canada.

R.E. Blackshaw, R.N. Brandt, and C.M. Geddes.* Agriculture and Agri-Food Canada, Lethbridge Research and Development Centre, 5403 1st Avenue South, Lethbridge, AB T1J 4B1, Canada.

Corresponding author: Charles M. Geddes (email: Charles.Geddes@agr.gc.ca).

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photosystème II comme l'imazamox/bentazon peuvent lutter efficacement contre la kochie résistante au glyphosate et aux inhibiteurs de l'ALS dans les champs de pois tout en freinant la sélection d'adventices encore plus résistantes par l'usage de désherbants efficaces aux multiples modes d'action. [Traduit par la Rédaction]

Mots-clés : acétolactate synthase, glyphosate, résistant aux herbicides, résistance, intendance des herbicides.

Introduction

Kochia [*Bassia scoparia* (L.) A.J. Scott] is an invasive, C_4 summer annual tumbleweed that can lead to considerable yield loss and harvest difficulty in agricultural crops like field pea (*Pisum sativum* L.). Kochia was introduced to North America from Eurasia as an ornamental garden forb in the 1800s, and has since escaped cultivation and naturalized (Friesen et al. 2009). This weed is found in cropped and non-cropped areas, including rangeland, oil well sites, and roadsides, among other ruderal areas (Friesen et al. 2009). Kochia is distributed across the Great Plains of North America (Friesen et al. 2009), and is the most abundant weed species present in annual crops after post-emergence (POST) herbicide application in the mixed grassland ecoregion of Alberta (Leeson et al. 2019). Kochia had the highest rate of spread compared with 40 other invasive weed species in the Northern Great Plains (Forcella 1985).

Kochia invasiveness and spread are facilitated by several unique biological characteristics. Early spring seedling emergence (Schwinghamer and Van Acker 2008) places emphasis on effective pre-plant (PP) weed control; however, the prolonged emergence periodicity exhibited by kochia (Schwinghamer and Van Acker 2008) can result in emergence up to, or following, POST herbicide applications. These uncontrolled late-emerging cohorts (emerging before 2140 growing degree days, T_{base} 0 °C) can produce viable seed before the end of the growing season and contribute to soil seedbank replenishment (Geddes and Davis 2021). Drought, heat, and salinity tolerance allow this weed to thrive in field areas prone to abiotic stress (Friesen et al. 2009). High genetic diversity (Martin et al. 2020) can result in rapid evolution when exposed to recurrent selection pressures, while protogynous flowering aids in cross-pollination and transfer of herbicide resistance traits (Beckie et al. 2016). Prolific seed production (up to 120 000 seeds plant^{-1}) and long-distance seed dispersal of this tumbleweed facilitate its spread among fields (Beckie et al. 2016). While short kochia seed longevity (about 1–2 yr) in the soil seedbank (Beckie et al. 2018; Geddes 2021) can hasten evolution and population turnover, rapid seedbank depletion also serves as a target for alternative weed control efforts (Geddes and Davis 2021).

Herbicide-resistant kochia is a growing problem in annual crops produced in the Great Plains of North America, and new biotypes with resistance to multiple herbicide modes-of-action further exacerbate the issue (Varanasi et al. 2015; Beckie et al. 2019). In Canada, acetolactate synthase (ALS) inhibitor-resistant kochia was reported first in Saskatchewan and Manitoba in 1988, and subsequently in Alberta in 1989 (Heap 2021). By 2007, this biotype had evolved in or spread to 85% of the kochia populations sampled in western Canada (Beckie et al. 2011); and later to all populations tested (Beckie et al. 2013, 2015, 2019). The first confirmations of glyphosate-resistant (GR) kochia in Canada were from chemical fallow fields in southern Alberta in 2011 (Beckie et al. 2013). A 2012 survey of Alberta reported that 4% of the kochia populations tested in Alberta were GR (Hall et al. 2014). Only 5 yr later, 50% of the kochia populations in Alberta were GR, representing unprecedented herbicide resistance evolution in or spread among kochia populations (Beckie et al. 2019). A similar increase in GR kochia was observed in Manitoba between 2013 and 2018 (Geddes et al. 2021*b*). The 2017 survey of Alberta also confirmed that 18% of the kochia populations in Alberta were dicamba-resistant (Beckie et al. 2019), while 13% were fluroxypyr-resistant (Geddes et al. 2021*a*). About 16% of the kochia populations in Alberta in 2017 were triple herbicide-resistant to ALS inhibitors, glyphosate, and at least one synthetic auxin herbicide (Geddes et al. 2021*a*).

Field pea is an important crop in western Canada because, when included in crop rotations dominated by cereals and oilseeds, it can serve to break disease cycles, reduce fertilizer inputs, and in certain cases increase yield in subsequent crops. Wheat (*Triticum aestivum* L.) and canola (*Brassica napus* L.) are the two most abundant crops grown in Canada (Statistics Canada 2021*a*), and nitrogen is the most limiting factor in their grain yield and quality (Harker et al. 2012). Field pea require less nitrogen fertilizer compared with non-legume crops because they can acquire plant-available nitrogen through biological nitrogen fixation (Walley et al. 2007). Including pulses in an oilseed-cereal rotation in western Canada reduced nitrogen fertilizer requirements, increased yields in the subsequent crop, and also improved overall yield stability of crop rotations (St. Luce et al. 2015, 2020). Canada is the world's largest exporter of peas for food, feed, and ingredients, accounting for 32% of global pea production in 2010 and 55% of global pea trade in 2008 (Canadian Agri-Food Trade Alliance 2021). Based on seeded area in 2020, 97% of pulse production in Canada was in the prairie provinces of Alberta, Saskatchewan, and Manitoba. The majority of the pulse seeded area in Canada was in Saskatchewan (69%), while 24% was in Alberta (Statistics Canada 2021*a*). Field pea was seeded on 1.7 million ha in the Canadian prairie provinces in 2020, where it was grown predominantly using reduced tillage systems (Statistics Canada 2021*a*, 2021*b*). In 2016, 87% of arable farmland in this region was seeded using conservation tillage practices (including zero- and minimum-tillage) (Statistics Canada 2021*b*). Glyphosate is a non-selective herbicide on which many farmers rely for cost-effective PP weed control in conservation tillage systems, among other usage windows; however, selection for weeds that evade control with glyphosate can hinder these production systems, resulting in management problems in important crops like field pea.

Glyphosate and imidazolinone (ALS-inhibiting) herbicides are the most common herbicides used PP and POST for broadleaf weed control in field pea, however, glyphosate and ALS inhibitor resistance render these herbicide options ineffective for management of glyphosate- and ALS inhibitor-resistant kochia biotypes (Beckie et al. 2011, 2013, 2019). This research was designed to determine which fall-applied, PP, and POST herbicide options effectively control glyphosate- and ALS inhibitor-resistant kochia in field pea.

Materials and Methods

Site descriptions

Field experiments were conducted at the Agriculture and Agri-Food Canada Lethbridge Research and Development Centre located near Lethbridge, Alberta (49.69° N, −112.77° W) in 2013–2015, and at Hamman Ag Research Inc. located near Coalhurst, Alberta (49.79° N, −112.99° W) in 2013–2014. Both locations had dark brown chernozemic soil with clay loam texture at Lethbridge (3.6% organic matter and pH 7.8) and loam texture at Coalhurst (2.5% organic matter and pH 8.3). The experiments at Lethbridge were established following an oat (*Avena sativa* L.) cover crop in 2013 and silage barley (*Hordeum vulgare* L.) in 2014 and 2015, while chemical fallow was used prior to experiment establishment at Coalhurst in both years.

Experimental design and treatment structure

In each of the five environments, the field experiment followed a split-block randomized complete block design with four experimental replications (blocks) and a two-way factorial treatment structure. The main plot size at Lethbridge was 2.5 × 7.5 m in 2013 and 3.0 × 7.5 m in 2014 and 2015, while at Coalhurst the main plot size was 2.5 × 7.5 m in 2013 and 2.5 × 6.0 m in 2014. Each experimental replication was split at random, where one half was seeded with glyphosate- and ALS inhibitor-resistant kochia (hereafter referred to as ALS/GR kochia) and the other half with ALS inhibitor-resistant but glyphosate-susceptible (GS) kochia (hereafter referred to as ALSR kochia). Both ALS/GR and ALSR populations were resistant to sulfonylurea and imidazolinone herbicides. The kochia populations were selected and maintained in the field over successive years using glyphosate (Roundup Transorb® HC, Bayer CropScience Inc., Calgary, AB) at 900 g ae ha^{-1} for ALS/GR kochia and thifensulfuron-methyl + tribenuron-methyl (Refine® SG; FMC Corporation, Philadelphia, PA) at 10 + 5 g ai ha^{-1} for ALSR kochia. A Fabro double-disk drill (Fabro Enterprises Ltd., Swift Current, SK) was used to seed field pea cv. AC Meadow and kochia concurrently along each experimental replication, perpendicular to the orientation of the herbicide treatments. An exception was made in Coalhurst 2014, where a Fabro hoe drill was used to seed the field pea. Each kochia accession was seeded in a different pass with the seeder. Each seeder pass included 10 rows of field pea spaced 23 cm apart (25 cm at Coalhurst 2014), with 9 rows of kochia seeded mid-row between the peas. Field pea was planted at a depth of 3.5 cm, while kochia seed was placed at 0.3 cm depth and compressed into the soil with the seeder packing tires. Field pea and kochia were seeded at target rates of 125 and 300 viable seeds m^{-2}, respectively. The pea seed was treated with CruiserMaxx® Vibrance® (in 2013) or CruiserMaxx® Pulses® (in 2014/2015) at 2.4 or 4.5 mL kg^{-1} seed, respectively (Syngenta Canada Inc., Guelph, ON). In Coalhurst 2014, a fertilizer mixture of 79–45–17–11 kg ha^{-1} (actual N-P-K-S) was placed in a side-row band while no fertilizer was applied in the other environments based on soil test recommendations. Cell-Tech® (in 2013) or TagTeam® granular inoculant (Novozymes BioAg, Saskatoon, SK) (in 2014/2015) was placed within the seed row at 6.0 or 4.5 kg ha^{-1}, respectively.

All weeds present were controlled before planting. At Lethbridge, glyphosate (Roundup Transorb® HC) was applied as a PP burndown at 890 g ae ha^{-1} in 2013, at 1334 g ae ha^{-1} in 2014, and glyphosate + bromoxynil (Koril®, Nufarm Canada, Calgary, AB) were applied in 2015 at a rate of 1334 + 348 g ai/ae ha^{-1}. At Coalhurst, glyphosate was applied at 900 g ae ha^{-1} in both years.

The herbicide treatments were chosen because they were either registered for control of kochia when applied prior to or within field pea, or because they were being considered for these use cases (Table 1). The herbicide treatments were applied either in the fall, spring PP (7–10 d before seeding), or POST (pea 3–6 node stage). Granular elthalfluralin treatments were applied using a Valmar spreader (Salford Group Inc., Salford, ON) calibrated to deliver 11.0 (fall) or 8.5 (spring PP) kg ha^{-1} product when travelling at 5 km h^{-1}. At Coalhurst, the liquid herbicides were applied using a 2.0 m hand-held propane-propelled sprayer with John Deere LDX01 nozzles (John Deere, Moline, IL) calibrated to deliver 100 L ha^{-1} solution with water carrier at 242 kPa and a speed of 4 km h^{-1}. At Lethbridge, the herbicides were applied using a 2.0 m (or 2.5 m in 2014/2015) bicycle CO_2 sprayer with Greenleaf Air Mix 110–010 nozzles (Greenleaf Technologies, Covington, LA) calibrated to deliver 100 L ha^{-1} solution with water carrier at 290 kPa and a speed of 5 km h^{-1}. Diquat (Reglone® Desiccant, Syngenta Canada Inc., Guelph, ON) was applied at

Table 1. Herbicide treatments assessed for control of glyphosate- and acetolactate synthase inhibitor-resistant kochia in field pea near Lethbridge, Alberta (2013–2015) and Coalhurst, Alberta (2013–2014).

Herbicide common name	Herbicide trade name	Timing[a]	Herbicide group	Concentration (% or g ai/ae L^{-1})	Formulation	Rate (g ai/ae ha^{-1})	Company[b]
Ethalfluralin	Edge® Microactiv®	Fall	3	10%	GR	1100	Gowan
Pyroxasulfone	F61801	Fall	15	85%	WDG	125	FMC
Flumioxazin	Valtera™	Fall	14	51%	WDG	80	Valent
Flumioxazin[c]	Valtera™	Fall	14	51%	WDG	105	Valent
Ethalfluralin + Pyroxasulfone[c]	Edge® Microactiv® + F61801	Fall + Fall	3 + 15	10% + 85%	GR + WDG	1100 + 125	Gowan + FMC
Ethalfluralin + Flumioxazin[c]	Edge® Microactiv® + Valtera™	Fall + Fall	3 + 14	10% + 51%	GR + WDG	1100 + 80	Gowan + Valent
Carfentrazone + Sulfentrazone	Aim® EC + Authority® 480[d]	PP + PP	14 + 14	240 + 480	EC + SN	9 + 105	FMC + FMC
Imazamox/Bentazon	Viper® ADV[e]	POST	2/6	20/429	SN	20/429	BASF
Ethalfluralin fb. Imazamox/Bentazon	Edge® Microactiv® fb. Viper® ADV[e]	Fall fb. POST	3 fb. 2/6	10% fb. 20/429	GR fb. SN	1100 fb. 20/429	Gowan fb. BASF
Saflufenacil fb. Imazamox/Bentazon	Heat[d] fb. Viper® ADV[e]	PP fb. POST	14 fb. 2/6	70% fb. 20/429	WG fb. SN	50 fb. 20/429	BASF fb. BASF

Note: EC, emulsifiable concentrate; fb., followed by; GR, granule; POST, post-emergence at field pea 3–6 node stage; PP, pre-plant 7–10 d before seeding; SC, suspension concentrate; SN, solution; WDG, water dispersible granule.

[a]All fall treatments were applied PP in 2013 at the following rates: Ethalfluralin, 850 g ai ha^{-1}; Pyroxasulfone, 125 g ai ha^{-1}; Flumioxazin, 80 g ai ha^{-1}.

[b]Full company names: BASF Canada Inc., Mississauga ON; Gowan Company LLC, Yuma, AZ; FMC of Canada Limited, Mississauga ON; Valent Canada Inc., Guelph, ON.

[c]Treatment not included in 2013.

[d]Applied with Merge® Adjuvant (BASF Canada Inc., Mississauga, ON) at 0.5% *v*/*v*.

[e]Applied with 28% UAN at 2% *v*/*v*.

409 g ai ha^{-1} [with ICPO® Ag-Surf® adjuvant at 0.1% *v*/*v* (Interprovincial Cooperative Limited, Saskatoon, SK)] as a harvest aid 10 d prior to harvesting field pea at Lethbridge 2014 and 2015.

Data collection

Field pea density was determined for each main plot by counting all plants in 1 m length of 2 rows at the 3–6 node stage. Each main plot was rated for visible injury of field pea as a percentage from 0% (visually similar to the untreated control) to 100% (complete necrosis) at 3 wk after the POST herbicide application (WAA) (Canadian Weed Science Society 2018). Grain yield was obtained by harvesting each subplot separately using a Zürn 150 plot combine (Zürn Harvesting GmbH & Co. KG, Schöntal-Westernhausen, Germany) at Coalhurst, or Wintersteiger Delta (Wintersteiger Inc., Saskatoon, SK) at Lethbridge, and cleaning the seed using a clipper seed cleaner and spiral separator. Clean seed yields were adjusted to 16.0% moisture.

Prior to the POST herbicide application, kochia plant density was determined for each kochia accession by counting all kochia plants within a randomly placed 0.25 m^2 quadrat in each subplot. Kochia visible control was evaluated within each subplot as a percentage from 0% (visually similar to the untreated control) to 100% (complete necrosis) at 3 WAA (Canadian Weed Science Society 2018). Kochia shoot biomass fresh weight was determined 8 WAA by removing and weighing all aboveground kochia biomass from a 0.5 m^2 area (3 rows by 0.72 m) within each subplot.

Statistical analysis

Field pea density and grain yield, and kochia density, visible control, and biomass data were analyzed using ANOVA in the GLIMMIX procedure of SAS version 9.4 (SAS Institute Inc., Cary, NC). Separate analyses were conducted for 2013 and for 2014/2015 due to an additional three treatments included in 2014/2015, and because fall-applied treatments (in 2014/2015) were applied PP in spring in 2013 (Table 1). The main and interaction effects of kochia accession, herbicide treatment, and environment were considered fixed effects, while experimental replication nested within environment, and the interaction effects of kochia accession and replication nested within environment in addition to herbicide treatment and replication nested within environment were considered random effects. An initial variance component analysis was conducted using the MIXED procedure to determine the relative variance explained by each factor in the models (Littell et al. 2006). All main and interaction effects including kochia accession were not significant ($\alpha = 0.05$) and accounted for <5% of the model variance. These effects were therefore pruned from the model, and data were analyzed across both kochia accessions.

Residual normality was assessed using the Shapiro-Wilk test in the UNIVARIATE procedure, while homoscedasticity was assessed visually by plotting the predicted and observed values. All response variables with the exception of kochia density and biomass were analyzed using the Gaussian distribution and identity link functions. Kochia density and biomass were analyzed using the lognormal distribution and identity link functions. The covariance structure of residuals was grouped by site (for kochia density, visible control, and pea density) or year (for kochia biomass) based on minimization of the Akaike Information Criterion and visual inspection of the residual variance. Extreme outliers were removed from the analyses based on Lund's test (Lund 1975). Means were compared for significant main or interaction effects using Tukey's Honest Significant Difference ($\alpha = 0.05$). Simple means were used to assess crop injury as an abundance of 0 values precluded these data from meeting the assumptions of ANOVA.

Results and Discussion

Climatic conditions

During 2013, 2014, and 2015, temperatures were on average about 1 °C warmer than the 30 yr climactic normal for this locality. The spring months of April, May, and June varied around climatic normal temperatures, however the summer months of July, August, and September were warmer than normal (Table 2). Cumulative growing season (April – October) precipitation varied among years, and ranged from about one-third greater than normal in 2013 and 2014 to one-third less than normal in 2015. The month of June experienced the greatest variability in precipitation, which also corresponded with the timing of POST herbicide application. Precipitation in June of 2013 and 2014 was about double that of the climatic normal, while precipitation in June 2015 was less than one-quarter of the climatic normal (Table 2). Weather data are presented for the Lethbridge site only due to absence of a weather station at Coalhurst and the close vicinity of these locations.

Field pea growth and development

Field pea and kochia response to herbicide treatment varied with the environment in which the herbicides were applied (Table 3). A significant herbicide treatment by environment interaction was observed for all response variables with the exception of field pea grain yield in 2013 as herbicide treatment did not impact yield in this year.

2013 Experiments

Inconsistent differences in field pea density were observed in response to the herbicide treatments in the two environments in 2013, however, these differences were relatively minor and did not correspond with yield estimates. Field pea density in 2013 ranged from 91 to 118 plants m^{-2} in Lethbridge and 100 to 119 plants m^{-2}

Table 2. Growing season monthly average temperature and precipitation at Lethbridge AB, in 2013, 2014, and 2015 compared with the 30 yr average (normal) monthly temperature and precipitation for this region.

	Mean monthly temperature (°C)				Total monthly precipitation (mm)			
Month	2013	2014	2015	30 yr normal	2013	2014	2015	30 yr normal
April	4.1	6.2	7.5	6.3	32	37	18	33
May	13.0	11.0	10.5	11.5	56	46	43	55
June	15.5	14.3	17.7	15.4	155	192	20	84
July	18.6	19.9	19.5	18.4	50	22	39	41
August	19.6	19.0	19.4	17.9	26	49	16	41
September	15.9	13.4	13.1	13.0	67	61	53	41
October	7.1	10.6	9.7	7.2	32	15	8	20

Note: Coalhurst received 50 mm of supplemental irrigation in July and August 2014. Lethbridge received 6, 25, and 25 mm of supplemental irrigation in May, June and July 2015, respectively.

in Coalhurst (Table 4). In Lethbridge, all herbicide treatments resulted in similar pea density as the untreated control with the exception of flumioxazin PP (80 g ai ha^{-1}) which reduced pea density by about 20%. In Coalhurst, however, both ethalfluralin PP (850 g ai ha^{-1}) and saflufenacil PP followed by (fb.) imazamox/bentazon POST (50 fb. 20/429 g ai/ae ha^{-1}) reduced field pea density by 13% and 16%, respectively (Table 4). Field pea visible injury at Coalhurst was considered minor (1%–3%) in 2013 (Table 4). The crop generally outgrows <10% visible injury absent of yield penalty [Pest Management Regulatory Agency (PMRA) 2016; Canadian Weed Science Society (CWSS) 2018]. However, several treatments at Lethbridge in 2013 resulted in unacceptable visible injury of field pea (CWSS 2018). Flumioxazin PP (80 g ai ha^{-1}), imazamox/bentazon POST (20/429 g ai/ae ha^{-1}), ethalfluralin PP fb. imazamox/bentazon POST (850 fb. 20/429 g ai/ae ha^{-1}), and saflufenacil PP fb. imazamox/bentazon POST (50 fb. 20/429 g ai/ae ha^{-1}) resulted in unacceptable field pea injury (14%–23% visible injury), while pyroxasulfone PP (125 g ai ha^{-1}) resulted in injury considered just acceptable (10%) (Table 4) (CWSS 2018). Despite slight differences in field pea density, and unacceptable visible injury in Lethbridge 2013, field pea grain yield did not vary among the herbicide treatments or the untreated control (P = 0.090) (Table 3). The reason for lack of difference in pea yield among the herbicide treatments is unclear, but it could be due to somewhat lower kochia densities present at these sites, potential impacts of other environmental stressors in 2013, or variability in grain yield estimates. It is possible that herbicide application at the 3–6 node stage of field pea is too late to manifest potential yield benefits from weed removal as critical interference took place before this time frame. Earlier weed removal in field pea (about 1–2 weeks after crop emergence) can mitigate yield penalties imposed by early-season weed interference in western Canada (Harker et al. 2001; May et al. 2003).

2014/2015 Experiments

The herbicide treatments had relatively minor impact on field pea in 2014 and 2015, and the slight differences that were observed were not consistent among environments (Tables 3 and 5). Field pea density was slightly lower in 2014 than in 2015 (P = 0.009) with densities among herbicide treatments of 89 (±2.0), 91 (±1.9), and 99 (±1.9) in Coalhurst 2014, Lethbridge 2014, and Lethbridge 2015, respectively (data not shown). Differences in pea density among herbicide treatments were observed only in Lethbridge 2014, where fall-applied ethalfluralin (1100 g ai ha^{-1}) and spring-applied carfentrazone + sulfentrazone PP (9 + 105 g ai ha^{-1}) resulted in 19%–21% lower pea density than the high rate of flumioxazin applied in the fall (105 g ai ha^{-1}), while all herbicide treatments resulted in field pea density that was similar to the untreated control (Table 5). Visible injury of field pea in response to the herbicide treatments was either non-existent (Lethbridge 2014) or minor (0%–4% in Coalhurst 2014 and Lethbridge 2015) (Table 5). Field pea grain yield did not differ among the herbicide treatments or the untreated control in the 2014 environments. In Lethbridge 2015, however, the high rate of flumioxazin applied in the fall (105 g ai ha^{-1}) resulted in a 27% yield increase compared with the untreated control, and it also yielded higher than the fall-applied treatments ethalfluralin (1100 g ai ha^{-1}) or ethalfluralin +flumioxazin (1100 + 80 g ai ha^{-1}) (Table 5). In Washington, sulfentrazone (28 or 42 g ai ha^{-1}) applied PP resulted in minimal injury of field pea (Yenish and Eaton 2002). Fall-applied flumioxazin (107 or 214 g ai ha^{-1}), carfentrazone + sulfentrazone (18 + 164 or 36 + 328 g ai ha^{-1}), and carfentrazone + pyroxasulfone (8 + 119 or 16 + 238 g ai ha^{-1}) also resulted in minimal visible injury (≤5%) of field pea at four locations in Montana (Jha and Kumar 2017). However, the high rate of fall-applied carfentrazone + pyroxasulfone (16 + 238 g ai ha^{-1}) reduced field pea yield by 18%–20% at two of these

Table 3. Analysis of variance (ANOVA) table showing the significance of main and interaction effects of herbicide treatment (H) and environment (E) on plant density, visible control, and aboveground biomass of glyphosate- and acetolactate synthase inhibitor-resistant kochia, and plant density and grain yield of field pea at Coalhurst, Alberta (2013–2014) and Lethbridge, Alberta (2013–2015).

	2013					2014/2015				
	Kochia			Pea		Kochia			Pea	
Fixed effect	Plant density (plants m^{-2})	Visible control (%)	Biomass (g m^{-2})	Plant density (plants m^{-2})	Grain yield (kg ha^{-1})	Plant density (plants m^{-2})	Visible control (%)	Biomass (g m^{-2})	Plant density (plants m^{-2})	Grain yield (kg ha^{-1})
H	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.090	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
E	0.080	0.257	0.075	0.098	**0.005**	**<0.001**	0.054	**0.021**	**0.009**	**<0.001**
H × E	**<0.001**	**<0.001**	**0.028**	**0.002**	0.070	**<0.001**	**<0.001**	**<0.001**	**0.034**	**0.009**

Note: Variance component analyses indicated that all main and interaction affects with kochia accession accounted for <5% of the model variance, and therefore these effects were removed from the ANOVA. Bold values indicate statistical significance at $P < 0.05$.

four locations compared with the untreated weed-free control, while the low rate (8 + 119 g ai ha^{-1}) reduced yield by 20% at one location (Jha and Kumar 2017).

Previous reports have noted variable impact of POST imazamox and bentazon on field pea injury, which depended on environmental conditions and the growth stage of field pea at the time of herbicide treatment. Imazamox alone did not result in visible injury or yield reduction of field pea in Alberta when applied at rates up to 40 g ai ha^{-1} (the highest rate tested) POST at the field pea 3–5 node stage (Blackshaw 1998). Field pea injury from imazamox (34 g ai ha^{-1}) reached up to 24% when applied POST at a more advanced growth stage (12 node stage) in Washington, but was considered acceptable (≤8%) when applied at earlier growth stages (≤10 node stage) (Yenish and Eaton 2002). Bentazon (560 g ai ha^{-1}) applied POST resulted in 14% visible injury of pea about 3 WAA in one of six environments in Washington, but minimal injury (≤5%) in the other five (Yenish and Eaton 2002). However, imazamox + bentazon (34 + 560 g ai/ae ha^{-1}) applied POST caused minimal visible injury (≤6%) of field pea in this same study (Yenish and Eaton 2002).

Kochia management

Despite minimal response of field pea to the herbicide treatments when compared with the untreated control, the true benefit of herbicidal control of kochia in field pea could manifest as a reduction in kochia population densities, biomass, or seed production and return to the soil seedbank. While kochia seed production was not assessed in the current study, kochia densities, visible control, and biomass may provide insight into the benefits of optimized herbicide programs in field pea.

2013 experiments

Several herbicide treatments applied in 2013 were effective for control of ALSR and ALS/GR kochia biotypes. The PP herbicide treatments alone reduced kochia plant densities at Lethbridge 2013, but not at Coalhurst 2013, likely due to lower kochia densities present in this environment (22 plants m^{-2} in the untreated control) resulting in lack of statistical difference at α = 0.05 (Table 6). Torbiak et al. (2021*b*) also noted reduced impact of PP sufentrazone (105 g ai ha^{-1}) on kochia density in spring wheat when the kochia population densities present were low overall. In Lethbridge 2013, pyroxasulfone PP (125 g ai ha^{-1}), flumioxazin PP (80 g ai ha^{-1}), and carfentrazone + sulfentrazone PP (9 + 105 g ai ha^{-1}) reduced kochia densities by 76%, 91%, and 91%, respectively (Table 6). Spring PP application of ethalfluralin (850 g ai ha^{-1}) or saflufenacil (50 g ai ha^{-1}) did not impact kochia plant densities in either environment. Kochia plant density was evaluated prior to applying the POST herbicides, and thus no difference was expected among POST herbicide treatments and the untreated control. The PMRA considers weed suppression as a visible control rating between 60% and <80%, while weed control is

Table 4. The impact of herbicide treatments on density, visible injury, and grain yield of field pea infested with glyphosate- and acetolactate synthase inhibitor-resistant kochia in two environments near Lethbridge and Coalhurst, Alberta in 2013.

		Lethbridge 2013			Coalhurst 2013		
Herbicide treatment and timing	Rate (g ai/ae ha^{-1})	Crop density (plants m^{-2})	Visible injury[a] (%)	Grain yield (kg ha^{-1})	Crop density (plants m^{-2})	Visible injury[a] (%)	Grain yield (kg ha^{-1})
Untreated	—	114ab	—	1795	119a	—	2638
Ethalfluralin (PP)	850	101abc	0 ± 0	1984	103bc	3 ± 1	2818
Pyroxasulfone (PP)	125	118a	10 ± 2	1499	110abc	1 ± 1	2560
Flumioxazin (PP)	80	91c	16 ± 1	1732	111abc	2 ± 1	2600
Carfentrazone + Sulfentrazone (PP)	9 + 105	114ab	0 ± 0	1798	124a	3 ± 1	2673
Imazamox/Bentazon (POST)	20/429	106abc	14 ± 1	1785	117ab	3 ± 1	2510
Ethalfluralin (PP) fb. Imazamox/Bentazon (POST)	850 fb. 20/429	98bc	14 ± 1	1493	115ab	1 ± 1	3121
Saflufenacil (PP) fb. Imazamox/Bentazon (POST)	50 fb. 20/429	96b,c	23 ± 1	1861	100c	1 ± 1	3086

Note: PP, pre-plant 7–10 d before seeding; POST, post-emergence at field pea 3–6 node stage; fb., followed by. Values are LS means. Within columns different letters indicate significant differences based on Tukey's Honest Significant Difference ($\alpha = 0.05$).

[a]Values are simple means ± standard error.

considered ≥80% (PMRA 2016). None of the herbicide treatments in 2013 resulted in excellent visible control (≥90%) among both environments, while all treatments resulted in at least kochia suppression (≥60%) (Table 6). Flumioxazin PP (80 g ai ha^{-1}), carfentrazone + sulfentrazone PP (9 + 105 g ai ha^{-1}), imazamox/bentazon POST (20/429 g ai/ae ha^{-1}) alone or preceded by spring-applied ethalfluralin (850 g ai ha^{-1}) or saflufenacil (50 g ai ha^{-1}) resulted in consistent visible control (≥80%) among the 2013 environments (Table 6). This corresponded directly with biomass estimates in Lethbridge 2013, where all of these treatments reduced kochia biomass by ≥80% compared with the untreated control (Table 6). In Coalhurst, however, only the treatments that included imazamox/bentazon POST (20/429 g ai/ae ha^{-1}) reduced kochia biomass by ≥80%.

2014/2015 experiments

Despite some variability in efficacy of the herbicide treatments among environments in 2014/2015, carfentrazone + sulfentrazone PP (9 + 105 g ai ha^{-1}), imazamox/bentazon POST (20/429 g ai/ae ha^{-1}), alone or preceded by saflufenacil PP (50 g ai ha^{-1}), resulted in ≥80% visible control or ≥80% biomass reduction in each of the three environments (Table 7). Fall-applied ethalfluralin + pyroxasulfone (1100 + 125 g ai ha^{-1}) and fall applied ethalfluralin fb. imazamox/bentazon POST (1100 fb. 20/429 g ai/ae ha^{-1}) resulted in kochia suppression at minimum among the 2014/2015 environments, and ratings of kochia control in one and two of the environments, respectively (Table 7). Kochia plant densities ranged among the three environments from 29 plants m^{-2} in Coalhurst 2014 to 284 plants m^{-2} in Lethbridge 2015 in the untreated control treatments (Table 7). Carfentrazone + sulfentrazone PP (9 + 105 g ai ha^{-1}) reduced kochia density (by 76%–100%) compared with the untreated control in each environment, while fall-applied ethalfluralin + pyroxasulfone (1100 + 125 g ai ha^{-1}) reduced kochia density by 70% in Lethbridge 2015 only (Table 7).

Among the 2013 and 2014/2015 experiments, carfentrazone + sulfentrazone PP (9 + 105 g ai ha^{-1}) was the only herbicide treatment that reduced kochia density consistently in each environment (excluding Coalhust 2014 due to lack of statistical difference in kochia densities) (Tables 6 and 7). Ethalfluralin applied in the fall or spring (PP) (at 1100 or 850 g ai ha^{-1}, respectively) did not reduce kochia density in any of the environments. The only treatments that resulted in ≥80% visible control of kochia among all 2013–2015 environments were carfentrazone + sulfentrazone PP (9 + 105 g ai ha^{-1}) and saflufenacil PP fb. imazamox/bentazon POST (50 fb. 20/429 g ai/ae ha^{-1}), while POST imazamox/bentazon alone (20/429 g ai/ae ha^{-1}) was the only treatment that resulted in ≥80% reduction in kochia biomass in each environment (however, this was not statistically different from the untreated control in Coalhurst 2014) (Tables 6 and 7). While carfentrazone + sulfentrazone PP fb. imazamox/bentazon POST (9 + 105 fb. 20/429 g ai/ae ha^{-1}) was not tested in the current study, our results suggest that excellent kochia control may be achieved when layering these herbicides prior to and within field pea.

The results observed in the current study correspond with previous reports assessing herbicidal control of kochia in the Northern Great Plains region. Fall-applied flumioxazin (107 or 214 g ai ha^{-1}) and carfentrazone + sulfentrazone (18 + 164 or 36 + 328 g ai ha^{-1}) resulted in excellent visible control (≥90%) of kochia in pulse crops

Table 5. The impact of herbicide treatments on density, visible injury, and grain yield of field pea infested with glyphosate- and acetolactate synthase inhibitor-resistant kochia in three environments near Lethbridge, Alberta (2014–2015) and Coalhurst, Alberta (2014).

		Lethbridge 2014			Coalhurst 2014			Lethbridge 2015		
Herbicide treatment and timing	Rate (g ai/ae ha^{-1})	Crop density (plants m^{-2})	Visible injury[a] (%)	Grain yield (kg ha^{-1})	Crop density (plants m^{-2})	Visible injury[a] (%)	Grain yield (kg ha^{-1})	Crop density (plants m^{-2})	Visible injury[a] (%)	Grain yield (kg ha^{-1})
Untreated	—	90ab		3656	82	—	3474	105		5099bcd
Ethalfluralin (Fall)	1100	80b	0 ± 0	3650	86	0 ± 0	3673	90	0 ± 0	4988cd
Pyroxasulfone (Fall)	125	92ab	0 ± 0	4189	88	3 ± 1	3845	101	0 ± 0	6159abc
Flumioxazin (Fall)	80	97ab	0 ± 0	3454	87	1 ± 1	2730	108	0 ± 0	5194abcd
Flumioxazin (Fall)	105	101a	0 ± 0	3808	104	3 ± 3	3415	96	0 ± 0	6460a
Ethalfluralin + Pyroxasulfone (Fall)	1100 + 125	92ab	0 ± 0	4056	87	1 ± 1	4020	93	0 ± 0	6148abc
Ethalfluralin + Flumioxazin (Fall)	1100 + 80	88ab	0 ± 0	3933	96	0 ± 0	3668	107	0 ± 0	4645d
Carfentrazone + Sulfentrazone (PP)	9 + 105	83b	0 ± 0	4641	85	1 ± 1	3694	97	0 ± 0	6404ab
Imazamox/Bentazon (POST)	20/429	88ab	0 ± 0	4259	88	3 ± 1	3403	101	4 ± 1	5394abcd
Ethalfluralin (Fall) fb. Imazamox/Bentazon (POST)	1100 fb. 20/429	92ab	0 ± 0	3938	84	0 ± 0	3710	92	1 ± 1	5634abcd
Saflufenacil (PP) fb. Imazamox/Bentazon (POST)	50 fb. 20/429	94ab	0 ± 0	4386	96	4 ± 2	3574	102	1 ± 1	5843abcd

Note: PP, pre-plant 7–10 d before seeding; POST, post-emergence at field pea 3–6 node stage; fb., followed by. Values are LS means. Within columns different letters indicate significant differences based on Tukey's Honest Significant Difference (α = 0.05).

[a]Values are simple means ± SE.

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Table 6. The impact of herbicide treatments on density, visible control, and biomass of glyphosate- and acetolactate synthase inhibitor-resistant kochia in field pea in two environments near Lethbridge and Coalhurst, Alberta in 2013.

Herbicide treatment and timing	Rate (g ai/ae ha^{-1})	Lethbridge 2013 Kochia density[a] (plants m^{-2})	Lethbridge 2013 Visible control (%)	Lethbridge 2013 Biomass (g m^{-2})	Coalhurst 2013 Kochia density[a] (plants m^{-2})	Coalhurst 2013 Visible control (%)	Coalhurst 2013 Biomass (g m^{-2})
Untreated	—	82a		415a	22	—	311a
Ethalfluralin (PP)	850	48ab	66d	256a	12	70b	440a
Pyroxasulfone (PP)	125	20b	68d	185ab	27	83ab	73ab
Flumioxazin (PP)	80	7c	91bc	26abc	12	83ab	117ab
Carfentrazone + Sulfentrazone (PP)	9 + 105	7c	100a	1c	33	82ab	68ab
Imazamox/Bentazon (POST)	20/429	71a	93abc	4c	33	83ab	9b
Ethalfluralin (PP) fb. Imazamox/Bentazon (POST)	850 fb. 20/429	53a	89c	7bc	16	94a	3b
Saflufenacil (PP) fb. Imazamox/Bentazon (POST)	50 fb. 20/429	86a	99ab	4c	31	89a	16b

Note: PP, pre-plant 7–10 d before seeding; POST, post-emergence at field pea 3–6 node stage; fb., followed by. Values are LS means. Within columns different letters indicate significant differences based on Tukey's Honest Significant Difference (α = 0.05).
[a]Kochia plant densities were evaluated before POST herbicide application and thus reflect the efficacy of PP herbicides only.

among four locations in Montana (Jha and Kumar 2017). Spring-applied flumioxazin (70 g ai ha^{-1}) and pyroxasulfone (118 g ai ha^{-1}) resulted in 66% and 61% visible control of ALSR kochia in Montana 8 WAA, but control quickly declined to 37% and 18%, respectively, by 12 WAA in the absence of crop interference (Kumar and Jha 2015). In contrast, spring-applied sulfentrazone (210 g ai ha^{-1}) resulted in excellent and sustained (91%–97%) residual control of ALSR kochia that lasted past 12 WAA (Kumar and Jha 2015). Also in Montana, saflufenacil (25 g ai ha^{-1}) applied in the absence of a crop when kochia reached 8–10 cm height resulted in 90%, 82%, and 67% visible control at 1, 3, and 5 WAA, respectively (Kumar and Jha 2015). Glyphosate + saflufenacil (450 + 50 g ai/ae ha^{-1}) applied to kochia plants when they reached 10 cm height resulted in consistent control of GR and GS kochia absent of crop interference among four environments in Alberta, while the same mixture at a lower rate resulted in consistent control of GS kochia, and controlled GR kochia in three of the four environments (Torbiak et al. 2021*a*). In the same experiment glyphosate + carfentrazone + sulfentrazone (450 + 9 + 53 or 450 + 9 + 105 g ai/ae ha^{-1}) resulted in excellent control of GR and GS kochia among the four environments, with the exception of the lower rate of sulfentrazone which controlled GR kochia in three of the four environments (Torbiak et al. 2021*a*). Similarly, sulfentrazone (105 g ai ha^{-1}) applied pre-emergence before spring wheat resulted in excellent visible control (≥95%) of GR and GS kochia 3 WAA of the POST treatments in all three environments tested in Alberta (Torbiak et al. 2021*b*).

Management implications

The growing body of research on herbicidal control of kochia in western Canada shows clear consistencies with the current study where the protoporphyrinogen oxidase (PPO) inhibiting-herbicides saflufenacil, carfentrazone, and sulfentrazone applied alone or in combination resulted in consistent control in several cropping scenarios, including chemical fallow, or before spring wheat or field pea (Tables 6 and 7) (Torbiak et al. 2021*a*, 2021*b*). However, farmers in western Canada should remain diligent and avoid overuse of PPO inhibitors when managing kochia populations in an effort to sustain this effective herbicide mode-of-action for kochia control. Rather, an approach is warranted where PPO inhibitors are strategically utilized in crop rotations prior to less competitive crops that have fewer effective herbicide options, like field pea. Indeed, such an approach will depend on the herbicide-resistant biotypes present within the localized kochia population, and therefore farmers are encouraged to take advantage of resistance diagnostics programs to aid in informed decision making. While the current research showed that POST imazamox/bentazon (20/429 g ai/ae ha^{-1}) is effective for kochia control when applied alone, it is important to recognize that all kochia populations tested in western Canada in recent years were ALS inhibitor-resistant (Beckie et al. 2013, 2015, 2019), meaning that the contact photosystem II-inhibiting herbicide bentazon was the only herbicide with sufficient action on ALSR or ALS/GR kochia. For this reason, it is important to layer other effective herbicide modes-of-action PP or before emergence of field pea to mitigate selection

Table 7. The impact of herbicide treatments on density, visible control, and biomass of glyphosate- and acetolactate synthase inhibitor-resistant kochia in field pea in three environments near Lethbridge, Alberta (2014-2015) and Coalhurst, Alberta (2014).

		Lethbridge 2014			Coalhurst 2014			Lethbridge 2015		
Herbicide treatment and timing	Rate (g ai ha^{-1})	Kochia density[a] (plants m^{-2})	Visible control (%)	Biomass (g m^{-2})	Kochia density[a] (plants m^{-2})	Visible control (%)	Biomass (g m^{-2})	Kochia density[a] (plants m^{-2})	Visible control (%)	Biomass (g m^{-2})
Untreated	—	73a	—	796a	29a	—	916a	284a	—	558a
Ethalfluralin (Fall)	1100	59a	46cd	466ab	19ab	61bcd	473a	185ab	53de	224ab
Pyroxasulfone (Fall)	125	68a	55c	226abc	23ab	56d	245a	220a	67cd	144abc
Flumioxazin (Fall)	80	71a	38d	425ab	37a	8e	1038a	220a	20f	526a
Flumioxazin (Fall)	105	78a	51cd	630ab	26ab	56cd	777a	201a	47e	175a
Ethalfluralin + Pyroxasulfone (Fall)	1100 + 125	34a	79b	82bcd	23ab	75abcd	226a	84b	82abc	116abc
Ethalfluralin + Flumioxazin (Fall)	1100 + 80	83a	60c	467ab	26ab	52d	466a	145ab	71bcd	607a
Carfentrazone + Sulfentrazone (PP)	9 + 105	0b	100a	0e	7b	88a	2b	0c	100a	0d
Imazamox/Bentazon (POST)	20/429	78a	93ab	13cd	24ab	81abc	136a	310a	76bc	83abc
Ethalfluralin (Fall) fb. Imazamox/Bentazon (POST)	1100 fb. 20/429	34a	94ab	14d	34a	68abcd	412a	169ab	86ab	18bc
Saflufenacil (PP) fb. Imazamox/Bentazon (POST)	50 fb. 20/429	40a	98a	7d	18ab	82ab	243a	267a	95a	12c

Note: PP, pre-plant 7–10 before seeding; POST, post-emergence at field pea 3–6 node stage; fb., followed by. Values are LS means. Within columns different letters indicate significant differences based on Tukey's Honest Significant Difference (α = 0.05).

[a]Kochia plant densities were evaluated before POST herbicide application and thus reflect the efficacy of fall-applied or PP herbicides only.

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pressure for photosystem II inhibitor-resistant kochia in western Canada.

While well-designed chemical programs remain effective for herbicide-resistant kochia management in western Canada, the herbicide options available for these programs are dwindling as a result of rapid evolution and spread of herbicide resistance in this species (Beckie et al. 2019; Geddes et al. 2021*a*, 2021*b*). Farmers are therefore urged to adopt other non-chemical tools to decrease herbicide selection pressure in these systems. Strategic design of crop rotations to include crops targeting the kochia critical period for weed seed control (Geddes and Davis 2021), while improving the competitiveness of less-competitive crops like field pea through the use of leafy pea cultivars, higher seeding rates, and spring-applied fertilizer (Harker et al. 2008; Blackshaw et al. 2005), could go a long way to reducing kochia seed production and return to the soil seedbank. The short seedbank persistence of kochia (Beckie et al. 2018; Geddes 2021) suggests that consistent mitigation of kochia seed return for a few years consecutively could cause rapid population decline, thereby reducing the rate at which the evolution of herbicide resistance takes place.

Competing interests

The authors declare there are no competing interests.

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Contributor statements

ATT: investigation, writing – original draft; REB: conceptualization, methodology, funding acquisition, supervision, validation; RNB and BH: investigation; CMG: supervision; formal analyses; visualization; writing – reviewing and editing.

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