Scientific Research Publishing

American Journal of Plant Sciences, 2020, 11, 1467-1477
https://www.scirp.org/journal/ajps
ISSN Online: 2158-2750
ISSN Print: 2158-2742

Weed Management in Azuki Bean with Postemergence Herbicides

Nader Soltani*, Lynette Brown, Peter H. Sikkema

University of Guelph Ridgetown Campus, Ridgetown, Ontario, Canada
Email: *soltanin@uoguelph.ca

How to cite this paper: Soltani, N., Brown, L. and Sikkema, P.H. (2020) Weed Management in Azuki Bean with Postemergence Herbicides. *American Journal of Plant Sciences*, **11**, 1467-1477.
https://doi.org/10.4236/ajps.2020.119106

Received: August 7, 2020
Accepted: September 25, 2020
Published: September 28, 2020

Abstract

A limited number of postemergence (POST) herbicides are available for weed management in azuki bean production in Ontario. A total of three field trials were conducted during 2017 to 2019 at the Huron Research Station, University of Guelph, Exeter, Ontario, Canada to evaluate the efficacy of various postemergence (POST) herbicides for weed control in azuki bean. Fomesafen, acifluorfen and acifluorfen + Assist® caused up to 6% crop injury and weed interference reduced azuki bean yield up to 42%. Bentazon, bentazon Forte, bentazon/acifluorfen, bentazon + fomesafen + Assist®, bentazon + fomesafen + Turbocharge® and bentazon Forte + fomesafen caused up to 16% injury and weed interference reduced azuki bean yield up to 53%. Fomesafen, acifluorfen, acifluorfen + Assist®, bentazon, bentazon Forte, bentazon/acifluorfen, bentazon + fomesafen + Assist®, bentazon + fomesafen + Turbocharge® and bentazon Forte + fomesafen provided 36% to 88% control of redroot pigweed (*Amaranthus retroflexus* L.), common ragweed (*Ambrosia artemesiifolia* L.), and common lambsquarters (*Chenopodium album* L.). Fomesafen, acifluorfen + Assist® and acifluorfen provided 59% to 83% control of flower-of-an-hour (*Hibiscus trionum* L.), but bentazon, bentazon Forte, bentazon/acifluorfen, bentazon + fomesafen + Assist®, bentazon + fomesafen + Turbocharge® and bentazon Forte + fomesafen provided 78% to 99% control of *H. trionum*. All POST herbicides evaluated provide 99% to 100% control of wild mustard (*Sinapis arvensis* L.) in azuki bean. Based on these results, none of the POST herbicide evaluated that included bentazon can be used safely for the control of annual broadleaved weeds in azuki bean under Ontario environmental conditions.

Keywords

Annual Weeds, Density, Dry Weight, Maturity, Seed Yield,

Phaseolus vulgaris, *Vigna angularis*

1. Introduction

Dry bean production is important to the economy and agriculture in Canada. Dry bean growers in Canada produced 249,000, 322,000, 341,000 and 317,000 tonnes of dry bean in 2016, 2017, 2018 and 2019, respectively [1]. Ontario farmers produce most of the dry beans grown in Canada. In 2019, dry bean growers in Ontario planted 53,000 hectares of dry bean including white, black, cranberry, kidney, azuki and other market classes with a total farm gate value of approximately $100,000,000 [2]. Azuki bean [*Vigna angularis* (Willd.) Ohwi & Ohashi] is a specialty market class of dry bean grown mostly for the export market to Asia where it is used in confectionery products [3]. Azuki bean thrives well under Ontario environmental conditions and has become popular among dry bean growers in Ontario. There was an increase of 46% in azuki production in 2019 compared to 2018 [2]. One of the largest production obstacles in azuki bean production is yield loss from weed interference [4]. The Weed Science Society of America (WSSA) reported that dry bean yield was reduced 71% compared to 50% in corn and 52% in soybean due to weed competition [5] [6] [7]. Azuki bean growers need new herbicide options to control problematic weeds in their production.

Fomesafen is a diphenyl ether herbicide that causes cell membrane destruction in susceptible plants [8]. Fomesafen can control/suppress problematic broadleaved weeds in Ontario including redroot pigweed (*Amaranthus retroflexus* L.), common ragweed (*Ambrosia artemesiifolia* L.), wild mustard (*Sinapis arvensis* L.), ladysthumb (*Polygonum persicaria* L.), and eastern black nightshade (*Solanum ptycanthum* Dun. *ex* DC. pp.) [9]. Fomesfen is primarily applied postemergence (POST) although it has some short residual activity against some broadleaved weeds [8].

Acifluorfen is another diphenyl ether POST herbicide that controls broadleaved weeds such as jimsonweed (*Datura stramonium* L.), *P. persicaria*, *S. arvensis*, *A. retroflexus*, *A. artemesiifolia* and *S. ptycanthum* [9]. Unlike fomesafen, acifluorfen has minimal to no residual activity against weeds [8].

Bentazon is a benzothiadiazole POST herbicide that inhibits photosynthesis at the photosystem II (PS II) in susceptible plants [9]. Bentazon can control key broadleaved weeds including common lambsquarters (*Chenopodium album* L.), *P. persicaria*, *S. arvensis*, *A. theophrasti*, *X. strumarium*, jimsonweed (*Datura stramonium* L.), purslane (*Portulaca oleracea* L.), wild radish (*Raphanus raphanistrum* L.), flower-of-an-hour (*Hibiscus trionum* L.), stinkweed (*Thlaspi arvense* L.), shepherdspurse (*Capsella bursa-pastoris* (L.) Medic) and common chickweed (*Stellaria media* (L.) Vill.) including group 2 and 5 resistant biotypes [8] [9]. Similar to acifluorfen, bentazon is applied POST and is absorbed by foliage (not translocated). It has no residual activity against weeds, therefore weeds

emerged after application will not be controlled [9].

Fomesafen, acifluorfen and bentazon are often used in combination with an adjuvant to improve weed control efficacy and provide a greater degree of weed control consistency under varying environments [8]. Assist® is a mineral oil/surfactant adjuvant that consists of 83% paraffin base mineral oil plus 17% surfactant blend that is often added to fomesafen or acifluorfen [8]. Turbocharge® is a surfactant/solvent adjuvant that consists of a 39.5% surfactant blend plus 50% solvent (mineral oil) and is often added to fomesafen [8]. Bentazon Forte does not require additional adjuvants [8].

Currently, fomesafen is the only POST herbicide registered for the control of broadleaved weeds in azuki bean production in Ontario [8]. Fomesafen does not adequately control common weeds in Ontario such as *C. album*, giant ragweed (*Ambrosia trifida* L.), *P. persicaria* and *A. theophrasti* [8]. The co-application of fomesafen with bentazon and bentazon with acifluorfen using different adjuvants available can be new herbicide options for weed management in azuki bean production.

There is little knowledge on the crop safety and effectiveness of fomesafen, acifluorfen and bentazon (with or without adjuvants), applied POST alone and in combination for weed control in azuki bean under Ontario environmental conditions. The co-application of these herbicides has the potential to produce efficacious full-season control of troublesome weeds in azuki bean in Ontario.

The purpose of this study was to determine the crop safety and effectiveness of fomesafen, acifluorfen, acifluorfen + Assist®, bentazon, bentazon Forte, bentazon/acifluorfen, bentazon + fomesafen + Assist®, bentazon + fomesafen + Turbocharge® and bentazon Forte + fomesafen to control common weeds in azuki bean production.

2. Materials and Methods

2.1. Experimental Methods

Field experiments were established in late May to early June of 2017, 2018 and 2019 at the Huron Research Station, University of Guelph, Exeter, Ontario, Canada with a five-crop rotation of winter wheat-corn-soybean-oats-azuki bean.

Each experiment was arranged in a randomized complete block design with 4 replicates. Treatments evaluated are listed in **Table 1**. The experimental plots were 3.0 m wide and 10.0 m long. Azuki bean "Erimo" was seeded 4 cm deep at the rate of approximately 200,000 seeds ha^{-1} in rows that were 75 cm apart in late May to early June.

Herbicide treatments were applied postemergence 3 - 4 weeks after seeding when azuki beans were at the 1 - 2 trifoliate leaf stage. Herbicides were applied with a CO_2-pressurized backpack sprayer calibrated to deliver 200 $L{\cdot}ha^{-1}$ at 240 kPa. The spray boom was 1.5 m long equipped with 4 ultra-low drift (ULD 120-02, Pentair-Hypro, New Brighton, Minnesota) nozzles spaced 0.5 m apart, producing a spray width of 2.0 m.

Table 1. Visible injury 2 and 4 WAT, percent moisture at maturity and yield of adzuki bean after various herbicides were applied POST at Exeter, ON, Canada (2017-2019). Means followed by a different letter within a column are significantly different according to a Tukey-Kramer multiple range test at $P < 0.05$.[a]

Treatment	Rate	Injury (%)		Moisture	Yield
	(g ai ha^{-1})	2 WAT	4 WAT	(%)	($t \cdot ha^{-1}$)
Weed-free control		0.0	0.0	14.5 a	1.9 a
Weedy control		0.0 a	0.0 a	15.7 c	0.5 d
Fomesafen[b]	240	4.4 b	0.7 ab	15.0 ab	1.1 bc
Acifluorfen[c]	300	6.1 b	2.3 abc	15.0 ab	1.2 b
Acifluorfen	600	6.3 b	2.6 abc	14.9 ab	1.1 bc
Bentazon[c]	1080	16.4 c	6.3 c	15.7 c	0.9 c
Bentazon Forte	1080	13.4 c	5.8 c	15.8 c	1.0 bc
Bentazon/acifluorfen[d]	840	14.1 c	5.3 c	15.3 bc	1.0 bc
Bentazon + fomesafen[e]	840 + 140	15.8 c	5.3 c	15.6 bc	1.1 bc
Bentazon + fomesafen[f]	840 + 140	14.8 c	4.9 bc	15.5 bc	1.2 b
Bentazon Forte + fomesafen	1080 + 140	15.9 c	5.1 c	15.7 c	1.1 bc

[a]Abbreviations: POST, postemergence; WAT, weeks after herbicide treatment; [b]Includes Turbocharge at 0.5% v/v; [c]Includes Assist at 0.5% v/v; [d]Includes Assist at 1.5 $l \cdot ha^{-1}$; [e]Includes Assist at 2.0 $l \cdot ha^{-1}$; [f]Includes Turbocharge at 0.5 $l \cdot ha^{-1}$.

Azuki bean visible injury was evaluated 2 and 4 weeks after herbicide application (WAT) and weed control were assessed 4 and 8 WAT on a scale of 0 (no injury/control) to 100% (total plant necrosis/weed control). Weed density and aboveground dry weight (biomass) were measured 8 WAT from two 0.25 m^2 quadrats placed between the centre two rows from each plot. Azuki bean seed yield (adjusted to 13% moisture) was determined by harvesting the middle two rows of each plot at maturity.

2.2. Statistical Analyses

The experimental design was a randomized complete block with 4 replications. Data were analyzed using the GLIMMIX procedure in SAS [10]. The fixed effect was herbicide treatment and random effects were year-location combinations (environment), replicate within environment and the environment by treatment interaction. The Shapiro-Wilk statistic, fit statistics, residual plots and the potential distributions were used to identify the best distribution and associated link function for each parameter. Least square means (LSMEANS) were calculated on the data scale by using the inverse link function, and pairwise comparisons were subjected to Tukey's adjustment before determining treatment differences at $P < 0.05$. The normal distribution and identity link were used for adzuki bean injury 4 WAT, percent visible weed control at 4 and 8 WAT for redroot pigweed, ragweed and common lambsquarters and percent adzuki bean moisture and yield at harvest. The arcsine square root distribution and identity link were used for

percent visible adzuki bean injury 2 WAT as well as percent visible weed control at 4 and 8 WAT for flower-of-an-hour and wild mustard. Weed density and dry biomass were analyzed using the lognormal distribution and identity link. The weedy control was assigned a value of 0 for injury and weed control, and the weed-free control was assigned a value of 0 for injury, weed density and biomass, or 100 for weed control and was excluded from the analysis due to zero variance. Comparisons were still possible between the other treatments and the value zero using the LSMEANS output and differences were identified. Arcsine square root and lognormal distributions were back-transformed for the presentation of results.

3. Results and Discussion

3.1. Crop Injury

At 2 and 4 WAE, fomesafen, acifluorfen (with Assist®), acifluorfen, bentazon, bentazon Forte, bentazon/acifluorfen, bentazon + fomesafen (with Assist®), bentazon + fomesafen (with Turbocharge®) and bentazon Forte + fomesafen caused as much as 4%, 6%, 6%, 16%, 13%, 14%, 16%, 15% and 16% injury in azuki bean, respectively (Table 1). Azuki bean seed moisture content was 1.2% higher in the weedy control indicating delayed maturity if weeds are not controlled. Fomesafen and acifluorfen (with/without Assist®) did not affect maturity but bentazon, bentazon Forte, bentazon/acifluorfen, bentazon + fomesafen (with Assist®), bentazon + fomesafen (with Turbocharge®) and bentazon Forte + fomesafen delayed maturity of azuki bean (Table 1). Weed interference reduced azuki bean yield 74% compared to the weed-free control. Additionally, weed interference in plots treated with fomesafen, acifluorfen (with Assist®), acifluorfen, bentazon, bentazon Forte, bentazon/acifluorfen, bentazon + fomesafen (with Assist®), bentazon + fomesafen (with Turbocharge®) and bentazon Forte + fomesafen reduced azuki bean yield 42%, 37%, 42%, 53%, 47%, 47%, 42%, 37% and 42%, respectively (Table 1). Results are similar to other studies in which fomesafen, acifluorfen and bentazon caused as much as 18%, 20% and 28% injury in azuki bean, respectively [11]. Another study found 5% to 20%, 4% to 18% and 19% to 28% injury in azuki bean with acifluorfen, fomesafen and bentazon applied POST in azuki bean, respectively [12]. Other studies have reported 14 to 28% injury with no effect on seed yield in azuki bean with fomesafen applied POST in azuki bean [13]. In contrast, other studies have shown less than 5% injury with bentazon (Forte) at 840 g ai ha^{-1}, fomesafen at 240 g ai ha^{-1} and bentazon Forte + fomesafen at 840 + 240 g ai ha^{-1} applied POST. in the *Phaseolus* market classes of dry beans [14].

3.2. Weed Control

Weeds selected for analysis needed to be present in at least 2 out of the 3 environments and included *A. retroflexus* (2/3), *A. artemesiifolia* (2/3), *C. album* (3/3), *H. trionum* (3/3) and *S. arvensis* (2/3).

3.2.1. Fomesafen

At 4 and 8 WAT, fomesafen applied POST at 240 g ai ha^{-1} controlled *A. retroflexus* 59% to 79%, *A. artemesiifolia* 74% to 83%, *C. album* 45% to 58%, *H. trionum* 63% to 77%, and *S. arvensis* 100% (Tables 2-6). Fomesafen applied POST at 240 g ai ha^{-1} did not reduce density or dry weight of weeds evaluated except for the dry weight of *A. artemesiifolia* which was reduced 92% and density and dry weight of *S. arvensis* which was reduced 100% compared to the weedy control (Tables 2-6). In other studies, Bailey *et al.* [15] reported 99% control of *A. artemesiifolia* and 90% control of *C. album* with fomesafen applied POST at 70 g ai ha^{-1}. Wilson [16] reported that fomesafen applied POST at 280 g ai ha^{-1} controlled *A. retroflexus* 94% and *C. album* 71%. In other studies, fomesafen applied POST at 240 g ai ha^{-1} controlled *A. retroflexus* 85% to 86%, *A. artemesiifolia* 90% to 93% and *C. album* 53% to 60% [14].

3.2.2. Acifluorfen

At 4 and 8 WAT, acifluorfen (300 g ai ha^{-1} applied with Assist®) or acifluorfen (600 g ai ha^{-1}) applied POST controlled *A. retroflexus* 77% to 88%, *A. artemesiifolia* 73% to 77%, *C. album* 38% to 57%, *H. trionum* 59% to 83%, and *S. arvensis* 99% to 100% (Tables 2-6). Acifluorfen (300 g ai ha^{-1} applied with Assist®) or acifluorfen (600 g ai ha^{-1}) did not reduce density or dry weight of *A. retroflexus*, *A. artemesiifolia*, *C. album* and *H. trionum*, but decreased density and biomass of *S. arvensis* 100% compared to the weedy control (Tables 2-6).

Table 2. Percent visible control 4 and 8 WAT, density and dry weight of redroot pigweed after various herbicides were applied POST at Exeter, ON, Canada (2017-2019). Means followed by a different letter within a column are significantly different according to a Tukey-Kramer multiple range test at $P < 0.05$.[a]

Treatment	Rate	Control (%)			
	(g ai ha^{-1})	4 WAT	8 WAT	Density (no. m^{-2})	Dry weight (g·m^{-2})
Weed-free control		100	100	0.0 a	0.0 a
Weedy control		0 d	0 d	13.1 c	46.0 c
Fomesafen[b]	240	79 ab	59 abc	7.1 bc	7.7 bc
Acifluorfen[c]	300	88 a	77 ab	4.9 b	0.9 ab
Acifluorfen	600	88 a	79 a	4.9 b	3.4 bc
Bentazon[c]	1080	64 c	47 abc	6.2 b	34.0 bc
Bentazon Forte	1080	58 c	46 abc	7.7 bc	30.1 bc
Bentazon/acifluorfen[d]	840	67 bc	46 abc	6.7 bc	26.3 bc
Bentazon + fomesafen[e]	840 + 140	65 c	43 bc	7.4 bc	19.5 bc
Bentazon + fomesafen[f]	840 + 140	70 bc	46 abc	6.0 b	21.1 bc
Bentazon Forte + fomesafen	1080 + 140	68 bc	36 c	8.5 bc	28.0 bc

[a]Abbreviations: POST, postemergence; WAT, weeks after herbicide treatment; [b]Includes Turbocharge at 0.5% v/v; [c]Includes Assist at 0.5% v/v; [d]Includes Assist at 1.5 l·ha^{-1}; [e]Includes Assist at 2.0 l·ha^{-1}; [f]Includes Turbocharge at 0.5 l·ha^{-1}.

Table 3. Percent visible control 4 and 8 WAT, density and dry weight of common ragweed after various herbicides were applied POST at Exeter, ON, Canada (2017-2019). Means followed by a different letter within a column are significantly different according to a Tukey-Kramer multiple range test at $P < 0.05$.[a]

Treatment	Rate	Control (%)			
	(g ai ha^{-1})	4 WAT	8 WAT	Density (no. m^{-2})	Dry weight ($g \cdot m^{-2}$)
Weed-free control		100	100	0.0 a	0.0 a
Weedy control		0 d	0 c	10.7 b	53.9 c
Fomesafen[b]	240	83 a	74 ab	6.1 ab	4.4 ab
Acifluorfen[c]	300	77 ab	76 a	7.5 b	5.2 abc
Acifluorfen	600	76 ab	73 ab	8.8 b	8.9 abc
Bentazon[c]	1080	51 c	53 ab	10.1 b	30.3 bc
Bentazon Forte	1080	61 bc	51 b	9.3 b	46.6 bc
Bentazon/acifluorfen[d]	840	66 bc	59 ab	10.7 b	23.3 bc
Bentazon + fomesafen[e]	840 + 140	66 bc	63 ab	6.7 ab	16.9 abc
Bentazon + fomesafen[f]	840 + 140	68 ab	72ab	8.4 b	20.9 bc
Bentazon Forte + fomesafen	1080 + 140	70 ab	69 ab	7.9 b	24.9 bc

[a]Abbreviations: POST, postemergence; WAT, weeks after herbicide treatment; [b]Includes Turbocharge at 0.5% v/v; [c]Includes Assist at 0.5% v/v; [d]Includes Assist at 1.5 $l \cdot ha^{-1}$; [e]Includes Assist at 2.0 $l \cdot ha^{-1}$; [f]Includes Turbocharge at 0.5 $l \cdot ha^{-1}$.

Table 4. Percent visible control 4 and 8 WAT, density and dry weight of lambsquarters after various herbicides were applied POST at Exeter, ON, Canada (2017-2019). Means followed by a different letter within a column are significantly different according to a Tukey-Kramer multiple range test at $P < 0.05$.[a]

Treatment	Rate	Control (%)			
	(g ai ha^{-1})	4 WAT	8 WAT	Density (no. m^{-2})	Dry weight ($g \cdot m^{-2}$)
Weed-free control		100	100	0.0 a	0.0 a
Weedy control		0 e	0 g	25.3 d	24.0 de
Fomesafen[b]	240	58 cd	45 def	18.7 bcd	21.2 cde
Acifluorfen[c]	300	57 cd	38 f	22.1 cd	29.8 cde
Acifluorfen	600	53 d	41 ef	25.4 d	31.9 e
Bentazon[c]	1080	66 bcd	55 bcde	13.3 bcd	12.9 bcde
Bentazon Forte	1080	87 a	78 a	8.4 b	8.2 b
Bentazon/acifluorfen[d]	840	72 abc	59 bcd	13.9 bcd	15.5 bcde
Bentazon + fomesafen[e]	840 + 140	61 cd	52 cdef	14.2 bcd	20.0 cde
Bentazon + fomesafen[f]	840 + 140	83 a	72 ab	8.1 b	10.6 bcd
Bentazon Forte + fomesafen	1080 + 140	82 ab	65 abc	9.1 bc	8.9 bc

[a]Abbreviations: POST, postemergence; WAT, weeks after herbicide treatment; [b]Includes Turbocharge at 0.5% v/v; [c]Includes Assist at 0.5% v/v; [d]Includes Assist at 1.5 $l \cdot ha^{-1}$; [e]Includes Assist at 2.0 $l \cdot ha^{-1}$; [f]Includes Turbocharge at 0.5 $l \cdot ha^{-1}$.

Table 5. Percent visible control 4 and 8 WAT, density and dry weight of flower-of-an-hour after various herbicides were applied POST at Exeter, ON, Canada (2017-2019). Means followed by a different letter within a column are significantly different according to a Tukey-Kramer multiple range test at $P < 0.05$.[a]

Treatment	Rate	Control (%)			
	(g ai ha^{-1})	4 WAT	8 WAT	Density (no. m^{-2})	Dry weight ($g \cdot m^{-2}$)
Weed-free control		100	100	0.0 a	0.0 a
Weedy control		0 d	0 d	13.54 d	8.35 e
Fomesafen[b]	240	77 bc	63 bc	6.94 d	5.77 de
Acifluorfen[c]	300	70 c	67 bc	5.96 cd	3.99 cde
Acifluorfen	600	83 abc	59 c	6.03 cd	3.14 bcde
Bentazon[c]	1080	98 a	97 ab	0.45 ab	0.15 ab
Bentazon Forte	1080	98 a	97 ab	0.81 ab	0.21 abc
Bentazon/acifluorfen[d]	840	88 abc	78 abc	2.21 abc	1.84 abcde
Bentazon + fomesafen[e]	840 + 140	96 ab	91 abc	1.94 abc	0.94 abcd
Bentazon + fomesafen[f]	840 + 140	97 a	99 a	0.48 ab	0.19 ab
Bentazon Forte + fomesafen	1080 + 140	98 a	96 abc	0.76 ab	0.12 ab

[a]Abbreviations: POST, postemergence; WAT, weeks after herbicide treatment; [b]Includes Turbocharge at 0.5% v/v; [c]Includes Assist at 0.5% v/v; [d]Includes Assist at 1.5 $l \cdot ha^{-1}$; [e]Includes Assist at 2.0 $l \cdot ha^{-1}$; [f]Includes Turbocharge at 0.5 $l \cdot ha^{-1}$.

Table 6. Percent visible control 4 and 8 WAT, density and dry weight of wild mustard after various herbicides were applied POST at Exeter, ON, Canada (2017-2019). Means followed by a different letter within a column are significantly different according to a Tukey-Kramer multiple range test at $P < 0.05$.[a]

Treatment	Rate	Control (%)			
	(g ai ha^{-1})	4 WAT	8 WAT	Density (no. m^{-2})	Dry weight ($g \cdot m^{-2}$)
Weed-free control		100	100	0.0 a	0.0 a
Weedy control		0 b	0 b	138.8 b	186.2 b
Fomesafen[b]	240	100 a	100 a	0.0 a	0.0 a
Acifluorfen[c]	300	99 a	100 a	0.0 a	0.0 a
Acifluorfen	600	100 a	100 a	0.0 a	0.0 a
Bentazon[c]	1080	100 a	100 a	0.2 a	0.1 a
Bentazon Forte	1080	99 a	100 a	0.3 a	0.1 a
Bentazon/acifluorfen[d]	840	100 a	100 a	0.0 a	0.0 a
Bentazon + fomesafen[e]	840 + 140	100 a	100 a	0.1 a	0.0 a
Bentazon + fomesafen[f]	840 + 140	100 a	100 a	0.0 a	0.0 a
Bentazon Forte + fomesafen	1080 + 140	100 a	100 a	0.0 a	0.0 a

[a]Abbreviations: POST, postemergence; WAT, weeks after herbicide treatment; [b]Includes Turbocharge at 0.5% v/v; [c]Includes Assist at 0.5% v/v; [d]Includes Assist at 1.5 $l \cdot ha^{-1}$; [e]Includes Assist at 2.0 $l \cdot ha^{-1}$; [f]Includes Turbocharge at 0.5 $l \cdot ha^{-1}$.

3.2.3. Bentazon

At 4 and 8 WAT, bentazon or bentazon Forte applied POST at 1080 g ai ha^{-1} controlled *A. retroflexus* 46% to 64%, *A. artemesiifolia* 51% to 61%, *C. album* 55% to 87%, *H. trionum* 97% to 98%, and *S. arvensis* 99% to 100% (Tables 2-6). There was generally no difference between bentazon and bentazon Forte for the control of weeds evaluated except for *C. album* which was controlled more effectively with bentazon Forte (78% to 87%) compared to bentazon (55% to 66%). Bentazon or bentazon Forte applied POST at 1080 g ai ha^{-1} did not reduce density or dry weight of *A. retroflexus* and *A. artemesiifolia*, but decreased density and dry weight of *H. trionum* up to 98% and *S. arvensis* 100% (Tables 2-6). Bentazon did not reduce density and dry weight of *C. album*, but bentazon Forte decreased density and dry weight of *C. album* 67% and 66%, respectively. In other studies, bentazon Forte applied POST at 840 g ai ha^{-1} controlled *A. retroflexus* 85% to 86%, *A. artemesiifolia* 63% to 66%, *C. album* 88% to 91% and *S. arvensis* 96% to 97% [14].

3.2.4. Bentazon/Acifluorfen

At 4 and 8 WAT, bentazon/acifluorfen (with Assist®) applied POST at 840 g ai ha^{-1} controlled *A. retroflexus* 46% to 67%, *A. artemesiifolia* 59% to 66%, *C. album* 59% to 72%, *H. trionum* 78% to 88%, and *S. arvensis* 100% (Tables 2-6). Bentazon/acifluorfen (with Assist®) applied POST at 840 g ai ha^{-1} did not reduce density or dry weight of *A. retroflexus*, *A. artemesiifolia* and *C. album*, but decreased density and dry weight of *H. trionum* as much as 84% and *S. arvensis* 100% (Tables 2-6).

3.2.5. Bentazon + Fomesafen

Bentazon + fomesafen (with Assist®), bentazon + fomesafen (with Turbocharge®) applied POST at 840 + 140 g ai ha^{-1} controlled *A. retroflexus* 43% to 70%, *A. artemesiifolia* 63% to 72%, *C. album* 52% to 83%, *H. trionum* 91% to 99%, and *S. arvensis* 100% (Tables 2-6). There were generally no statistical differences between bentazon + fomesafen (with Assist®) and bentazon + fomesafen (with Turbocharge®) for the control of weeds evaluated. Bentazon + fomesafen (with Assist®) and bentazon + fomesafen (with Turbocharge®) applied POST at 840 + 140 g ai ha^{-1} did not reduce density or dry weight of *A. artemesiifolia*, but decreased density of *A. retroflexus* and *C. album* 54% and 68%, respectively. These herbicides also reduced *H. trionum* density 86% to 96% and dry weight 89% to 98%. The density and dry weight of *S. arvensis* was reduced by 100% compared to the weedy control (Tables 2-6). In other studies, bentazon + fomesafen applied POST provided 77% to 87% control of *C. album* in dry bean [16].

3.2.6. Bentazon Forte + Fomesafen

At 4 and 8 WAT, bentazon Forte + fomesafen applied POST at 1080 + 140 g ai ha^{-1} controlled *A. retroflexus* 36% to 68%, *A. artemesiifolia* 69% to 70%, *C. album* 65% to 82%, *H. trionum* 96 to 98%, and *S. arvensis* 100% (Tables 2-6). Bentazon Forte + fomesafen applied POST at 1080 + 140 g ai ha^{-1} did not reduce

density or dry weight of *A. retroflexus* and *A. artemesiifolia*, but reduced *C. album*, *H. trionum* and *S. arvensis* density 64%, 94% and 100% and dry weight 63%, 99% and 100%, respectively (Tables 2-6). In other studies, bentazon Forte + fomesafen applied POST at 840 + 140 g ai ha^{-1} controlled *A. retroflexus* 84% to 86%, *A. artemesiifolia* 91% to 93% and *C. album* 84% to 87% [14].

4. Conclusion

This study concludes that fomesafen, acifluorfen (with Assist®) and acifluorfen (without adjuvants) cause up to 6% crop injury and weed interference with these herbicides reduced azuki bean yield up to 42%. Additionally, bentazon, bentazon Forte, bentazon/acifluorfen, bentazon + fomesafen (with Assist®), bentazon + fomesafen (with Turbocharge®) and bentazon Forte + fomesafen can cause up to 16% crop injury and weed interference with these herbicides can reduce azuki bean yield up to 53%. Fomesafen and acifluorfen (with/without Assist®) did not affect maturity, but bentazon, bentazon Forte, bentazon/acifluorfen, bentazon + fomesafen (with Assist®), bentazon + fomesafen (with Turbocharge®) and bentazon Forte + fomesafen delayed maturity of azuki bean (Table 1). Weed interference reduced azuki bean yield 74% compared to the weed-free control. Fomesafen, acifluorfen (with Assist®), acifluorfen, bentazon, bentazon Forte, bentazon/acifluorfen, bentazon + fomesafen (with Assist®), bentazon + fomesafen (with Turbocharge®) and bentazon Forte + fomesafen generally provided inadequate control of *A. retroflexus*, *A. artemesiifolia* and *C. album*. Fomesafen, acifluorfen (with Assist®) and acifluorfen (without adjuvants) did not adequately control of *H. trionum*, but bentazon, bentazon Forte, bentazon/acifluorfen, bentazon + fomesafen (with Assist®), bentazon + fomesafen (with Turbocharge®) and bentazon Forte + fomesafen provided good to excellent control of *H. trionum*. All herbicides evaluated provide excellent control of *S. arvensis* in azuki bean. Results indicate that all herbicide programs that include bentazon do not have an adequate margin of crop safety for weed management in azuki bean in Ontario.

Acknowledgements

Funding for this project was provided in part by the Ontario Bean Growers (OBG).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Statista (2020) Production Volume of Dry Beans in Canada from 2016/17 to 2019/20. https://www.statista.com/statistics/819203/production-volume-of-dry-beans-canada

[2] OMAFRA (2020) 2019 Dry Edible Bean Summary.

http://www.omafra.gov.on.ca/english/crops/field/reports/2019summary-ediblebean.htm

[3] Lumpkin, T.A. and McClary, D.C. (1994) Azuki Bean: Botany, Production and Uses. CAB International, Wallingford.

[4] McClary, D.C., Hang, A.N., Gilliland, G.C., Babcock, J.M., Lumpkin, T.A., Ogg, A.G. and Tanigoshi, L.K. (1993) Herbicides for Azuki Production. In: Janick, J. and Simon, J.E., Eds., *New Crops*, Wiley, New York, 590-594.

[5] Soltani, N., Dille, J.A., Burke, I.C., Everman, W.J., VanGessel, M.J., Davis, V.M. and Sikkema, P.H. (2016) Potential Corn Yield Losses from Weeds in North America. *Weed Technology*, **30**, 979-984. https://doi.org/10.1614/WT-D-16-00046.1

[6] Soltani, N., Dille, J.A., Burke, I.C., Everman, W.J., VanGessel, M.J., Davis, V.M. and Sikkema, P.H. (2017) Perspectives on Potential Soybean Yield Losses from Weeds in North America. *Weed Technology*, **31**, 148-154. https://doi.org/10.1017/wet.2016.2

[7] Soltani, N., Dille, J.A., Burke, I.C., Everman, W.J., VanGessel, M.J., Davis, V.M. and Sikkema, P.H. (2018) Potential Yield Loss in Dry Bean Crops Due to Weeds in the United States and Canada. *Weed Technology*, **32**, 342-346. https://doi.org/10.1017/wet.2017.116

[8] Ontario Ministry of Agriculture and Food and Rural Affairs (OMAFRA) (2019) Guide to Weed Control, Publication 75. Toronto, 1-396.

[9] Shaner, D. (2014) Herbicide Handbook. Tenth Edition, Weed Sci. Soc. Am., Champaign, 458 p.

[10] SAS Institute Inc. (2016) Base SAS® 9.4 Procedures Guide: Statistical Procedures. Fifth Edition, SAS Institute Inc., Cary.

[11] Stewart, C.L., Nurse, R.E., Gillard, C.L. and Sikkema, P.H. (2010) Tolerance of Adzuki Bean (*Vigna angularis*) to Preplant-Incorporated, Pre-Emergence and Post-Emergence Herbicides in Ontario, Canada. *Weed Biology and Management*, **10**, 40-47. https://doi.org/10.1111/j.1445-6664.2010.00365.x

[12] Soltani, N., Shropshire, C. and Sikkema, P.H. (2017) Sensitivity of Adzuki Bean (*Vigna angularis*) to Acifluorfen, Fomesafen, Bentazon, Imazethapyr and Halosulfuron-Methyl Applied Postemergence. *American Journal of Plant Sciences*, **8**, 1092-1099. https://doi.org/10.4236/ajps.2017.85072

[13] Powell, G., Sprague, C. and Renner, K.A. (2004) Adzuki Bean: Weed Control and Production Issues. *North Central Weed Science Proceedings*, Vol. 59, 32.

[14] Soltani, N., Nurse, R.E. and Sikkema, P.H. (2013) Weed Management in White Beans with Postemergence Herbicide Tankmixes. *Canadian Journal of Plant Science*, **93**, 669-674. https://doi.org/10.4141/cjps2012-273

[15] Bailey, W.A., Wilson, H.P. and Hines, T.E. (2003) Weed Control and Snap Bean (*Phaseolus vulgaris*) Response to Reduced Rates of Fomesafen. *Weed Technology*, **17**, 269-275. https://doi.org/10.1614/0890-037X(2003)017[0269:WCASBP]2.0.CO;2

[16] Wilson, R.G. (2005) Response of Dry Bean and Weeds to Fomesafen and Fomesafen Tank Mixtures. *Weed Technology*, **19**, 201-206. https://doi.org/10.1614/WT-04-166R