Response of four market classes of dry bean to acifluorfen, bentazon, and bentazon/acifluorfen applied postemergence

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Abstract
Three distinct studies consisting of a total of 11 field trials were carried out from 2016 to 2019 in Ontario to assess the tolerance of four market classes of dry bean to acifluorfen, bentazon, and bentazon/acifluorfen applied postemergence (POST) at various rates. In Study 1, acifluorfen (265 and 530 g ai ha\(^{-1}\)) and bentazon (577 and 1144 g ai ha\(^{-1}\)) caused up to 13% and 8% visible injury, respectively, but did not affect the relative stand, height, seed moisture, or yield of dry bean. Bentazon/acifluorfen (842 and 1684 g ai ha\(^{-1}\)) caused up to 32% visible injury in dry bean but did not affect the relative stand, height, moisture, or seed yield except at the 2× rate which reduced dry bean biomass, height, and yield 43%, 11%, and 11%, respectively. The preformulated mixture of bentazon/acifluorfen caused a synergistic increase in dry bean injury. In Study 2, acifluorfen (600 and 1200 g ai ha\(^{-1}\)) and bentazon (1080 and 2160 g ai ha\(^{-1}\)) injured dry bean up to 12% and to 9%, respectively, but did not affect the relative stand, height, moisture, or yield. Bentazon/acifluorfen (840 and 1680 g ai ha\(^{-1}\)) injured dry bean up to 16% but did not affect the relative stand, height, moisture, or yield of dry bean except at the high rate which reduced biomass, height, and yield 17%, 9%, and 5%, respectively. In Study 3, acifluorfen (420 and 480 g ai ha\(^{-1}\)) and bentazon (1080 and 2160 g ai ha\(^{-1}\)) injured dry bean up to 24 and 16%, respectively, but did not affect the relative stand, height, seed moisture content, or yield except for the relative biomass which was reduced up to 17%. Bentazon/acifluorfen (840 and 1680 g ai ha\(^{-1}\)) injured dry bean up to 45% but did not affect the relative stand, height, seed moisture, or yield except for biomass, height, and seed yield which were decreased 44%, 11%, and 12% at the high rate. This study concludes that acifluorfen alone or preformulated with bentazon applied POST at rates assessed cannot be safely used dry bean.

KEYWORDS
acifluorfen, bentazon, biomass, height, Phaseolus vulgaris, sensitivity, stand, Vigna angularis, visible injury
1 | INTRODUCTION

Dry bean (Phaseolus vulgaris L.) is a major legume crop produced in Canada, mostly for exportation to the United States, Europe, and Asia (Hensall District Co-operative, 2020). Growers in Canada produced approximately 341,000 metric tons of dry bean in 2018/2019 crop years (Statista, 2020). Approximately one third of the dry bean grown in Canada is produced in Ontario. In 2017, growers in Ontario produced approximately 121,000 tons of dry bean on 55,000 ha with a value of nearly Can$93,000,000 (Ontario Ministry of Agriculture and Food and Rural Affairs [OMAFRA], 2017). The common cultivated dry bean is botanically classified as P. vulgaris; however, there are many other species of dry bean including azuki bean (Vigna angularis) and runner bean (Phaseolus coccineus L.) produced in Canada (Alberta Pulse Growers, 2020). The most common market classes of dry bean grown in Ontario in 2019 in descending order are white (navy) (25,074 ha, 47%), azuki (8085 ha, 15%), kidney (6713 ha, 13%), cranberry (5140 ha, 10%), black (4285 ha, 8%), and other market classes (3604 ha, 7%). Dry bean yield can be decreased if weeds are not adequately controlled. A study by the Weed Science Society of America, looking at 10 years of data from various bean growing regions of North America, estimated an average of 74% loss in seed yield of dry bean if weeds were not controlled (Soltani et al., 2018). Despite such great losses, there are currently few herbicides registered for weed control in dry bean. Dry bean is not a large market in terms of hecatrage in North America compared with other field crops, and agro-chemical companies have not invested a lot of resources to develop new herbicides for this niche market crop. New research is needed to determine the tolerance of dry bean to herbicides registered for the control of weeds in other crops such as soybean.

Acifluorfen is a Group 14 diphenyl ether contact herbicide that is currently registered for use in soybean production in Ontario (OMAFRA, 2020). It is taken up through foliage and inhibits the enzyme protoporphyrinogen oxidase (PPO or Protox) that is needed for the synthesis of chlorophyll and heme (involved in the maintenance of redox balance and the energy state in cells). Acifluorfen controls key annual broadleaved weeds in Ontario (OMAFRA, 2020).

Bentazon is a Group 6 benzothiadiazole, contact herbicide that in susceptible plants displaces plastoquinone in photosystem II resulting in an increase in reactive oxygen species, cell membrane destruction, and plant death (OMAFRA, 2020; Shaner, 2014). Bentazon controls annual broadleaved weeds including wild mustard, cocklebur, and common lambsquarters, including Group 2 and 5 resistant biotypes (OMAFRA, 2020; Shaner, 2014).

Currently, only three postemergence herbicides are available for broadleaved weed control in dry bean, bentazon, fomesafen, and halosulfuron. Bentazon does not provide adequate control of red-root pigweed, waterhemp, common ragweed, giant ragweed, and Canada fleabane (OMAFRA, 2020). Additionally, fomesafen provides weak/inadequate control of Canada fleabane, cocklebur, common lambsquarters, and velvetleaf. Halosulfuron, applied POST, is weak on annual nightshades and common lambsquarters in dry bean production.

Acifluorfen and bentazon/acifluorfen premixed are not registered to be used in dry edible beans in Ontario. Bentazon/acifluorfen premixed can control common annual broadleaved weeds in dry bean. Tolerance of dry bean to POST application of acifluorfen and acifluorfen/bentazon premixed needs to be determined under Ontario environmental conditions. This manuscript summarizes the results of three studies on the tolerance of dry edible beans to acifluorfen, bentazon and bentazon/acifluorfen applied POST. The purpose of this research was to ascertain the tolerance of azuki, kidney, small red, and white beans to acifluorfen, bentazon, and bentazon/acifluorfen applied POST at various rates.

2 | MATERIALS AND METHODS

Three distinct studies were established from 2016 to 2019 in southwestern Ontario. Study 1 included a total of four field trials carried out carried out at Exeter, ON (2016, 2017, and 2018) and Ridgetown, ON (2018). Study 2 included a total of three field trials carried out in 2016, 2017, and 2019 at Exeter, ON. Study 3 included a total of four field trials carried out at Exeter, ON (2018 and 2019) and Ridgetown, ON (2018 and 2019).

Experiments in each study were designed as a split-block, with treatment (TRT) assigned as the whole plot factor and dry bean type (DB) as subplots. Treatments for Studies 1–3 are shown in Tables 1–4, 5 and 6, and 7–9, respectively. The ratio of acifluorfen to bentazon in the formulation mixture evaluated was 1:2.18 which included 265 g ai ha⁻¹ of acifluorfen + 577 g ai ha⁻¹ of bentazon = 842 g ai ha⁻¹ of acifluorfen/bentazon (representing the 1× rate) and 530 g ai ha⁻¹ of acifluorfen + 1154 g ai ha⁻¹ of bentazon = 1684 g ai ha⁻¹ of acifluorfen/bentazon (representing the 2× rate). Therefore, the rates of bentazon and acifluorfen in the premix are the same rate used in the stand-alone products. The current commercial formulations of acifluorfen and bentazon (as used in this study) do not require the addition of an adjuvant (the adjuvant is already included in the commercial formulation). In contrast, an adjuvant must be added to the commercial formulation of acifluorfen/bentazon as recommended on the product label. The adjuvant used and rate applied was recommended by the manufacturer at the time the study was initiated.

The experimental plots were 6.0 m wide (eight rows spaced 0.75 m apart) and 10.0 m long at Exeter and 8.0 m long at Ridgetown. Each plot consisted of two rows of azuki ("Erimo"), kidney ("Red Hawk"), small red ("Merlot"), and white ("T9905") beans. Azuki, kidney, small red, and white beans were seeded 3–4 cm deep in late May to early June at the rate of approximately 280,000, 190,000, 210,000, and 250,000 seed ha⁻¹, respectively. Herbicides were sprayed POST at the 1–2 trifoliate stage (3–4 weeks after seeding) with a CO₂ pressurized backpack sprayer (calibrated to deliver 200 L ha⁻¹ at 240 kPa). The spray boom was 2.5 m long equipped with six ultralow drift nozzles spaced 0.5 m apart producing a spray width of 3.0 m. All plots were maintained free of weeds during the entire season.
Dry bean injury was determined at 1, 2, 4, and 8 weeks after herbicide treatment (WAT) on a scale of 0% (no visible injury) to 100% (plant death). The relative plant stand (percent of the control) and dry weight (biomass) were assessed 2 WAT by determining the number of plants in 1 m row within each subplot, harvesting the aboveground portion and drying at 60°C (48 h). Average plant height was determined at 5 WAT (10 randomly selected plants per subplot). A small-plot combine was used to harvest dry bean at maturity.

For all studies, the GLIMMIX procedure in Statistical Analysis Systems (SAS, 2013) was used to carry out a mixed model analysis of variance for each response variable. Fixed effects consisted of TRT, DB, and their interaction. Random effects consisted of environment (year–location combinations), TRT by DB by environment interaction, replicate nested within environment, and its interaction with TRT. The significance of fixed and random effects was ascertained with an F test and likelihood ratio test, respectively. A significance level of alpha = 0.05 was chosen for all statistical analyses. Different distributions for each response variable were assessed using studentized residual plots and the Shapiro–Wilk statistic; in each case, the distribution that best met the variance analysis assumptions (normally distributed, homogeneous residuals with a mean of zero) was selected. All response variables except dry bean visible injury were converted to a percent of the untreated control within each replicate in order to minimize year-to-year variation in absolute measurements. For analysis of percent injury at 1, 2, 4, and 8 WAT, untreated control was excluded due to zero variance.

For Study 1, the relative dry bean stand, biomass, height, and yield followed a Gaussian distribution. An arcsine square root transformation and Gaussian distribution was used to analyze estimates of percent visible dry bean injury 1, 2, 4, and 8 WAT. For each variable, dry bean responses to the two combined bentazon/acifluorfen treatments were tested for additivity, synergism, or antagonism. Expected values for percent dry bean visible injury were calculated for each rate of the herbicide combination by replicate using Colby’s equation (Colby, 1967):

\[ E = \frac{(G + H) - GH}{100}. \]  

In this equation, E is assumed to be the expected dry bean visible injury for the herbicide combination and G and H are the dry bean

### TABLE 1  Least square means and significance of main effects and interaction for percent injury of four dry bean market classes treated with bentazon, acifluorfen, and bentazon/acifluorfen in trials conducted near Exeter, ON (2016–2018) and Ridgetown, ON (2018)

| Main effects | Visible injury* (%) |
|--------------|---------------------|
|              | 1 WAT | 2 WAT | 4 WAT | 8 WAT |
| Dry bean market class |       |       |       |       |
| Azuki        | 16 b  | 12 b  | 8     | 3 b   |
| Kidney       | 12 a  | 7 a   | 4     | 1 a   |
| Small red    | 11 a  | 7 a   | 3     | 1 a   |
| White        | 12 a  | 7 a   | 3     | 1 a   |
| DB P value   | 0.0054| 0.0014| <0.0001| <0.0001 |
| Herbicide treatment | Rate (g ai ha⁻¹) |       |       |       |
| Untreated control | 0 a  | 0 a   | 0     | 0 a   |
| Acifluorfen  | 265   | 7 b   | 4 b   | 2     | 0.2 ab |
| Acifluorfen  | 530   | 13 cd | 9 cd  | 4     | 0.6 bc |
| Bentazon     | 577   | 5 b   | 3 b   | 2     | 0.4 bc |
| Bentazon     | 1154  | 8 bc  | 5 bc  | 3     | 0.8 bc |
| Bentazon/acifluorfen | 842 | 17 d (12) | 11 d (8) | 6 | 1.7 c (0.7) |
| Bentazon/acifluorfen | 1684 | 32 e (20) | 24 e (14) | 15 | 4.5 d (1.6) |
| TRT P value  | <0.0001 | <0.0001 | <0.0001 | <0.0001 |

Interaction | DB x TRT P value | 0.7004 | 0.2415 | 0.0162 | 0.3569 |

Note: Means for a main effect were separated only if the interaction involving the main effect was negligible. Means followed by a different letter within a column differ significantly according to a Tukey–Kramer multiple range test at P < 0.05.

Abbreviations: DB, dry bean market class; TRT, herbicide treatment; WAT, weeks after herbicide application.

*Expected values for herbicide combinations based on Colby’s equation (Equation 1) are shown in parentheses following observed values.

**Significant difference of P < 0.05, between observed and expected values based on a two-sided t test.

***Significant difference of P < 0.01, respectively, between observed and expected values based on a two-sided t test.
visible injury with bentazon and acifluorfen, respectively, when applied individually. For the other parameters, expected values were determined with a modified form of Colby’s equation, expressing data as a percentage of the control:

\[ E_1 = \frac{G_1 H_1}{100}, \]  

(2)

where \( E_1 \) is the expected the relative dry bean stand, biomass, height, moisture, and yield with the herbicide combination and \( G_1 \) and \( H_1 \) are the measured parameter values with bentazon and acifluorfen, respectively, when applied individually.

All expected values were compared with the corresponding observed value using a two-sided \( t \) test at \( P < 0.05 \). The effect of the herbicide combination was considered to be additive if the \( t \) test was nonsignificant. If the observed percent visible injury or the relative moisture was higher than expected, or the relative stand, biomass, height, or yield was lower than expected, the effect of the herbicide combination was considered to be synergistic. If the converse was true, the effect of the herbicide combination was considered antagonistic.

For Study 2, the relative crop stand, biomass, height, and yield followed a Gaussian distribution. An arcsine square root transformation and Gaussian distribution was used to analyze estimates of percent visible dry bean visible injury 1, 4, and 8 WAT. The Poisson distribution was used to analyze estimates of percent visible dry bean visible injury 2 WAT. Recognizing that overdispersion is a concern with the Poisson distribution, the Pearson chi-square/df was confirmed to be less than 1 for all dry bean injury. The relative crop biomass and seed moisture content were analyzed using a lognormal distribution.

For Study 3, the relative dry bean stand, height, and followed a Gaussian distribution. The Poisson distribution was used to analyze estimates of percent visible dry bean visible injury 1, 2, 4, and 8 WAT. Recognizing that overdispersion is a concern with the Poisson distribution, all expected values were compared with the corresponding observed value using a two-sided \( t \) test at \( P < 0.05 \). The effect of the herbicide combination was considered to be additive if the \( t \) test was nonsignificant. If the observed percent visible injury or the relative moisture was higher than expected, or the relative stand, biomass, height, or yield was lower than expected, the effect of the herbicide combination was considered to be synergistic. If the converse was true, the effect of the herbicide combination was considered antagonistic.

### Table 2

| Main effects                  | Relative stand/m | Relative stand/plant | Relative height | Relative seed moisture | Relative yield |
|-------------------------------|------------------|----------------------|-----------------|------------------------|----------------|
| Dry bean market class         |                  |                      |                 |                        |                |
| Azuki                         | 99               | 71                   | 72              | 95 b                   | 102            | 93 b          |
| Kidney                        | 97               | 80                   | 85              | 99 a                   | 103            | 98 ab         |
| Small red                     | 95               | 82                   | 87              | 96 b                   | 102            | 101 a         |
| White                         | 96               | 80                   | 81              | 96 b                   | 104            | 101 a         |
| DB P value                    | 0.5206           | 0.0014               | <0.0001         | 0.0122                 | 0.5316         | 0.0003        |
| Herbicide treatment           | Rate (g ai ha\(^{-1}\)) |                   |                 |                        |                |
| Untreated control             |                  |                      |                 |                        |                |
| Acifluorfen                   | 265              | 98                   | 89              | 91                     | 100 a          | 98 a          |
| Acifluorfen                   | 530              | 96                   | 80              | 83                     | 98 ab          | 102 a         | 99 a          |
| Bentazon                      | 577              | 96                   | 84              | 89                     | 100 a          | 101 a         | 103 a         |
| Bentazon/acifluorfen\(^b\)   | 842              | 100 (96)             | 76              | 73                     | 95 b (98)\(^*\) | 102 a (105)   | 100 a (101)   |
| Bentazon/acifluorfen\(^c\)   | 1684             | 96 (90)              | 57              | 60                     | 89 c (97)\(^**\) | 112 b (106)\(^*\) | 89 b (100)\(^**\) |
| TRT P value                   | 0.8306           | <0.0001              | <0.0001         | <0.0001                | 0.0001         | 0.0003        |
| Interaction                   |                  |                      |                 |                        |                |
| DB \( \times \) TRT P value   | 0.7749           | 0.0324               | 0.0194          | 0.2997                 | 0.5206         | 0.7121        |

Note: Means for a main effect were separated only if the interaction involving the main effect was negligible. Means followed by a different letter within a column differ significantly according to a Tukey–Kramer multiple range test at \( P < 0.05 \).

Abbreviations: DB, dry bean market class; TRT, herbicide treatment; WAT, weeks after herbicide application.

\(^e\)Expected values for herbicide combinations based on Colby’s percent-of-control equation (Equation 2) are shown in parentheses following observed values for all relative parameters.

\(^b\)Included assist (1.5 L ha\(^{-1}\)).

\(^c\)Included assist (3.0 L ha\(^{-1}\)).

\(^*\)Significant difference of \( P < 0.05 \), between observed and expected values based on a two sided \( t \) test. \(^**\)Significant difference of \( P < 0.01 \), between observed and expected values based on a two-sided \( t \) test.
distribution in particular, the Pearson chi-square/df was confirmed to be less than 1 for all dry bean injury. A lognormal distribution was used for the analysis of relative biomass and seed moisture.

For Studies 1–3, pairwise comparisons of least square means were adjusted using the Tukey–Kramer method. If the TRT by DB interaction was nonnegligible, comparisons among simple effects were adjusted using the Tukey–Kramer method.

### TABLE 3
Least square means for percent injury 4 WAT of four dry bean market classes treated with bentazon, acifluorfen and bentazon/acifluorfen near Exeter, ON (2016–2018) and Ridgetown, ON (2018)

| Herbicide treatment          | Rate (g ai ha⁻¹) | Dry bean injury (%) |
|-----------------------------|------------------|--------------------|
|                             |                  | Azuki  | Kidney | SR    | White  |
| Untreated control           |                  | 0 d    | 0 c    | 0 c   | 0 c    |
| Acifluorfen                 | 265              | 2 c    | 1 bc   | 1 bc  | 2 b    |
| Acifluorfen                 | 530              | 4 bc   | 4 b    | 4 b   | 4 b    |
| Bentazon                    | 577              | 7 bc   | Z      | 1 bc  | Y      | 1 bc   |
| Bentazon                    | 1154             | 10 b   | Z      | 2 b   | Y      | 1 bc   |
| Bentazon/acifluorfen        | 842              | 10 b   | Z (10) | 5 b   | YZ (2) | 4 b    | Y (3)  |
| Bentazon/acifluorfen        | 1684             | 24 a   | Z (14)*| 15 a  | Y (7)* | 12 a   | Y (6)* |

Note: Means followed by the same letter within a column (a–c) or row (Y–Z) are not significantly different according to a Tukey–Kramer multiple range test at P < 0.05. Rows without an uppercase letter have no differences among market classes.

Abbreviations: SR, small red; WAT, weeks after herbicide application.

*Expected values for herbicide combinations based on Colby’s equation (Equation 1) are shown in parentheses following observed values.

bIncluded assist (1.5 L ha⁻¹).

cIncluded assist (3.0 L ha⁻¹).

*Significant difference of P < 0.05, between observed and expected values based on a two-sided t-test. **Significant difference of P < 0.01, between observed and expected values based on a two-sided t-test.

### TABLE 4
Least square means for above ground dry biomass per m of row and per plant, relative to the untreated control, of four dry bean market classes treated with bentazon, acifluorfen, and bentazon/acifluorfen near Exeter (2016–2018) and Ridgetown, ON (2018)

| Herbicide treatment          | Rate (g ai ha⁻¹) | Relative dry bean biomass (%) |
|-----------------------------|------------------|-------------------------------|
|                             |                  | Azuki  | Kidney | SR    | White  |
| Per m of row                |                  |       |       |       |        |
| Acifluorfen                 | 265              | 84 ab | 95 a   | 89 a  | 87 a   |
| Acifluorfen                 | 530              | 88 a  | 77 ab  | 77 b  | 78 ab  |
| Bentazon                    | 577              | 71 ab | Y     | 88 a  | YZ     | 90 a   | Z     |
| Bentazon                    | 1154             | 65 bc | Y     | 85 a  | Z      | 94 a   | Z     |
| Bentazon/acifluorfen        | 842              | 73 ab | (61)  | 81 a  | (85)   | 76 ab  | (75)  | 74 ab  | (72)  |
| Bentazon/acifluorfen        | 1684             | 45 c  | Y (57) | 55 b  | YZ (66) | 64 b  | Z (67) | 62 b  | YZ (73) |
| Per plant                   |                  |       |       |       |        |
| Acifluorfen                 | 265              | 88 a  | 99 a   | 93 a  | 87 ab  |
| Acifluorfen                 | 530              | 85 ab | 86 a   | 83 ab | 79 abc |
| Bentazon                    | 577              | 76 ab | Y     | 93 ab | Z      | 98 a   | Z     | 91 a   | YZ    |
| Bentazon                    | 1154             | 70 ab | Y     | 88 ab | Z      | 101 a  | Z     | 98 a   | Z     |
| Bentazon/acifluorfen        | 842              | 66 b  | (64)  | 78 bc | (91)   | 82 ab  | (94)* | 68 bc  | (78)  |
| Bentazon/acifluorfen        | 1684             | 44 c  | Y (59)*| 66 c  | Z (76) | 67 b  | Z (78)*| 62 c  | Z (78)*|

Note: Means followed by the same letter within a column (a–d) or row (Y–Z) are not significantly different according to a Tukey–Kramer multiple range test at P < 0.05. Rows without an uppercase letter have no differences among market classes.

Abbreviations: SR, small red; WAT, weeks after herbicide application.

*Expected values for herbicide combinations based on Colby’s percent-of-control equation (Equation 2) are shown in parentheses following observed values.

bIncluded assist (1.5 L ha⁻¹).

cIncluded assist (3.0 L ha⁻¹).

*Significant difference of P < 0.05, between observed and expected values based on a two-sided t-test. **Significant difference of P < 0.01, between observed and expected values based on a two-sided t-test.
TABLE 5  Least square means and significance of main effects and interaction for percent injury and for stand count, above ground dry biomass per m of row and per plant, height, seed moisture, and yield relative to the untreated control of four dry bean market classes treated with bentazon, acifluorfen, and bentazon/acifluorfen in trials conducted near Exeter, ON (2016–2017 and 2019)

| Main effects | Visible injury | Relative biomass | Interaction DB × TRT P value |
|--------------|----------------|------------------|----------------------------|
|              | 1 WAT | 2 WAT | 4 WAT | 8 WAT | Relative stand | Relative biomass | Relative moisture | Relative yield |<0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.3146 | 0.0136 | 0.0001 | 0.1612 | 0.0186 | <0.0001 |
| Dry bean market class |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |
| Azuki        | 12    | 10    | 5     | 3     | 97    | 83 b    | 83 c    | 94    | 103 ab | 94 c |
| Kidney       | 10    | 7     | 3     | 1 b   | 97    | 93 ab   | 92 ab   | 97    | 104 ab | 98 b |
| Small red    | 9     | 7     | 2     | 1 b   | 103   | 90 ab   | 89 bc   | 95    | 105 b  | 104 a |
| White        | 8     | 6     | 2     | 1 b   | 98    | 95 a    | 102 a   | 95    | 100 a  | 101 a |
| Herbicide treatment | Rate (g ai ha⁻¹) |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |
| Untreated control | 0      | 0     | 0     | 0     | 0 a    | 94 ab   | 97 a    | 97 a  | 101 a  | 102 a |
| Acifluorfen  | 600   | 7     | 6     | 1     | 0.2 ab | 100     | 94 ab   | 97 a  | 97 a  | 101 a |
| Acifluorfen  | 1200  | 12    | 9     | 4     | 2.0 cd | 100     | 96 a    | 96 a  | 95 ab | 104 ab |
| Bentazon     | 1080  | 6     | 5     | 2     | 0.6 bc | 101     | 90 ab   | 89 ab | 97 a  | 101 a |
| Bentazon     | 2160  | 9     | 7     | 3     | 2.1 cd | 96      | 83 b    | 90 ab | 95 ab | 104 ab |
| Bentazon/acifluorfenb | 840 | 10     | 7     | 3     | 1.4 bcd | 95      | 91 ab  | 96 a  | 95 ab | 102 ab |
| Bentazon/acifluorfenb | 1680 | 16    | 12    | 5     | 2.9 d  | 99      | 86 ab  | 83 b  | 91 b  | 109 b |
| TRT P value  | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.3146 | 0.0136 | 0.0001 | 0.1612 | 0.0186 | <0.0001 |

*Note: Means for a main effect were separated only if the interaction involving the main effect was negligible. Means followed by the same letter within a column are not significantly different according to a Tukey–Kramer multiple range test at P < 0.05.

Abbreviations: DB, dry bean market class; TRT, herbicide treatment; WAT, weeks after herbicide application.

*included assist (1.5 L ha⁻¹).

bIncluded assist (3.0 L ha⁻¹).
obtained using the SLICEDIFF command to ensure only comparisons of interest were calculated. Main effect differences for TRT and DB were measured only if their interaction was negligible. Comparisons of dry bean injury to zero were possible by using the \( P \) value included in LSMEANS output.

### RESULTS AND DISCUSSION

#### 3.1 Study 1

This study was carried out mainly to determine if there is a synergistic increase in injury of dry bean when bentazon is combined with acifluorfen.

#### 3.1.1 Main effects of herbicides

There was a significant impact of the herbicides on the visible injury, biomass, height, moisture, and yield (Tables 1 and 2). A synergistic increase in injury with the preformulated mixture for almost all the parameters in dry bean evaluated was observed (Tables 1–3).

Acifluorfen caused 7%, 4%, 2%, and 0% injury at 265 g ai ha\(^{-1}\) and 13%, 9%, 4%, and 1% injury at 530 g ai ha\(^{-1}\) assessed 1, 2, 4, and 8 WAT, respectively. Acifluorfen had no effect on relative stand, height, moisture, or seed yield (Table 2).

Bentazon caused 5%, 3%, 2%, and 0% injury at 577 g ai ha\(^{-1}\) and 8%, 5%, 3%, and 1% injury at 1154 g ai ha\(^{-1}\) assessed 1, 2, 4, and 8 WAT, respectively. Injury decreased with time. Bentazon did not affect the relative stand, height, moisture, or seed yield (Table 2).

#### Table 6

Least square means for percent injury of four dry bean market classes treated with bentazon, acifluorfen, and bentazon/acifluorfen near Exeter, ON (2016–2017 and 2019)

| Herbicide treatment | Rate (g ai ha\(^{-1}\)) | Dry bean injury (%) |
|---------------------|--------------------------|---------------------|
|                     |                          | Azuki               |
|                     |                          | Kidney              |
|                     |                          | SR                  |
|                     |                          | White               |
| 1 WAT               |                          |                    |
| Untreated control   | 0 a                      | 0 a                 |
| Acifluorfen         | 600                      | 5 b                 |
| Acifluorfen         | 1200                     | 11 c                |
| Bentazon            | 1080                     | 11 c                |
| Bentazon            | 2160                     | 16 cd               |
| Bentazon/acifluorfen| 840                      | 13 cd               |
| Bentazon/acifluorfen| 1680                     | 18 d                |
| 2 WAT               |                          |                    |
| Untreated control   | 0 a                      | 0 a                 |
| Acifluorfen         | 600                      | 5 b                 |
| Acifluorfen         | 1200                     | 8 bc                |
| Bentazon            | 1080                     | 12 cd               |
| Bentazon            | 2160                     | 15 d                |
| Bentazon/acifluorfen| 840                      | 10 bcd              |
| Bentazon/acifluorfen| 1680                     | 17 d                |
| 4 WAT               |                          |                    |
| Untreated control   | 0 a                      | 0 a                 |
| Acifluorfen         | 600                      | 0.5 ab              |
| Acifluorfen         | 1200                     | 2.6 bc              |
| Bentazon            | 1080                     | 6.4 cd              |
| Bentazon            | 2160                     | 8.7 d               |
| Bentazon/acifluorfen| 840                      | 4.3 cd              |
| Bentazon/acifluorfen| 1680                     | 9.7 d               |

Note: Means followed by the same letter within a column (a–e) or row (X–Z) are not significantly different according to a Tukey–Kramer multiple range test at \( P < 0.05 \). Rows without an uppercase letter have no differences among market classes.

Abbreviations: SR, small red; WAT, weeks after herbicide application.

*\(^{a}\)Included assist (1.5 L ha\(^{-1}\)).

*\(^{b}\)Included assist (3.0 L ha\(^{-1}\)).
Bentazon/acifluorfen caused 17%, 11%, 6%, and 2% injury at 842 g ai ha\(^{-1}\) and 32%, 24%, 15%, and 5% injury at 1684 g ai ha\(^{-1}\) assessed 1, 2, 4, and 8 WAT, respectively. A synergistic increase in dry bean injury with the preformulated mixture of bentazon/acifluorfen (both rates) was observed at 1, 2, and 8 WAT. Observed injury with bentazon/acifluorfen was 5%, 3%, and 1% greater than expected injury at 842 g ai ha\(^{-1}\) and 12%, 10%, and 3% greater than expected visible injury at 1684 g ai ha\(^{-1}\) assessed 1, 2, and 8 WAT, respectively (Table 1). These findings are different than those found by Moran et al. (2011), Weinberg et al. (2007), Lycan and Hart (1999), and Bauer et al. (1995) indicating that bentazon can decrease injury in dry bean and other crops when tankmixed with injurious herbicides like imazethapyr, saflufenacil, thifensulfuron, and tritosulfuron.

Bentazon/acifluorfen applied at 842 g ai ha\(^{-1}\) did not affect the relative stand, height, moisture, or yield. Bentazon/acifluorfen applied at 1684 g ai ha\(^{-1}\) did not decrease plant stand but decreased dry bean height and yield 40% and 11%, respectively (Table 2). The seed moisture content was also increased by 12% indicating delayed maturity (Table 2). There was a synergistic decrease in relative height (1 \times \text{rate}) and yield (2 \times \text{rate}) and a synergistic increase in seed moisture content (2 \times \text{rate}) with the preformulated mixture of bentazon/acifluorfen (Table 2).

### Simple effects

#### Visible injury

Acifluorfen caused up to 4% visible injury in dry bean (Table 3). Bentazon produced up to 10% injury in azuki bean and ≤2% visible injury in other dry bean market classes. Bentazon/acifluorfen caused 10% to 24%, 5% to 15%, 4% to 12%, and 4% to 12% visible injury in azuki, kidney, small red, and white bean, respectively (Table 3). A synergistic...
increase in injury with the preformulated mixture of bentazon/ acifluorfen was observed in azuki bean (2× rate), kidney bean (1× and 2× rates), small red (2× rate), and white bean (2× rate) (Table 3). Generally, injury was greater in azuki bean compared with other dry bean types with bentazon and bentazon/acifluorfen. In other studies, Powell and Renner (2013) reported 12% injury 1 WAT in white beans with acifluorfen + bentazon POST, but the injury was transient and did not affect seed yield under Michigan environmental conditions.

**Biomass**

Generally, there was a greater decrease in azuki bean than other bean types with bentazon and bentazon/acifluorfen. Acifluorfen decreased biomass (dry weight m plant⁻¹) 12% to 15%, 1% to 14%, 7% to 17%,
and 13% to 21% in azuki, kidney, small red, and white beans, respectively (Table 4). Bentazon decreased biomass (dry weight plant⁻¹) 24% to 30%, 7% to 12%, 0% to 2%, and 2% to 9% in azuki, kidney, small red, and white beans, respectively (Table 4). Bentazon/acifluorfen premixed reduced biomass (dry weight plant⁻¹) 34% to 56%, 22% to 34%, 18% to 33, and 32% to 38% in azuki, kidney, small red, and white beans, respectively (Table 4). There was a synergistic rise in biomass reduction (dry weight plant⁻¹) with bentazon/acifluorfen in azuki bean (2/2 rate), small red bean (1/2 and 2/2 rate), and white bean (2/2 rate).

### 3.2 | Study 2

#### 3.2.1 | Main effects of herbicides

**Acifluorfen** applied at 600 and 1200 g ai ha⁻¹ caused 7% and 12% injury at 1 WAT, visible injury decreased with time, and there was 0.2% and 2% visible injury at 8 WAT, respectively (Table 5). Acifluorfen did not affect the relative dry bean stand, biomass, height, seed moisture content, or yield of dry bean evaluated (Table 5). Bentazon applied at 1080 and 2160 g ai ha⁻¹ injured dry bean 6% and 9% at 1 WAT, but visible injury decreased with time, and there was only 1% and 2% visible injury at 8 WAT, respectively (Table 5). Bentazon did not affect the relative dry bean stand, dry weight plant⁻¹, height, moisture, or yield of dry bean evaluated (Table 5). Bentazon reduced dry bean dry weight m row⁻¹ (2/2 rate).

**Bentazon/acifluorfen** at 840 and 1680 g ai ha⁻¹ caused 10% and 16% injury at 1 WAT, but the visible injury decreased with time, and there was only 1% and 3% visible injury at 8 WAT, respectively (Table 1). Bentazon/acifluorfen at the 840 g ai ha⁻¹ did not affect the relative dry bean stand, biomass, plant height, moisture, or seed yield of dry bean evaluated (Table 5). Bentazon/acifluorfen at 1680 g ai ha⁻¹ did not decrease plant stand and biomass (g m row⁻¹), but there was a reduction in dry weight plant⁻¹, height, and seed yield of 17%, 9%, and 5%, respectively (Table 5). The seed moisture content was also increased by 9% indicating delayed maturity (Table 5).

#### 3.2.2 | Simple effects

**Visible injury**

Generally, higher injury was observed in azuki bean in comparison with the other dry bean market classes with bentazon and bentazon/acifluorfen at rates evaluated (Table 6). Responses of other dry bean types were generally similar with all herbicide treatments evaluated at 2 and 4 WAT (Table 6). At 2 WAT, bentazon caused greater injury in kidney bean in comparison with small red and white beans (Table 6).

At 1 WAT, acifluorfen caused 5% to 11%, 7% to 13%, 8% to 12%, and 9% to 13% visible injury in azuki, kidney, small red, and white bean, respectively (Table 6). Bentazon produced 11% to 16%, 7% to 10%, 4% to 6%, and 3% to 6% visible injury in azuki, kidney, small red, and white bean, respectively (Table 6). Bentazon/acifluorfen caused 13% to 18%, 10% to 16%, 8% to 17%, and 9% to 14% visible injury in...
azuki, kidney, small red, and white bean, respectively (Table 6). Injury decreased over time. At 4 WAT, acifluorfen caused 1% to 3%, 1% to 4%, 2% to 3%, and 1% to 4% visible injury in azuki, kidney, small red, and white bean, respectively (Table 6). Bentazon caused 6% to 9%, 2% to 3%, 0% to 1%, and 0% to 1% visible injury in azuki, kidney, small red, and white bean, respectively (Table 6). Bentazon/acifluorfen pre-mixed caused 4% to 10%, 3% to 7%, 2% to 3%, and 2% to 3% visible injury in azuki, kidney, small red, and white bean, respectively (Table 6).

### 3.3 | Study 3

The rate of acifluorfen was reduced in Study 3 due to unacceptably high injury in Study 2.

#### 3.3.1 | Main effects of herbicides

Acifluorfen caused 14%, 10%, 4%, and 4% injury at 420 g ai ha⁻¹ and 24%, 18%, 10%, and 8% injury at 840 g ai ha⁻¹ assessed 1, 2, 4, and 8 WAT, respectively (Table 7). Injury decreased with time. Acifluorfen did not affect the relative dry bean stand, height, seed moisture, or yield (Table 7).

Bentazon produced 9%, 8%, 4%, and 3% injury at 1080 g ai ha⁻¹ and 16%, 13%, 8%, and 6% injury at 2160 g ai ha⁻¹ assessed 1, 2, 4, and 8 WAT, respectively. Injury decreased with time. Bentazon had no effect the relative dry bean stand, height, moisture, or seed yield (Table 7).

Bentazon/acifluorfen caused 26%, 20%, 12%, and 7% injury at 840 g ai ha⁻¹ and 45%, 41%, 24%, and 14% injury at 1680 g ai ha⁻¹ assessed 1, 2, 4, and 8 WAT, respectively. Bentazon/acifluorfen applied POST at 840 g ai ha⁻¹ did not affect the relative dry bean stand, height, moisture, or yield. Bentazon/acifluorfen applied POST at 1680 g ai ha⁻¹ did not decrease plant stand but reduced height and yield 11% and 12% (Table 7). Dry bean moisture was also 13% higher than the untreated control (Table 7).

#### 3.3.2 | Simple effects

**Visible injury**

Dry bean injury was variable based on the herbicide treatment and dry bean market class (Table 8). Injury was similar among bean types at 1, 2, and 8 WAT (Table 8). At 4 WAT, acifluorfen caused higher injury in kidney bean (6%) than azuki bean (3%). Generally, bentazon produced higher injury in azuki bean in comparison with the other bean types. The injury with bentazon/acifluorfen was comparable among dry bean types at 1, 2, 4, and 8 WAT (Table 8).

At 1 WAT, there was 12% to 20%, 14% to 25%, 14% to 24%, and 17% to 28% injury with acifluorfen; 19% to 34%, 9% to 13%, 6% to 11%, and 6% to 12% injury with bentazon; and 27% to 49%, 24% to 43%, 27% to 41% and 26% to 46% injury with bentazon/acifluorfen in azuki, kidney, small red, and white bean, respectively (Table 8). Injury decreased over time. At 8 WAT, there was 3% to 6%, 3% to 9%, 5% to 10%, and 5% to 8% injury with acifluorfen; 6% to 10%, 2% to 4%, 3% to 5% and 2% to 4% injury with bentazon; and 6% to 14%, 7% to 13%, 8% to 15%, and 7% to 13% injury with bentazon/acifluorfen in azuki, kidney, small red, and white bean, respectively (Table 8).

Other research has reported 7% visible injury with no decrease in azuki bean height or yield with acifluorfen applied POST at 600 or 1200 g ai ha⁻¹ (Stewart et al. 2010). In the same study, POST application of bentazon (1080 or 2160 g ai ha⁻¹) injured azuki bean 66% and decreased azuki bean biomass, height, and seed yield 90%, 27%, and 57%, respectively (Stewart et al., 2010). Variable responses have been reported with bentazon on *P. vulgaris* dry bean species. VanGessel et al. (2000) found up to 20% injury in dry bean with bentazon, but Soltani et al. (2005) reported only 3% injury with bentazon in dry bean. Additionally, Wall (1995) reported 21% decrease in dry bean yield with the POST application of bentazon. However, Blackshaw et al. (2000) and Burnside et al. (1994) showed no decrease in yield with the POST application of bentazon in dry bean.

#### Biomass

Generally, the herbicide treatments evaluated caused a higher biomass reduction in azuki bean than the other dry bean market classes (Table 9). Acifluorfen decreased biomass (dry weight m⁻¹) 8% to 20%, 2% to 20%, 5% to 15%, and 5% to 12% in azuki, kidney, small red, and white beans, respectively (Table 9). Bentazon decreased biomass (dry weight m⁻¹) 37% to 53%, 3% to 8%, 0%, and 0% to 4% in azuki, kidney, small red, and white beans, respectively (Table 9). Bentazon/acifluorfen reduced biomass (dry weight m⁻¹) 41% to 55%, 16% to 41%, 18% to 42%, and 17% to 38% in azuki, kidney, small red, and white beans, respectively (Table 9). Biomass reductions per plant followed the same trends as per m⁻¹ for all dry bean types studied (Table 9).

### 4 | CONCLUSION

Acifluorfen at rates assessed caused significant initial injury but generally had no effect on the relative dry bean stand, biomass, plant height, moisture, or seed yield. Bentazon at rates assessed caused significant initial injury in azuki bean but generally did not affect the final yield of other dry bean types evaluated. However, bentazon/acifluorfen preformulated applied POST caused significant initial injury and a reduction on of relative dry bean biomass, height, and seed yield of the dry bean studied. There was a synergistic increase in injury with the preformulated mixture of bentazon/acifluorfen for most parameters evaluated. Injury responses to acifluorfen were generally similar among dry bean studied. However, there was generally higher injury responses in azuki bean in comparison with other dry bean types evaluated with bentazon and bentazon/acifluorfen pre-mixed at rates evaluated. The visible injury was generally comparable between kidney, small red, and white beans with all herbicide
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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Nader Soltani conceptualized the study, curated the data, conducted the formal analysis, designed the methodology, prepared the software, and supervised the study. Christy Shropshire curated the data, conducted the formal analysis, acquired the funding, designed the methodology, and supervised the study.

DATA AVAILABILITY STATEMENT

The source data are available upon request.

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