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Weed control in corn with diflufenican plus isoxaflutole

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Abutilon theophrasti Medik.; *Amaranthus powellii* S. Watson; *Ambrosia artemisiifolia* L.; barnyardgrass; *Chenopodium album* L.; common ragweed; common lambsquarters; corn; Diflufenican; *Echinochloa crus-galli* (L.) P. Beauv.; green foxtail; green pigweed; isoxaflutole; *Setaria viridis* (L.) P. Beauv.; velvetleaf; *Zea mays* L.

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Abstract

Diflufenican is a selective phenyl ether, Group 12 herbicide. Limited information exists on the weed control efficacy of diflufenican and the potential improvement in weed control when it is co-applied with isoxaflutole. Three field studies were conducted in Ontario to evaluate preemergence applications of isoxaflutole and diflufenican alone and in combinations for weed control in corn. Isoxaflutole applied at 52.5, 79, and 105 g ai ha^{-1} provided effective control of velvetleaf (83% to 89%, 91% to 98%, and 92% to 97%), green pigweed (73% to 85%, 85% to 91%, and 94% to 97%), common ragweed (81% to 86%, 93% to 97%, and 95% to 97%), and common lambsquarters (88% to 89%, 96% to 99%, and 98% to 100%), respectively when evaluated at 2, 4, and 8 wk after treatment (WAT). Diflufenican applied alone at 75 to 150 g ai ha^{-1} provided ≤3% control of velvetleaf, ≤38% of green pigweed, ≤7% of common ragweed, and ≤20% of common lambsquarters. Isoxaflutole applied alone provided 16% to 75% control of barnyardgrass, while diflufenican was ineffective (<3%). The co-application of isoxaflutole + diflufenican improved control to 34% to 86%, with synergistic effects of barnyardgrass control observed at several rates. Isoxaflutole and diflufenican, applied alone controlled green foxtail by 15% to 72% and 0% to 12%, respectively. The co-application of isoxaflutole + diflufenican improved green foxtail control to 25% to 89% with synergistic responses at some rates and evaluation timings. There was minimal corn injury with these treatments. Weed interference reduced corn yield by up to 69%. Weed interference with diflufenican applied alone resulted in corn yields of 4570 to 4750 kg ha^{-1}, which is similar to yields from the nontreated control (3.33 T ha^{-1}). Reduced weed interference with isoxaflutole alone and in mixtures with diflufenican resulted in corn yields of 8.36 to 10.83 T ha^{-1}, which is higher than yields from both the nontreated control plots and those that received diflufenican treatments. Overall, isoxaflutole provided consistent broadleaf weed control, while synergistic interactions with diflufenican enhanced barnyardgrass and green foxtail suppression.

Introduction

Weed interference remains one of the most significant constraints to achieving optimum corn yields (Soltani et al. 2016, 2022). Weeds compete with corn for light, water, nutrients, and space, and early-season weed interference can significantly reduce corn yield (Kaur et al. 2018; Rana 2016; Reddy 2018). In Ontario and much of the North Central United States, key problematic weeds in corn production include broadleaf species such as velvetleaf, green pigweed, common ragweed, and common lambsquarters, as well as grass species such as barnyardgrass and green foxtail (OMAFRA 2024). Effective control of these species with preemergence herbicides is critically necessary for minimizing corn yield loss from early-season weed interference and for improving the efficacy of postemergence herbicides by reducing weed density and size at the time of postemergence herbicide application. Moreover, combining multiple herbicides helps lower the selection intensity for the evolution of herbicide-resistant weed populations (Owen 2016). In Canada, no new herbicide mode of action has been registered for corn production in more than 25 yr. As a result, corn growers urgently need new herbicide options to effectively manage challenging weed species in their cropping systems.

Diflufenican is a selective herbicide belonging to the phenyl ether family and is categorized as a Group 12 herbicide by the Weed Science Society of America (WSSA). Diflufenican has both contact and residual activity against key weeds and has long been used in European agriculture, particularly for weed control in cereal and pulse crops such as lentils (Effertz 2021). In North America, diflufenican represents a novel mode of action for major crops; it was recently registered for use in Canada by the Pest Management Regulatory Agency (PMRA) in February 2024 for preplant and preemergence weed control in corn and soybean production (PMRA 2024a) and is currently under review by the U.S. Environmental Protection Agency (US EPA 2025) for potential registration for use in corn and soybean.

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The introduction of diflufenican into North American crop production for weed management in corn and soybean is significant, because no other WSSA Group 12 herbicide is registered for use on these crops (Effertz 2021). Diflufenican is registered for use in Canada either preplant or preemergence for the control of redroot pigweed, green pigweed, waterhemp, and Palmer amaranth (PMRA 2024a), The preformulated mixture of isoxaflutole + diflufenican is registered for the control of five annual grasses and 14 annual broadleaf weeds in Canada (PMRA 2024b). The co-application of diflufenican with other herbicides has demonstrated effectiveness against a range of annual grass and broadleaf weeds, particularly when included in mixtures with herbicides that possess complementary modes of action (Effertz 2021; Haynes and Kirkwood 1992; Tejada 2009).

Diflufenican is absorbed primarily through the shoots of emerging seedlings, with minimal systemic movement within the plant (Haynes and Kirkwood 1992). Diflufenican is a phytoene desaturase inhibitor that prevents carotenoid biosynthesis, thereby depriving chlorophyll of its protective pigments. By interfering with this process, diflufenican causes the accumulation of phototoxic intermediates, leading to photobleaching, cellular damage, and eventual plant death under light exposure (Haynes and Kirkwood 1992; Miras-Moreno et al. 2019). From environmental and toxicological perspectives, diflufenican exhibits several favorable characteristics (Bending et al. 2006). It has low water solubility and minimal volatility, which reduces the risk of off-target movement. Additionally, it has low toxicity to non-target organisms such as mammals and pollinators, including honeybees, and it degrades relatively quickly in soil, thereby limiting its persistence in the environment (Ashton et al. 1994; Bending et al. 2006).

Isoxaflutole is widely used in corn production for the control of a broad range of weed species, and can be applied preplant, preemergence, or early postemergence (Grichar et al. 2005; Sprague 1999). Isoxaflutole inhibits 4-hydroxyphenylpyruvate dioxygenase following rapid transformation within the plant to form a biologically active diketonitrile metabolite (Bayer 2017; Lee et al. 1997; Pallett et al. 1998). This metabolite interferes with the biosynthesis of plastoquinone, a critical component in carotenoid production (Pallett et al. 1998). As a result, treated weeds exhibit bleaching symptoms followed by tissue death (Bayer 2017; Lee et al. 1997; Pallett et al. 1998; Sprague 1999). Isoxaflutole is particularly effective against broadleaf weeds and suppresses some grass species (Sprague 1999; Steckel et al. 2003). Its residual activity and broad-spectrum efficacy make it a reliable herbicide option for weed management in corn (Bayer 2017; Pallett et al. 1998; Shaner 2014). However, its performance can be inconsistent against certain small-seeded grasses, such as green foxtail and barnyardgrass, with control often influenced by application rate, soil characteristics, and rainfall after application (Smith 2019; Sprague 1999; Steckel et al. 2003).

Limited data exists on the weed control efficacy of diflufenican in corn and its enhanced weed control when co-applied with isoxaflutole. Diflufenican and isoxaflutole offer different spectrums of activity and modes of action against key problematic weeds, thus the co-application of these herbicides may increase the spectrum of weeds that can be controlled, extend their residual activity, and reduce the evolution of herbicide-resistant biotypes. Herbicide mixtures with multiple effective modes of action are a cornerstone of integrated weed management strategies by helping to delay the onset of resistance in weed populations (Ofosu et al. 2023; Owen 2016). Additionally, there is limited information on the interaction between isoxaflutole and diflufenican for the control of troublesome weeds under Ontario field conditions. It remains unclear whether the co-application of isoxaflutole and diflufenican results in antagonistic, additive, or synergistic interactions across common annual broadleaf and grass weed species in Ontario corn production, and the effects of these combinations on corn safety and yield performance have not been well documented. Therefore, the objectives of this study were to 1) assess the effectiveness of isoxaflutole, diflufenican, and their combination applied preemergence at various rates for the control of common annual broadleaf and grass weed species; and 2) determine the effects of these treatments on corn injury and grain yield.

Materials and Methods

Field experiments were carried out in 2019 at the Huron Research Station in Exeter, Ontario (43.315497°N, 81.887765°W), and in both 2018 and 2019 at the University of Guelph campus in Ridgetown, Ontario (42.448644°N, 81.510569°W). The soil at Exeter was classified as Brookston clay loam, consisting of 29% sand, 44% silt, 27% clay, and 4.5% organic matter, pH 7.8. At Ridgetown, the soil was Fox sandy loam. In 2018, it contained 33% sand, 34% silt, 33% clay, and 3.8% organic matter, pH 6.7. In 2019, the composition was 41% sand, 28% silt, 31% clay, and 4.0% organic matter, pH 7.1. Prior to planting, all sites were prepared using fall mouldboard plowing, followed by two spring passes with a field cultivator with rolling basket harrows to create a suitable seedbed.

The field experiments were established using a randomized complete block design with four replications. Treatments included a nontreated control, three rates of isoxaflutole (Balance Flexx) applied preemergence at 52.5, 79, and 105 g ai ha^{-1} and three rates of diflufenican applied preemergence at 75, 105, and 150 g ai ha^{-1}. In addition, combinations of isoxaflutole and diflufenican were applied preemergence at corresponding rates of 52.5 + 75, 79 + 105, and 105 + 150 g ai ha^{-1}. Each plot measured either 8 or 10 m long and 3 m wide, consisting of four corn rows spaced 0.75 m apart. Glyphosate- and glufosinate-resistant corn hybrids (DKC 53-56, DS79C56, or PIONEER P9998AM) were seeded at approximately 85,000 plants per hectare.

Herbicides were applied 1 to 3 d after seeding using a CO_2-pressurized backpack sprayer calibrated to deliver 200 L ha^{-1} at 240 kPa. The spray boom was 1.5 m wide and fitted with four ULD120-02 nozzles (Hypro; Pentair, New Brighton, MN), spaced 50 cm apart to produce a 2 m spray pattern.

Visible assessments of crop injury were conducted at 1, 2, 4, and 8 wk after corn emergence (WAE), while visible weed control was evaluated at 2, 4, and 8 wk after treatment application (WAT). Both types of evaluations used a percentage scale ranging from 0% (no injury or weed suppression) to 100% (complete plant death). At harvest maturity, the center two rows in each plot were harvested using a small-plot combine. Grain yield and moisture content were recorded; yield data were adjusted to a standard moisture level of 15.5% prior to statistical analysis.

Data analysis was carried out using the GLIMMIX procedure in SAS software (v.9.4; SAS Institute Inc., Cary, NC) and the level of significance threshold for hypothesis testing was $\alpha = 0.05$. The generalized linear mixed model included herbicide treatment as the fixed effect and environment (year-location combinations), environment by herbicide treatment, and replicate within environment as the random effects. The Gaussian distribution

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Table 1. Velvetleaf control with isoxaflutole and diflufenican alone or in combination, applied preemergence to corn at Ridgetown in 2018 and 2019.[a–d]

Treatment	Rate	Velvetleaf control		
		2 WAT	4 WAT	8 WAT
	g ai ha^{-1}	%		
Nontreated control		0 b	0 c	0 b
Isoxaflutole	52.5	89 a	88 ab	83 a
Isoxaflutole	79	98 a	96 a	91 a
Isoxaflutole	105	97 a	96 a	92 a
Diflufenican	75	0 b	0 c	0 b
Diflufenican	105	2 b	0 c	0 b
Diflufenican	150	3 b	1 c	0 b
Isoxaflutole + diflufenican	52.5 + 75	85 a (89)	80 b (88)	73 a (83)
Isoxaflutole + diflufenican	79 + 105	96 a (98)	94 ab (96)	88 a (91)
Isoxaflutole + diflufenican	105 + 150	96 a (97)	96 a (96)	93 a (92)

[a]Abbreviation: WAT, weeks after herbicide application.
[b]Expected values for control with herbicide combinations based on Colby's equation (Eq. 1) are shown in parentheses following observed values.
[c]Means were separated according to the Tukey-Kramer multiple range test at $\alpha = 0.05$.

best satisfied the assumptions of analysis, and all weed control evaluations, except velvetleaf control, which were arcsine square root transformed prior to analysis; these means were back-transformed for presentation. Treatments for a given variable with a value of zero and zero variance across environments were excluded from the analysis. Comparisons between these treatments and non-zero treatments were made using the P-value included in the LSMEANS output table.

Expected values of visible percent control for herbicide mixture treatments were compared to observed values using a two-sided *t*-test for the purpose of determining additive, synergistic, or antagonistic effects. If the *t*-test was nonsignificant, the effect of the herbicide combination in the mixture was additive. If the observed percent control was higher than expected, the effect was considered synergistic. Conversely, if the observed percentage control was lower than expected, the effect was considered antagonistic. Colby's equation was used to calculate expected values for the mixture treatments (Colby 1967):

$$E = (X + Y) - XY/100 \quad (1)$$

where E is the expected weed control for the herbicide mixture, and X and Y are the weed control with the two individual herbicides.

Results and Discussion

The predominant weed species present at the study sites were velvetleaf, green pigweed, common ragweed, common lambsquarters, barnyardgrass, and green foxtail.

Velvetleaf Control

Isoxaflutole applied preemergence at 52.5, 79, and 105 g ai ha^{-1} provided 83% to 89%, 91% to 98%, and 92% to 97% velvetleaf control at 2, 4, and 8 WAT, respectively (Table 1). Diflufenican applied preemergence at 75, 105, and 150 g ai ha^{-1} controlled velvetleaf by ≤3%. A mixture of isoxaflutole and diflufenican applied preemergence improved velvetleaf control compared with diflufenican alone but control was equivalent to that of isoxaflutole applied alone (Table 1). There were no antagonistic or synergistic interactions between isoxaflutole and diflufenican applied preemergence at the tested rates for velvetleaf control; all interactions were additive (Table 1).

In other studies, Effertz (2021) reported that diflufenican applied preemergence at rates of 18.75, 37.5, and 75 g ai ha^{-1} provided velvetleaf control of 17% to 51%, 13% to 60%, and 23% to 77%, respectively. When isoxaflutole was applied preemergence at 13.13, 26.25, and 52.5 g ai ha^{-1} velvetleaf control was 85% at the lowest rate, and to up to 99% at all three rates (Effertz 2021). When applied in combination, diflufenican + isoxaflutole at 18.75 + 13.13, 37.5 + 26.25, and 75 + 52.5 g ai ha^{-1} provided even greater control, ranging from 93% to 99% (Effertz 2021). Bhowmik et al. (1999) reported that isoxaflutole applied at 6.1 g ai ha^{-1} reduced velvetleaf biomass by 80% (ED_{80}), a significantly lower rate than the rates used in this study. However, Knezevic et al. (1998) reported a much higher ED_{80} of 90 g ai ha^{-1} for velvetleaf control. Sprague et al. (1999) reported similar levels of velvetleaf control to those in this study when isoxaflutole was applied at rates of 79 and 105 g ai ha^{-1}. Similarly, Smith (2019) reported comparable results to the results of the current study, showing that preemergence applications of isoxaflutole at 52.5, 79, and 105 g ai ha^{-1} provided 82% to 95%, 96% to 98%, and 93% to 100% control of velvetleaf, respectively.

Green Pigweed Control

Isoxaflutole applied preemergence at 52.5, 79, and 105 g ai ha^{-1} provided 85%, 91%, and 97% control of green pigweed at 2 WAT. When assessed at 8 WAT, control levels dropped to 73%, 85%, and 94%, respectively, for those same application rates (Table 2). Diflufenican applied preemergence at 75, 105, and 150 g ai ha^{-1} provided ≤38% control of green pigweed. Control improved significantly when the isoxaflutole + diflufenican combination was applied preemergence, with the highest rate combination providing 99% to 100% control; however, control was statistically similar to that of isoxaflutole applied alone (Table 2). No antagonistic or synergistic interactions with isoxaflutole and diflufenican applied preemergence were observed at the rates tested; all interactions were additive (Table 2). Lower-than-expected green pigweed control with diflufenican treatments may be due to environmental conditions or biotype variability, which underscores the need to integrate diflufenican with other management practices.

In previous studies, Effertz (2021) reported that preemergence applications of diflufenican at rates of 18.75, 37.5, and 75 g ai ha^{-1} controlled redroot pigweed 73% to 99%, 97% to 99%, and 98% to

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Table 2. Green pigweed control with isoxaflutole and diflufenican alone or in combination, applied preemergence to corn at Ridgetown in 2018 and 2019.[a–c]

Treatment	Rate	Green pigweed control		
		2 WAT	4 WAT	8 WAT
	g ai ha^{-1}	%		
Nontreated control		0 d	0 e	0 e
Isoxaflutole	52.5	85 abc	82 abc	73 abc
Isoxaflutole	79	91 ab	89 abc	85 abc
Isoxaflutole	105	97 a	96 ab	94 a
Diflufenican	75	15 cd	10 de	8 de
Diflufenican	105	28 bc	17 cde	16 cde
Diflufenican	150	38 abc	34 bcd	31 bcd
Isoxaflutole + diflufenican	52.5 + 75	90 ab (88)	89 ab (84)	85 ab (75)
Isoxaflutole + diflufenican	79 + 105	98 a (95)	96 ab (91)	94 a (87)
Isoxaflutole + diflufenican	105 + 150	100 a (99)	100 a (98)	99 a (96)

[a]Abbreviation: WAT, weeks after herbicide application.
[b]Expected values for control with herbicide combinations based on Colby's equation (Eq. 1) are shown in parentheses following observed values.
[c]Means were separated according to the Tukey-Kramer multiple range test at $\alpha = 0.05$.

Table 3. Common ragweed control with isoxaflutole and diflufenican alone or in combination, applied preemergence to corn at Ridgetown in 2018 and 2019, and Exeter in 2018.[a–c]

Treatment	Rate	Common ragweed control		
		2 WAT	4 WAT	8 WAT
	g ai ha^{-1}	%		
Nontreated control		0 c	0 e	0 d
Isoxaflutole	52.5	86 a	81 c	83 bc
Isoxaflutole	79	97 a	94 ab	93 ab
Isoxaflutole	105	97 a	97 a	95 a
Diflufenican	75	0 c	0 e	0 d
Diflufenican	105	1 bc	3 d	0 d
Diflufenican	150	7 b	5 d	3 d
Isoxaflutole + diflufenican	52.5 + 75	89 a (86)	83 bc (81)	80 c (83)
Isoxaflutole + diflufenican	79 + 105	96 a (97)	95 a (94)	93 ab (92)
Isoxaflutole + diflufenican	105 + 150	96 a (97)	96 a (97)	93 ab (95)

[a]Abbreviation: WAT, weeks after herbicide application.
[b]Expected values for control with herbicide combinations based on Colby's equation (Eq. 1) are shown in parentheses following observed values.
[c]Means were separated according to the Tukey-Kramer multiple range test at $\alpha = 0.05$.

99%, respectively. Isoxaflutole applied preemergence at 13.13, 26.25, and 52.5 g ai ha^{-1} provided, respectively, 88% to 99%, 96% to 98%, and 99%, control of redroot pigweed (Effertz 2021). When applied in combination, diflufenican + isoxaflutole at 18.75 + 13.13, 37.5 + 26.25, and 75 + 52.5 g ai ha^{-1} controlled redroot pigweed by 98% to 99% (Effertz 2021). Smith (2019) found that preemergence applications of isoxaflutole at 52.5, 79, and 105 g ai ha^{-1} provided 34% to 87%, 56% to 98%, and 69% to 99% control of pigweeds, respectively. Similarly, Sprague et al. (1999) reported up to 88% control of pigweed in corn with isoxaflutole applications of 79 and 105 g ai ha^{-1}. Knezevic et al. (1998) observed that an ED_{90} of 100 g ai ha^{-1} was required to effectively reduce pigweed biomass.

Common Ragweed Control

Isoxaflutole applied preemergence at 52.5, 79, and 105 g ai ha^{-1} provided 86%, 97%, and 97% control of common ragweed at 2 WAT, respectively. When assessed at 8 WAT, control was determined to be 83%, 93%, and 97%, respectively, for those application rates (Table 3). In contrast, diflufenican applied preemergence at 75, 105, and 150 g ai ha^{-1} was ineffective, providing ≤7% control at 2 WAT at the highest rate of the herbicide, and only 3% control at 8 WAT. The preemergence co-application of isoxaflutole + diflufenican improved common ragweed control compared with diflufenican alone but control levels were similar to those of isoxaflutole applied alone (Table 3). There were no antagonistic or synergistic interactions with isoxaflutole and diflufenican applied preemergence; all interactions were additive (Table 3).

Results from this study are comparable to those reported by Smith (2019) that preemergence applications of isoxaflutole at 52.5, 79, and 105 g ai ha^{-1} provided 97%, 82% to 100%, and 93% to 100% control of common ragweed, respectively. Similarly, Sprague et al. (1999) observed greater than 95% control of common ragweed with preemergence applications of isoxaflutole at 79 and 105 g ai ha^{-1}.

Common Lambsquarters Control

Isoxaflutole applied preemergence at 52.5, 79, and 105 g ai ha^{-1} provided, respectively, 89%, 99%, and 100% control of common lambsquarters at 2 WAT; and 88%, 96%, and 98% control at those respective rates when assessed at 8 WAT (Table 4).

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Table 4. Common lambsquarters control with isoxaflutole and diflufenican alone or in combination, applied preemergence to corn at Ridgetown in 2018 and 2019, and Exeter in 2018.[a–c]

Treatment	Rate	Common lambsquarters control		
		2 WAT	4 WAT	8 WAT
	g ai ha^{-1}	%		
Nontreated control		0 c	0 d	0 c
Isoxaflutole	52.5	89 a	89 b	88 a
Isoxaflutole	79	99 a	97 ab	96 a
Isoxaflutole	105	100 a	99 a	98 a
Diflufenican	75	9 bc	3 cd	5 bc
Diflufenican	105	14 b	7 cd	13 bc
Diflufenican	150	20 b	9 c	20 b
Isoxaflutole + diflufenican	52.5 + 75	93 a (90)	90 ab (89)	87 a (88)
Isoxaflutole + diflufenican	79 + 105	99 a (99)	97 ab (97)	96 a (96)
Isoxaflutole + diflufenican	105 + 150	99 a (100)	98 a (99)	97 a (98)

[a]Abbreviation: WAT, weeks after herbicide application.
[b]Expected values for control with herbicide combinations based on Colby's equation (Eq. 1) are shown in parentheses following observed values.
[c]Means were separated according to the Tukey-Kramer multiple range test at $\alpha = 0.05$.

Table 5. Barnyardgrass control with isoxaflutole and diflufenican alone or in combination, applied preemergence to corn at Ridgetown in 2018 and 2019.[a–d]

Treatment	Rate	Barnyardgrass control		
		2 WAT	4 WAT	8 WAT
	g ai ha^{-1}	%		
Nontreated control		0 c	0 c	0 d
Isoxaflutole	52.5	38 b	34 b	16 cd
Isoxaflutole	79	58 ab	51 b	35 bc
Isoxaflutole	105	75 ab	64 ab	49 ab
Diflufenican	75	0 c	0 c	0 d
Diflufenican	105	2 c	0 c	0 d
Diflufenican	150	3 c	0 c	0 d
Isoxaflutole + diflufenican	52.5 + 75	56 ab (38)*	51 b (34)	34 bc (16)
Isoxaflutole + diflufenican	79 + 105	74 ab (59)*	66 ab (51)*	56 ab (35)*
Isoxaflutole + diflufenican	105 + 150	86 a (76)*	79 a (65)	71 a (49)*

[a]Abbreviation: WAT, weeks after herbicide application.
[b]Expected values for control with herbicide combinations based on Colby's equation (Eq. 1) are shown in parentheses following observed values.
[c]Means were separated according to the Tukey-Kramer multiple range test at $\alpha = 0.05$.
[d]An asterisk (*) denotes a significant difference of $P<0.05$ between observed and expected values based on a two sided *t*-test.

Diflufenican applied preemergence at 75, 105, and 150 g ai ha^{-1} provided ≤20% control. Control improved when isoxaflutole + diflufenican was applied preemergence compared with diflufenican alone, but the control was similar to that when isoxaflutole was applied alone (Table 4). There were no antagonistic or synergistic interactions between isoxaflutole and diflufenican when applied preemergence in these experiments; all interactions were additive (Table 4).

In studies with isoxaflutole, Bhowmik et al. (1999) reported that the calculated dose to reduce common lambsquarters biomass by 80% (ED_{80}) was only 13 g ai ha^{-1}, suggesting that the species is highly susceptible to isoxaflutole. However, Knezevic et al. (1998) reported that a broader ED_{80} range of isoxaflutole (60 to 130 g ai ha^{-1}) is needed to control common lambsquarters, indicating that some variability in sensitivity exists.

Barnyardgrass Control

Isoxaflutole applied preemergence at 52.5, 79, and 105 g ai ha^{-1} provided 38%, 58%, and 75% control of barnyardgrass at 2 WAT, respectively. When assessed at 8 WAT, control was 16%, 35%, and 49% at those rates (Table 5). In contrast, diflufenican applied preemergence at 75, 105, and 150 g ai ha^{-1} was essentially ineffective, providing ≤3% control. Isoxaflutole + diflufenican provided better barnyardgrass control than diflufenican alone but it was similar to that of isoxaflutole applied alone. There was a synergistic improvement in the control of barnyardgrass with isoxaflutole + diflufenican at 52.5 + 75 g ai ha^{-1} at 2 WAT; 79 + 105 g ai ha^{-1} at 2, 4, and 8 WAT; and 105 + 150 g ai ha^{-1} at 2 and 8 WAT; all other interactions were additive (Table 5).

Results from the current study are consistent with those reported by Smith (2019), that preemergence applications of isoxaflutole at 52.5, 79, and 105 g ai ha^{-1} provided 37% to 53%, 71% to 81%, and 87% to 89% control of barnyardgrass, respectively. In contrast, Bhowmik et al. (1999) reported 99% barnyardgrass control with isoxaflutole at 72 g ai ha^{-1}, exceeding the levels observed in the current study. Similarly, Meyer et al. (2017) reported 99% control at 4 wk after application (WAA) of 100 g ai ha^{-1} isoxaflutole applied preemergence; however, control declined to 75% by 7 WAA. The same study found that combining isoxaflutole with metribuzin (100 + 414 g ai ha^{-1}) resulted in a 9% decrease in weed control over time. In contrast, Smith (2019) observed both additive and synergistic effects when the two herbicides were applied preemergence.

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Table 6. Green foxtail control with isoxaflutole and diflufenican alone or in combination, applied preemergence to corn at Ridgetown in 2018 and 2019, and Exeter in 2018.[a–d]

Treatment	Rate	Green foxtail control		
		2 WAT	4 WAT	8 WAT
	g ai ha^{-1}	%		
Nontreated control		0 e	0 e	0 e
Isoxaflutole	52.5	40 bc	32 bc	15 d
Isoxaflutole	79	60 ab	48 ab	34 bcd
Isoxaflutole	105	72 ab	60 ab	46 abc
Diflufenican	75	9 d	12 cd	0 e
Diflufenican	105	12 cd	6 de	0 e
Diflufenican	150	10 cd	8 cde	0 e
Isoxaflutole + diflufenican	52.5 + 75	60 ab (45)*	49 ab (41)	25 cd (15)
Isoxaflutole + diflufenican	79 + 105	75 ab (64)	62 ab (51)	50 ab (34)*
Isoxaflutole + diflufenican	105 + 150	89 a (75)*	78 a (64)*	72 a (46)*

[a]Abbreviation: WAT, weeks after herbicide application.
[b]Expected values for control with herbicide combinations based on Colby's equation (Eq. 1) are shown in parentheses following observed values.
[c]Means were separated according to the Tukey-Kramer multiple range test at $\alpha = 0.05$.
[d]An asterisk (*) denotes a significant difference of $P<0.05$ between observed and expected values based on a two sided *t*-test.

Green Foxtail Control

Isoxaflutole applied preemergence at 52.5, 79, and 105 g ai ha^{-1} provided 40%, 60%, and 72% control of green foxtail at 2 WAT, respectively. When assessed at 8 WAT, control levels fell to 15%, 34%, and 46%, respectively, at those rates (Table 6). Diflufenican applied preemergence at 75, 105, and 150 g ai ha^{-1} provided ≤12% control. Applications of isoxaflutole + diflufenican provided somewhat better control of green foxtail than diflufenican alone, but the percentages were similar to those when isoxaflutole was applied alone (Table 6). Significant increases in observed control over expected values were detected for the isoxaflutole + diflufenican mixture at 52.5 + 75 g ai ha^{-1} at 2 WAT; 79 + 105 g ai ha^{-1} at 8 WAT; and 105 + 150 g ai ha^{-1} at 2, 4, and 8 WAT, indicating synergistic interactions between isoxaflutole and diflufenican for the control of green foxtail while all other herbicide interactions exhibited additive interactions (Table 6).

In other studies, Effertz (2021) reported that preemergence applications of diflufenican at rates of 18.75, 37.5, and 75 g ai ha^{-1} provided, respectively, 48% to 96%, 88% to 99%, and 96% to 99% control of giant foxtail. Preemergence applications of isoxaflutole at 13.13, 26.25, and 52.5 g ai ha^{-1} controlled giant foxtail by 7% to 79%, 28% to 76%, and 94% to 99%, respectively (Effertz 2021). When applied in combination, diflufenican + isoxaflutole applied at rates of 18.75 + 13.13, 37.5 + 26.25, and 75 + 52.5 g ai ha^{-1} provided 65% to 99% control of giant foxtail (Effertz 2021). Smith (2019) reported that preemergence applications of isoxaflutole at 52.5, 79, and 105 g ai ha^{-1} provided 24% to 28%, 41% to 76%, and 52% to 83% control of foxtail species, respectively. In addition, Sprague et al. (1999) noted that in trials with corn, preemergence applications of isoxaflutole at 79 and 105 g ai ha^{-1} resulted in highly variable giant foxtail control, with effectiveness ranging from 23% to 89%.

Corn Injury and Yield

Minimal visible corn injury was observed at 1, 2, 4, and 8 WAE; therefore, the data were not analyzed (data not shown). These findings align with reports from previous research showing that preemergence applications of diflufenican and isoxaflutole, whether applied individually or together at different rates, caused little to no injury to corn (Effertz 2021; Grichar et al. 2005; Janak and Grichar 2016; Soltani et al. 2024a, 2024b; Sprague 1999). In contrast, other studies have shown slight to moderate phytotoxicity in corn when high rates of isoxaflutole were applied alone or in combination with other herbicides (Benoit et al. 2019; Bhowmik et al. 1999; Brown et al. 2016; Geier and Stahlman 1997; Johnson et al. 2012; Taylor-Lovell and Wax 2001; Willemse et al. 2021). Preemergence applications of diflufenican at rates ranging from 60 to 210 g ai ha^{-1} also resulted in no observable corn injury (Soltani et al. 2024a)

Table 7. Corn yield from treatments with isoxaflutole and diflufenican alone or in combination, applied preemergence at Ridgetown in 2018 and 2019, and Exeter in 2018.[a]

Treatment	Rate	Yield
	g ai ha^{-1}	kg ha^{-1}
Nontreated control		3,300 b
Isoxaflutole	52.5	8,400 a
Isoxaflutole	79	9,500 a
Isoxaflutole	105	10,400 a
Diflufenican	75	4,700 b
Diflufenican	105	4,800 b
Diflufenican	150	4,600 b
Isoxaflutole + diflufenican	52.5 + 75	9,000 a
Isoxaflutole + diflufenican	79 + 105	10,400 a
Isoxaflutole + diflufenican	105 + 150	10,800 a

[a]Means were separated according to the Tukey-Kramer multiple range test at $\alpha = 0.05$.

Weed interference reduced corn yield by up to 69% in this study (Table 7). Diflufenican applied alone at 75, 105, and 150 g ai ha^{-1} resulted in corn yields of 4600 to 4800 kg ha^{-1}, which is similar to the weedy control. In contrast, isoxaflutole applied alone at 52.5, 79, and 105 g ai ha^{-1} minimized weed interference and significantly increased corn yields to 8400, 9500, and 10400 kg ha^{-1}, respectively (Table 7). Reduced weed interference with the preemergence co-application of isoxaflutole + diflufenican significantly improved yields compared to the nontreated control or diflufenican, with isoxaflutole + diflufenican mixtures applied preemergence at 52.5 + 75, 79 + 105, and 105 + 150 g ai ha^{-1}, producing corn grain yields of 9000, 10400, and 10800 kg ha^{-1}, respectively. Yields from all isoxaflutole-alone and herbicide mixture treatments were statistically similar and significantly higher than both the weedy control and diflufenican-alone treatments (Table 7). These results are similar to a number of studies that have shown no or minimal corn injury or yield reduction with diflufenican or isoxaflutole

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(Benoit et al. 2019; Bhowmik et al. 1999; Brown et al. 2016; Effertz 2021; Geier and Stahlman 1997; Johnson et al. 2012; Soltani et al. 2024a; Taylor-Lovell and Wax 2001; Willemse et al. 2021).

In conclusion, isoxaflutole provided acceptable control of velvetleaf, common ragweed, and common lambsquarters; and partial control of green pigweed, barnyardgrass, and green foxtail. Diflufenican alone was largely ineffective but showed utility when it was co-applied with isoxaflutole to control green pigweed, barnyardgrass, and green foxtail. The isoxaflutole + diflufenican combination is a viable preemergence weed control option for broad-spectrum weed control with minimal corn injury. These findings suggest that diflufenican, with its distinct mode of action, could be a component of an integrated weed management approach for managing certain weed species that grow among corn crops. Further research is needed to evaluate the effectiveness of preemergence applications of diflufenican at various rates, in combination with other effective herbicides, as part of an integrated weed management strategy for controlling troublesome weeds in corn production.

Practical Implications

This study demonstrates that isoxaflutole, applied preemergence, is an effective herbicide for managing key broadleaf weeds such as velvetleaf, green pigweed, common ragweed, and common lambsquarters in corn production. Control levels of these species consistently exceeded 85% at application rates of 79 to 105 g ai ha^{-1}. In contrast, diflufenican applied alone, even at rates of up to 150 g ai ha^{-1}, was largely ineffective against all broadleaf species, offering ≤38% control.

Isoxaflutole applied alone provided moderate suppression of barnyardgrass (16% to 75%) and green foxtail (15% to 72%), while diflufenican alone was ineffective (≤12% control). However, the isoxaflutole + diflufenican combination provided a significant improvement in grass weed control. The highest mixture rate (105 + 150 g ai ha^{-1}) provided 71% to 86% control of barnyardgrass and 72% to 89% control of green foxtail. Synergistic interactions were identified at multiple rate combinations and evaluation timings, particularly for grass species, highlighting the benefit of the co-application of both herbicides.

Corn showed no signs of injury from any of the herbicide treatments evaluated in this study. However, weed interference led to yield losses of up to 69%. Corn yields were significantly improved ranging from 8.4 to 10.8 T ha^{-1} when isoxaflutole was applied, whether alone or in combination with diflufenican. In contrast, when diflufenican was applied alone, weed suppression was insufficient, and corn yields remained comparable to those of the nontreated control.

These findings show that diflufenican, due to its distinct mode of action, may be effective in controlling specific weed biotypes in corn when used in combination with isoxaflutole, highlighting the importance of integrating herbicide modes of action with cultural and mechanical strategies for consistent control of problematic weeds.

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