ORIGINAL RESEARCH

Flumioxazin and Flufenacet as possible options for the control of multiple herbicide-resistant littleseed canarygrass (*Phalaris minor* Retz.) in wheat

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Abstract

We conducted field trials and pot experiment to evaluate the effectiveness of two herbicides - flumioxazin and flufenacet - for weed control in wheat (*Triticum aestivum* L.), particularly targeting littleseed canarygrass (*Phalaris minor* Retz.). In the field studies, conducted over four seasons (2012-13 to 2015-16), the littleseed canarygrass populations encountered in the fields were sensitive to herbicides. In the pot studies, the responses of both multiple herbicide-resistant (resistant to isoproturon, clodinafop, and sulfosulfuron) and sensitive populations were examined against flumioxazin and flufenacet. In the field trials, application of pre-emergence flumioxazin at 125-150 g a.i./ha effectively controlled littleseed canarygrass and several broad-leaved weeds, such as toothed dock (*Rumex dentatus* L.) and bur clover (*Medicago denticulata* Willd). However, flumioxazin was less effective against a second dominant grass weed, wild oat (*Avena ludoviciana* Dur.), which infested the field plots. Pendimethalin, which was used in the trials for comparison, at 1000 g a.i./ha, was less effective than flumioxazin in controlling wild oat. Compared with the unweeded control (weedy check) and the plots that received the pendimethalin treatments, the treatments with flumioxazin, at 125-150 g a.i./ha, produced much higher grain yields (i.e., up to 159% and up to 49% increased yield gain, respectively). The highest rate of flumioxazin (250 g a.i./ha) did not increase the weed control achieved, compared with the lower rates, but caused average crop phytotoxicity of 31% at 40 days after the herbicide application or 20 days after the first irrigation. In other field experiments, flufenacet (200-300 g a.i./ha), applied as early post-emergence at 20 days after sowing (one day before the first irrigation), was highly effective in the control of both littleseed canarygrass and wild oat. However, flufenacet was not effective in controlling broad-leaved weeds. Overall, the weed control and the wheat yield obtained with flufenacet 250 g a.i./ha were not significantly different from those obtained with the standard treatment used in the study (i.e., clodinafop, 60 g a.i./ha at 35 days after sowing).

In pot bioassay studies, flumioxazin and flufenacet were tested against multiple herbicide-resistant littleseed canarygrass, known to be resistant to acetyl-coA carboxylase (ACCase), acetolactate synthase (ALS) and photosystem II site A (PS-II) inhibitor herbicides, such as clodinafop, sulfosulfuron, and isoproturon, respectively. The results of the pot study indicated effective control (up to 100%) of the herbicide-resistant littleseed canarygrass population by both flumioxazin and flufenacet. Our combined studies of field trials and pot experiment, therefore, indicate that both flumioxazin and flufenacet have the potential to be alternative herbicide options in wheat, particularly for littleseed canarygrass control. As discussed in this paper, while we have demonstrated the potential, further studies are needed, incorporating other agronomic practices in wheat cultivation with flumioxazin and flufenacet, to explore their full potential for the control of multiple herbicide-resistant littleseed canarygrass.

Keywords: wheat, flumioxazin, flufenacet, littleseed canarygrass, *Phalaris minor*, clodinafop, herbicide resistance, isoproturon, pendimethalin, sulfosulfuron.

Introduction

Globally, the evolution of a large number of herbicide-resistant weeds in wheat (*Triticum aestivum* L. emend. Fiori and Paol.) has restricted the effective chemical weed control options for the crop. Heap (2019) reported that, globally, in wheat, there are 72 cases of resistance development in weeds, which primarily show resistance to acetyl-CoA carboxylase (ACCase) inhibitor herbicides. In addition, there are also 19 cases of resistance for acetolactate synthase (ALS) inhibitors across many of the wheat-producing countries.

In India, among herbicide-resistant weeds infesting wheat, the most problematic is the multiple herbicide-resistant littleseed canarygrass (*Phalaris minor* Retz), which has evolved resistance against PS-II (photosynthesis at the photosystem-II site-A), ACCase and ALS inhibitor herbicides (Chhokar and Sharma, 2008; Chhokar et al., 2018). It is known that littleseed canarygrass infests about 50% (15 million ha) of the cultivated wheat areas in India. Of this area, the multiple herbicide-resistant littleseed canarygrass affects about three million ha of wheat. The affected area is increasing every year, posing a significant threat to wheat production and profitability of farmers (Chhokar et al., 2018; Singh and Chhokar, 2015). For managing populations of the herbicide-resistant littleseed canarygrass, it is essential to evaluate and identify alternative herbicides, which have different mechanisms of actions to those that are commonly used in northern Indian plains, such as, clodinafop, sulfosulfuron, and pinoxaden.

Flumioxazin is a contact herbicide, which belongs to a protoporphyrinogen oxidase (Protox) inhibitor (an enzyme important in the synthesis of chlorophyll) group. It is absorbed by both roots and foliage of treated plants (Dayan and Duke, 1997). So, when applied to the soil, susceptible weed seedlings die as they begin to emerge, whereas foliar contact of susceptible plants results in rapid desiccation, followed by necrosis (Hutchinson, 2007). Previous research has reported the effectiveness of flumioxazin in a range of crops, such as cotton (*Gossypium hirsutum* L.), corn (*Zea mays* L.), peanut (*Arachis hypogaea* L.), soybean [*Glycine max* (L.) Merr.], field peas (*Pisum sativum* L.), potato (*Solanum tuberosum* L.) and wheat, as well as in bermudagrass [*Cynodon dactylon* (L.) Pers.] turf and in other non-crop situations (Bunting et al., 2003; Cranmer et al., 2000; Hutchinson, 2007; Senseman, 2007; Flessner et al., 2013).

Although flumioxazin is recommended for use in many crops, its most common use is for pre- and post-emergence weed control in legume crops (Senseman, 2007; Howey, 2012). Also, flumioxazin is known to significantly increase the speed of kill of various grasses and broad-leaved weeds when applied with glyphosate, paraquat or diquat, before sowing (Howey, 2012). This herbicide has also demonstrated effective control on some of the hard-to-kill weeds, such as wild radish (*Raphanus raphanistrum* L.), capeweed [*Arctotheca calendula* (L.) Levyns] and wireweed (*Polygonum aviculare* L.). Despite such knowledge about the strengths of flumioxazin, up to now, not much work has been done on its potential use for weed control in wheat, which is an objective of our present studies.

Flufenacet, an oxyacetamide herbicide, has also been shown to control many kinds of grass and broadleaf weeds by inhibiting long-chain fatty acid biosynthesis in plants (Senseman, 2007). Flufenacet has also been registered for use in various crops, such as corn, soybean, wheat, barley (*Hordeum vulgare* L.), rice (*Oryza sativa* L.), peanut, and potato, either alone, or in combination with other herbicides (such as diflufenican, metribuzin, metosulam, or triallate) depending on the crop (Diehl and Benz 1998; Brinkmann and Dahmen, 1997; Chhokar et al., 2006b; Kleemann et al., 2016; Koepke-Hill et al., 2011). In wheat, flufenacet combinations with diflufenican and metribuzin have been shown to control a range of weeds (Koepke-Hill et al., 2011; Lawrence and Burke, 2014). Our early studies (Chhokar et al., 2006a) showed that flufenacet, in wheat, can be applied pre- or early post-emergence, for effectively control of isoproturon-resistant littleseed canarygrass, although the crop may suffer from some phytotoxicity. In rice also, flufenacet phytotoxicity had been noted, but effects varied depending on the cultivars. We found that scented rice cultivars, such as Taraori Basmati and Sugandha, were more sensitive to flufenacet, compared with the coarser rice cultivar IR-64 (Chhokar et al., 2006b).

In the northern Indian plains, the reduced efficacy of post-emergence herbicides against herbicide-resistant littleseed canarygrass and other weeds in wheat has forced the farmers to use herbicides more frequently and at higher rates. Many farmers currently use three or four herbicides in sequence, or in combinations, thus, incurring heavy costs of weed control and risks of crop injury (Chhokar et al., 2018; Singh and Chhokar, 2015).

Therefore, to address the problems of managing herbicide-resistant littleseed canarygrass and other weeds in wheat, it is essential to identify new or alternative effective herbicides, with different mechanisms of actions. Flumioxazin and flufenacet have different mechanisms of action. With their usage in numerous crops, only a few cases of resistant weeds against these herbicides have been reported up to now (Heap, 2019). These two herbicides, therefore, have the potential to be alternatives to manage littleseed canarygrass and other weeds in wheat in India. Figures 1 and 2 are photographs showing wheat fields severely infested with herbicide-resistant littleseed canarygrass.

Figure 1. Littleseed canarygrass infesting a wheat field in Haryana, India

Figure 2. Multiple herbicide-resistant littleseed canarygrass infesting a wheat field harvested for fodder in Punjab, India

Given the above, the primary objective of our studies was to evaluate the potential of flumioxazin and flufenacet for the control of littleseed canarygrass and other weeds in wheat. To achieve this objective, we conducted both field trials and pot experiment. Firstly, we conducted a series of field trials, over four growing seasons (2012-13 and 2015-16), to evaluate the effectiveness of flumioxazin and flufenacet for controlling littleseed canarygrass and other weeds, infesting wheat.

Secondly, we conducted separate pot studies on population of known, multiple herbicide-resistant (PS-II, ACCase and ALS inhibitor) littleseed canarygrass, to ascertain the potential of the two herbicides for the control of such populations.

Materials and Methods

In this research, we conducted field and pot studies to determine the efficacy of flumioxazin and flufenacet for weed control in wheat with an emphasis on littleseed canarygrass (*P. minor*) control. The studies were conducted at the Resource Management Field Block of the Indian Council of Agricultural Research (ICAR)-Indian Institute of Wheat and Barley Research, Karnal (29° 42’ N, 76° 59’ E and 235 m AMSL), India. The field site had been in a rice-wheat rotation during and prior to the present experiments. The soil of the experimental field was a sandy loam, with a pH in the range of 8.1-8.3 and an organic carbon content in the range of 0.37-0.42%. In the fields, the populations of littleseed canarygrass encountered were demonstrably susceptible to herbicides; hence, not known to be herbicide-resistant.

However, for the pot studies, we used two populations of littleseed canarygrass, known to respond differentially to herbicides. One population (Sagga-1) was collected in April 2015 from a farmer’s field in the village Sagga of the District Karnal, Haryana State. It was known to be multiple herbicide-resistant (resistant to isoproturon, clodinafop, and sulfosulfuron). The second was from a population of herbicide-susceptible (IIWBR population) canarygrass collected from our institute’s Resource Management research block. The seeds of both these populations are maintained at ICAR-IIWBR, Karnal.

Field studies

Evaluation of pre-emergence flumioxazin in wheat

The field experiments were conducted in a randomized block design with three replications during two seasons, i.e., the 2014-15 and 2015-16 cropping seasons, to evaluate flumioxazin 50% SC

(Sumi Max) for weed control in wheat. Wheat cultivars, WH 1105 and HD 2967, were sown using a seed rate of 100 kg/ha at 20 cm row spacing on 5 November 2014; and, then, in the following season, on 21 November 2015. The wheat cultivar, HD 2967 was selected during the second season (2015-16), because of its known stability under varied sowing timing, different tillage and irrigation levels, as well as broader adoption by farmers, compared to WH 1105 (Chhokar et al., 2018).

The weed control treatments (see Table 1) consisted of pre-emergence applications of flumioxazin at 100, 125, 150, and 250 g a.i./ha. For comparison, pendimethalin 30 EC (Stomp), a standard herbicide of wheat, was also included in the study (applied at 1000 g a.i./ha). The trials included standard, un-weeded control plots ('weedy' check) and 'weed-free' check control plots. For the 'weed-free' treatment, all weeds in the plots were manually removed, starting at 20 DAS, followed by hand weeding at every 10-15 days intervals.

The pre-emergence flumioxazin and pendimethalin treatments were applied at one to two days after sowing (DAS) using a carrier volume of 400 L water/ha with a knapsack sprayer fitted with two flat fan nozzles on a boom at 50 cm distance. Visual assessment of crop phytotoxicity was conducted at 40 days after application (DAA) of flumioxazin on a 0 to 100% scale, where 0% is no injury, and 100% means complete kill. The crop phytotoxicity assessments were based on necrosis, chlorosis, and suppression or stunting of wheat crop plants in the herbicide treated plots, compared with the untreated control plots.

Evaluation of early post-emergence flufenacet in wheat

During two consecutive winter seasons (2012-13 and 2013-14), flufenacet was evaluated for weed control as an early post-emergence application at 20 DAS. In these studies, wheat cultivars. PBW 550 and HD 2967 were sown on 31 December 2012 (season 1); and on 10 November 2013 (season 2), respectively. The cultivar PBW 550, a short duration variety, was selected for delayed sowing (31 December 2012) during the first season of studies. However, in the second season of the studies, the longer duration (5 months to maturity), high yielding, double-dwarf cultivar (HD 2967) was grown, because of early sowing time (10 November 2013) of the experiment.

At 20 DAS (one day before first irrigation), flufenacet rates of 200, 250 and 300 g a.i./ha, were applied with a knapsack sprayer fitted with two flat fan nozzles, using a carrier volume of 350 L water/ha (see Table 3). For comparison, plots of a 'weedy' check (un-weeded plots), and 'weed-free' check were included in the field trials, along with other plots that received treatments of a widely used, post-emergence, graminicide (grass-killing herbicide)–clodinafop, 60 g a.i./ha, applied at around 35 DAS. Clodinafop was also applied as spray solutions in carrier volumes of 350 L/ha, using a knapsack sprayer, fitted with two flat fan nozzles. In the 'weed-free' control plots, all weeds were manually removed, by hand weeding, initially at 20 DAS, and thereafter, at every 10-15 days intervals.

Visual assessments of crop phytotoxicity (%) were conducted at 30 days after application (DAA) of flufenacet, on a 0 to 100% scale, where 0% is no injury, and 100% means complete kill, based on the growth reduction of wheat plants, compared with those in the un-weeded control.

General

The fields used for the wheat experiments were prepared after pre-sowing irrigation, to have a fine tilth and for which cross operations, each of harrow, cultivator, rotary tiller, and planker/leveller were performed in a sequence. The selected wheat cultivars for each experiment were sown using a seed-cum-ferti-drill, with an inclined plate seed drilling mechanism, which delivered a seed rate of about 100 kg/ha (The seed rate was adjusted by considering 38 g, as the weight of 1000 seeds). The size of each field plot was 2 m × 11 m, with 10 rows per plot and a row-to-row spacing of 20 cm. Fertilization and irrigation applications for the fields were made according to the recommended package of practice for wheat in India (Coventry et al., 2011). The fertilizer application consisted of 150 kg N, 60 kg P_2O_5, 40 kg K_2O/ha. One-third N and full P and K were applied at the time of sowing. The remaining 2/3rd of nitrogen was applied in two equal splits, at the time of first and second irrigations, which were applied at 21 and 42 DAS, respectively.

In the flumioxazin evaluation studies, the observations on the abundance of the weed populations (no/m^2) were taken at 58-60 DAS by placing a quadrat of 50 cm x 50 cm at two locations in each plot and counting the number of plants of significant weed species present. Weed dry weights were recorded at 120 DAS in all of the studies, except during 2012-13 (season 1) in the flufenacet studies, where they were recorded at 100 DAS. To obtain the dry weed weights, weeds within each quadrat were cut close to the ground and separated according to the significant weed taxa. After initial air drying, the weeds were dried in an oven to a constant weight (drying at 60±2 ºC for three days). For data analyses and reporting, the population and dry weights of minor weeds, which appeared in low abundance, were pooled as 'other weeds'.

In each field trial, the wheat grain yield data were obtained by harvesting the central nine rows of each plot excluding the border area (two outer rows and 1.5 m across rows from both sides of a plot). The plots were manually harvested, and the grains were threshed using a small plot thresher. The final grain yields were corrected to 12% seed moisture.

Pot bioassays

Evaluation of flumioxazin and flufenacet against multiple herbicide resistant P. minor

The responses of multiple herbicide-resistant (resistant to ALS, ACCase, and PS-II inhibitor) and susceptible (S) populations of littleseed canarygrass were studied against flumioxazin and flufenacet in pot experiment during 2015-16. Three other herbicides (sulfosulfuron, clodinafop, and isoproturon), commonly used in wheat in India, were also included in the studies, for comparison.

For this herbicide-resistance study, 50 seeds per pot of the herbicide-resistant or susceptible littleseed canarygrass were sown in pots at about two cm depth. The soil for filling pots (4.5 kg soil per pot) was taken from the field, which had no previous littleseed canarygrass infestations. Pots were filled with this soil, mixed at a ratio of 6:1 (v/v) with decayed Farmyard Manure (FYM), which passed through a 2-mm sieve. The pot studies involved the determination of the relative growth reductions of the two littleseed canarygrass populations (resistant and susceptible) by nine herbicide treatments, in comparison with the un-weeded controls.

There were 20 treatment combinations, and each treatment was replicated four times, and the experiment arranged as a completely randomized design. The herbicide treatments consisted were: (1) pre-emergence flumioxazin (25 and 50 g a.i./ha) applied at three DAS; (2) early post-emergence flufenacet (37.5, 75, 150 and 300 g a.i./ha) applied at 15 DAS; and (3) post-emergence sulfosulfuron (25 g a.i./ha), clodinafop (60 g a.i./ha) and isoproturon (1000 g a.i./ha), evaluated at 21 DAS. The measured quantity of each dose of herbicide for an area of 20 m^2 was dissolved in the 800 mL water and applied on to the pots after placing the pots randomly within the 20 m^2 area (2 m × 10 m).

The herbicide applications were made using a knapsack sprayer fitted with two nozzles on a boom with a swath of one meter. Spraying was done in such a manner that each pot had only one pass of spray. The control evaluation was based on percentage reduction of fresh biomasses of *P. minor* per pot at 42 DAS, compared with untreated pots.

Statistical analyses

We used the Statistical Analysis System (SAS, version 9.2) software for data analyses. The data on the field evaluation of flumioxazin were statistically analyzed in a combined block design, whereas, the flufenacet experimental data were analyzed as simple block design. Since the effects of the year and year x treatment interactions were not significant, the data of the flumioxazin studies were pooled by treatment over a year. The pooling of the results did not alter the interpretations. In contrast, in the flufenacet studies, pooling of data was not done, since, there were notable variations in the abundance of weeds, as a result of which, the statistical interpretation varied between pooled analysis and individual (year to year) analysis. In the combined analysis, the variances were partitioned into the fixed effects of herbicide treatments and the random effects of the study year.

The experimental data from the pot studies were statistically analyzed in a factorial completely randomized design (CRD), in which the two factors in the 20 treatment combinations were evaluated. Weed and crop data in various experiments were subjected to analyses of variance, and the Fisher's Protected Least Significant Difference (LSD) was used to separate treatment means (P=0.05). The data on the weed population, weed dry weight, and visual crop phytotoxicity (%) were square root {$\sqrt{(x+1)}$} transformed before analysis. The original weed data are presented in the results tables with a comparison of means for significant differences. In the flumioxazin evaluation studies, results from the weed-free plots were not included in the statistical analysis of weed data. However, data from the weed-free plots were included in the flufenacet evaluation studies to have a sufficient degree of freedom for estimation of error variances. To avoid the bias in the data analysis, due to the inclusion of the two controls (weed-free and un-weeded control) and also, to determine the relative treatment efficacy for the reduction in weed dry weights and gains in crop yields in the flufenacet experiments, a single degree of freedom contrasts were also performed (Onofri et al., 2009; Gomez and Gomez, 1984)..

Results

Field evaluation of pre-emergence flumioxazin in wheat

Since no significant year-by-treatment interactions were observed, the data were pooled, and the results of the analysis of pooled data on weeds and crop are presented in Tables 1 and 2. The main weeds infesting the experimental plots were: littleseed canarygrass, wild oat (*Avena ludoviciana* Dur.), and a range of broad-leaf weeds, mainly, bur clover (*Medicago denticulata* Willd), toothed dock (*Rumex dentatus* L.), and lesser swine cress (*Coronopus didymus* L.). Among these, the most dominant weed during both seasons was littleseed canarygrass. The mean population and dry weight of littleseed canarygrass in the un-weeded control (weedy check) were 360 plants/m^2 and 346 g/m^2, respectively (Table 1). Wild oat was the second most dominant grass weed (dry weight accumulation 111 g/m^2). Compared to the weedy check, all the herbicide treatments caused significant reductions in the total densities of weeds and their dry weights.

Pre-emergence treatments of flumioxazin drastically reduced the littleseed canarygrass densities, and dry weights in the treated plots, and the reductions increased as the dose of flumioxazin increased from 100 to 250 g a.i./ha. Flumioxazin applications at 150 and 250 g a.i./ha were significantly superior in littleseed canarygrass control achieved compared with the lower dose of 100 g a.i./ha. Weed control achieved by the two higher doses were, however, not significantly different. Also, there was no significant difference between the littleseed canarygrass control achieved by flumioxazin doses of 125 and 150 g a.i./ha. Flumioxazin was less effective against wild oat, but, compared with pendimethalin (1000 g a.i./ha), control was significantly higher. However, pendimethalin was quite effective in controlling toothed dock. Also, flumioxazin, at 125 g a.i./ha, or higher rates was better than pendimethalin in reducing the densities and dry weights of littleseed canarygrass and bur clover. Some flushes of weeds, which emerged along with the crop, were killed by the flumioxazin treatments after the first irrigation.

Based on the total weed dry weights, the weed control efficiencies of flumioxazin at 125 and 150 g a.i./ha were approximately 79 and 86%, respectively, compared with weed dry weights in the un-weeded control. In contrast, the weed control efficiency of pendimethalin 1000 g a.i./ha was considerably low (overall, 48%) compared with the un-weeded controls. Overall, based on the reduction of weed dry weights compared with the un-weeded check (Table 1), the control of littleseed canarygrass obtained by the applications of flumioxazin at 125-150 g a.i./ha was superior to pendimethalin and ranged from 94-97%. The reduction of littleseed canarygrass obtained by pendimethalin (1000 g a.i./ha) was significantly less than flumioxazin and was about 71% only, compared with the un-weeded check.

With regard to the effects of the herbicide applications on wheat, as shown in Table 2, the various herbicide treatments significantly influenced the tillering, crop biomass, and grain yield of wheat. The yield attributes (effective tillering and 1000 grain weight) were significantly higher in the flumioxazin treated plots than with plots, which received the pendimethalin applications. The uncontrolled weed growth throughout the crop season (un-weeded check) resulted in the lowest wheat biomass and grain yield (Table 2). The 1000 grains weight was also significantly lower in weedy-check control (34 g). Although pendimethalin significantly improved the grain weight (35 g) compared to the weedy control, its weed control effectiveness was significantly lower than the range of flumioxazin rates tested.

The highest wheat grain yield was obtained with the weed-free check (5.12 t/ha). In comparison, season-long competition from weeds (un-weeded check) produced a 62.7% lower grain yield (1.91 t/ha). All herbicide treatments increased the wheat grain yields over the unweeded check by at least 74%. Flumioxazin at 125-150 g a.i./ha, provided increased grain yields (1.12-1.62 t/ha higher) compared to pendimethalin (1000 g a.i./ha) but these increased yields were statistically not different to the weed-free check. Among the herbicide treatments, the highest average grain yield was with the application of 150 g a.i./ha flumioxazin (4.95 t/ha), which was not statistically different to the productivity obtained with application of 125 and 250 g a.i./ha flumioxazin (4.77 and 4.94 t/ha, respectively).

The application of flumioxazin caused phytotoxicity on the wheat crop, which became much distinct in the form of leaf necrosis after the first irrigation. Phytotoxicity symptoms on the crop increased as the dose rate of flumioxazin increased from 100 to 250 g a.i./ha. The flumioxazin at the rate of 250 g a.i./ha provided the lowest weed dry weight (34 g/m^2) but caused phytotoxicity to wheat, which was rated as 31% visual damage. In contrast, at lower doses (125-150 g a.i./ha), the phytotoxicity was visually 8-12% at 19-20 days after first irrigation i.e., around 40 days after herbicide application (Table 2). However, over time, the crop recovered sufficiently, and the yields in the flumioxazin 125-150 g a.i./ha treated plots were finally not significantly different to those attained by the weed-free check.

Evaluation of early post-emergence flufenacet in wheat

Flufenacet (200, 250, and 300 g a.i./ha) applied as early post-emergence (20 DAS) was tested for the control of two major grass weeds, which infested the field plots, namely, *P. minor* and *A. ludoviciana.* Among broad-leaved weeds: *Medicago denticulata, Rumex dentatus*, and *Coronopus didymus* were also present but less abundant. The two years of weed dry weights and wheat yield data are presented year-wise, in Table 3, because of the variations in the weed flora (*A. ludoviciana* was present in the second year only) and the significant herbicide treatment and year interactions observed for data on crop and weeds. There were significant weed dry weights differences among the various treatments. In the un-weeded control plots, the total weed dry weights accumulated were 211 and 403 g/m^2, respectively, during the first and second year (Table 3).

Littleseed canarygrass was the most dominant weed, which accounted for 99% (209 g/m^2) and 73% (294 g/m^2) of weed abundance, respectively, during the first and the second year of field trials. Based on weed dry weights, wild oat was the second-most dominant weed during the second year. The early post-emergence applications of flufenacet drastically reduced the dry weights of both these grasses, although, flufenacet was not effective against broad-leaved weeds (Table 3). The dry weight reductions in littleseed canarygrass on the flufenacet treated plots at 200, 250, and 300 g a.i./ha were 88, 97, and 99%, respectively, compared with the unweeded control. Much higher weed control was obtained by the higher doses of flufenacet (250-300 g a.i./ha) compared with the lower dose (200 g a.i./ha).

During the second crop season (2013-14), the wild oat dry weights in the plots were reduced by 81%, 94%, and 95%, respectively, by the rates of 200, 250, and 300 g a.i./ha, of flufenacet. However, the wild oat control with flufenacet at the higher dose range (250-300 g a.i./ha) was not statistically different to that obtained with clodinafop 60 g a.i./ha, which indicated that clodinafop, at the tested rate, was equally effective as flufenacet in wild oat control.

Also, littleseed canarygrass control with the highest rate of flufenacet 300 g a.i./ha was not significantly different from the control achieved by the standard check herbicide– clodinafop, during the trials in both years. However, 250 g a.i./ha flufenacet was equally effective as 300 g a.i./ha flufenacet and clodinafop 60 g a.i./ha in reducing the dry weights of littleseed canarygrass in the treated plots during the crop season of 2012-13 but was inferior during the second season of 2013-14. Overall, based on reductions of dry weights of all weeds dry weights, the control achieved by the two higher rates of flufenacet (250 and 300 g a.i./ha) was not significantly different from that obtained by clodinafop. Weed abundance in the study plots in 2013-14 (Table 3) also showed that flufenacet was ineffective against the broadleaf weeds infested the plots, but it achieved the effective grass weed control. The field trials showed a tendency for broadleaf weeds to grow in greater abundance in the flufenacet treated plots, compared with the unweeded control plots, as the herbicide reduced the occurrence of the grasses infesting the plots.

Weed control with flufenacet had significant effects on the gains in wheat grain yield ($p<0.0001$) compared to un-weeded control. As shown in Table 3, uncontrolled weed growth throughout the season resulted in the lowest grain yields of 3.58 and 2.33 t/ha, during the first and second crop seasons, respectively. The maximum wheat grain yields were obtained from the weed-free control plots (5.82 and 5.70 t/ha, respectively, in 2012-13 and 2013-14 seasons). Wheat grain yields under flufenacet treatments increased by 51% to 145% over the unweeded check. Treatments with flufenacet, at the two higher dose rates (250 and 300 g a.i./ha), resulted in significantly higher grain yields compared to the lowest dose of 200 g a.i./ha. As shown by the contrast analyses, these yield levels were not significantly different from the yields in the plots treated with the standard herbicide – clodinafop and the weed-free control plots.

Table 1. Influence of pre-emergence application of flumioxazin on weed density and dry weight in wheat (Pooled data of two years)

Herbicide	Dose/ha (g a.i.)	Weed Density (no/m^2)						Weed Dry Weight (g/m^2)					
		Phalaris minor	*Avena ludoviciana*	*Rumex dentatus*	*Medicago denticulata*	Other weeds	Total	*Phalaris minor*	*Avena ludoviciana*	*Rumex dentatus*	*Medicago denticulata*	Other weeds	Total
Flumioxazin	100	43.0^{BC}	10.3^{ABC}	2.3^{B}	10.0^{B}	12.7^{A}	78.3^{C}	30.7^{C}	88.7^{AB}	1.3^{B}	10.1^{B}	1.5^{A}	132.4^{C}
Flumioxazin	125	27.7^{CD}	9.7^{BC}	1.3^{B}	4.3^{BC}	6.7^{AB}	49.7^{CD}	20.3^{CD}	74.7^{AB}	0.1^{B}	2.2^{CD}	1.5^{A}	98.9^{CD}
Flumioxazin	150	16.3^{DE}	6.0^{C}	0.3^{B}	3.0^{C}	3.7^{B}	29.3^{DE}	9.5^{DE}	52.4^{BC}	0.0^{B}	2.3^{CD}	1.4^{A}	65.6^{DE}
Flumioxazin	250	6.3^{E}	2.3^{D}	0.0^{B}	1.7^{C}	3.0^{B}	13.3^{E}	1.8^{E}	29.9^{C}	0.3^{B}	0.3^{D}	1.4^{A}	33.7^{E}
Pendimethalin	1000	71.3^{B}	16.0^{A}	0.0^{B}	43.3^{A}	11.7^{AB}	142.3^{B}	99.9^{B}	125.0^{A}	0.0^{B}	22.0^{A}	0.7^{A}	247.6^{B}
Weedy-check (control)	-	360.3^{A}	12.7^{AB}	23.7^{A}	39.0^{A}	17.0^{A}	452.7^{A}	346.0^{A}	110.7^{A}	5.6^{A}	8.1^{BC}	1.8^{A}	472.2^{A}
p-Value		<0.001	0.0005	<0.001	<0.001	0.0582	<0.001	<0.0001	0.0040	<0.0001	<0.0001	0.8377	<0.0001

Original values were square root transformed (√x+1) for statistical analysis and based on which the upper-case letters have been mentioned with original values for interpretation. Means within column having at least one letter common are not significantly different according to Fisher's Least Significant Difference at 5% level of significance.

Table 2. Performance of pre-emergence application of flumioxazin in wheat (Pooled data of two years)

Herbicide	Dose/ha (g a.i.)	Phytotoxicity % 40 DAA^{Ť}	Tiller/m^2	Biomass (t/ha)	1000 Grains weight (g)	Grain Yield (t/ha)
Flumioxazin	100	3.3^{D}	346.3^{B}	12.08^{B}	36.72^{A}	4.44^{C}
Flumioxazin	125	7.9^{C}	369.2^{AB}	12.70^{AB}	36.92^{A}	4.77^{B}
Flumioxazin	150	11.7^{B}	367.8^{AB}	12.73^{AB}	37.02^{A}	4.95^{AB}
Flumioxazin	250	30.8^{A}	347.2^{B}	12.55^{AB}	36.37^{AB}	4.94^{AB}
Pendimethalin	1000	0.0^{E}	295.1^{C}	10.50^{C}	35.21^{B}	3.32^{D}
Weed-free check (control)	-	0.0^{E}	372.6^{A}	12.88^{A}	36.86^{A}	5.12^{A}
Weedy-check (control)	-	0.0^{E}	232.9^{D}	9.14^{D}	33.56^{C}	1.91^{E}
p-Value		<0.0001	<0.0001	<0.0001	<0.0001	<.0001

Means, within a column, with at least one letter common, are not significantly different at P<0.05. Mean separations were performed using Fisher's Least Significant Difference at 5% level of significance; ŤDAA= days after application.

Table 3. Performance of early post -emergence application of flufenacet against weeds in wheat

Herbicide	Dose/ha (g a.i.)	Time of application (DAS)[†]	2012-13 ‡Weed Dry Weight (g/m^2) *Phalaris minor*	2012-13 ‡Weed Dry Weight (g/m^2) Broadleaf weeds	2012-13 ‡Weed Dry Weight (g/m^2) Total weeds	2012-13 Wheat Grain Yield (t/ha)	2013-14 ‡Weed Dry Weight (g/m^2) *Phalaris minor*	2013-14 ‡Weed Dry Weight (g/m^2) *Avena ludoviciana*	2013-14 ‡Weed Dry Weight (g/m^2) Broadleaf weeds	2013-14 ‡Weed Dry Weight (g/m^2) Total weeds	2013-14 Wheat Grain Yield (t/ha)
Clodinafop	60	35	1.0 ^{C}	14.4 ^{A}	15.4 ^{C}	5.66 ^{A}	0.2 ^{D}	0.0 ^{B}	16.3 ^{A}	16.4 ^{C}	5.42 ^{A}
Flufenacet	200	20	24.8 ^{B}	13.4 ^{A}	38.2 ^{B}	5.40 ^{B}	35.0 ^{B}	19.1 ^{B}	17.6 ^{A}	71.7^{B}	4.96 ^{B}
Flufenacet	250	20	5.7 ^{C}	10.3 ^{AB}	16.0 ^{C}	5.64 ^{A}	12.6 ^{C}	6.7 ^{B}	18.8 ^{A}	38.1 ^{BC}	5.38 ^{A}
Flufenacet	300	20	1.5 ^{C}	15.^{A}	17.3 ^{C}	5.61 ^{AB}	2.6 ^{D}	5.2 ^{B}	20.9 ^{A}	28.7 ^{C}	5.42 ^{A}
Weed-free check (control)	-	-	0.0 ^{C}	0.0 ^{C}	0.0 ^{D}	5.82 ^{A}	0.0 ^{D}	0.0 ^{B}	0.0 ^{B}	0.0 ^{D}	5.70 ^{A}
Weedy-check (control)	-	-	208.5 ^{A}	2.8 ^{BC}	211.3 ^{A}	3.58 ^{C}	294.3 ^{A}	102.3 ^{A}	6.2 ^{AB}	402.9 ^{A}	2.33 ^{C}
p-Value			<0.0001	0.0059	<0.0001	<0.0001	<0.0001	0.0006	0.0227	<0.0001	<0.0001
Contrasts*				p-Value					p-Value		
Flufenacet 200 g/ha vs Flufenacet 250 g/ha			0.0013	0.5043	0.0196	0.0493	0.0068	0.2760	0.9175	0.0629	0.0194
Flufenacet 250 g/ha vs Flufenacet 300 g/ha			0.2497	0.4821	0.9633	0.7838	0.0212	0.9061	0.5998	0.6267	0.7877-
Flufenacet 200 g/ha vs Clodinafop 60 g/ha			0.0001	0.9895	0.0156	0.0326	<0.0001	0.0752	0.8110	0.0039	0.0122
Flufenacet 250 g/ha vs Clodinafop 60 g/ha			0.2240	0.5125	0.9106	0.8321	0.0034	0.4241	0.8929	0.1337	0.7927
Flufenacet 300 g/ha vs Clodinafop 60 g/ha			0.9443	0.9607	0.9471	0.6277	0.3014	0.4926	0.5120	0.2847	0.9958
Weedy check vs Herbicides			<0.0001	0.0450	<0.0001	<0.0001	<0.0001	<0.0001	0.2002	<0.0001	<0.0001

[†] DAS= days after sowing; [‡] Original weed dry weight values were square root transformed (√x+1) for statistical analysis and based on which the upper-case letters have been mentioned with original; *Single degree linear contrast analysis (p-value)

Pot Study Evaluation of flumioxazin and flufenacet against multiple herbicide resistant *P. minor*

Of the five herbicides evaluated in the pot study against the two populations of littleseed canarygrass (susceptible population and the multiple herbicide-resistant population), only, flumioxazin and flufenacet were effective in controlling both these populations. As shown in Figure 3, the results indicated that sulfosulfuron, isoproturon, and clodinafop were not effective against the multiple herbicide-resistant littleseed canarygrass. These three herbicides did not kill the littleseed canarygrass plants and only caused fresh weigh biomass reductions of 31, 28, and 16%, respectively. However, plants from the susceptible littleseed canarygrass population were readily controlled by all of the tested herbicides. Isoproturon, at 1000 g a.i./ha; sulfosulfuron, at 25 g a.i./ha; and clodinafop at 60 g a.i./ha; provided >99% biomass reductions of the susceptible littleseed canarygrass population (Figure 3). The results of the study showed that both the susceptible and herbicide-resistant populations were well controlled by flumioxazin and flufenacet.

The application of flufenacet, at a range of rates (75-300 g a.i./ha) as early post-emergence, and flumioxazin, at less than (50 g a.i./ha) the optimum field rates (125-150 g a.i./ha), as pre-emergence, provided excellent control (98-100% biomass reductions) of both types of littleseed canarygrass populations.

Discussion and Conclusions

Our studies indicated that pre-emergence applications of flumioxazin effectively controlled littleseed canarygrass and several broad-leaved weeds, but the herbicide was less effective against wild oat. In earlier studies, Grichar and Colburn (1996) and Askew et al. (1999), had reported the effectiveness of flumioxazin for the control of several grasses and broad-leaved weeds. Some of the weeds flushes in our plots, which emerged with the crop, were killed by the pre-emergent flumioxazin after the first irrigation application, which indicated its soil residual activity against specific weeds.

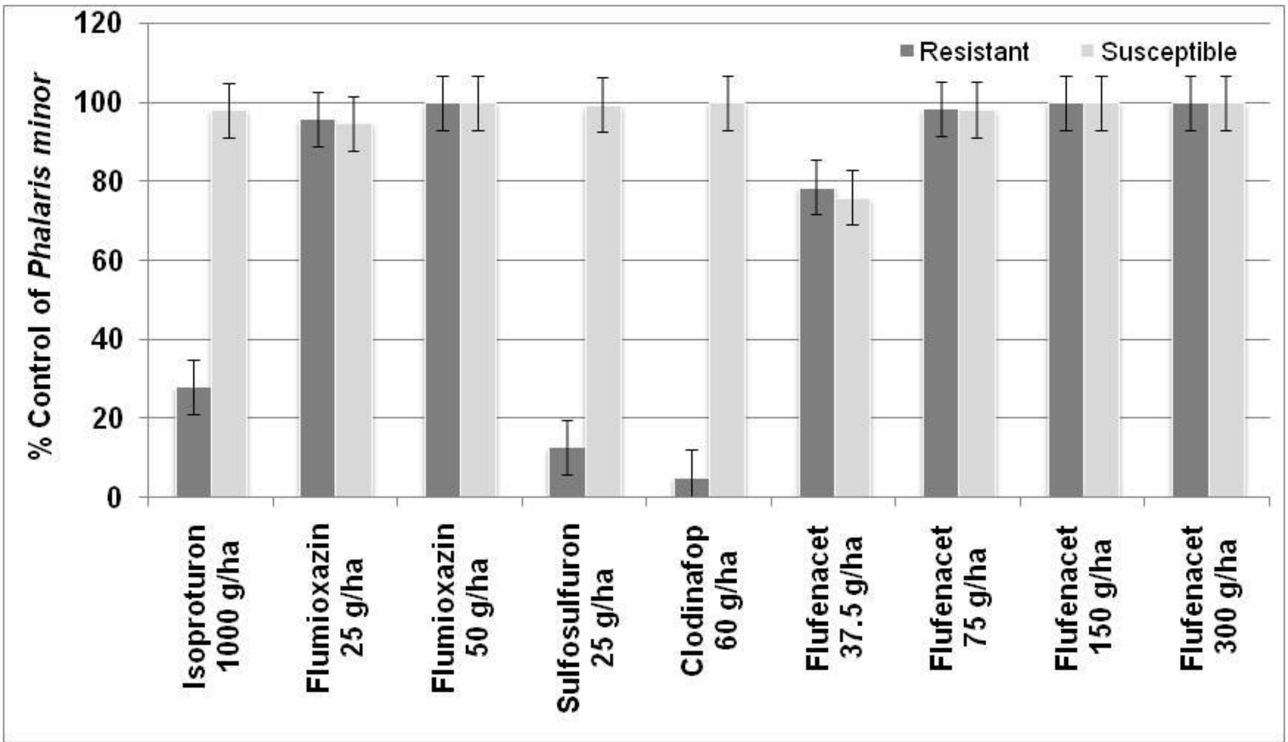

Figure 3. Control of susceptible and multiple-herbicide resistant populations of littleseed canarygrass (*Phalaris minor*) with flumioxazin and flufenacet. Vertical bars represent ± LSD (0.05) =6.92 for population x herbicide interaction

The various herbicide treatments had significant effects on the tillering and the wheat crop biomass, influencing the wheat grain yield. Overall, flumioxazin was more effective than pendimethalin in controlling littleseed canarygrass, wild oat and bur clover, and as a result, flumioxazin usage (100-150 g a.i./ha) also produced 34-49% higher grain yield over pendimethalin, applied at 1000 g a.i./ha. Therefore, flumioxazin is a better alternative to pendimethalin.

Nevertheless, phytotoxicity to wheat was noted with pre-emergence flumioxazin applications after the first irrigation. Flumioxazin rates of 125, 150 and 250 g a.i./ha caused respective crop phytotoxicities of 8, 12 and 31% at 40 DAA, or 19 days after first irrigation However, the wheat grain yields obtained with 150 and 250 g a.i./ha flumioxazin were similar to the standard weed-free treatment, indicating no adverse effect of flumioxazin phytotoxicity on the wheat yield. Similar results have been reported by others. For instance, Taylor-Lovell et al. (2001), Swann (2002), Price et al. (2002), Askew et al. (2002), Jordan et al. (2009), have all reported flumioxazin phytotoxicity to different crops, with no particular adverse effect on yields. The crop phytotoxicity due to flumioxazin may vary, depending on its rate and timing of applications (Johnson et al., 2006; Jordan et al., 2009), crop cultivars (Main et al., 2003) and specific environmental conditions (Taylor-Lovell et al., 2001; Main et al., 2003; Berger et al., 2012; Belfry et al., 2016).

Swann (2002) reported that the splashing of flumioxazin-treated soil or surface water containing flumioxazin on to the emerged peanut seedlings causes herbicide injury if rainfall occurred between flumioxazin application and peanut emergence. The rainfall before emergence would likely move flumioxazin from the soil surface into the soil profile and this reduces the potential of herbicide injury due to rain splash. Also, pre-emergence flumioxazin treated peanut, when irrigated immediately after flumioxazin application, or 12 days after crop emergence, caused less injury to peanuts compared to irrigated at emergence, or 2, 4 and 8 days after emergence (Price et al., 2004). These results show the effect of irrigation timing and method are critically important factors, which need further investigations in relation to flumioxazin applications in wheat.

The usage of herbicide safeners is a promising solution to prevent or minimize crop injury from herbicides (Davies and Caseley, 1999). Recently, Steppig et al. (2018), reported a reduction in crop injury from flumioxazin application, when soybean seeds were treated with the insecticide thiamethoxam. Moreover, there are also possibilities of improved crop safety and weed control if reduced doses of flumioxazin are combined with other herbicides. Grichar and Colburn (1996) reported improved weed control in peanuts with flumioxazin combined with either pyroxasulfone, pendimethalin or trifluralin. These studies have reported superior weed control with the application of pre-emergence flumioxazin + pyroxasulfone (90%) to flumioxazin alone (66%) or pyroxasulfone alone (61%) at 8 weeks after treatment.

As pendimethalin, pyroxasulfone, and trifluralin are also selective herbicides in wheat, their combinations with flumioxazin can also be viable herbicide options. However, if flumioxazin is applied alone, some weeds, such as wild oat, might escape, and may need to be controlled by a post-emergence herbicide. A combination strategy of a pre-emergence herbicide, followed by a post-emergence herbicide, may reduce the antagonism and crop phytotoxicity that may be encountered with post-emergence tank mixes to control a broad spectrum of weeds (Zhang et al., 1995). Presently, such crop phytotoxicities are being noted in northern Indian plains, where farmers are tank mixing metribuzin with either pinoxaden or clodinafop or sulfosulfuron to control multiple herbicide-resistant *P. minor* and other broad-leaved weeds. Also, where farmers are tank mixing 2,4-D or metsulfuron with clodinafop or fenoxaprop, there is reduced grass weed control due to antagonism of the herbicides in tank mixtures (Chhokar et al., 2012; Singh and Chhokar, 2015).

In addition to pre-emergence applications, flumioxazin can also be a pre-planting (PP) option, either alone, or in combination with foliar-acting herbicides, to improve the control of existing weeds, before planting in a no-till system. Such an option would broaden the weed control spectrum, as well as extend the weed control potential for a longer period.

The soil residual activity of flumioxazin is an additional advantage, which is missing with many foliar-applied herbicides, such as glyphosate or paraquat, commonly used pre-plant in no-till wheat cropping. However, the time duration between the pre-planting herbicide application and crop seeding should have a minimum residual adverse effect on the crop. Askew et al. (2002) reported that no-till cotton, planted in cotton and corn stubbles, was injured 12% if flumioxazin was applied as pre-emergence on the day of planting. This injury was much less (3%), if the application was made at least two weeks before planting.

Similarly, Price et al. (2002) reported that the pre-planting flumioxazin as a 'burn down' option at 71 g a.i./ha should be used at least 30 d before planting cotton. The inclusion of a residual herbicide, such as flumioxazin in a pre-planting treatment, can reduce the early-season weed interference in conservation agriculture, which does not use tillage at planting. Research trials in peanut with flumioxazin have also shown useful levels of residual weed control (Askew et al., 1999).

Although no-till wheat production system under a rice-wheat sequence reduces the incidence of littleseed canarygrass in wheat (Chhokar et al., 2007), the inclusion of pre/pre-plant flumioxazin in such a system has the potential to further improve littleseed canarygrass control, due to the residual soil activity of the herbicide. However, the application timing and doses of flumioxazin, as a pre-planting option in no-till wheat, need to be optimized and standardized, to avoid causing crop injury.

Also, to lower the risks of flumioxazin injury to wheat and any potential grain yield reductions, the role of other agronomic factors, such as increased seeding depth, higher seed rates (125-150 kg/ha) and the use of crop safeners need to be investigated. Additionally, other interventions, such as sub-surface drip irrigation and bed planting options, may also be explored for reducing any phytotoxicity on wheat, in comparison to standard methods of irrigation. Swann, (2002) had shown increased phytotoxicity, when flumioxazin comes in to contact with the crop foliage, either as splash after rainfall, or applied as a solution after irrigation.

The results of the second field experiment showed that early post-emergence applications of flufenacet at 250-300 g a.i./ha were very effective in controlling both the dominant grass weeds, but was ineffective against broad-leaved weeds, which infested the fields (Table 3). Nevertheless, the effectiveness of flufenacet for controlling a wide variety of economically relevant weeds in maize, soybean, potato, cotton, peanuts, rice (*Oryza sativa* L.), sunflower (*Helianthus annuus* L.), tomato (*Lycopersicon esculentum* L.**)** and wheat is well documented (Bloomberg, 1997; Brinkmann and Dahmen, 1997; Kremer, 1997; Diehl and Benz, 1998). The grass weed control with flufenacet at 300 g a.i./ha did not significantly differ with the standard graminicide check of clodinafop at 60 g a.i./ha.

The flufenacet treatments recorded higher broad-leaved weeds dry weight compared to the un-weeded control due to the removal of grass weed competition in flufenacet treated plots whereas, in the un-weeded control plots, the competition from dominant grass weeds decreased the broad-leaved weeds biomass. Earlier studies had also showed the effectiveness of flufenacet against grasses and not on broad-leaved weeds in wheat under Indian conditions (Chhokar et al., 2006a).

Keeping in view the ineffectiveness of flufenacet against broad-leaved weeds, a broad-leaved herbicide partner may be required, and it would be better if it is from different chemical group presently being used and is also effective against grass weeds. This strategy, in addition to providing broad-spectrum weed control, may also help in managing the existing resistance problem and delaying the further extension of herbicide resistance in grass weeds, thereby improving the opportunities for sustainable wheat production.

Also, the wheat grain yields under flufenacet 250-300 g a.i./ha, clodinafop, and weed-free check treatments were statistically in the same group but significantly better (57 to 63% and 133 to 144% higher grain yield) than un-weeded control. The better yields under these treatments were due to excellent control of dominant competitive weeds (littleseed canarygrass and wild oat). The highly competitive nature of littleseed canarygrass has also been reported earlier (Chhokar and Malik, 2002; Chhokar et al., 2008). Slight stunting (about 6-8%) was observed in flufenacet treatment after the first irrigation did not affect grain yield. Earlier studies also reported flufenacet phytotoxicity (stunted growth) in wheat (Ritter and Menbere, 2002; Chhokar et al., 2006a; Kleemann et al., 2016).

Our studies indicated the effectiveness of pre-emergence flumioxazin and early post-emergence flufenacet in controlling littleseed canarygrass, including the multiple herbicide-resistant populations. Presently, the multiple herbicide-resistant littleseed canarygrass is spreading continuously and impacting the large wheat acreages in north-western Indian plains. Still, farmers are widely using clodinafop, pinoxaden, and sulfosulfuron at higher rates in resistant prone areas due to the non-availability of effective alternative herbicides. As a result, there are yield penalties. To curtail the yield losses due to herbicide resistance, there is an urgent need for suitable alternative herbicides. Our studies show that flufenacet and flumioxazin can be alternative options in the resistance management programs in wheat, particularly against canarygrass.

Flessner et al. (2013) reported the control of annual bluegrass (*Poa annua* L.) with the post-emergence application of flumioxazin in bermudagrass [*Cynodon dactylon* (L.) Pers.] turf. Annual bluegrass also infests late-sown wheat crop, and most of the widely used herbicides in wheat (clodinafop, fenoxaprop, and sulfosulfuron) are not effective against this weed (Chhokar et al., 2012). Annual bluegrass is also known to be resistant to several herbicides, including glyphosate, sulfonylureas, and triazines (Heap, 2019). Therefore, we contend that flumioxazin can be helpful in resistance management, as well as in controlling this problematic weed in wheat fields.

Compared to flumioxazin, which is more suited as pre-plant and pre-emergence applications, flufenacet has a more extensive window of applications, as it can be applied as pre-plant, pre-emergence or early post-emergence (Bunting et al., 2003; Chhokar et al., 2006a). Moreover, its combination with other herbicides, such as diflufenican, metribuzin, or triallate, gives an opportunity to manage a broad spectrum of weeds in wheat (Koepke-Hill et al., 2011; Lawrence and Burke, 2014; Kleemann et al., 2016).

Bunting et al., (2003) reported that Giant foxtail (*Setaria faberi* Herrm.) control with flufenacet plus metribuzin applied at 60, 45, 30, and 15 days before planting and at planting (pre-emergence). The control achieved was insensitive to application timing from 60 days before planting to pre-emergence. In contrast, Koepke-Hill et al. (2011) reported higher levels of Italian ryegrass (*Lolium multiflorum* Lam.) control with post-application of flufenacet plus metribuzin (77 to 99% control) than pre-application of the herbicide mixture (73-77% control). Therefore, further studies are required to identify the suitable application timing and companion herbicides for flufenacet to control a broad spectrum of weeds.

In fields, having wild oat infestations, particularly the ALS and ACCase resistance, flufenacet should be opted, as both flumioxazin and pendimethalin are ineffective for its control. Since flufenacet and flumioxazin are also selective in soybean and other pulses, these herbicides can also be useful tools for the management of ACCase and ALS inhibitor-resistant grasses in legume crops. Recently, in India also, jungle rice (*Echinochloa colona* L. Link) in soybean and rice has shown resistance to ALS inhibitor herbicides, and these herbicides (flufenacet in rice and both flumioxazin and flufenacet in soybean) can also be targeted for management of herbicide-resistant jungle rice in these crops. Although flufenacet and flumioxazin have been registered for use in multi crops, yet low incidences of resistance in weeds have been reported against these herbicides (Heap, 2019).

Our studies indicate that both pre-emergence flumioxazin and early post-emergence flufenacet are quite effective for the control of littleseed canarygrass, including populations, which are multiple herbicide-resistant (resistant to isoproturon, clodinafop, and sulfosulfuron). Therefore, these herbicides can be alternative options for resistance management programme in wheat. A comparison between flumioxazin and flufenacet showed the edge flumioxazin has over flufenacet for the control of the broad-leaved weed flora. However, in fields infested with wild oat, the application of flufenacet should be preferred over pre-emergence applications of either flumioxazin or standard pendimethalin, as these two herbicides are not adequate for wild oat control.

It should be noted that in the past two decades, herbicides with new modes of action have not been introduced (Green, 2014). Therefore, we suggest that the few effective, available herbicide options should be used judiciously, integrated with non-chemical methods, in such a manner that their effectiveness is prolonged. As discussed by Norsworthy et al. (2012), Walsh et al. (2013) and Shaner and Beckie (2014), the effective herbicides should be integrated with all possible non-chemical options, such as cover crops, tillage, crop rotation, and harvest and destruction of weed seeds to reduce weed seed banks. In addition, managing herbicide-resistance in wheat-growing areas would also require crop rotation, including the use of ‘break crops’, such as oilseed, pulses, corn or sugarcane or fodder crops, in those fields, which have herbicide-resistant weed populations.

Broadly, the integration of chemical and non-chemical tools would provide an opportunity to use the alternative herbicide chemistries, thereby reducing the risk of resistance evolution and further build-up of herbicide-resistant weed populations.

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