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Weed control efficacy and dry bean response to preemergence herbicide incorporation timing

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Abstract

Field experiments were conducted in 2021 and 2022 to evaluate the effect of irrigation timing on *S*-ethyl-*N*,*N*-dipropylthiocarbamate (EPTC), flumioxazin, pyroxasulfone, and flumioxazin + pyroxasulfone weed control efficacy and safety in dry bean (*Phaseolus vulgaris* L.). Treatments consisted of EPTC (3430 g ai ha^{-1}), flumioxazin (53.6 g ai ha^{-1}), pyroxasulfone (119 g ai ha^{-1}), and flumioxazin + pyroxasulfone (70.4 + 89.3 g ai ha^{-1}) incorporated with overhead irrigation at 1, 4, and 8 days after herbicide treatment (DAT). A nontreated and hand-weeded check were included for comparison. Delaying irrigation until 8 DAT resulted in 11% and 19% injury in the pyroxasulfone and flumioxazin + pyroxasulfone treatments, respectively, but the crop recovered within 5 weeks after treatment. Delaying irrigation until 8 DAT increased total weed dry weight by 52%. Generally, flumioxazin + pyroxasulfone provided better weed control compared to flumioxazin or pyroxasulfone applied alone. Irrigation timing did not influence dry bean yield. Seed yield was 160 kg ha^{-1} in the nontreated check and 2521 kg ha^{-1} in the hand-weeded check. Seed yield in the flumioxazin + pyroxasulfone treatment (2425 kg ha^{-1}) was similar to the hand-weeded check. Flumioxazin + pyroxasulfone provided very good weed control with acceptable crop safety. While irrigation timing may play a role in flumioxazin or pyroxasulfone injury, other soil and environmental factors may influence dry bean response to these herbicides.

1 | INTRODUCTION

Dry edible bean (*Phaseolus vulgaris* L.) is a high-value crop with major economic significance for growers, contributing more than \$5.7 billion to the US economy in 2021 (USDA-NASS, 2022). It is a herbaceous annual that is highly vulnerable to weed interference, because of its short stature, particularly in the early stages of vegetative development (Ghamari & Ahmadvand, 2012; LeQuia et al., 2021). It was reported that dry bean yield would be reduced by 208 kg ha^{-1} for every 1000 kg of weeds present (Wilson et al., 1980). Estimates from North America have shown that if weeds are left uncontrolled, a potential yield loss of 71% could occur, which translates into more than \$600 million in value (Soltani, Dille, et al., 2018). Aside from yield loss, weeds can also hinder the efficiency of bean harvesting and stain the beans, which greatly lowers the quality of dry bean.

In dry bean production systems, major broadleaf weeds that interfere with production are redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters (*Chenopodium album* L.), and hairy nightshade (*Solanum physalifolium* Rusby) (LeQuia et al., 2021). Herbicides remain the most important

Abbreviations: DAT, days after herbicide treatment; EPTC, *S*-ethyl-*N*,*N*-dipropylthiocarbamate; WAT, weeks after herbicide treatment.

practice for controlling these weeds. However, there is a relatively limited number of herbicides for broadleaved weed control in dry beans compared to other crops. Thus, there is a need to identify other effective herbicides that are safe to use in dry bean.

It has been shown that herbicides, such as flumioxazin and pyroxasulfone, could either be safe or provide good residual weed control in dry bean (Adjesiwor et al., 2020; Soltani et al., 2020; Taziar et al., 2016). Flumioxazin is an *N*-phenylphthalimide herbicide that inhibits protoporphyrinogen oxidase (Niekamp et al., 1999), while pyroxasulfone is an isoxazoline herbicide that inhibits very long chain fatty acid synthesis in broadleaf weeds (Tanetani et al., 2009). These herbicides often result in crop injury and stand loss, thereby reducing yield. Soltani et al. (2005) reported that flumioxazin produced greater injury to dry beans when applied preemergence than pre-plant incorporated, and the injury was greater in the market classes of black and white beans than to cranberry and kidney beans. Injury induced by pyroxasulfone was also documented by Soltani, Shropshire, et al. (2018), describing pyroxasulfone as the herbicide that caused the most injury of four studied group 15 herbicides on dry beans, reducing plant height by up to 15% and seed yield by up to 17%.

Injury from these herbicides is often due to the timing of incorporation rainfall or irrigation. Severe precipitation following the preemergence application of herbicides to crops may cause increased bioavailability of the herbicide, causing increased herbicide uptake and greater crop damage. High rainfall at the time of dry bean emergence is also reported to make them more susceptible to crop injury because rain causes herbicides like flumioxazin to splash from the soil surface on to the crop's hypocotyls, cotyledons, and growth point, making the crop more susceptible to damage (Soltani et al., 2005). In fact, new labels for flumioxazin state that high winds, splashing, heavy rains, and cool temperatures near the time of dry bean emergence may increase flumioxazin injury (Valent, 2021). A delay in rainfall/irrigation allows for the dry bean crop to emerge prior to the herbicide infiltrating the soil, resulting in the splashing of herbicide onto emerged beans during irrigation/rainfall events (Yoshida et al., 1991). This was confirmed in another study that found that a 7-day delay in flumioxazin incorporation increased injury compared to a 4-day delay (Priess et al., 2020). The potential of crop injury of flumioxazin also increases with cool temperatures and high soil moisture after herbicide application (Niekamp et al., 1999; Soltani et al., 2005; Taylor-Lovell et al., 2001). Adjesiwor et al. (2020) found that high soil moisture near the time of pinto bean emergence could explain the high crop injury when sprayed with flumioxazin. This suggests that in semi-arid regions where dry bean is grown under irrigation, the timing of irrigation after herbicide application can be used to reduce injury from herbicides, such as flumioxazin. In dry bean, *S*-ethyl-*N*,*N*-dipropylthiocarbamate (EPTC) is a preemergence and early postemergence thiocarbamate herbicide used to control broadleaves, grasses, and sedges (US EPA, 1999). It is one of the widely used herbicides and it requires immediate incorporation (mechanically or with irrigation water) after application to be effective (Gowan Company, 2022). Thus, EPTC was included in this study for comparison. The objective of this study was to evaluate the effect of irrigation timing on EPTC, flumioxazin, pyroxasulfone, and flumioxazin + pyroxasulfone weed control efficacy and safety in dry edible bean.

Core Ideas

- Delaying irrigation until 8 days after herbicide application resulted in 11%–19% crop injury.
- Delaying irrigation until to 8 days after herbicide application reduced stand density by up to 14%.
- Delaying irrigation until 8 days after herbicide application increased total weed dry weight by 52%.
- Flumioxazin + pyroxasulfone provided good weed control with acceptable crop safety.
- Irrigation timing did not influence dry bean seed yield.

2 | MATERIALS AND METHODS

Field experiments were conducted at the University of Idaho Kimberly Research and Extension Center (42.549877°, −114.349615°) in 2021 and 2022 to evaluate the effect of irrigation timing on EPTC, flumioxazin, pyroxasulfone, and flumioxazin + pyroxasulfone weed control efficacy and safety on dry edible bean. The soil was a Portneuf silt loam (coarse-silty, mixed, superactive, and mesic Durinodic Xeric Haplocalcid) with 22% sand, 72% silt, and 6% clay. In 2021, the soil had a pH of 8.4, organic matter (OM) of 1.49%, and a cation exchange capacity (CEC) of 17.4 meq 100 g^{-1} soil. In 2022, the soil had a pH of 8.3, OM of 1.21%, and CEC of 17.7 meq 100 g^{-1} soil.

Othello pinto bean, a medium-sized market class and one of the widely grown market classes (Burke et al., 1995), was planted in 56-cm rows at a density of about 240,000 seeds ha^{-1} on May 29, 2021 and June 2, 2022 using a Great Plains 3P806NT drill (Great Plains Ag). The experiment was a 3×4 factorial arranged in a randomized complete block with four replications. Factor A (irrigation timing) had three levels: overhead irrigation (2.5 cm of water) at 1, 4, and 8 days after herbicide treatment (DAT) to incorporate herbicides (Table 1; Figure 1). Factor B (herbicide) was composed of four

FIGURE 1 Sprinkler irrigation setup that enabled randomization of irrigation timing treatments, Kimberly, ID. Herbicides were incorporated with 2.5 cm of sprinkler irrigation water.

TABLE 1 Weed control treatments, herbicide rates, and irrigation timings used in the study in 2021 and 2022 at Kimberly, ID.

Herbicide and rate (g ai ha^{-1})	Irrigation timing[a] (days after herbicide treatment)
EPTC (3430) [b]	1
Flumioxazin (53.6) [c]	4
Pyroxasulfone (119) [d]	8
Flumioxazin (70.4) + pyroxasulfone (89.3) [e]	

[a]Herbicides were incorporated with 2.5 cm of sprinkler irrigation water.
[b]Eptam7E (Gowan Company).
[c]Valor SX (Valent).
[d]Zidua (BASF).
[e]Fierce EZ (Valent).

levels: EPTC (3430 g ai ha^{-1}), flumioxazin (53.6 g ai ha^{-1}), pyroxasulfone (119 g ai ha^{-1}), and flumioxazin + pyroxasulfone (70.4 + 89.3 g ai ha^{-1}). A nontreated (weedy) check and hand-weeded (weed-free) check were included for comparison. The herbicide rates used are the labeled use rates for the products. EPTC was included for comparison with the other herbicide treatments because it requires immediate incorporation (mechanically or with irrigation water) after application (Gowan Company, 2022). Although the flumioxazin label does not state the ideal incorporation time to reduce dry bean injury, it is recommended that the herbicide is incorporated within 2 days for certain crops (e.g., fruit trees) (Valent, 2021). The herbicide labels for pyroxasulfone and flumioxazin + pyroxasulfone do not specify any recommended time to incorporate the herbicides after preemergence application (BASF, 2017; Valent, 2022). The irrigation timing treatments were applied using a custom-built sprinkler irrigation system that allowed complete treatment randomization (Figure 1). Individual plot size was 4.6 × 9.1 m. Herbicides were applied using a CO_2-pressurized bicycle sprayer delivering 144 L ha^{-1} at 207 kPa with TeeJet DG11002 nozzles the same day dry bean was planted. Bentazon (700 g ai ha^{-1}) + imazamox (32 g ai ha^{-1}) was applied to all plots except the nontreated and hand-weeded check 6 weeks after preemergence herbicide application. The postemergence treatment contained urea ammonium nitrate (UAN 28-0-0, Agrium) at 2.5% v/v + nonionic surfactant (Preference, WinField Solutions) at 0.25% v/v.

Flags were placed 3 m apart within the two center rows in each plot after bean emergence and beans were counted weekly for 4 weeks to evaluate any stand loss due to herbicide injury. Weed control efficacy (by weed species) was visually assessed in each plot on a scale of 0%–100%, with 0% being no weed control and 100% being complete weed control. In 2022, a quadrat (0.5 m^2) was randomly placed within each plot, and aboveground weed biomass within the quadrat area was clipped using rice knives and ovendried to a constant weight at 60°C for 72 h. Dry bean yield was assessed by harvesting 3 m within the middle two rows in 2021 and 2022. Plants were harvested on September 15 and September 27 in 2021 and 2022, respectively.

2.1 | Data analysis

All data analyses were performed in R statistical language version 4.2.1 (R Core Team, 2023) using the LMERTEST and EMMEANS packages (Kuznetsova et al., 2017; Lenth, 2022). Weed control, weed biomass, dry bean density, and yield

TABLE 2 Cumulative monthly precipitation and average air temperature in 2021 and 2022 and the 30-year average near the study site at Kimberly, ID.

	Mean air temperature (˚C)			Precipitation (mm)		
Month	2021	2022	30 years	2021	2022	30 years
June	21.7	17.5	17.8	0.5	5.1	16.9
July	24.4	24.0	22.2	2.5	1.0	5.1
August	20.1	23.7	20.9	14.2	2.5	9.9
September	16.2	18.5	16.1	7.1	1.0	10.8
Annual	10.4	8.8	9.5	208	181	257

Note: Data from the AgriMet cooperative agricultural weather network database (https://www.usbr.gov/pn/agrimet/agrimetmap/twfida.html).

were analyzed using a mixed-effects model, where irrigation timing, herbicide, and irrigation timing × herbicide were considered fixed effect, and block and year were considered random effects. Estimated marginal means were calculated from the model, and Tukey's honest significant difference (HSD) was used for treatment comparisons at $\alpha = 0.05$ using the EMMEANS and MULTCOMP package (Hothorn et al., 2008; Lenth, 2022). Data analyses figures were plotted using the *ggplot* function of the TIDYVERSE package (Wickham et al., 2019).

3 | RESULTS AND DISCUSSION

The Kimberly, ID, area is semi-arid, characterized by cold winter and spring, and warm and dry summer (Table 2). Dry bean production is heavily reliant on irrigation to supplement precipitation. Air temperatures were slightly warmer in 2021 than in 2022. Further, precipitation in 2021 was greater than in 2022 but precipitation in both years was less than the 30-year average. However, the difference in moisture between 2021 and 2022 was negated through irrigation. No rainfall was received within 8 days after herbicide application in both years.

There was herbicide by irrigation timing interaction effect on crop injury 3 weeks after herbicide application (Figure 2). Delaying irrigation until 8 DAT resulted in 11% and 19% crop injury in the pyroxasulfone and flumioxazin + pyroxasulfone treatments, respectively. Previous research has shown that pyroxasulfone applied preplant incorporated caused 12%–14% injury to various dry bean cultivars within 4 weeks after treatment (Soltani, Shropshire, et al., 2018). Irrigation timing did not affect the crop injury for flumioxazin. This contradicts previous findings that a delay in rainfall or irrigation and high soil moisture near the time of dry bean emergence could explain the high crop injury when sprayed with flumioxazin (Adjesiwor et al., 2020; Priess et al., 2020). At 5 weeks after treatment, crop injury was 3%–4%, which was not significantly influenced by herbicide or irrigating timing (Table 3). It is very common for dry bean to recover quickly from preemergence herbicide injury. For example, pyroxasulfone caused 12%–14% injury to various dry bean market classes within 4 weeks after treatment but injury was less than 5% after 8 weeks (Soltani, Shropshire, et al., 2018). While irrigation or rainfall timing may play a role in flumioxazin injury, it appears there are other important soil and environmental factors that may influence dry bean response to flumioxazin. Soltani et al. (2005) showed that different market classes of dry bean respond differently to the preemergence application of flumioxazin. The authors reported that small-seeded market classes (white and black beans) were more sensitive to flumioxazin compared to larger-seeded market classes (cranberry and kidney beans). Thus, market classes, such as great northern and pintos, might show different sensitivity to flumioxazin. It was reported that flumioxazin, when used preemergence at 140 g ha^{-1}, produced up to 34% injury and decreased plant height by 23% –28% and shoot dry weight by 35%–39% in black and white beans. The rate of flumioxazin used in this study (53.6 g ai ha^{-1}) was far less than the rate (140 g ai ha^{-1}) used by Soltani et al. (2005). This might also explain why flumioxazin did not cause very high crop injury in this study. While herbicide rainfall or irrigation timing after the application of flumioxazin or pyroxasulfone may play a role in crop injury, it appears there are other important soil and environmental factors that may influence dry bean response to these herbicides. For example, soil properties, such as texture, pH, and organic matter, may affect preemergence herbicide uptake and crop injury (Alister et al., 2008; Kurtenbach et al., 2019; Sebastian et al., 2017). The effects of these factors on results in this study remain unclear as the sites used in the studies had similar soil properties. Flumioxazin is adsorbed to fine-textured soils and soils with high organic matter (Alister et al., 2008). The soils at the study sites had 6% clay and 1.2%–1.5% organic matter. This may have reduced flumioxazin adsorption and later release during crop emergence to cause dry bean injury. This may explain the low injury from flumioxazin in this study. In a previous study that observed significant crop injury from flumioxazin, organic matter at the study sites was 3.4%–4.6%, which was far greater than the organic matter at the sites in the present study (Soltani et al.,

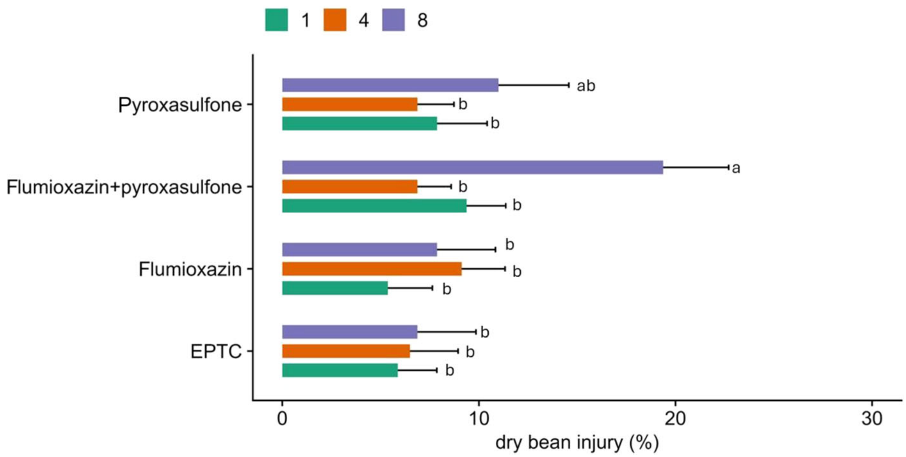

FIGURE 2 Dry bean injury at 3 weeks after herbicide application by the interaction effect of herbicide × irrigation timing ($p = 0.02$). Herbicides were incorporated with 2.5 cm of sprinkler irrigation water at 1, 4, and 8 days after herbicide treatment application (DAT). EPTC, *S*-ethyl-*N*,*N*-dipropylthiocarbamate. Bars followed by the same letters are not different at the 0.05 probability level according to Tukey's HSD.

TABLE 3 Weed control efficacy and crop injury from herbicide treatments at 3 and 5 weeks after herbicide treatment (WAT) in 2021 and 2022, Kimberly, ID.

	3 WAT (%)				5 WAT (%)				
Factor	CLQ	RRPW	HNS	BYG	CLQ	RRPW	HNS	BYG	Injury (%)
Irrigation timing (days)									
1	88	86	90	89	70	72a	76a	74a	3.7
4	88	87	90	92	68	68ab	75ab	72ab	3.3
8	85	84	87	85	58	57b	61b	59b	3.7
p-value	0.54	0.63	0.54	0.07	0.10	0.02	0.02	0.03	0.72
Herbicide									
EPTC	86	85	87	88	53b	50c	58b	59b	3.6
Flumioxazin	87	84	86	88	74a	72ab	79a	73ab	3.6
Pyroxasulfone	82	83	85	87	51b	55bc	59b	61b	3.5
Flumioxazin + pyroxasulfone	82	92	94	91	83a	86a	86a	82a	3.8
p-value	0.09	0.06	0.10	0.74	<0.001	<0.001	<0.001	0.004	0.97
Irrigation × herbicide	0.36	0.60	0.70	0.50	0.34	0.10	0.11	0.13	0.44

Note: Within a column, means followed by the same letters are not different at the 0.05 probability level according to Tukey's HSD. Weeds evaluated include the following: CLQ, common lambsquarters (*Chenopodium album*); RRPW, redroot pigweed (*Amaranthus retroflexus*); HNS, hairy nightshade (*Solanum physalifolium*); BYG, barnryardgrass (*Echinochloa crus-galli*).
Abbreviation: EPTC, *S*-ethyl-*N*,*N*-dipropylthiocarbamate.

2005). In addition, high moisture at the time of crop emergence increases crop injury from preemergence herbicides (Kurtenbach et al., 2019). Precipitation within 3–4 weeks after herbicide application was 0.5 mm in 2021 and 5.1 mm in 2022 (Table 2). This is a very low amount of moisture and may have resulted in low crop injury observed in the study.

Weed control efficacy was not significantly influenced by herbicide or irrigation timing treatments at 3 weeks after treatment (Table 3). However, weed control efficacy was influenced by treatments at 5 weeks after treatment. Irrigation timing did not affect *Chenopodium album* control. *Amaranthus retroflexus*, *Solanum physalifolium*, and barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] control were reduced when irrigation was delayed until 8 days after herbicide application. This was driven primarily by the poor efficacy of EPTC at the 8-day irrigation timing. Delaying irrigation until 8 days reduced EPTC efficacy by 48%–59%, which was because EPTC is highly volatile and needs to be incorporated immediately after treatment (Gowan Company, 2022).

Flumioxazin and flumioxazin + pyroxasulfone were generally more effective for *Chenopodium album*, *Amaranthus retroflexus*, *Solanum physalifolium*, and barnyardgrass

TABLE 4 Weed density and biomass as influenced by herbicide treatments at 5 weeks after herbicide treatments and irrigation timing in 2021 and 2022, Kimberly, ID.

	Weed density (m^{-2})					Weed dry weight ($g\ m^{-2}$)				
Factor	**CLQ**	**RRPW**	**HNS**	**BYG**	**Total**	**CLQ**	**RRPW**	**HNS**	**BYG**	**Total**
Irrigation timing (days)										
1	11b	6	8	12	37	60	21	0.8	14	96b
4	16ab	8	8	13	45	76	25	1.8	11	114ab
8	21a	9	9	14	53	90	37	0.4	19	146a
p-value	0.04	0.73	0.96	0.80	0.11	0.13	0.48	0.20	0.66	0.02
Herbicide										
EPTC	24a	18a	13a	5b	61a	84b	54a	1.5ab	9	147ab
Flumioxazin	9b	3b	7ab	21a	40ab	60bc	38ab	0.1b	20	119b
Pyroxasulfone	25a	7b	11a	12ab	55a	142a	13ab	2.3a	18	176a
Flumioxazin + pyroxasulfone	6b	1b	1b	15ab	23b	15c	5b	0b	11	32c
p-value	<0.001	<0.001	<0.001	0.008	<0.001	<0.001	0.01	0.04	0.57	<0.001
Irrigation × herbicide	0.18	0.85	0.90	0.31	0.61	0.55	0.99	0.83	0.44	0.64

Note: Within a column, means followed by the same letters are not different at the 0.05 probability level according to Tukey's HSD. Weeds evaluated include the following: CLQ, common lambsquarters (*Chenopodium album*); RRPW, redroot pigweed (*Amaranthus retroflexus*); HNS, hairy nightshade (*Solanum physalifolium*); BYG, barnryardgrass (*Echinochloa crus-galli*).
Abbreviation: EPTC, *S*-ethyl-*N*,*N*-dipropylthiocarbamate.

control compared to EPTC or pyroxasulfone. Although the efficacy of flumioxazin was statistically similar to flumioxazin + pyroxasulfone, for proactive and reactive resistance management, it is recommended that herbicides are applied in mixtures to reduce selection pressure for herbicide resistance (Beckie & Reboud, 2009; Evans et al., 2016; Kniss et al., 2022). Although previous studies have shown that herbicide resistance best management practices, including effective herbicide mixtures, tend to be more expensive than standard weed control practices (Edwards et al., 2014; Weirich et al., 2011; Wilson et al., 2011), this will be important in reducing the risk of herbicide resistance. Generally, weed control in the flumioxazin + pyroxasulfone treatment was similar to the hand-weeded check. Thus, the premix or tankmix of flumioxazin + pyroxasulfone would be an effective herbicide option with an acceptable margin of safety for weed control in dry bean.

Irrigation timing influenced *Chenopodium album* density (Table 4). Delaying irrigation timing to 8 days almost doubled *Chenopodium album* density compared to 1-day treatment. Although this did not influence *Chenopodium album* dry weight, total weed dry weight was influenced by irrigation timing. Delaying irrigation timing to 8 days increased total weed dry weight by 52%.

Weed density and weed dry weight were influenced by herbicide treatments (Table 4). Flumioxazin + pyroxasulfone generally provided better *Chenopodium album*, *Amaranthus retroflexus*, and *Solanum physalifolium* control compared to the other herbicides. This resulted in less total weed density and biomass in the flumioxazin + pyroxasulfone treatment. The nontreated check had weed density of 78 weeds m^{-2}, which was statistically similar to EPTC and pyroxasulfone. The weed biomass data showed that although weed density in flumioxazin + pyroxasulfone treatments was similar to flumioxazin, these weeds were very small in size resulting in very low total weed biomass (Table 4).

Dry bean stand density was influenced by irrigation timing starting at 3 weeks after treatment (Table 5). Delaying irrigation timing to 8 DAT reduced stand density by up to 14% compared to 4-day treatment. Stand density in the 8 DAT irrigation timing was statistically similar to the 1 day irrigation timing. No significant stand reduction was observed due to herbicide treatments (Table 5). In a previous study, Taziar et al. (2016) found that pyroxasulfone applied at 100 and 200 g ai ha^{-1} did not reduce the density of four market classes of dry bean (Adzuki, kidney, small red Mexican, and white bean). Dry bean stand reduction due to flumioxazin application was observed in a previous study (Adjesiwor et al., 2020). This was attributed to cool temperatures and high moisture at the time of dry bean emergence (Adjesiwor et al., 2020).

Irrigation timing did not influence dry bean yield (Table 4). However, seed yield was lower in the pyroxasulfone treatment compared to flumioxazin + pyroxasulfone. This was likely due to poor early season weed control and slight numerical reduction in dry bean stand density from the pyroxasulfone treatment. Flumioxazin and flumioxazin + pyroxasulfone treatments did not cause enough injury or stand reduction to reduce dry bean seed yield. Wilson and Sbatella (2014) reported that although flumioxazin reduced dry bean stand density, seed yield was not reduced. However, any significant reduction in stand density may reduce seed yield (Adjesiwor et al., 2020).

TABLE 5 Dry bean stand density at 2–5 weeks after herbicide treatment (WAT) and seed yield influenced by herbicide treatments at 5 weeks after herbicide treatment in 2021 and 2022, Kimberly, ID.

Factor	Stand density (plants ha^{-1}) 2 WAT	3 WAT	4 WAT	5 WAT	Seed yield (kg ha^{-1})
Irrigation timing (days)					
1	142,927	162,376ab	160,633ab	158,248ab	2150
4	157,147	174,944a	176,962a	169,715a	2072
8	146,964	152,560b	152,285b	154,119b	1874
p-value	0.07	<0.001	0.003	0.04	0.30
Herbicide					
EPTC	153,752	171,978	172,956	169,042	1956ab
Flumioxazin	147,514	160,969	165,373	160,847	1965ab
Pyroxasulfone	139,808	156,810	155,832	153,875	1783b
Flumioxazin + pyroxasulfone	154,976	163,415	159,012	159,012	2425a
p-value	0.14	0.12	0.16	0.25	0.02
Irrigation × herbicide	0.47	0.22	0.36	0.34	0.36

Note: Within column and for each afctro (irrigation timing and herbicide), means followed by the same letters are not different at the 0.05 probability level according to Tukey's HSD.

Abbreviation: EPTC, *S*-ethyl-*N*,*N*-dipropylthiocarbamate.

Yields from all herbicide treatments were similar to the hand-weeded check. Uncontrolled weeds reduced dry bean yield by 91% compared to the hand-weeded check. It has been estimated that dry bean growers in North America could potentially lose 31%–94% of dry bean yield if weeds are left uncontrolled (Soltani, Dille, et al., 2018).

4 | CONCLUSIONS

Irrigation timing affected weed control efficacy. Delaying irrigation timing until 8 days after herbicide application reduced weed control efficacy. Although delaying irrigation until 8 days resulted in up to 19% crop injury, the injury was very transient, and the crop recovered within a few weeks. Although flumioxazin + pyroxasulfone provided similar weed control as flumioxazin or EPTC, the mixture treatment provided more consistent weed control. Flumioxazin and pyroxasulfone will have to be applied as a tankmix or together with other herbicides for effective weed control and for proactive resistance management in dry bean. Delaying irrigation timing to 8 DAT reduced dry bean stand density by up to 14% but this was not enough to cause any significant yield reduction. There was no significant stand reduction due to herbicide treatments but flumioxazin + pyroxasulfone treatment produced the greatest seed yield, which as similar to the hand-weeded check. While irrigation timing may play a role in flumioxazin or pyroxasulfone injury, it appears there are other important soil and environmental factors that may influence dry bean response to flumioxazin.

AUTHOR CONTRIBUTIONS

Albert Adjesiwor: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; supervision; writing—original draft; writing—review and editing. **Prayusha Bhattarai**: Writing—original draft; writing—review and editing. **Chandra Montgomery**: Data curation; investigation; writing—review and editing. **James Gomm**: Investigation; project administration; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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