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Efficacy and Crop Safety of Reduced dose Herbicide Mixtures for Weed Management in Alfalfa (*Medicago sativa* L.)

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

A major perennial legume throughout the world, alfalfa (*Medicago sativa*) is becoming more popular in Africa, where sustainable production depends on effective weed management. The most popular approach is chemical weed control, which mostly uses the herbicide imazethapyr. However, depending solely on one herbicide may result in inconsistent weed control in the field and cause environmental issues due to the use of greater pesticide concentrations. To address this issue, a two-year (2024 and 2025) field study was carried out to reduce the use of herbicides and find eco-friendly ways to manage weeds using herbicide combinations in Navrongo, Ghana during the rainy season. Imazapic, prometryn, imazethapyr, and 2,4-DB were shown to be safe and efficient in managing broadleaf weeds during the initial screening. Each broadleaf herbicide was combined with haloxyfop-R-methyl to increase the control spectrum and reduce the overall herbicide dosage. Haloxyfop-R-methyl + imazethapyr (36.5 + 56.5 g a. i. ha^{-1})

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effectively reduced herbicide input by at least 25% of the acceptable dose while providing broad spectrum weed control without impairing alfalfa performance. Furthermore, the combination of 2,4-DB (36.5 + 506.5 g a. i. ha-1) and haloxyfop-R-methyl produced excellent broad-spectrum weed control, enhanced alfalfa yield, and reduced total herbicide input by almost 25% of the prescribed dose. Imazethapyr controlled all the broadleaf weeds (*Biden pilosa* and *Amaranthus spinosus* L.) and grass weeds (>98%) effectively. Haloxyfop-R-methyl + imazethapyr exhibited a mixed dose response; a higher application dose resulted in to a drop in plant height and an increase in fresh and dry weight. The leaf area was 10% greater, the crop biomass at 36.5 + 56.5 g a. i. ha-1 was not substantially different from the weed-free control, and the weed control was more than 98% for both grass and broadleaf weeds. The mixture of haloxyfop-R-methyl + 2,4-DB at a dosage of 36.5 + 506.5 enhanced the leaf area by 8% while the crop's fresh and dry weights were approximately equivalent to those in the weed-free control. These combinations provide a crucial alternative for managing broadleaf weeds and reduce the need for frequent imazethapyr treatments. Therefore, these herbicide mixes provide safe, effective, and sustainable ways to manage weeds in alfalfa production.

Keywords: Post-emergence herbicide; medicavo sativa; broadleaf weed management; dose reduction.

1. Introduction

One of the most important forage plants in the world's livestock production is alfalfa *(Medicago sativa*) (Russelle, 2001; Barney et al, 2025). It improves feed conversion efficiency and raises the quality of meat and dairy products due to its nutritional profile (Qiao *et al.*, 2026). Alfalfa production has significantly expanded because of the growing demand for animal products worldwide (Huo et al, 2024; Jiang et al, 2024). Alfalfa production is severely hampered by weeds, particularly broadleaf ones, as their seedlings develop comparatively slowly (Raoofi and Alebrahim, 2017; Dillehay and Curran, 2010; Yang et al, 2024). In addition to fiercely competing with alfalfa for essential resources, weeds, particularly broadleaf ones and grasses, also change the composition of the forage, lower its quality, and reduce its market value by about 30–60% (Raoofi and Alebrahim, 2017; Yi et al, 2018; Kanatas et al, 2021). Alfalfa production thus depends on efficient weed control, particularly during seedling establishment (Bradley *et al.*, 2010; Montgomery *et al.*, 2023; Noorozi *et al.*, 2022). Recent field research in newly established alfalfa found that a mixture of foliar herbicides improved weed suppression, although phytotoxicity and reduced forage yield were also observed, emphasising the need to evaluate crop safety alongside weed control (Jeong *et al.*, 2024). A separate evaluation of sequential pre- and post-emergence herbicide applications in alfalfa reported differences in weed suppression and crop response among treatments, further supporting the assessment of both outcomes when selecting herbicide programmes (Bao *et al.*, 2026). Studies in other crops also indicate that herbicide programmes require crop-specific assessment: post-emergence herbicide application has been examined in relation to weed management and sorghum productivity, while herbicide treatments in moth bean have been associated with changes in biochemical indicators (Hameed *et al.*, 2026; Sajal *et al.*, 2026).

However, evidence concerning the weed-control efficacy and crop safety of reduced-dose mixtures of haloxyfop-R-methyl with selected broadleaf herbicides under alfalfa-growing conditions in northern Ghana remains limited. This gap warrants field-based evaluation of weed suppression and alfalfa growth responses across mixture doses.

Chemical weed management has become popular in agriculture because of its effectiveness and affordability. Because it works well against grasses and broadleaf weeds in legume crops, imazethapyr is one of the most popular post-emergence herbicides (Meighani et al, 2024; Motamedi et al, 2022; Kumar et al, 2025; Govindasamy et al, 2021). However, reliance on a single herbicide for weed management may result in uneven weed control under various field circumstances and may cause environmental issues when greater application rates are used (Yi et al, 2018). To guarantee adequate weed control, farmers typically increase treatment dosages. While repeated use of the same herbicide may result in the development of herbicide resistance, this occurrence may raise environmental concerns as well due to high input of the chemical (Neve and Powles, 2005; Damalas and Koutroubas, 2024). Imazethapyr resistance has been reported in the cultivation of peanuts, soybeans, corn, and cotton (Horak and Peterson, 1995; Heap, 2025). Resistance typically results in higher application rates and dosages, which exacerbates problems with weed control. Therefore, lowering the total amount of herbicide used and finding workable solutions to lessen reliance on the exclusive and frequent use of imazethapyr are essential for the sustainable production of alfalfa. When compared to solo full rate applications, herbicide combinations administered below their individual recommendations can effectively control weeds (Soltani et al, 2007; Yukhymuk et al, 2023; Norsworthy et al, 2012). Despite this, there is still a dearth of information, particularly in Africa, on the effectiveness and crop safety of such lower dose rate combinations in alfalfa. Thus, haloxyfop-R-methyl and four broadleaf herbicides—imazapic, prometryn, imazethapyr, and 2,4-DB—were used in a two-year field trial to evaluate the efficacy of reduced dose herbicide mixtures on post-emergence weeds for weed control and alfalfa performance. The study's goals were to: (a) lower the dosage using herbicide mixtures and (b) find new and better weed management strategies to increase alfalfa yield.

2. Material and Methods

2.1 Study Area

Kassena Nankana Municipality is one of the 275 Metropolitan, Municipal and District Assemblies (MMDAs) in the Upper East Region of Ghana which has 15 Municipalities and Districts. The Guinea Savannah forests are home to the Kassena Nankana Municipality. It is approximately between 10°1' West and 11°10' and 10°3' North. Navrongo is the administrative capital of the Municipality. The Municipality is bordered to the East by Bolgatanga Municipality and Bongo District. The Municipality is bordered by Burkina Faso to the north, West Mamprusi Municipal to the south and Builsa South District, Kassena Nankana West District and Builsa North District to the west respectively. The total land mass of the district is 865 km². The municipality has a unimodal rainfall pattern.

2.2 Plant Material and Field Experiment

Alfalfa seeds were purchased with a germination rate >85%. Seeds were planted in rows 15 cm apart, and within a 5m × 5m block on 15th June, 2024 and 21st June, 2025. The post-emergence herbicide treatments were compared using a randomised complete block design with three replications for both planting seasons. Each replication and the treatments were separated by one meter. The study included an untreated control (water only, weedy) and a weekly hand weeded treatment. In every experimental plot, soil moisture was kept at field capacity throughout the duration of the trial. Six of the herbicides frequently used to manage broadleaf weeds and post-emergence grass in legumes were selected. A flat fan nozzle backpack sprayer that can spray 450L ha^{-1} at 0.3MPa was filled with the recommended dosage of the chosen herbicides. While the alfalfa plants were at roughly the 3-5 trifoliate leaf stage, the herbicides were applied when the major weed species were at the 3–5-leaf stage. Every herbicide treatment was done in under ideal weather conditions, including moderate temperatures, low wind speeds, and no rainfall. Five of the herbicides were determined to be safe for alfalfa plants and effective at controlling weeds. Imazapic, prometryn, imazethapyr, 2,4-DB, and haloxyfop-R-methyl were the five herbicides.

Haloxyfop-R-methyl was then evaluated in combinations with each of the other four herbicides in order to broaden the range of weed control and reduce the overall chemical input. As shown in Table 1, three distinct rates were used for each blend

Table 1. Mixtures of haloxyfop-R-methyl at three mixture rates with four additional herbicides

Mixed formulation	Codes	Dosages (g a. i. ha^{-1})
Haloxyfop-R- methyl + Prometryn	HP1	24.5 + 468.5
	HP2	36.5 + 703.5
	HP3	48.5 + 937.5
Haloxyfop- R-methyl + Imazethapyra	HI1	24.5 + 37.5
	HI2	36.5 + 56.0
	HI3	48.5 + 75.0
Haloxyfop-R- methyl + Imazapic	HF1	24.5 + 36.0
	HF2	36.5 + 56.0
	HF3	48.5 + 72.0
Haloxyfop-R- methyl + 2,4-DB	HB1	24.5 + 337.5
	HB2	36.5 + 506.0
	HB3	48.5 + 675.0

2.3 Effects of Herbicides on Alfalfa Growth

Thirty days after treatment, the effects of herbicides on alfalfa plant height and fresh weight were assessed. Plants were gathered from randomly selected 1 m × 1 m quadrats within each plot. Total dried matter was estimated after oven drying the samples for 24h at 70 °C. The plants receiving the four herbicide combinations and the weedy control and weed-free control were sampled 30 days following the herbicide application for Alfalfa leaf. For the purpose of measuring leaf area, healthy, disease-free leaves were chosen from the fourth node of representative stems. According to Zhou *et al.* (2023), a leaf area meter was used to calculate the leaf area.

2.4 Weed Control Efficacy Assessment

Weed species composition was assessed in three 1 m × 1 m quadrats in each plot, which were randomly placed. All the weeds in each quadrat were identified by species and counted after 30 days of treatment. The efficacy for weed control was computed as:
Weed control efficacy = Number of weeds in weedy - number of weeds in treatments × 100/Number of weeds in weedy.

2.5 Data Analysis

A linear mixed-effect model was used to evaluate the data, employing block nested within year as a random variable and treatment, year, and treatment x year interaction as fixed effects. Initially, the constancy of treatment effects over years was examined using the treatment × year interaction. Since this interaction was not significant, data from different years were combined, and only the pooled treatment means are shown. Prior to analysis, the Shapiro-Wilk test was used to determine the residuals' normality, and Levene's test was used to determine the homogeneity of variance. Tukey's honestly significant difference (HSD) test was used to compare means for significant treatments at $p < 0.05$. SAS 9.4 and Office Excel 2019 were used for statistical analysis.

3. Results

3.1 Effects of Herbicides on Alfalfa Growth

The effects of the applied herbicides varied significantly in their phytotoxicity to alfalfa plants (Table 2). 2,4-DB had the highest alfalfa safety effect, followed by imazapic. The four best performing herbicides, namely 2,4-DB, prometryn, imazapic and imazethapyr were individually mixed with haloxyfop-R- methyl to further evaluate their effectiveness in low dosages.

3.2 Herbicide Weed Control Efficacy

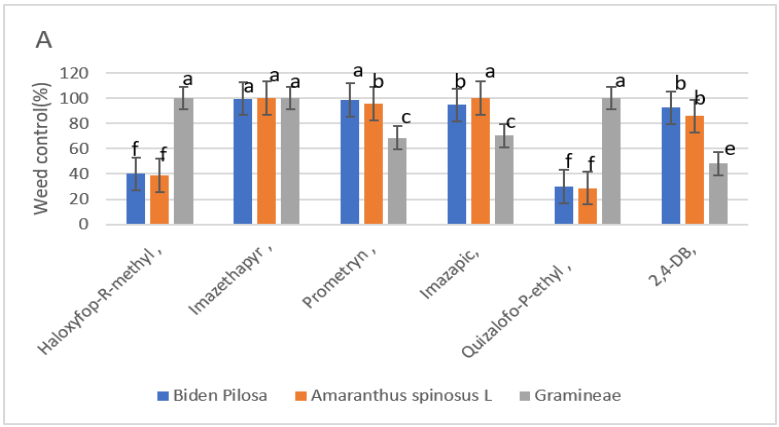
Weed control effectiveness was different among herbicides and weed species. Imazethapyr controlled all the broadleaf weeds (*Biden pilosa* and *Amaranthus spinosus* L.) and grass weeds (>98%) effectively as shown in Fig. 1A. While prometryn and imazapic

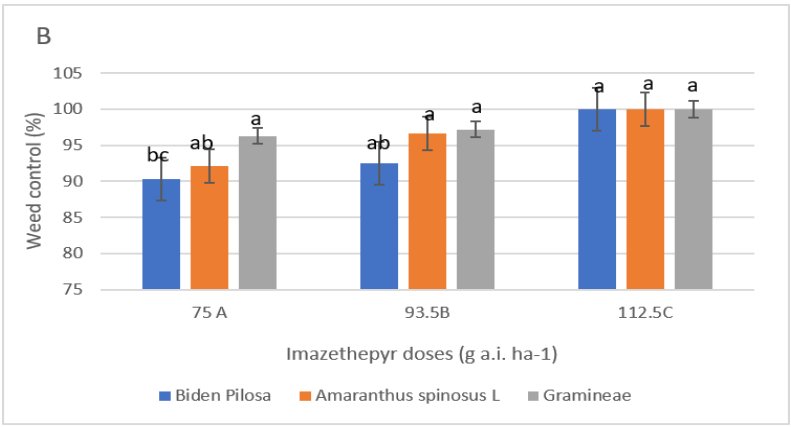
were less effective (>65%) on grass, they were quite efficient (>89%) against broadleaf weeds (Fig. 1A). 2,4-DB had an impact on grass weeds of >42% and broadleaf weeds of >87% (Fig. 1A). On broadleaf species, all four herbicides worked well. The most effective herbicides were found to be imazethapyr, imazapic, prometryn, haloxyfop-R-methyl, and 2,4-DB.

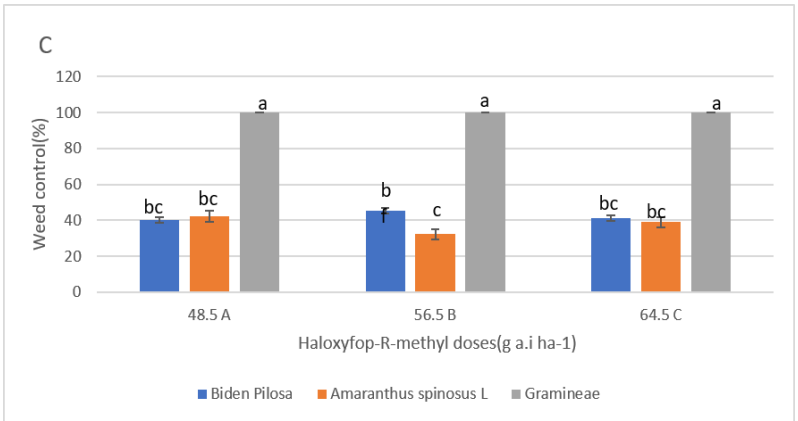
Table 2. Effect of post-emergence herbicide treatment on alfalfa crop

Treatment	Plant Height (cm)	Fresh Weight (kg ha^{-1})	Dry Weight(kg^{-1})
Haloxyfop-R-methyl	36.4±0.6cd	2098.4±149.4bc	356.5±26.4bc
Prometryn	31.0±1.1d	2272.6±140.9b	374.1±17.0b
Imazethapyra	34.8±3.1d	2412.9±167.4b	386.7±22.9ab
Imazapic	29.8±6.5de	2460.7±168.2b	399.4±26.6b
Quizalofo-P-ethyl	37.2±1.2bcd	1994.8±120.2c	326.8±26.4c
2,4-DB	46.3±3.4a	3380.1±227.6a	552.4±34.8a
Weedy	38.7±2.4bc	2168.8±125.2b	360.8±24.7b
Weedy-free	41.9±2.8ab	3146.6±242.6a	518.0±37.6a

Means within the same column with different letters show significant difference at p< 0,05







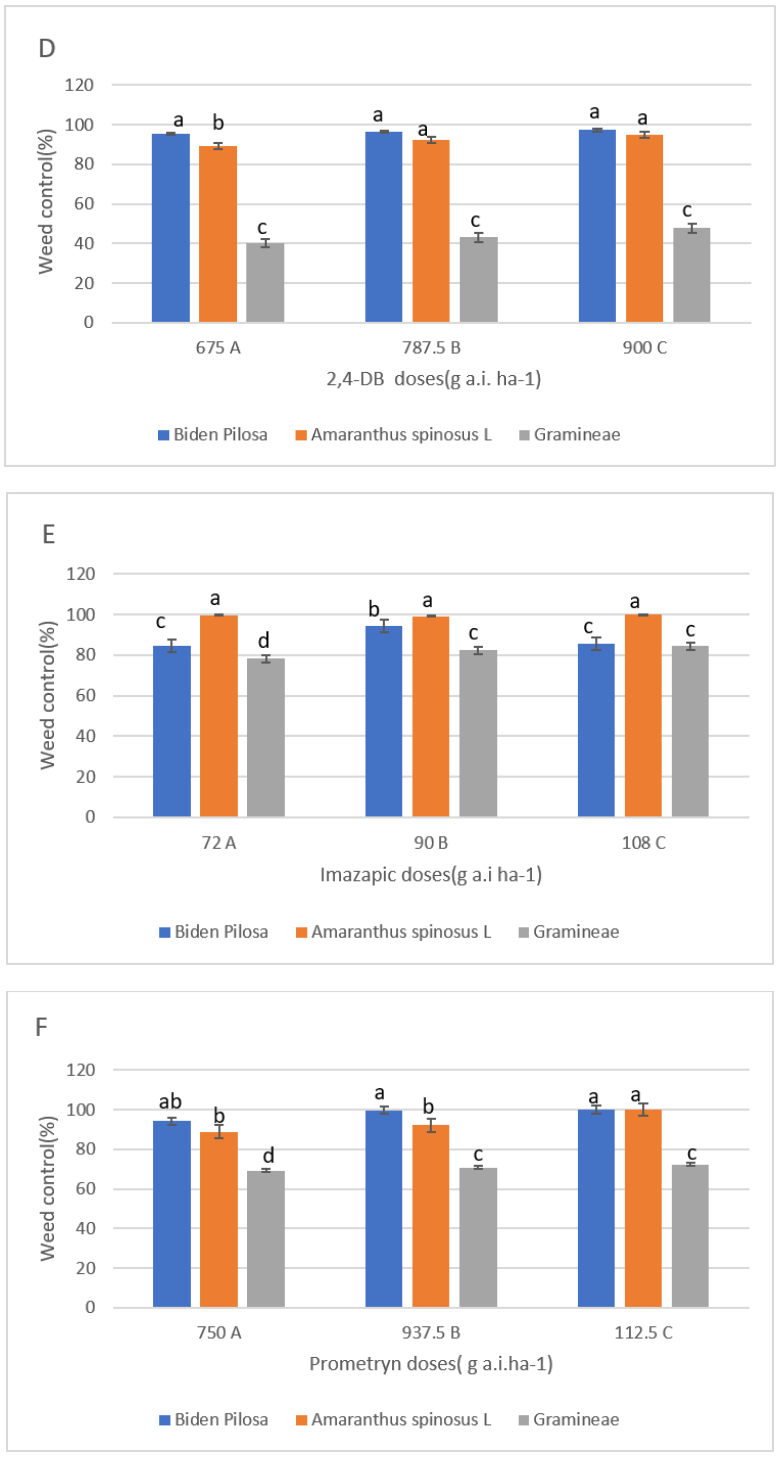


Fig. 1. Effect of post-emergence herbicides on broadleaf weeds and grasses after 30 days of treatment. (A) Effect of post-emergence herbicide on weed control in different treatment s., (B) Weed control of different concentrations of imazethapyr, 75A, 93.5B and 112.5C, concentrations at 75, 93.5 and 112.5 respectively, (C) Haloxyfop-R-methyl, 48.5A, 56.5B and 64.5C, Concentrations at 48.5, 56.5 and 64.5 respectively, (D) 2,4-DB, 675A, 787.5B and 900C, concentrations at 675, 787.5 and 900 respectively, (E) imazapic, 72A, 90B and 108C, concentrations at 72, 90 and 108 respectively, (F) prometryn, 750A, 937.5B and 112.5C, concentrations at 750, 937.5 and 112.5 respectively

3.3 Effects of Different Post-Emergence Herbicide Doses on Weed Control and Alfalfa Growth

In comparison to the two higher doses, imazethapyr administered at 75 g a. i. ha^{-1} produced higher alfalfa fresh and dry weight while controlling both broadleaf and grass weeds by >90% (Fig. 1B, Table 3). More than 98% of grass weeds were controlled by

haloxyfop-R-methyl at 48.5 g a. i. ha^{-1} (Fig. 1C). At 675 g a. i. ha^{-1}, 2,4-DB had >92% of both broadleaf weeds and >43% of grass control (Fig. 1D). Imazapic at 72 g a. i. ha^{-1} produced more alfalfa biomass than higher rates and >95% control of *Amaranthus spinosus* L, *Biden pilosa,* and grasses by >82% (Fig. 1E, Table 3). Prometryn maintained >94% control of *Biden pilosa* and >88% control of *Amarantus spinosus* L. at 750 g a. i. ha^{-1}, although grasses control was lower (>69%) (Fig. 1F). Alfalfa fresh and dry weights at this rate did not differ significantly from those at the two higher rates (Table 3). Therefore, for imazethapyr, imazapic, prometryn, 2,4-DB, and haloxyfop-R-methyl, the optimal dosages were 75, 72, 750, 675, and 48.5 g a. i. ha^{-1}, respectively.

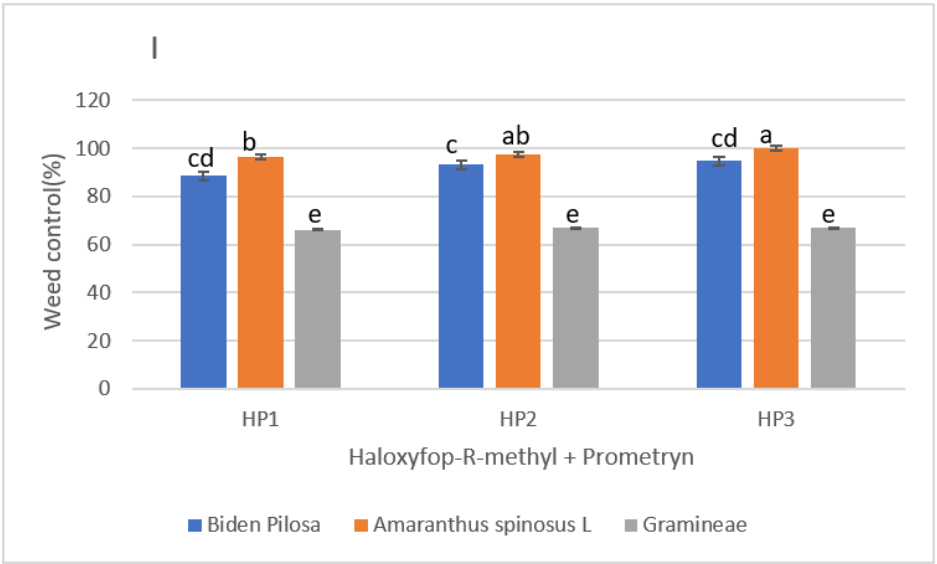
Table 3. Effect of different post-emergence herbicides doses on alfalfa crop

Treatment	Dosage (g a. i. ha^{-1})	Plant Height(cm)	Fresh Weight (kg ha^{-1})	Dry Weight (kg ha^{-1})
Imazethapyr	75	44.6±2.6ab	3864.5±206.8b	973.6±36.7b
	93.5	43.2±1.8ab	3571.6±182.6bc	879.6±39.1bc
	112.5	40.6±2.2bc	3492.8±152.2c	843.8±33.8c
Haloxyfop-R-methyl	48.5	39.4±1.8de	1763.4±86.4g	432.4±20.2h
	56.5	41.2±2.6cd	1790.7±89g	446.8±19.3h
	64.5	43.7±2.1cd	2489.4±144.6e	721.6±33.2ef
2,4-DB	675	46.2±2.2ab	4821.6±234.1a	1194.2±48.2a
	787.5	49.6±3.4a	4792.8±201.6a	1190.4±50.1a
	900	39.4±1.6cd	2654.4±148.6e	652.8±24.6de
Imazapic	72	44.2±1.8bc	3580.6±145.2c	896.2±59.1c
	90	43.6±2.6bc	3501.4±162.2c	871.4±42.9c
	108	36.4±2.8e	2246.7±130.4f	546.6±22.4g
Prometryn	750	43.4±2.4bc	2890.6±124.6d	689.6±24.5d
	937.5	42.2±2.7abc	2901.3±127.4d	728.4±26.4d
	112.5	36.4±1.8de	2436.4±129.2ef	598.6±29.2f
Weedy	-	42.3±1.2bc	1780.2±92.4g	458.4±18.6h
Weedy-free	-	47.6±2.4a	4942.4±248.6a	1286.6±54.6a

Means within the same column with different letters show significant difference at p< 0,05

3.4 Effects of Post-Emergence Herbicide Mixtures on Weed Control and Alfalfa Growth

Biden pilosa and *Amaranthus spinosus* L. were controlled by more than 80% by imazapic, prometryn, 2,4-DB, and imazethapyr alone (Fig. 1). But only grass weeds responded well to haloxyfop-R-methyl (Fig. 1A and C). To widen the weed control scope and lower the overall amount of herbicide used, holoxyfop-R-methyl was evaluated in binary combination with the four broadleaf control herbicides. These mixes were then evaluated for crop safety and weed control effectiveness. In comparison to the weed-free control, the combination of haloxyfop-R-methyl + imazapic dramatically decreased the fresh weight of alfalfa by 35–40% and the dry weight by 37–45% (Table 4). Similarly, haloxyfop-R-methyl + prometryn decreased the study crop's fresh weight by 20–32% and its dry weight by 22–37% (Table 4). Haloxyfop-R-methyl + imazethapyr, on the other hand, exhibited a mixed dose response; a higher application dose resulted in to a drop in plant height and an increase in fresh and dry weight. The leaf area was 10% greater, the crop biomass at 36.5 + 56.5 g a. i. ha-1 was not substantially different from the weed-free control, and the weed control was more than 98% for both grass and broadleaf weeds (Table 4, Fig. 2 II). Increasing the herbicide mixture's dosage decreased plant height but had no effect on the crop's biomass accumulation (haloxyfop-R-methyl + 2,4-DB mixture). The mixture at a dosage of 36.5 + 506.5 enhanced the leaf area by 8% while the crop's fresh and dry weights were approximately equivalent to those in the weed-free control (Table 4).



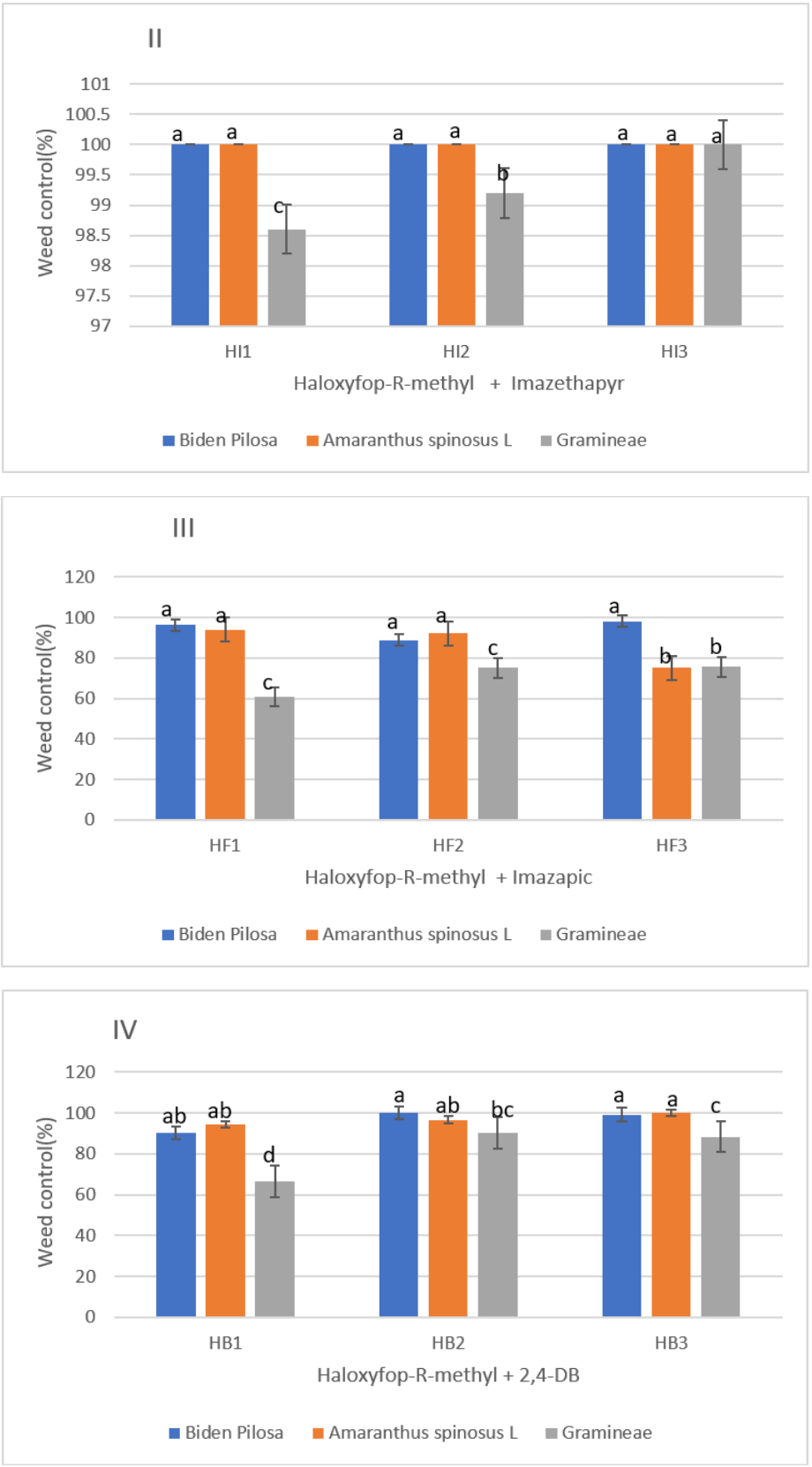


Fig. 2. Effect of different herbicide mixtures on weed in different treatments after 30 days. Weed control of different doses of Haloxyfop-R-methyl + prometryn (I), Haloxyfop-R-methyl + imazethapyr (II), Haloxyfop-R-methyl + imazapic (III), Haloxyfop-R-methyl + 2,4-DB (IV). Means with different letters show significance at p< 0.05

Table 4. Effects of post-emergence herbicide mixing on alfalfa

Mixed Formulation	Codes	Dosage (g a.i. ha^{-1})	Plant Height (cm)	Fresh Weight (kg ha^{-1})	Dry Weight (kg ha^{-1})	Leaf Area(mm^2)
Haloxyfop-R-methyl +Prometryn	HP1	24.5 + 468.5	26.7±1.4g	3806.2±132.6e	982.6±48.6e	349.8±15.4g
	HP2	36.5 +703.5	22.4±0.8h	4187.5±162.4d	1052.4±52.4de	238.6±11.8h
	HP3	48.5 +973.5	21.8±1.5h	4420.5±158.6d	1098.±56.4d	198.5±12.8i
Haloxyfop-R-methyl + Imazethapyr	HI1	24.5+ 37.5	38.6±1.6bc	5468.2±246.2c	1321.8±68.2c	493.6±21.4bcd
	HI2	36.5+ 56.5	35.2±1.8cd	6224.6±258.4ab	1562.6±72.1ab	652.4±32.1a
	HI3	48.5 +75.0	34.3±2.6d	6628.8±264.1a	1706.2±79.2a	494.6±17.4cde
Haloxyfop-R-methyl + Imazapic	HF1	24.5 + 36.0	29.8±1.6f	3671.2±139.6f	852.7±28.8f	478.4±18.2de
	HF2	36.5 + 54.0	32.6±2.7de	3782.8±142.3f	878.2±34.6f	462.6±17.6ef
	HF3	48.5 + 72.0	32.9±1.8de	3798.4±144.8f	882.4±43.8f	462.6±17.6ef
Haloxyfop-R-methyl + 2,4-DB	HB1	24.5 + 337.5	43.1±2.6a	5589.6±198.2bc	1562.6±82.1ab	486.2±18.2de
	HB2	36.5 + 506.5	40.2±1.6b	5856.2±204.6ab	1692.7±66.4ab	693.3±34.3a
	HB3	48.5 + 675.0	36.8±1.8cd	6984.6±280.4a	1645.2±72.6ab	5021.6±18.6bc
Weedy	-	-	34.4±1.8ef	2482.4±160.3g	629.6±40.2g	526.1±19.4f
Weed-free	-	-	48.6±1.4a	5670.2±284.6ab	1562.4±60.8ab	642.8±22.4b

Means within the same column with different letters show significant difference at p< 0,05

4. Discussion

Alfalfa seedlings grow slowly in the early stages and are susceptible to competition from weeds, which frequently invade and retard alfalfa establishment (Dillehay and Curran, 2010, Yang et al,2024). Weed control continues to be a problem in the production of alfalfa. Imazethpyr is currently the most popular herbicide for post-emergence control of alfalfa. Farmers will frequently apply more herbicide to achieve effective control of weeds. These practices may have long-term adverse environmental impacts and could also be a concern regarding potential toxicological impacts on human and animal health. Therefore, relying on the same herbicide application method repeatedly could increase selection pressure on weeds and result in weed resistance evolution.

Imazethapyr, when applied alone, effectively controlled a broad spectrum of weeds without reducing alfalfa yield compared with the weed-free control in the present study (Fig. 1B; Table 2). These findings are consistent with previous field observations involving orchard grass (*Dactylis glomerata*), where herbicide application was undertaken at the seedling stage, often around the first cutting of alfalfa (Curran *et al.*, 1999). Cudney and Lanini (2000) reported that post-emergence application of imazethapyr at rates of 100–150 g a.i. ha^{-1} substantially reduced the number of *Cuscuta campestris* seedlings in alfalfa fields when the initial infestation level was low. Similarly, Noroozi *et al.* (2022) demonstrated that imazethapyr applied at 100 g a.i. ha^{-1} was more effective than several other herbicides in reducing weed density while maintaining alfalfa forage yield. Interestingly, the present study indicated that the effective application rate of imazethapyr in alfalfa could be reduced by 25%, to 75 g a.i. ha^{-1}, compared with the rates reported in previous studies. This reduced rate is consistent with the recommended application rate in Ontario, Canada (Soltani *et al.*, 2007).

Herbicide mixtures are widely employed in intensive agricultural systems to broaden the spectrum of weed control, enhance efficacy, reduce application rates and associated costs, improve crop safety, minimise persistent herbicide residues in soil and mitigate the development of herbicide resistance (Gandini *et al.*, 2020; Ndikuryayo & Yang, 2023). These advantages are particularly relevant when individual herbicides are applied at lower concentrations in mixtures than those used in conventional single-herbicide applications (Ndikuryayo & Yang, 2023). In the present study, the combined application of imazethapyr and haloxyfop-R-methyl effectively broadened the spectrum of weed control while reducing the overall herbicide input (Fig. 2 II; Table 3). Haloxyfop-R-methyl inhibits acetyl-CoA carboxylase, a key enzyme involved in fatty acid biosynthesis (Alok *et al.*, 2025). In this study, haloxyfop-R-methyl exhibited high selectivity, achieving more than 98% control of grass weeds without causing appreciable injury to alfalfa plants (Fig. 1C; Tables 2 and 3). The combination of haloxyfop-R-methyl and imazethapyr demonstrated improved efficacy, particularly at the lower application rates of 36.5 + 56.5 g a.i. ha^{-1}. This treatment did not substantially reduce alfalfa yield compared with the weed-free control. Furthermore, it maintained effective control (more than 99%) of major broadleaf and grass weeds while achieving at least a 25% reduction in total herbicide input relative to the recommended application rates for individual herbicide treatments.

Additionally, a combination of 2,4DB and haloxyfop-R-methyl showed an improvement at a rate of 36.5 + 506.5 g a. i. ha^{-1}. The application of 2,4DB chemical is generally recommended in alfalfa to control a large number of annual and perennial broadleaf dicotyledonous weeds, and some species of the Thistle and Brassicaceae families (Charles et al, 2000, Raoofi and Alebrahim,2017). This study confirms earlier reports of the crop safety and effectiveness of 2,4-DB against major broadleaf weeds (36), in that 2,4-DB applied at 675 g a. i. ha^{-1} controlled >90% of the broadleaf weeds without reducing yields of alfalfa. The mixture of 2,4-DB and haloxyfop-R-methyl (36.5 + 506.5 g a. i. ha^{-1}) produced >90% control of broadleaf weeds and approximately 80% of the grass weed control without causing any significant decrease in yields of alfalfa compared to the weed free control. At least 25% reduction in the recommended dose of herbicide was needed to achieve these results as compared to the conventional single herbicide application. These ‘low- dose' mixtures should not be used on a regular basis, but as rotation mixtures. The weed control of the mixtures studied produced an acceptable yield of alfalfa crop.

5. Conclusions

The two-year field investigation demonstrated that selected reduced-dose herbicide mixtures provided effective weed suppression while maintaining satisfactory alfalfa growth and biomass production under the evaluated conditions. Among the treatments, haloxyfop-R-methyl + imazethapyr at 36.5 + 56.5 g a.i. ha^{-1} provided effective control of the evaluated broadleaf weeds and grasses, with crop biomass comparable to that of the weed-free treatment. Similarly, haloxyfop-R-methyl + 2,4-DB at 36.5 + 506.5 g a.i. ha^{-1} provided satisfactory broadleaf weed control and maintained alfalfa biomass. In contrast, mixtures containing imazapic and prometryn generally resulted in lower biomass accumulation relative to the weed-free control. The findings suggest that carefully selected herbicide combinations may offer an alternative to the repeated application of imazethapyr alone. However, the suitability of these combinations should be considered in relation to the weed species present, treatment dose and crop response. Further evaluation of rotational herbicide strategies, forage quality and longer-term crop performance is warranted before broader recommendations are made.

6. Limitations

This investigation was conducted over two growing seasons at a single field location, which may limit the generalisability of the findings to other environments, soil conditions and weed communities. Treatment responses were assessed 30 days after herbicide application; consequently, the findings do not establish longer-term weed suppression or crop safety. The evaluation focused on weed-control efficacy and selected alfalfa growth and biomass parameters. Forage nutritional quality, herbicide residues and resistance development were not evaluated. Further multi-location and longer-term studies are required to establish the consistency of treatment performance.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. ChatGPT, Claude and Perplexity were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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