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Management of herbicide-resistant *Phalaris minor* in wheat by sequential or tank-mix applications of pre- and post-emergence herbicides in north-western Indo-Gangetic Plains

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ABSTRACT

Development of cross resistance or multiple cross resistance in *Phalaris minor* in wheat will continue to increase, as the weed develops mechanisms of resistance against new herbicides. This weed is a major threat to wheat productivity in north-western India, and as such needs to be addressed with integrated weed management approaches, including crop and herbicide rotations, herbicide combinations along with cultural and mechanical methods. Three field experiments were conducted during 2008–09 to 2012–13 along with large plot adaptive trials during 2012–13 with the objective to evaluate the efficacy of sequential applications of pendimethalin applied pre-emergent followed by clodinafop, sulfosulfuron, or pinoxaden applied post-emergent and tank-mix applications of metribuzin with these post-emergence herbicides for the management of herbicide-resistant *P. minor* in wheat. Clodinafop 60 g ha^{-1} or sulfosulfuron 25 g ha^{-1} at 35 days after sowing (DAS) and pendimethalin 1000 g ha^{-1} as pre-emergence did not provide consistently effective control of *P. minor* in wheat. An increase in the dose of clodinafop from 60 to 75 g ha^{-1} and of sulfosulfuron from 25 to 30 g ha^{-1} also did not improve their efficacy to a satisfactory level. However, pinoxaden 50 g ha^{-1} provided effective control (97–100%) of *P. minor* but not of broadleaf weeds. The tank-mix application of metribuzin with clodinafop 60 g ha^{-1} or sulfosulfuron 25 g ha^{-1} at 35 DAS and the sequential application of pendimethalin 1000 g ha^{-1} or trifluralin 1000 g ha^{-1} just after sowing followed by clodinafop 60 g ha^{-1} or sulfosulfuron 25 g ha^{-1} at 35 DAS provided 90–100% control of *P. minor* along with broadleaf weeds in wheat, thus resulting in improved grain yields (4.72–5.75 t ha^{-1}) when compared to clodinafop 60 g ha^{-1} (3.85–5.60 t ha^{-1}) or sulfosulfuron 25 g ha^{-1} alone (3.95–5.10 t ha^{-1}). The efficacy of mesosulfuron + iodosulfuron (a commercial mixture) 14.4 g ha^{-1} against *P. minor* was not consistent across the experiments and over the years. The ready-mix combination of fenoxaprop + metribuzin (100 + 175 g ha^{-1}) at 35 DAS provided effective control of weeds but its varietal sensitivity needs to be determined before its use in field conditions. The tank-mix or sequential application of herbicides would be a better option than their applications alone to manage the serious problem of herbicide-resistant *P. minor* in wheat.

1. Introduction

Wheat (*Triticum aestivum* L.) is the second most important food grain of India with a production area of 31.2 million ha, a production of 95.9 million tonnes, and an average productivity of 3075 kg ha^{-1} (Anonymous, 2014a). Haryana is the major wheat growing state in India with an area of 2.5 million ha (8% area of the total national level), 11.8 million tonnes of production (12.3% production share at the national level), and productivity of 4722 kg ha^{-1} (Anonymous, 2014b). Haryana still has the potential to increase the productivity of wheat with improved agronomic practices, including weed management. Weeds are a serious cause

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of concern for wheat productivity. *Phalaris minor* Retz. is a common weed of wheat in the rice-wheat cropping system in Haryana, Punjab, and Western Uttar Pradesh states of the north-western Indo-Gangetic Plains of India. The sustainability of the rice-wheat system has been repeatedly questioned over the last two decades. Harrington et al. (1992), after an exploratory survey, concluded that infestation of *P. minor* in wheat and a decline in soil productivity were the two most important constraints for the declining total factor in productivity of the rice-wheat cropping system.

Phenyl-urea herbicides (metoxuron, methabenzthiazuron, and isoproturon) were recommended in India or Haryana in 1978. However, farmers relied on the single herbicide isoproturon due to its consistent weed control since the 1980s. Its use resulted in significant improvements in wheat yields, but its continuous use for 10–15 years resulted in the evolution of resistance in *P. minor* in wheat in the rice-wheat cropping system against this herbicide in the early 1990s (Malik and Singh, 1993, 1995; Malik, 1995, 1996; Walia et al., 1997). This caused the most serious case of herbicide resistance in the world, resulting in total crop failure from heavy weed infestations (2000–3000 plants m^{-2}) (Malik and Singh, 1995). The resistance to isoproturon affected area ranged between 0.8 and 1.0 million ha in north-western India, mostly in the states of Haryana, Punjab, parts of Delhi, Uttarakhand, and other foothill plains areas which accounts for 3 million ha of the rice-wheat cropping system out of India's 10 million ha in this cropping system and about 35% of wheat production (Malik and Singh, 1994, 1995; Yadav and Malik, 2005).

The GR_{50} (dose of a herbicide required to cause 50% growth reduction) of isoproturon in resistant biotypes of *P. minor* from different parts of Haryana was reported to increase by 2–11 times as compared to its susceptible populations (Malik and Singh, 1995; Yadav et al., 1996; Malik and Yadav, 1997; Chhokar and Malik, 2002). Resistance was also quantified and confirmed against isoproturon in various biotypes of *P. minor* from Punjab and north-western India (Yadav et al., 1996; Malik et al., 1998). Resistance in *P. minor* against isoproturon was found to be metabolic in nature (Malik et al., 1995; Singh et al., 1996a, b; Kirkwood et al., 1997; Kulshrestha et al., 1999; Yaduraju and Bhowmik, 2005) and resistance in different biotypes multiplied with the increasing number of seasons of exposure to isoproturon (Yadav et al., 2002). Also, the behaviour of resistant and susceptible biotypes of *P. minor* against other phenyl-urea herbicides like methabenzthiazuron and metoxuron was almost similar to that of isoproturon, confirming resistance to other phenyl-urea herbicides (Yadav and Malik, 2005). Dhawan et al. (2008) observed herbicide resistance in *P. minor* with a molecular diversity in its populations.

Due to the large scale failure of isoproturon, the recommendation of this herbicide was withdrawn during 1997–98 from the resistance affected rice-wheat growing areas of Haryana. Based on surveys, monitoring, and multi-locational trials particularly at farmers' fields in Haryana, Punjab, and Uttar Pradesh, four alternate herbicides (clodinafop, fenoxaprop, sulfosulfuron, and tralkoxydim) were recommended in 1998 (Yadav and Malik, 2005). Clodinafop 60 g ha^{-1}, fenoxaprop 120 g ha^{-1}, sulfosulfuron 25 g ha^{-1}, and tralkoxydim 350 g ha^{-1} applied at the 3-leaf stage reduced the dry weight of the resistant and susceptible biotypes by 82–95% (Yadav et al., 2004; Yadav and Malik, 2005). These herbicides played a crucial role in restoring the productivity of wheat in this part of the country. Dependence on the continuous use of these alternate herbicides alone was doubted due to the possibilities of resistance or cross resistance (Yadav et al., 2002). Malik et al. (1998) speculated and advised that if newly introduced herbicides in wheat were not used properly, they would result in an even more rapid resistance development than isoproturon. Vincent and Quirke (2002) had also assumed that if an integrated weed management approach was not adopted properly, the herbicide resistance incidence of the early 1990s would repeat by 2007. Therefore, the suite of herbicides needs to be integrated with other management strategies like zero-tillage (Malik et al., 2000, 2002), the use of weed-competitive varieties (Chauhan et al., 2001a, b), early sowing, crop rotation, herbicide mixtures and sequences, herbicide rotation (Yadav and Malik, 2005), and proper spray techniques (Miller and Bellinder, 2001). The new herbicide, pinoxaden, was also found to be an alternative herbicide for the control of isoproturon-resistant *P. minor* (Yadav et al., 2009a) and was recommended for its control in 2009. Earlier studies have indicated that the pre-emergence applications of dinitroanilines, like pendimethalin and trifluralin, provided excellent control of isoproturon-resistant *P. minor* (Yaduraju et al., 2000).

Cross resistance development has however, also started at many places in this part of the country. The first herbicide suspected to have led to cross resistance was fenoxaprop. Mahajan and Brar (2001) reported the suspicions of cross resistance development in *P. minor* against fenoxaprop, and predicted that the order of occurrence of cross resistance would be fenoxaprop followed by clodinafop and sulfosulfuron. Yadav and Malik (2005) also reported an increased resistance factor (3.0–9.3) against fenoxaprop in some of the *P. minor* biotypes from Karnal district in Haryana. The long-term monitoring of herbicide resistance since 1997–98 at permanent sites in Karnal began to reveal signs of cross resistance in the year 2004–05. Fenoxaprop was the first to reveal the signs of complete failure followed by sulfosulfuron and clodinafop (Yadav, 2008). Dhawan et al. (2009) reported increases in GR_{50} values from 1999–2000 to 2006–07 by 10-fold in fenoxaprop, 8-fold in sulfosulfuron, and 3-4-fold in clodinafop, indicating the evolution of cross resistance to these herbicides in *P. minor*. Dhawan et al. (2010) reported cross resistance against a newly launched herbicide, pinoxaden, also within a short span of time after its launch. The evolution of metabolic resistance against aryloxyphenoxypropionate herbicides has been confirmed in Iranian *P. minor* populations as well (Gherekhloo et al., 2011, 2012).

Chhokar and Sharma (2008) reported development of multiple resistance in *P. minor* across three modes of action of herbicides (photosystem II, ACCase, and ALS inhibitors). However, in further studies, populations resistant to six herbicide site of action groups (phenylurea, sulfonylurea, aryloxyphenoxypropionic, cyclohexene oxime, phenylpyrazole, and triazolopyrimidinesulfonamide) were found susceptible to triazine (metribuzin and terbutryn) and dinitroaniline (pendimethalin) herbicides (Chhokar and Sharma, 2008; Chhokar et al., 2010). This finding indicated the suitability of these herbicides for the management of cross resistance. Pendimethalin has already been recommended for the control of *P. minor* in wheat in Haryana. This herbicide was not adopted by farmers due to its high cost and requirement for high moisture at the time of spray application. Dinitroanilines provided similar control of isoproturon-resistant and susceptible biotypes (Yadav and Malik, 2005), indicating their suitability for use when cross resistance is suspected. Metribuzin has been observed to cause phytotoxicity at high doses; however, its use as a mixture at lower doses may be advantageous in management of cross resistance.

Combinations of herbicides with different modes of action may be helpful to avert or delay the development of resistance. To withstand application from multiple herbicides, many genes would be required for herbicide tolerance trait, thus the probability of this occurring in one plant is extremely low. Therefore, herbicide mixtures can reduce the rate of development of resistant populations. Weeds resistant to more vulnerable herbicides will be killed by the mixing partners or at least be rendered relatively unfit to produce seeds compared to the wild types (Anonymous, 1990).