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Herbicide Resistance Management in Wheat: An Integrated Approach for Sustainable Weed Management

*Ankur Chaudhary and Rajbir Singh Khedwal
Chaudhary Charan Singh Haryana Agricultural University, Hisar-125004 (Haryana)
*Corresponding Author's email: ankurchaudhary292@gmail.com

Wheat is a major component of the rice-wheat production system of north-western India and plays a central role in regional and national food security. However, the sustainability and productivity of wheat production are increasingly threatened by herbicide-resistant weeds. The problem is particularly serious because wheat is generally grown at close spacing, making mechanical interculture difficult, while intensive rice-wheat systems provide limited opportunities for diversification of weed-management practices. Consequently, farmers have increasingly relied on herbicides for economical and timely weed control. Repeated and intensive use of herbicides with similar modes of action, however, has exerted strong selection pressure on weed populations and contributed to the evolution and spread of herbicide resistance. Herbicide resistance is not a new phenomenon in Indian agriculture, but its importance has increased considerably with the intensification of chemical weed management. In wheat, resistance has been documented in important grassy and broadleaf weeds such as *Phalaris minor*, *Avena ludoviciana*, and *Rumex dentatus*, against acetolactate synthase (ALS)- and ACCase-inhibiting herbicides, including sulfonylurea and related herbicides such as clodinafop, pinoxaden, sulfosulfuron, and metsulfuron. These developments clearly demonstrate that resistance is no longer restricted to a single weed species or herbicide group.

Why herbicide resistance is increasing

Herbicides have transformed weed management by reducing dependence on labour-intensive manual and mechanical operations. Their adoption has been particularly rapid in crops where mechanical weed control is difficult. Herbicides are used over a large area of the country's cropland, and their importance in weed management has increased with labour scarcity, rising labour costs and the need for timely crop establishment. Although modern low-dose herbicides have reduced the quantity of active ingredient required per hectare, this does not eliminate the biological risk associated with repeated selection for resistance.

The fundamental problem arises when the same herbicide or herbicides with the same mode of action are repeatedly used against a weed population. Initially, most susceptible weeds are killed, while rare naturally occurring resistant individuals survive. Continued use of the same herbicide increases the relative abundance of these survivors. Over several generations, the resistant population can become dominant, resulting in apparent herbicide failure. Thus, herbicide resistance should not be considered simply as a failure of a particular product. It is a consequence of evolutionary selection and must be addressed through changes in the overall weed-management system.

Herbicide resistance in wheat weeds

Littleseed canarygrass (*Phalaris minor*) remains one of the most important weeds of wheat in north-western India. Its close association with wheat, high competitiveness, prolific seed production and similar growth habit make it particularly difficult to manage. Historically, herbicides provided highly effective and economical control, but repeated use of the same herbicide groups resulted in the selection of resistant populations.

The resistance problem has subsequently become more complex. *P. minor* has developed resistance to both ALS- and ACCase-inhibiting herbicides. This is particularly important because these herbicide groups have historically been important components of post-emergence weed management in wheat. Once resistance to one group develops, farmers may shift rapidly to another herbicide group, which can subsequently increase selection pressure for resistance to that group as well. *Avena ludoviciana* has also evolved resistance to ACCase inhibitors. Resistance in this species is particularly concerning because wild oat species can be highly competitive with wheat and may escape control when herbicide application is delayed or environmental conditions are unsuitable. Resistance is not restricted to grassy weeds. *Chenopodium album* and *Rumex dentatus*, two important broadleaf weeds of wheat, have also evolved resistance to ALS-inhibiting herbicides. This highlights the need for a broad-spectrum resistance-management strategy. A herbicide program that controls *P. minor* effectively but allows resistant broadleaf weeds to survive may still result in significant yield loss and replenishment of the soil weed seed bank.

Herbicide resistance is a whole-system problem

The occurrence of multiple resistant species demonstrates that herbicide resistance cannot be managed by simply replacing one herbicide with another. In intensive wheat production systems, the same weed population may be exposed to several herbicide groups over successive seasons. If these herbicides are used without adequate diversification, selection pressure may continue even when the commercial products are different. Furthermore, resistance can involve different biological mechanisms. Target-site resistance occurs when changes at the herbicide's site of action reduce herbicide sensitivity. Non-target-site mechanisms may involve enhanced metabolism, reduced uptake or translocation, sequestration, or other physiological processes. Therefore, simply increasing the herbicide dose may not restore effective control and can intensify selection pressure.

An important distinction should also be made between true resistance and herbicide escape. Poor spray coverage, incorrect dose, late application, unsuitable soil moisture, adverse weather, or excessively large weeds can all result in poor control. Suspected resistance should therefore be confirmed through appropriate dose-response studies before management recommendations are developed.

Integrated herbicide resistance management

The most effective approach to herbicide resistance is to integrate several weed-management practices rather than depend exclusively on herbicides. The objective should be to reduce weed emergence, suppress surviving weeds, prevent seed production and diversify selection pressures.

1. Rotate herbicide modes of action

Herbicide rotation is one of the fundamental principles of resistance management. Rotation should be based on mode of action, not merely on the commercial product or brand name. Changing from one commercial formulation to another that has the same mode of action does not provide meaningful resistance management. Repeated use of ALS inhibitors, for example, can maintain strong selection pressure on ALS-resistant populations. Similarly, repeated dependence on ACCase inhibitors can select for resistant *P. minor* and *A. ludoviciana* populations. Where effective and agronomically compatible, herbicides with different modes of action should be rotated across seasons or used in effective combinations. However, a mixture is useful only when both components are effective against the target weed at appropriate rates. Adding a herbicide that has little or no activity against the resistant population does not constitute effective resistance management.

2. Use pre-emergence and residual herbicides

Greater emphasis should be placed on pre-emergence and residual herbicides as part of diversified weed-management programs. Early suppression reduces the number and size of weeds that subsequently require post-emergence control. Pyroxasulfone is particularly relevant in this context. Research conducted in conservation-tillage wheat under the rice–wheat production system of north-western India has demonstrated the potential of pyroxasulfone alone and in combination with other herbicides for controlling difficult weed populations, including *P. minor*. Studies involving research-station sensitive populations and farmer-field populations with resistance problems showed substantial reductions in *P. minor* biomass when pyroxasulfone-based programs were appropriately selected and timed. The value of pyroxasulfone lies in providing an alternative mode of action and residual activity. However, its repeated use as the sole resistance-management tool should be avoided. Like every herbicide, it must be integrated into a diversified program to preserve its effectiveness. List of herbicides is given in Table 1.

3. Apply herbicides at the correct time and dose

Correct timing is critical for both weed control and resistance management. Herbicides generally provide better control when weeds are small and actively growing. Delayed application allows weeds to become larger and more difficult to control and increases the probability of survival. Underdosing should be avoided because partially controlled weeds may survive and reproduce. At the same time, indiscriminate increases in dose are not an appropriate resistance-management strategy. The recommended label rate should be used with suitable water volume, spray quality and environmental conditions. Appropriate timing can substantially improve weed suppression and reduce the opportunity for weeds to escape.

4. Cultural practices

Management of herbicide-resistant *P. minor* should begin before wheat is sown. Fields with a history of resistance should be identified and monitored carefully. The initial weed population can be reduced through stale seedbed techniques, timely sowing and proper field preparation. Timely wheat sowing and rapid crop establishment are especially important because a vigorous wheat crop can compete more effectively with *P. minor*. Maintaining an optimum plant population, balanced fertilization and good crop establishment can further increase crop competitiveness. Where resistance is suspected, farmers should avoid repeatedly applying the herbicide that has failed in the field. Instead, an effective herbicide with a different mode of action should be selected, preferably as part of an integrated program involving residual activity and non-chemical practices. Most importantly, resistant plants should not be allowed to produce seed. Even a small number of surviving resistant plants can replenish the soil seed bank and increase the resistant population in subsequent seasons. Suspected resistant patches should therefore be monitored and, where feasible, controlled separately. A treatment that provides excellent grass control but poor broadleaf control should not be considered a complete weed-management program. This is also an important consideration when evaluating new herbicide combinations. Differential responses of broadleaf weeds to individual herbicides can influence both yield and the future weed spectrum.

Role of crop rotation and diversification

Crop rotation is one of the most effective non-chemical strategies for resistance management because it changes the selection environment. Different crops provide opportunities to use different herbicides, cultivation practices and weed-control timings. Where agronomically feasible, diversification of the rice–wheat system can reduce continuous selection pressure. Crop rotation also changes weed emergence patterns and can prevent a particular weed species from becoming continuously adapted to one crop and its associated herbicide program.

Conservation agriculture and residue management

Conservation tillage and in-situ rice-residue management are increasingly important in north-western India because they can facilitate timely wheat sowing, reduce soil disturbance and provide alternatives to residue burning. However, changes in tillage and residue distribution can also alter weed emergence and herbicide behaviour. Research conducted under rice–wheat–moongbean systems has demonstrated that residue retention and tillage influence weed dynamics, soil temperature, crop establishment and wheat productivity. Residue mulch can alter soil moisture and temperature and may modify the movement and performance of soilapplied herbicides. Studies with pyroxasulfone-based treatments have shown that herbicide performance can also be influenced by spray volume and placement relative to rice residue.

Preventing the spread of resistant weeds

Resistance management should also focus on preventing the movement of resistant weed seeds between fields. Agricultural machinery can transport weed seeds and soil from heavily infested fields to clean fields. Harvesting, tillage and sowing equipment should therefore be cleaned where practical after operating in fields with severe infestations. Field boundaries, irrigation channels and uncultivated areas should also be monitored because they can serve as sources of weed seeds. Resistant weed patches should be identified and managed before seed production. Prevention is generally more economical than attempting to eradicate a well-established resistant population.

Monitoring and early detection

Regular field scouting is essential for early detection of resistance. Farmers should inspect fields after herbicide application and identify unusual patches where weeds survive while surrounding susceptible plants have been controlled. However, survival alone should not immediately be labelled as resistance. Application errors, poor spray coverage, incorrect dose, late weed emergence, unsuitable soil moisture or environmental conditions can also cause poor control. Suspected resistant populations should therefore be collected and tested using appropriate dose-response procedures. Research-based resistance monitoring can provide early warning of resistance development and allow management recommendations to be modified before resistant populations become widespread.

A practical resistance-management program for wheat in north-western India can be organized around the following principles:

1. Know the weed spectrum and resistance history of the field.
2. Use pre-emergence or residual herbicides wherever appropriate.
3. Rotate herbicides according to mode of action.
4. Use effective herbicide mixtures rather than mixtures containing weak or ineffective partners.
5. Apply herbicides at the recommended dose and optimum growth stage.
6. Avoid repeated use of ALS- or ACCase-inhibiting herbicides alone.
7. Integrate pyroxasulfone-based programs where appropriate, particularly in fields with difficult *P. minor* populations.
8. Maintain timely wheat sowing and a competitive crop stand.
9. Use crop rotation and diversification wherever feasible.
10. Retain and manage crop residues appropriately under conservation agriculture.
11. Scout fields after herbicide application and identify surviving weed patches.
12. Prevent suspected resistant plants from producing seed.
13. Clean farm machinery to minimize movement of weed seeds.
14. Confirm suspected resistance through appropriate testing before making long-term recommendations.

Future direction

The increasing occurrence of herbicide resistance in wheat weeds in India demonstrates the need to move from a herbicide-dependent approach to an integrated resistance-management approach. Future research should emphasize long-term field experiments involving herbicide rotation, effective mixtures, residual herbicides, crop diversification, residue management, conservation tillage and non-chemical weed-control practices. Particular attention should be given to populations showing resistance to multiple herbicide mechanisms. Research should also examine how resistance interacts with changing production systems, including zero tillage, residue retention, altered sowing dates and diversification of the rice–wheat system. Extension programs should focus on helping farmers recognize resistance, distinguish resistance from poor herbicide application, select herbicides according to mode of action, and prevent resistant plants from producing seed. Pyroxasulfone-based programs provide an important additional tool for managing difficult *P. minor* populations, particularly when integrated with other effective modes of action and non-chemical practices. Nevertheless, no herbicide should be considered a permanent solution to resistance. An integrated, field-specific and long-term approach is therefore essential for maintaining wheat productivity and sustaining weed-management options in the rice–wheat system of north-western India.

Table 1. Herbicides for weed management in wheat

Type of weed flora	Herbicide	Dose product (g or ml/ acre)	Dose (g ai/ha)	Time of application
Mixed flora	Sulfosulfuron 75% + Metsulfuron 5%	16	30+2	Post emergence
Phalaris minor and wild oat	Clodinafop 15 WP	160	60	Post emergence
Phalaris minor and wild oat	Sulfosulfuron 75 WG	13	25	Post emergence
	Flufenacet 41 SC	244-292	250-300	One day before first irrigation/ Post emergence
Resistant *Phalaris minor*	Pyroxasulfone 85 WG	60	127.5	Pre-emergence and one day before first irrigation
Resistant *Phalaris minor* + mixed flora	Pyroxasulfone 85 WG + Pendimethalin 30 EC	60+ 1300	127.5 + 1000	Pre-emergence
	*Mesosulfuron methyl 3% + Iodosulfuron methyl sodium 0.6 WDG	160	60	Post emergence
	Metribuzin 42% + clodinafop propargyl 12% WG	200	270	Post emergence
Phalaris minor	Pinoxaden 5.1 EC	400	50	Post emergence
Broad leaf weeds	Metsulfuron methyl 20 WP	8	4	Post emergence
Broad leaf weeds including *Medicago*, *Vicia*, *Lathyrus*, *Physalis*	Carfentrazone ethyl 40 DF	20	20	Post emergence
Broad leaf weeds including Medicago, Vicia, Lathyrus, Physalis	Metsulfuron 10% + Carfentrazone 40%	20	5 + 20	Post emergence
Broad leaf weeds	2,4-D sodium (80 WP), ester (38 EC), and amine (58 SL) salts	300-500	400-600	Post emergence

* *Avoid succeeding crops like maize or sorghum*