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Original Article

Herbicide resistance in weeds: current status in Iran

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Abstract

Weeds are a major threat to sustainable production of agricultural products. Introduction of herbicide made the arduous operations of weed control remarkably less challenging. However, repeated application of herbicides with similar modes of action has resulted in herbicide resistance in weeds. Thus, weed control has become more difficult, and meticulous plans should be devised to tackle this issue. In recent decades, crop production in Iran is also seriously affected by herbicide resistance. To confront this challenge, it is essential to be informed of the latest status of herbicide resistance in the country. Therefore, the present paper will review the brief status of herbicide resistance across the world, the history of herbicide resistance in Iran, mechanisms of resistance observed in the country, drivers of resistance evolution in Iran, fitness cost studies carried out in the country, management strategies to overcome herbicide resistance, key challenges and research gaps in Iran, and future directions.

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مقاله پژوهشی

مقاومت به علف‌کش‌ها در علف‌های هرز: وضعیت کنونی در ایران

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چکیده

علف‌های هرز تهدیدی جدی برای تولید پایدار محصولات کشاورزی هستند. معرفی علف‌کش‌ها موجب تسهیل عملیات کنترل علف‌های هرز شد. با این حال، کاربرد مداوم علف‌کش‌هایی که نحوه عمل یکسانی دارند، موجب بروز مقاومت به علف‌کش‌ها در علف‌های هرز شده است. بنابراین، کنترل علف‌های هرز دشوارتر شده و جهت حل این معضل، نیاز به تدوین برنامه‌های دقیق‌تری می‌باشد. تولید محصولات زراعی در ایران نیز در چند دهه اخیر به شدت تحت تأثیر مقاومت به علف‌کش‌ها قرار گرفته است. جهت مقابله با این چالش، اطلاع از آخرین وضعیت مقاومت به علف‌کش‌ها در کشور ضروری می‌باشد. بنابراین، مقاله حاضر، به بررسی وضعیت کنونی مقاومت به علف‌کش‌ها در دنیا، تاریخچه مقاومت به علف‌کش‌ها در ایران، مکانیسم‌های مقاومت مشاهده شده در کشور، عوامل ایجاد مقاومت، مطالعات شایستگی نسبی انجام شده در ایران، راهبردهای مدیریتی جهت مقابله با مقاومت به علف‌کش‌ها، معضلات اساسی و خلاء های تحقیقاتی و نیز آینده این تحقیقات خواهد پرداخت.

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Introduction

From the dawn of agriculture, weeds have been infesting crop cultivation fields and humans have struggled to mitigate their detrimental impact on crop yield (Gonzalez-Andujar, 2023). Weeds compete with crops over nutrients, water and radiation (Singh et al., 2022; Karlsson et al., 2025). Consequently, they reduce crop yield and quality (Wang et al., 2024), Increase the costs of plant production (Nath et al., 2024), act as hosts for diseases and pests (Barman et al., 2022), interfere with harvesting operations (Walsh et al., 2022), and sometimes have allelopathic characteristics (Gam et al., 2024). According to Oerke (2006), weeds can potentially lead to approximately 34% yield loss in crops, whereas yield loss by insects and diseases are 18 and 16%, respectively. This further highlights the detrimental impact of weeds.

Introduction of herbicides to the market enabled the farmers to control weeds more efficiently in a rapid manner (Ofosu et al., 2023). However, over-reliance on herbicides has resulted in the emergence of herbicide-resistant weeds (Rani et al., 2025). Herbicide resistance can be defined as the inherited ability in a plant to withstand and procreate after being exposed to herbicide doses that are lethal for its wild type population (Leon, 2024). This phenomenon has further exacerbated the problems imposed by weeds.

Insufficient control of weeds due to herbicide resistance can result in further yield loss and thus, significant economic losses for farmers. According to Soltani et al. (2016), poor control of herbicide-resistant weeds reduced maize yields up to 50%. Moreover, farmers will be compelled to adopt more intricate and costly methods to manage weeds, including increasing rates of herbicide application or using alternative and more expensive herbicides (Hassanpour-bourkheili et al., 2024).

Herbicide resistance also limits the chemical options for weed management (Cai et al., 2022). Adding to these challenges, introduction of herbicides with new modes of action has proven to be an arduous and time-consuming challenge (Duke & Dayan, 2022). Moreover, they might need to use mechanical or manual weeding methods that require more manual labor and are not cost-effective (Beltran al., 2012).

Another outcome of herbicide resistance is weed flora shift. Weed species that were once dominant will be replaced by herbicide-resistant weeds that are more difficult to control (Andreasen & Streibig, 2011). Furthermore, excessive use of herbicide due to herbicide resistance threatens the abundance and biodiversity of the environment's fauna (Prosser et al., 2016). Increased energy use and emission of greenhouse gasses (Hassanpour-bourkheili et al., 2024) and further environmental toxicity and pollution (Parven et al., 2025) are also among the harmful impacts of herbicide resistance in weeds.

Iran is also among the countries that are struggling with the issues raised by herbicide resistance. Given the aforementioned risks of herbicide resistance, it is necessary to systematically review the status of this issue in the country. Such study was conducted before by Gherekhloo et al. (2016). However, the situation has exacerbated since then and new cases of herbicide resistance have been reported across the country. Therefore, the present paper will review the current status of herbicide resistance in Iran. The paper will discuss the brief status of herbicide resistance across the world, history of herbicide resistance, drivers of resistance evolution, management strategies to overcome herbicide resistance, mechanisms of resistance observed, fitness cost studies, key challenges and research gaps, and future directions in Iran.

Global overview of herbicide resistance

The alarming increase in the number of herbicide resistance cases started in the late 70s and early 80s. Currently, 534 cases of herbicide resistance have been reported across the world so far. This figure includes 273 species, 156 of which are dicots and 117 are monocots. Out of 31 known herbicide sites of action, weeds have shown resistance against 21, and resistance to 168 unique herbicides has been documented. Also, herbicide resistant weeds have been reported in 102 crops in 75 countries (Heap, 2025).

Out of the aforementioned cases, 176 belong to weeds resistant to acetolactate synthase (ALS) inhibitors, making them the most frequent site of action for herbicide resistance (33% of total cases). Photosystem II (PS II), enolpyruvyl shikimate phosphate synthase (EPSPS), and acetyl CoA carboxylase (ACCase) inhibitors, auxin mimics, and photosystem I (PS I) inhibitors are ranked next with 87, 60, 51, 44, and 33 cases, respectively (Heap, 2025).

Approximately two-thirds of herbicide-resistant weeds belong to Poaceae, Asteraceae, Brassicaceae, Cyperaceae, and Amaranthaceae families, with 92, 46, 22, 12, and 11 cases, respectively (Heap, 2025). In addition, 86 cases of herbicide-resistant weeds have been reported in wheat, and maize, rice, and soybean are ranked subsequently with 66, 57, and 53 cases, respectively. Among the herbicide-resistant weeds, annual bluegrass (*Poa annua* L.) is reported to exhibit resistance to herbicides with 10 different sites of action. Rigid ryegrass (*Lolium rigidum* Gaud.) with nine, and palmer amaranth (*Amaranthus palmeri* S. Watson), wild oat (*Avena fatua* L.), and Indian goosegrass (*Eleusine indica* (L.) Gaerten) with seven different sites of action are ranked next (Heap, 2025)

United States has documented the highest number of herbicide resistance cases with 132, followed by Australia, Canada, Brazil, and China with 91, 56, 50, and 50, respectively. Currently, 13 cases of herbicide resistance have been reported from Iran, out of which one belongs to auxin mimics, seven to ACCase inhibitors and five to ALS inhibitors (Heap, 2025). These figures underline the critical necessity of measures to mitigate herbicide resistance in Iran.

History and Evolution of Herbicide Resistance in Iran

In Iran, research on herbicide resistance in weeds has been ongoing for over two decades (Zand, 2025). The first report of herbicide resistance was published in 2004, when Zand et al. (2004) documented resistance to fenoxaprop-P-ethyl in a wild oat (*Avena ludoviciana*) population collected from wheat fields in Fars Province. Since then, the spread of herbicide-resistant weeds particularly grass species has steadily increased across various crops. Currently, according to a survey in Golestan province, 53.6% of the wheat fields are infested by herbicide-resistant weed species (Gherekhloo and Haghnama, 2021). The situation can more or less be similar in some other provinces. Wheat has received the most attention due to its extensive cultivation and strategic importance. Consequently, research in Iran has primarily focused on detecting resistance in key grass weed species such as wild oat (*Avena* spp.), canary grass (*Phalaris* spp.), and annual ryegrass (*Lolium rigidum*), owing to their prevalence and the challenges associated with chemical control. A map of herbicide resistance in Iran is presented in Figure 1.

Major arable crops include wheat (*Triticum aestivum*), rice (*Oryza sativa*), barley (*Hordeum vulgare*), maize (*Zea mays*), sugar beet (*Beta vulgaris*) legume crops such as chickpea (*Cicer arietinum*), oil crops such as sunflower (*Helianthus annuus*), and industrial crops such as potato (*Solanum tuberosum*) (IPAD, 2025). Herbicides have been a primary tool for managing weeds in these arable systems due to their efficiency and cost-effectiveness. However, herbicide-resistant weeds have so far been documented mainly in a few crops, most notably wheat and canola (in rotation with wheat), while evidence from other major crops such as rice, sugarcane, barley, or chickpea remains scarce. This indicates a significant knowledge gap, as systematic surveys and resistance monitoring efforts have largely focused on cereals, leaving the status of herbicide resistance in other crop systems underexplored.

Early studies estimated that grass weed resistance to acetyl-CoA carboxylase (ACCase)-inhibiting herbicides the most commonly used group had spread extensively across wheat fields in the provinces of Khuzestan, Fars, Kermanshah, Golestan, and Ilam (Zand et al., 2010). Rastgoo et al. (2006) reported resistance to fenoxaprop, diclofop-methyl, and clodinafop-propargyl in wild oat populations. Gherekhloo et al. (2008) identified 14 and 7 resistant populations of canary grass (*Phalaris minor*) from wheat fields in Fars and Golestan provinces, respectively, with varying levels of resistance to fenoxaprop-P-ethyl and diclofop-methyl. Further studies by Zand et al. (2006), Benakashani et al. (2007a, 2007b) and Sasanfar et al. (2009a, 2009b) on winter wild oat populations revealed different levels of resistance and cross-resistance to ACCase-inhibiting herbicides.

In the most recent nationwide assessment in Iran, 1,174 grass weed populations from wheat fields were analyzed, including 848 wild oat, 205 canary grass, and 121 annual ryegrass samples (Zand et al., 2022). The results confirmed widespread resistance to both ACCase- and acetolactate synthase (ALS)-inhibiting herbicides. Over the past 25 years, resistance was detected in 67% of wild oat, 49% of canary grass, and 59% of annual ryegrass populations. Resistance to ALS inhibitors, often considered an alternative to manage resistance to Group 1 herbicides, was also detected in 76% of wild oat (293 populations), 24% of canary grass (41 populations), and 65% of annual ryegrass (65 populations). Also, various reports are available on resistance to ACCase (Najjari Kalantari et al., 2013; Tatari et al., 2018; Heravi et al., 2020; Soufizadeh et al., 2022) and ALS (Derakhshan & Gherekhloo, 2012; Hatami Moghaddam et al., 2016; Heravi et al., 2017) inhibiting herbicides.

Moreover, multiple resistance to both ACCase and ALS inhibitors was identified in 62%, 7%, and 54% of wild oat, canary grass, and annual ryegrass populations, respectively (Zand et al., 2022). Similarly, in *E. crus-galli*, resistance was identified in a population from a rice field in Golestan, which showed resistance to the ALS inhibitors, penoxsulam and bispyribac-sodium (Haghnama & Mennan, 2020).

Overall, resistance and cross-resistance to ACCase inhibitors were observed in 63% and 17% of 1,174 and 642 studied populations, respectively (Zand et al., 2022). Similarly, resistance and cross-resistance to ALS inhibitors were reported in 69% and 44% of 399 and 360 populations, respectively. Multiple resistance to both ACCase and ALS inhibitors was confirmed in 55% of cases and is suspected to be developing in an additional 13%, accounting for 68% of the 399 studied grass populations (Zand et al., 2022).

Auxinic herbicide resistance, although less commonly reported than resistance to ALS inhibitors, has started to appear in certain broadleaf weed species across Iran. For instance, *G. aparine* populations from western regions have been documented to show resistance to 2,4-D, a widely used auxinic herbicide (Moradi et al., 2024). Similarly, *Malva parviflora* populations from Khuzestan have developed resistance to the 2,4-D + MCPA mixture (Kamaei et al., 2019). Notably, these *M. parviflora* populations were also resistant to the ALS inhibitor tribenuron-methyl (Table 2), indicating the emergence of multiple resistance in this species. These findings emphasize the increasing threat of auxinic herbicide resistance and highlight the need for diversified weed management strategies to prevent further resistance development.

In Iran, the primary rotational crops in winter wheat systems are canola (*Brassica napus*) and, to a lesser extent, sugar beet (*Beta vulgaris*). However, the dominant grass weeds infesting these rotational crops are often the same as those found in wheat fields. Moreover, the graminicides commonly used in these crops are mainly ACCase inhibitors (Group 1), which share the same site of action as herbicides applied in wheat. The continuous and repeated use of these herbicides across rotational crops has accelerated the development and spread of herbicide resistance, including cross-resistance, among grass weed populations.

In one study, 52 grass weed populations including 29 wild oat (*Avena ludoviciana*), 15 annual ryegrass (*Lolium rigidum*), and 8 canary grass (*Phalaris minor*) populations were collected from canola fields in the provinces of Fars, Mazandaran, and Ardabil. Among the annual ryegrass populations, resistance was confirmed in 86.7%, 66.7%, and 60% of populations to haloxyfop-R-methyl, sethoxydim, and cycloxydim, respectively. In canary grass, 25% of populations were resistant to haloxyfop-R-methyl, and 12.5% showed suspected resistance to sethoxydim. Among the wild oat populations, 31% exhibited resistance to haloxyfop-R-methyl, and one population was resistant to clethodim. No confirmed resistance to the other 'dim' herbicide, including cycloxydim, was observed in wild oat populations (Sasanfar et al., 2021). In a subsequent study (Sasanfar et al., 2024), 45 grass weed populations were collected from canola fields across various provinces including Golestan, Mazandaran, Fars, and Tehran and screened for resistance to commonly used ACCase-inhibiting herbicides. Resistance was detected in 47%, 47%, and 22% of populations to haloxyfop-R-methyl, sethoxydim, and clethodim, respectively. All populations remained susceptible to cycloxydim. Cross-resistance to ACCase inhibitors was observed in 36% of the tested populations. Additionally, a study by Hassanpour-Bourkheili et al. (2021a) found that among 22 winter wild oat populations within canola fields in Golestan province, five were resistant to haloxyfop-R-methyl. These resistant populations exhibited cross-resistance to clodinafop-propargyl and sethoxydim, but remained susceptible to pinoxaden and the ALS-inhibiting combination of mesosulfuron-methyl + iodosulfuron-methyl. These findings underscore the need for effective herbicide rotation and integrated weed management strategies, particularly in regions with intensive wheat–canola cropping systems (Sarani et al. 2014).

The first documented case of herbicide resistance in broadleaf weeds within Iranian wheat systems dates back to 2010, when wild mustard (*Sinapis arvensis* L.) was reported to exhibit resistance to the ALS-inhibiting herbicide tribenuron-methyl in Golestan Province (Aqqala County) (Derakhshan et al., 2015). Since then, the incidence of resistance has escalated considerably. To date, resistance has been confirmed in 11 broadleaf weed species: *S. arvensis* (wild mustard), *Rapistrum rugosum* L. (All) (turnip weed), *Galium aparine* L. (cleavers), *Malva* spp. (mallow), *Silybum marianum* (L.) Gaertn (milk thistle), *Ammi majus* L. (bishop's weed), *Descurainia sophia* (L.) Webb (flixweed), *Vaccaria* spp. (cowcockle), *Melilotus officinalis* (L.) Pall (yellow sweet clover), *Raphanus raphanistrum* L. (wild radish), and *Lepidium draba* L. (hoary cress) (Table 1).

Geographically, herbicide resistance in broadleaf weeds has been reported in 11 provinces. Khuzestan ranks highest, with six resistant species identified, followed by Ilam and Kermanshah (five species each), Golestan (two species), and Fars, Ardabil, Razavi Khorasan, Lorestan, Kerman, Tehran, and Markazi (each with at least one confirmed case). Spatial analyses suggest that resistance evolution initially emerged in northern (Golestan), western (Kermanshah), and southwestern (Khuzestan) regions, progressively expanding toward central (Tehran) and eastern provinces (Kerman and Mashhad) (Heap, 2025; Lotfifar et al., 2013; Derakhshan et al., 2012; 2015; Gherekhloo et al., 2016; Khalil Tahmasebi et al., 2024) (Table 1).

Development of herbicide resistance in broadleaf weeds over time in Iran

The temporal progression of herbicide resistance in these systems can be delineated into three distinct phases. The first phase (2001–2011) was characterized by the emergence of single resistance, beginning with *S. arvensis* in Golestan in 2010. Subsequent reports followed in Kermanshah in 2012 (Zand et al., 2019). This phase peaked in 2019 with the detection of *S. arvensis* populations resistant to multiple ALS inhibitors specifically, iodosulfuron + mesosulfuron + mefenpyr-diethyl, tribenuron-methyl, and a four-way mixture including diflufenican in eight provinces (Khalil Tahmasebi et al., 2024).

The second phase (2011–2016) marked the onset of cross-resistance. During this period, *S. arvensis* evolved resistance to two ALS-inhibiting herbicides; *Malva* spp. exhibited resistance to three ALS inhibitors in Khuzestan (Elahifard et al., 2017); and *S. marianum* developed cross-resistance to three ALS herbicides across Khuzestan, Golestan, and Kermanshah (Tahmasebi et al., 2019).

The third phase (2016–present) has been defined by the emergence of complex and highly concerning multiple resistance cases. Noteworthy examples include: *Malva* spp. populations in Ramhormoz (Khuzestan) resistant to four herbicide modes of action (ALS inhibitors, synthetic auxins, photosystem II inhibitors, and carotenoid biosynthesis inhibitors); *S. arvensis* resistant to both ALS inhibitors and synthetic auxins in Kermanshah; *R. raphanistrum* resistant to four herbicide classes in Kerman; and widespread multiple resistance of *Malva* spp. in Khuzestan (Khalil Tahmasebi et al., 2019).

As of 2025, several major challenges hinder the effective identification and management of broadleaf weed resistance in Iran. These include: the lack of comprehensive studies on resistance mechanisms (target-site and non-target-site) in identified species; insufficient resistance surveillance in strategic crops other than wheat; the emergence of new, inherently tolerant species such as *Lepyrodiclis holosteoides* (C.A. Mey.) Fenzl ex Fisch. & C.A. Mey.) in West Azerbaijan naturally tolerant to ALS inhibitors; the sharp decline in efficacy of inexpensive herbicides like tribenuron-methyl (particularly in Khuzestan and Golestan), and of key commercial herbicides such as iodosulfuron + mesosulfuron and bromoxynil + MCPA (especially in Khuzestan); and the absence of crop rotation or alternative crops in regions heavily infested with resistant broadleaf weeds.

Key drivers of the resistance crisis in Iran include: the overwhelming dominance of continuous wheat monoculture accounting for over 80% of arable land in Khuzestan, Golestan, and Kermanshah without rotation; poor herbicide stewardship, notably overuse of ALS inhibitors (often applied two to three times per season); and the near-complete dependence on chemical control methods, with over 90% of weed management relying on herbicides (Zand et al., 2023).

Table 1. Herbicide-resistant weed species in Iran, classified by mechanism of action (MOA) groups and reported distribution across major agricultural provinces.

Common name	Scientific name	Site of action	First report	Group	Province
Small canary grass	*Phalaris minor*	ACCase	2004	1	1,2,3
Winter wild oat	*Avena sterilis ssp.* ludoviciana	ACCase and ALS	2006	1	1,2,3,4,7
Annual ryegrass	*Lolium rigidum*	ACCase and ALS	2007	1	1,2,3,4,7
Common wild oat	*Avena fatua*	ACCase	2007	1	1,2,3,4,7
Awned canary-grass	*Phalaris paradoxa*	ACCase	2007	1	2
Jungle rice	*Echinochloa colona*	PS II (triazines)	2009	5	1
Wild mustard	*Sinapis arvensis*	ALS and Carotenoid inhibitors	2009	2,12	1,2,3,4,5.6.7,8
Turnip weed	*Rapistrum rugosum*	ALS	2010	2	3,11
Shortspike canarygrass	*Phalaris brachystachys*	ACCase	2014	2	3
Cleavers	*Galium aparine*	ALS, Auxin Mimics	2016,2024	2	4,8
Mallow	*Malva* spp.	ALS, Carotenoid inhibitors, PS II and Auxin Mimics	2024	2,12, 5, 4	1,4
Milk thistle	*Silybum marianum*	ALS, Carotenoid inhibitors, PS II and Auxin Mimics	2024	2,12, 5, 4	1
Bishop's weed	*Ammi majus*	ALS	2024	2	1,8
Flixweed	*Descurainia sophia (L.)* Webb	ALS	2024	2	1,9
Cowcockle	*Vaccaria* spp.	ALS	2024	2	4,8,10
Yellow sweet clover	*Melilotus indicus*	ALS	2024	2	1
Wild radish	*Raphanus Raphanistrum* L.	ALS, Carotenoid biosynthesis inhibitors, PS II and Auxin Mimics	2024	2,12, 5, 4	5,8
Hoary cress	*Lepidium draba L*	ALS	2024	2	6

1: Khuzestan, 2: Fars, 3: Golestan, 4: Kermanshah, 5: Kerman, 6: Tehran, 7: Ardabil, 8: Ilam, 9: Razavi Khorasan, 10: Lorestan, 11: Markazi (Heap, 2025; Nosrati & Muhammadyari, 2019; Zamanii et al., 2019, 2021; Joumi et al., 2022; Khalil-Tahmasebi et al., 2024).

Mechanisms of Resistance Observed in Iran

In general, mechanisms of resistance are categorized into target-site (TSR) and non-target-site resistance (NTSR) mechanisms. The first involves gene alteration that is able to change the interaction with the encoded target protein/enzyme so that the herbicide fails to bind the target site or gene overexpression. On the other hand, non-target-site resistance (NTSR) mechanisms do not involve the target protein and can reduce the amount of herbicide reaching the site of action to sub-lethal levels, allowing plants to survive. Occasionally, any mechanism protecting plants from herbicide damage is also referred as NTSR (Torra & Alacantara-de la cruz, 2023). NTSR mechanisms include reduced herbicide uptake/translocation, enhanced metabolism of the herbicide, decreased rate of herbicide activation, and/or sequestration (Jugulam & Shayam, 2019). It must be noted that herbicide metabolism is especially a serious threat. While herbicide metabolism usually results in low resistance factors, the unpredictable nature of this mechanism makes it very difficult to manage (Dimaano & Iwakami, 2021).

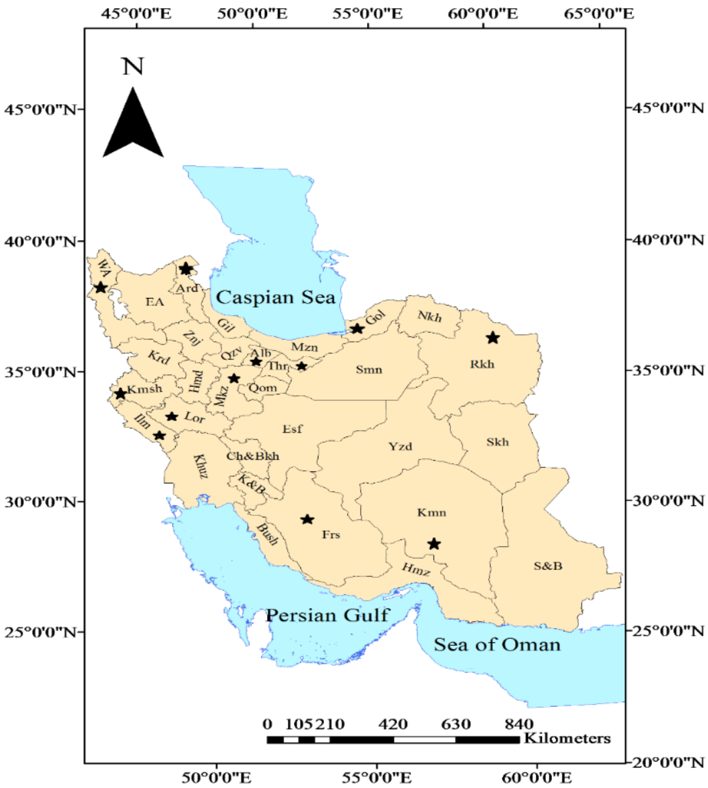

Figure 1. Map of Iran highlighting provinces with reported herbicide resistance (specified with *).
Abbreviations: Alb: Alborz; Ard: Ardabil; Bush: Bushehr; Ch&Bkh: Chahar Mahaal and Bakhtiari; EA: East Azarbaijan; Esf: Isfahan; Frs: fars; Gil: Gilan; Gol: Golestan; Hmd: Hamedan; Hmz: Hormozgan; Ilm: Ilam; K&B: Kohgiluyeh and Boyer-Ahmad; Khuz: Khuzestan; Kmn: Kerman; Kmsh: Kermanshah; Krd: Kurdistan; Lor: Lorestan; Mkz: Markazi; Mzn: Mazandaran; Nkh: North Khorasan; Qom: Qom; Qzv: Qazvin; Rkh: Razavi Khorasan; S&B: Sistan and Baluchistan; Skh: South Khorasan; Smn: Semnan; Thr: Tehran; WA: West Azarbaijan; Yzd: Yazd; Znj: Zanjan.

Knowledge about the mechanisms of herbicide resistance in weeds cannot be underestimated. Knowledge of these mechanisms enables the design of management practices, including the rotation or combination of herbicides with different modes of action, thereby delaying the evolution and spread of resistance (Powles & Yu, 2010). Moreover, insights into molecular and biochemical resistance pathways facilitate the early detection of resistant populations through molecular diagnostics, allowing timely intervention before infestations become widespread (Beckie & Harker, 2017). Such mechanistic understanding also supports the discovery of new herbicides and safeners that can overcome existing resistance, ensuring long-term weed control and crop productivity (Délye, 2013).

It must be noted that herbicide resistance studies in Iran which contain resistance mechanism are mostly associated with ACCase and ALS inhibitors, and there is only one such report for PSII inhibitors (Table 2). The species on which resistance mechanisms have been conducted in Iran include *A. ludoviciana*, (Zand et al., 2013; Benakashani et al., 2014) *L. rigidum* (Dastoori et al., 2011; Sabet Zangeneh et al., 2018a), *P. minor* (Gherekhloo et al., 2012), P. *brachystachys* (Golmohammadzadeh et al., 2020), *S. arvensis* (Bahmani Fathabadi et al., 2016; Khaledi et al., 2019; Hanifehzadeh Erdi et al., 2024) , *R. rugosum* (Hatami et al., 2016), and *E. colona* (Elahifard et al., 2013) (Table 2).

Most reports on herbicide resistance in the country concern TSR. However, there are cases reported from Iran that involve NTSR mechanisms. Study of NTSR mechanisms in Iran are rare and include studies on *P. minor* (Gherekhloo et al., 2010; 2012), *P. brachystachys* (Golmohammadzadeh et al., 2020), *R. rugosum* (Hatami et al., 2016), *S. arvensis* (Gherekhloo et al., 2018), *A. ludoviciana* (Hassanpour-bourkheili et al., 2020), and *L. rigidum* (Tavassoli et al., 2023).

This is due to the lack of required facilities and equipment as well as the low level of international collaborations. Resistance to ACCase and ALS inhibitors in *A. ludoviciana* has also been reported by Adim et al. (2021; 2025) in a proteomics-based study. A detailed list of the herbicide resistance cases with their respective mechanisms of resistance is presented in Table 2.

Fitness of Herbicide-Resistant Weeds

The most effective strategies for managing herbicide-resistant weeds (i.e., twelve key recommendations) were outlined by Norsworthy et al. (2012). One of these emphasizes the importance of understanding the biology and ecology (i.e., the fitness) of herbicide-resistant weed populations (Keshtkar et al., 2019). Fitness is defined as the number of offspring produced by a population relative to another population in the same population (Keshtkar et al., 2019; Vila-Aiub et al., 2009). In other words, it refers to a plant's reproductive success under varying environmental conditions (Holt, 1990). From a herbicide-resistance perspective, fitness is defined as the number of offspring produced by a resistant population relative to a non-resistant population (Keshtkar et al., 2019). Fitness of herbicide resistant populations can be positive, negative, or neutral relative to susceptible population. A population with positive fitness will gradually increase in frequency within the population over successive generations, whereas a population with negative fitness will decline due to producing fewer offspring (Keshtkar, 2025). The frequency of populations with neutral fitness remains stable within the population (Cousens & Fournier-Level, 2018). According to evolutionary and ecological theory, herbicide-resistant populations may exhibit lower fitness than susceptible populations in the absence of herbicide application. This fitness reduction of herbicide resistant populations, known as the fitness cost or cost of resistance, reflects potential trade-offs associated with resistance traits (Keshtkar et al., 2019; Vila-Aiub et al., 2009).

Fitness cost is, in fact, the result of negative pleiotropic effects of resistance-conferring alleles (Vila-Aiub et al., 2015). According to this theory, herbicide-susceptible individuals, due to their higher fitness are expected to become dominant in the field after several generations (i.e., growing seasons) without herbicide application. In other words, in the absence of herbicide selection pressure, the frequency of resistant individuals is likely to decline over time as a consequence of their lower fitness that is known as backward selection (Keshtkar et al., 2019). However, fitness costs associated with herbicide resistance cannot always be observed in all resistant weed species. The costs associated with resistance vary depending on the specific mutation and might only occur under certain environmental conditions (Lehnhoff et al., 2013; Vila-Aiub et al., 2009). Therefore, it's vital to evaluate and measure the fitness costs for each herbicide-resistant population individually (Lehnhoff et al., 2013).

Although some researchers, such as Cousens & Fournier-Level (2018), claim that fitness studies should focus merely on the number of offspring produced, understanding separate fitness components is highly useful and necessary. This is because a plant's dominance within a population (i.e., its overall fitness) is ultimately determined by the combined effects of various fitness-related parameters (Keshtkar et al., 2019). Therefore, it is important to examine all components of plant fitness, from pre-germination to reproduction and seed production. These components include seed fitness (e.g., germination percentage, germination rate, dormancy, seed size, seed longevity in soil, and seed dispersal ability); vegetative fitness (e.g., plant height, biomass production, growth rate, establishment ability, competitive ability, competitive response, and competitive effect); and reproductive fitness (e.g., seed yield, pollen viability, pollen production, competition between pollen from resistant and susceptible plants, and ovule size). In other words, finding these components can shed light on the relative strengths and weaknesses of herbicide-resistant weeds compared to their corresponding susceptible under different environmental conditions. Accordingly, investigating the fitness of herbicide-resistant weeds is essential. One of the main objectives of fitness studies is to identify tools and strategies for managing herbicide-resistant weeds (Cousens and Fournier-Level, 2018). Comprehensive knowledge of the relative fitness of herbicide-resistant weeds in Iran is also a critical issue that can enhance the effectiveness of management strategies (Gherekhloo et al., 2016). However, a review of research conducted in Iran reveals that the fitness of herbicide-resistant weeds has received limited attention from researchers. The authors' investigation indicates that, to date, a limited number of papers has been published by Iranian researchers on the fitness of herbicide-resistant weeds (Table 3). These studies have focused on three grass weed species (*Alopecurus myosuroides*, *Avena sterilis* ssp. ludoviciana, and *Lolium rigidum*) and two broadleaf species (*Rapistrum rugosum* and *Sinapis arvensis*) that are resistant to various herbicides. Most of these studies have examined seed fitness, while only two have investigated all three major fitness components seed, vegetative, and reproductive fitness of herbicide-resistant and susceptible weed populations.

In most studies on the fitness of herbicide-resistant weeds, both in Iran and globally, poor experimental design and insufficient attention to the prerequisites of fitness testing have often led to misinterpretation of results (Keshtkar et al., 2019; Neve, 2007). The most common limitation in fitness experiments is the lack of controlling the genetic background of resistant and susceptible populations. Choosing herbicide-resistant and susceptible populations that share a closely related genetic background is a crucial first step when studying relative fitness and estimating the potential cost of herbicide resistance (Holt, 1990; Menchari et al., 2008; Vila-Aiub et al., 2009; Vila-Aiub et al., 2005). This issue is particularly serious in Iran, where only two of the studies by Iranian researchers have controlled the genetic background of plant materials (Table 3).

When the genetic background of the plant materials is controlled, it reduces variation between the susceptible and resistant populations, so any differences observed in fitness of populations can be more confidently linked to the resistance gene(s) or even to specific resistance alleles (Vila-Aiub et al., 2011). Several strategies for achieving genetic background homogenization and control have been thoroughly compiled and explained by Vila-Aiub et al. (2011).

There are other important prerequisites to consider before studying the fitness of herbicide-resistant populations. Therefore, the authors strongly encourage researchers who want to evaluate the fitness of herbicide-resistant and susceptible populations to closely follow the guidelines and methods described elsewhere (Keshtkar et al., 2019; Keshtkar, 2025; Vila-Aiub et al., 2009; Vila-Aiub et al., 2011; Vila-Aiub et al., 2005).

Strategies for Managing Herbicide-Resistant Weeds in the World: Possibility of use in Iran

Despite the increasing threat of HR weeds, many farmers only adopt resistance management strategies reactively, after experiencing control failures (Beckie, 2006). A paradigm shift toward proactive, diversified, and integrated weed management is essential for sustaining herbicide efficacy and agricultural productivity.

Herbicide-Based Management Strategies

Herbicide Rotation and Sequencing

Rotating herbicides with different modes of action (MOAs) between years and crops can significantly delay the development of resistance. Herbicide sequencing applying multiple herbicides with different MOAs within a single crop season also helps reduce selection pressure by exposing weed populations to varied biochemical targets (Wrubel & Gressel, 1994).

Table 2. Summary of documented resistance cases to ACCase, ALS, and PS II inhibitors in grass weeds, and their corresponding target-site mutations in Iran.

Mutation	Substitution	Non-target site resistance	Species	APP	CHD	PPZ	Reference
				Resistance Level			
***ACCase* gene**							
Ile 1781	Leu		*A. sterilis* subsp. *ludoviciana*	Clodinafop propargyl, Diclofop methyl and Fenoxaprop- P-ethyl (L-H)	Setoxydim (L-H)	Pinoxaden (L-H)	Zand et al., 2009; Zand et al., 2013; Rastgoo et al., 2012; Benakashani et al., 2014; Sasanfar et al., 2017; Akbarabadi et al., 2019
			Lolium rigidum Guadin.	Clodinafop propargyl, Diclofop methyl and Fenoxaprop- P-ethyl (L-H)	Setoxydim, and Clethodim (L-H)	Pinoxaden (L-H)	Dastoori et al., 2011; Sabet Zangeneh et al., 2018
	Thr	Metabolism	*Phalaris brachystachys* Link.	clodinafop propargyl (M-H) diclofop methyl (M)	cycloxydim (L)		Golmohammadzadeh et al., 2019; 2020
Ile 2041	Asn		*Avena sterilis* subsp. *ludiviciana*	Clodinafop propargyl (L-H)	Setoxydim (L-H)	Pinoxaden (L-H)	Zand et al., 2013; Sasanfar et al., 2017
			Avena sterilis subsp. *ludoviciana*	clodinafop propargyl (H) and haloxyfop-R-methyl (H)	Sethoxydim (M)		Akbarabadi et al., 2019; Hassanpour-bourkheili et al., 2021a
			Lolium rigidum Guadin	Clodinafop propargyl, Diclofop methyl (L-H)	Setoxydim, and Clethodim(L-H)	Pinoxaden (L-H)	Benakashani et al., 2013; Sabet Zangeneh et al., 2018
Asp 2078	Gly		*A. sterilis* subsp. *ludoviciana*	Clodinafop propargyl, Diclofop methyl and Fenoxaprop- P-ethyl (L-H)	Setoxydim (L-H)	Pinoxaden (L-H)	Zand et al., 2013; Benakashani et al., 2014
			Phalaris minor Retz.	Clodinafop propargyl, Diclofop methyl and Fenoxaprop- P-ethyl (L-M)		Pinoxaden (S/R)[b]	Gherekhloo et al., 2012; 2021
Trp 2027	Cys		*P. minor* Retz.	Clodinafop propargyl, Diclofop methyl and Fenoxaprop- P-ethyl (L-M)		Pinoxaden (S/R)[b]	Gherekhloo et al., 2012; 2021
Asp 2078	Gly		*P. minor* Retz.	Clodinafop propargyl, Diclofop methyl and Fenoxaprop- P-ethyl (L-M)		Pinoxaden (S/R)[b]	Gherekhloo et al., 2012; 2021

Mutation	Substitution	Non-target site resistance	Species	APP	CHD	PPZ	Reference
				Resistance Level			
***ALS* gene**							
Thr 122	Ala		*S. arvensis* L	Tribenuron-methyl Mesosulfuron-methyl+iodosulfuron-methyl			Khaledi et al., 2019
Pro 197	Ser		*L. rigidum* Guadin *R. rugosum* L.	Mesosulfuron-methyl+iodosulfuron-methyl (H)			Tavassoli et al., 2023
		Metabolism		Tribenuron-methyl (H) Flurasulam (H) Flucarbazone (M) Bispyribac-sodium (M)			Hatami et al., 2016
	Ala			Tribenuton-methyl Mesosulfuron-methyl+iodosulfuron- methyl			Khaledi et al., 2019
	Thr		*L. rigidum* Guadin	Mesosulfuron-methyl+iodosulfuron-methyl (Not determined)			Hanifehzadeh Erdi et al., 2024
Asp 376	Glu		*S. arvensis* L.	Mesosulfuron-methyl+iodosulfuron-methyl(M)			Bahmani Fathabadi et al., 2016
	Gly		*S. arvensis* L.	Tribenuton-methyl Mesosulfuron-methyl+iodosulfuron-methyl			Khaledi et al., 2019
Trp 574	Leu			Tribenuton-methyl			Khaledi et al., 2019
			S. arvensis L.	Mesosulfuron-methyl+iodosulfuron-methyl			Gherekhloo et al., 2018
			L. rigidum Guadin	Mesosulfuron-methyl+iodosulfuron-methyl (Not determined)			Hanifehzadeh Erdi et al., 2024
***psbA* gene (PSII inhibitors)**							
Ser 264	Gly		*E. colona* (L.) Link.	Ametryn Metribuzin			Elahifard et al., 2013
Gly 282	Ser		*E. colona* (L.) Link.	Ametryn Metribuzin			Elahifard et al., 2013

Abbreviations: APP, aryloxyphenoxypropionate; CHD, cyclohexanedione; PPZ, phenylpyrazoline (pinoxaden). [a]Resistance level: S = not resistant (<2); L = low resistance (2-5); M = moderate resistance (6-10); H = high resistance (>10); [b]Resistance level was not determined.

However, adoption of rotation has been historically limited due to economic constraints, lack of farmer knowledge, and inadequate herbicide labeling. For example, in Canada, fewer than 50% of farmers practiced herbicide rotation by 1998, though this increased to 70–90% in some provinces after extension efforts and improved labeling policies. It is important to apply herbicides at full recommended rates to avoid selecting for resistant populations, especially where target-site resistance prevails (Beckie, 2006).

Herbicide Mixtures

Combining herbicides with different MOAs in tank mixtures or pre-formulated products is generally more effective than rotation alone in slowing resistance evolution, provided that all active ingredients are equally efficacious and persistent in the soil. Mixtures reduce the probability that a resistant individual survives any single herbicide. However, improper mixtures such as those including sublethal doses or ineffective components can accelerate the development of multiple resistance (Rubin, 1991; Renton et al., 2014).

Use of Herbicide-Resistant (HR) Crops

The advent HR crops, especially those resistant to glyphosate or glufosinate, has reshaped weed management. While these crops provide flexibility and broad-spectrum weed control, their continuous and exclusive use has led to resistance evolution in key species such as *Conyza canadensis*, *Amaranthus palmeri*, and *Ambrosia artemisiifolia* in North America (Beckie et al., 2006).

To preserve HR crop utility, it is critical to diversify herbicide modes of action within the cropping system, avoid repeated plantings of the same HR crop consecutively, and integrate non-chemical weed control tactics.

Site-Specific and Reduced-Rate Applications

Precision agriculture technologies allow site-specific herbicide application based on weed mapping, which reduces unnecessary herbicide use and selection pressure (Beckie & Harker, 2017). However, applying herbicides at sublethal doses whether intentionally or due to environmental variability can promote quantitative resistance, particularly in outcrossing species such as *Lolium* and *Kochia* (Neve & Powles, 2005; Beckie & Kirkland, 2003). Therefore, maintaining full recommended herbicide rates in targeted areas is advised.

Changing the process of discovering new herbicides

For the future of herbicide discovery, several innovative strategies have been proposed to accelerate the development of new herbicidal compounds for herbicide resistance weeds including:

***Development of multi-target herbicides*:** Creating active compounds that inhibit two or more enzyme targets simultaneously to reduce the likelihood of resistance development (Gressel, 2020).

***Use of metabolomics and proteomics*:** Applying metabolomics to identify enzyme targets whose inhibition leads to the accumulation of toxic metabolites in vivo, and using proteomics to detect low-abundance targets that can be inhibited with low herbicide doses (Dayan & Duke, 2020).

***Design of smart and flexible inhibitors*:** Engineering molecules that bind to substrate recognition regions of enzymes or possess conformational flexibility, making them less prone to resistance mutations (Qu et al., 2021).

***Integration of advanced technologies*:** Employing artificial intelligence, big data analytics, and both in vivo and target-based high-throughput screening methods to identify novel herbicide candidates with the desired activity (Dayan, 2019).

Table 3. Published studies on the fitness cost of herbicide resistance by Iranian scientists up to 2025.

Weed	Herbicide/group	Fitness components			Genetic background control	References
		Seed	Vegetative	Reproductive		
Alopecurus myosuroides	Fenoxaprop ethyl	*			Yes (single population approach)	(Ghazali et al., 2020)
Avena ludoviciana	Aryloxyphenoxypropionate	*			No	(Tahmasebi et al., 2011)
Avena ludoviciana	Clodinafop-propargyl	*			No	(Benakashani et al., 2021; Fakhri et al., 2024)
Avena ludoviciana	Aryloxyphenoxypropionates and Cyclohexanediones	*	*	*	No	(Hassanpour-bourkheili et al., 2018; 2020; 2021b)
Avena ludoviciana	Clodinafop propargyl, Diclofop-methyl		*		No [a]	(Izadi-Darbandi et al., 2014)
Echinochloa colona	PSII inhibitors	*			No	(Elahifard and Mijani, 2014)
Lolium Rigidum	Clodinafop-Propargyl	*			Yes (Multiple population approach)	(Zamani et al., 2023)
Lolium rigidum.	Clodinafop-propargyl	*	*		No	(Sabet Zangeneh et al., 2018)
Lolium rigidum.	Clodinafop-propargyl	*	*	*	No	(Sabet Zangeneh et al., 2016)
Lolium rigidum.	ALS inhibitors	*			No	(Dastoori et al., 2010)
Lolium rigidum.	ACCase and ALS inhibitors	*	*	*	No	(Tavassoli, 2024)
Phalaris brachystachys	ACCase inhibitors	*	*	*	No	(Golmohammadzadeh et al., 2022; 2024)
Rapistrum rugosum	Tribenuron methyl	*			No	(Abdollahipour et al., 2016a)
Sinapis arvensis	Tribenuron methyl, mesosulfuron methyl+Iodosulfuron methyl sodium, metsulfuron-methyl+sulfosulfuron		*	*	No[a]	(Lotfifar et al., 2015)
Sinapis arvensis	Tribenuron methyl	*			No	(Axhgar et al., 2022)
Sinapis arvensis	Tribenuron methyl	*	*	*	No[a]	(Abdollahipour et al., 2016b)
Sinapis arvensis	Tribenuron methyl	*			No[a]	(Abdollahipour et al., 2013)
Sinapis arvensis	Tribenuron methyl, mesosulfuron methyl+Iodosulfuron methyl sodium, metsulfuron-methyl+sulfosulfuron	*	*		No	(Mottaghi et al., 2017)
Sinapis arvensis	Tribenuron Methyl 2,4-D+MCPA		*		No	(Khamani et al., 2023)

[a], Multiple populations approach was used but statistical analysis and interpretation of results were not fulfilled based on the used approach.

Non-Herbicide Approaches as Integrated Weed Management (IWM)

Heavy reliance on herbicides alone often lacks diversity, accelerating resistance evolution. Integrated approaches that combine cultural, mechanical, biological, and chemical controls reduce selection pressure on weeds and prolong herbicide efficacy:

Cultural Control

***Crop Rotation and Diversity*:** Rotations involving diverse crops with different growth habits and herbicide programs disrupt weed life cycles and reduce seedbanks. For example, including legumes, cereals, and broadleaf crops has been shown to suppress problematic species like *Avena fatua* and *Setaria viridis* (Beckie & Harker, 2017; Beckie et al., 2004). Diverse rotations also influence weed germination cues and emergence timing, complicating weed adaptation (Owen, 2016).

***Increasing Crop Competitiveness*:** Practices such as increasing seeding rates, narrowing row spacing, and using competitive cultivars create denser crop canopies, limiting light and nutrients available to weeds. Field studies have demonstrated that dense stands of hybrid canola, barley, and wheat reduce HR weed biomass and seed production significantly (Beckie & Harker, 2017).

***Delayed Planting and Stale Seedbed Techniques*:** Delaying planting allows pre-plant weed control, targeting early-germinating weeds. Stale seedbeds where irrigation or rainfall induces weed germination followed by non-selective control before planting reduce the initial weed population and seedbank inputs (Dyer et al., 1993).

***Mulching*:** Mulching involves applying organic (crop residues, straw, compost) or synthetic (plastic films) materials on soil surfaces. Mulches suppress weed emergence by physically blocking light, modifying soil temperature and moisture, and creating unfavorable conditions for weed seedling establishment. Mulching not only reduces weed pressure but also improves soil moisture retention and health, indirectly enhancing crop competitiveness. In perennial and specialty cropping systems, mulching has proven effective at limiting weed establishment and seedbank replenishment, thereby reducing selection pressure for herbicide resistance (Owen, 2016; Beckie & Harker, 2017).

Mechanical and Physical Controls

Tillage: Although conservation tillage preserves soil structure and reduces erosion, it often increases reliance on herbicides like glyphosate, potentially exacerbating resistance. Strategic, occasional tillage such as shallow disturbance or moldboard plowing can bury weed seeds deeper in the soil, reducing emergence of surface-germinating species (Beckie, 2006; Owen, 2016).

***Harvest Weed Seed Control (HWSC)*:** HWSC techniques such as the Harrington Seed Destructor, chaff carts, and narrow windrow burning mechanically destroy weed seeds retained at harvest, preventing seedbank replenishment. This approach has shown reductions of over 90% in seed return for species with high seed retention, including *Lolium rigidum* (Beckie & Harker, 2017; Owen, 2016).

***Patch Management and Sanitation*:** Targeted management of resistant weed patches before seed set significantly limits spatial spread. A long-term study reported that managed patches of resistant *Avena fatua* expanded 330% less than unmanaged ones (Beckie et al., 2004). Equipment sanitation and border controls further prevent resistant seed dispersal between fields.

***Thermal weed control*:** which uses heat to kill weeds, can be a valuable tool in managing herbicide-resistant weeds. Methods like flaming, steam, hot water, and microwaves can be used to disrupt plant cell structure and cause weed death, offering an alternative to herbicide-based approaches. Thermal weed control relies on the principle of applying heat to plant tissues, causing cellular damage and ultimately plant death. This can be achieved through various methods, including: Flaming: Using flames to quickly heat and disrupt plant cells. Steam/Hot Water: Applying high-temperature steam or hot water to achieve similar effects as flaming. Microwaves: Using microwave radiation to heat and disrupt plant cells. Hot Foam: Using heated foam to coat and dehydrate weeds (Li et al., 2021).

Biological Control

Biological management uses living organisms or their products to suppress weed populations (Charudattan, 2005). While biological control is an active research area, its use in herbicide resistance management is context-dependent and not yet widespread (Liu et al., 2021).

Although integrated management methods are very effective and essential in controlling herbicide-resistant weeds, but several behavioral and structural barriers hinder adoption of IWM, including:

***Short-Term Profit Focus*:** Farmers often prioritize immediate returns, neglecting long-term sustainability.

***Land Tenure Instability*:** Tenants may lack incentives to invest in IWM practices.

***Complexity and Labor Intensity*:** IWM demands more knowledge and time, which can discourage farmers.

***Lack of Policy and Incentives*:** Few regulatory or financial incentives exist to encourage non-chemical weed control.

***Misunderstanding of Herbicide MOAs*:** Confusion over herbicide groups and labels can impede proper rotation and mixtures (Beckie & Harker, 2017; Owen, 2016).

Further helpful tools: Scouting, Record-Keeping, and Collaborative Management

***Early Detection*:** Regular scouting before and after herbicide applications enables early identification of resistance, facilitating timely intervention (Beckie, 2006).

***Technological Advances*:** Tools such as drone-assisted scouting, GPS mapping, and AI-driven weed identification enhance precision and efficiency (Fernandez-Quintanilla et al., 2022; Beckie & Harker, 2017; Owen, 2016).

***Record-Keeping*:** Maintaining detailed field records including herbicide applications, weed escapes, and cropping history is essential for long-term management planning.

Sanitation: Cleaning machinery and controlling field borders prevent movement of resistant seeds between fields.

***Landscape-Level Management*:** Resistance management requires cooperative action beyond individual farms, including shared scouting, joint investment in HWSC tools, coordinated extension services, and cost-sharing incentives (Owen, 2016).

***Decision-support systems (DSS)*:** DSS assist farmers in selecting optimal combinations of integrated weed management (IWM) practices to delay or control herbicide-resistant (HR) weeds. The most advanced example is the RIM (Resistance and Integrated Management) model developed in Australia, which evaluates agronomic and economic outcomes of various management strategies over time (Monjardino et al., 2003; Pannell et al., 2004). When regularly updated, such DSS tools provide valuable guidance for effective HR weed management.

Robotics, Drones, and New Technologies: Harvest-time weed seed management can reduce seedbanks but is ineffective alone and complicated by multiple resistances. Robotics offers precise, integrated control of individual weeds, improving efficiency, though technical challenges remain. Drones enable faster scouting but face issues in weed-crop differentiation, legal restrictions, and uncertain cost-effectiveness. Ground sensors could enhance postemergence control by identifying weed hotspots. Some Australian seedbank tactics like residue burning are impractical in U.S. high-residue crops. Alternative methods like flame weeding suit organic systems. Overall, emerging technologies promise improved HR weed management but require overcoming technical, economic, and regulatory barriers (Oven et al., 2016).

Herbicide-Resistant Weed Management in Iran

Although considerable scientific research has enhanced our understanding of resistance mechanisms and potential management approaches, practical implementation of these strategies at the farm level remains insufficient. This gap highlights the urgent need for a coordinated national strategy that encompasses farmer education, policy-level interventions, and the promotion of integrated weed management (IWM) practices. Key components of IWM such as crop rotation, herbicide rotation, and the use of tank mixtures or sequential applications with different modes of action have been recommended and, to some extent, promoted in wheat-growing regions. Nonetheless, adoption has been limited, largely due to economic constraints, insufficient farmer training, and restricted access to a wider array of herbicide options (Gherekhloo et al., 2016).

Recent research by Iry et al., (2024) demonstrated the effectiveness of pyroxasulfone, a pre-emergence herbicide belonging to the VLCFA (very long-chain fatty acid) synthesis inhibitor group, in managing herbicide-resistant populations of *Lolium rigidum* (annual ryegrass), *Avena ludoviciana* (winter wild oat), and *Phalaris minor* (littleseed canarygrass) in wheat fields. Pyroxasulfone has shown high efficacy in suppressing these problematic species and is considered crop-safe for wheat, meaning that it provides effective weed control without adversely affecting crop growth or yield. In another study in Golestan province, it was revealed that *A. ludoviciana, P. minor, and L. rigidum* populations that were resistant to ACCase and/or ALS inhibitors were successfully controlled using pyroxasulfone, flumioxazin, chlorotoluron+ isoxaben, and chlorotoluron+ difflufenican herbicides. Common herbicides including pinoxaden and mesosulfuron-methyl+ iodosulfuron-methyl-soidium had still good efficacy in the township of Gonbad-Kavus. This was attributed to the lack of selection pressure imposed by herbicide application, as farmers in this township use herbicides only in years with good rainfall (Gherekhloo & Haghnama, 2022).

Addressing herbicide resistance in Iran requires a paradigm shift from sole reliance on chemical control toward an integrated, knowledge-based approach. Long-term sustainability will depend on proactive resistance management, diversification of weed control strategies, and strong collaboration among researchers, extension services, policy-makers, and farmers.

Conclusion

This paper reviewed the current status of herbicide resistance in Iran. The rapid proliferation of multiple resistance calls for an urgent paradigm shift in weed management strategies. Knowledge of mechanism of resistance can help to detect the resistance pattern and devise suitable management measures. Also, studying the fitness cost associated with herbicide resistance would be beneficial, as the differences between resistant and susceptible populations can be exploited to manage herbicide resistance. There is a need to adopt proactive measures-as opposed to reactive ones- to mitigate herbicide resistance, i.e. acting before herbicide resistance occurs to prevent or delay this issue. Priorities must include, implementing effective and diversified crop rotations, routinely monitoring resistance mechanisms, and adopting integrated weed management (IWM) approaches particularly in high-risk provinces. Also, these measures should be adopted in low-risk provinces to prevent the onset of herbicide resistance. It can be said that, there is no single tactic can sustainably manage herbicide-resistant weeds. Resilience emerges from diversity in chemical modes of action, cropping systems, mechanical and cultural controls, and collaborative decision-making. Integrated weed management, combining herbicide rotation, mixtures, cultural practices like mulching, mechanical controls such as HWSC, scouting, and landscape-level cooperation, offers the best pathway to delay resistance evolution and sustain agroecosystem health. Fundamental shifts in farmer behavior, policy support, and education are essential complements to technological advances for long-term success.

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