

Weed Resistance in Cereals and Ways to Limit it

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Cereal cultivation has an irreplaceable place in agricultural production. Crops such as wheat and barley are subject to various pressures during their growth. A major challenge for growers is controlling weeds in cereal crops. The spectrum of weeds has expanded in recent years, and frequent reliance on chemical protection has led to another challenge in the form of weed resistance to herbicides. In our study, we focused on the causes and mechanisms of resistance and supplemented these findings with an alternative strategy of mechanical treatment of crops at the beginning of the growing season and during the growing season. Among the reasons contributing to the development of resistance, we pointed out the excessive reliance on the same group of active substances and adherence to the dosage of active substances. The work specifically describes two different ways in which weed resistance occurs. It distinguishes between monogenic resistance, in which there is a change in the target site on which the active ingredient of herbicide acts. The second type of resistance occurs outside the target site, resulting in multiple mutations, and is typical for weed resistance to the active ingredient glyphosate. As an alternative to chemical protection in weed control, we have introduced mechanical treatment of crops, which is also suitable for cereals that respond to suitable to this method of control. Weed resistance as a common part of production will continue to require sensitive work with active ingredients, which will need to be chosen correctly, but it will also be important to alternate them when controlling dangerous species. As our review shows, it will be important to test and search for new ways to successfully control weeds.

Keywords: cereal, weed control, monogenic resistance, polygenic resistance, mechanical treatment, alternative methods, inter-row cultivation, HRAC group

1 Impact of Weeds on Cereals and Their Interactions

Cereals are the most traded and cultivated crops worldwide, used in food production, but also for animal feed and industrial purposes. As with other crops, cereal production is significantly affected by harmful factors, including weeds, which contribute to reduced yields (Benjamin et al., 2024). The spread of annual and perennial weed species is largely caused and influenced by the high proportion of cereals in crop rotations, but it is also contributed to by reduced tillage methods and the frequent use of herbicides, which have the same mechanism of action (Gerhards et al., 2020). Weeds are characterized by rapid growth and competition for space, water, nutrients, and solar energy, and they have negative impact on both crop yield and production quality and also these undesirable species can reduce yields by up to 42% and also Agricultural practice currently uses several

methods to eliminate weeds, including the use of pre-emergence and post-emergence herbicides and these measures have various environmental and economic impacts, and reducing these impacts poses considerable challenges (García-Navarette et al., 2024). Crop yields can be significantly reduced by the presence of weeds in crops. The use of herbicides in crop production has become a very effective method, controlling 90–99% of target weed species. Crop protection therefore depends mostly on chemical methods, and herbicides play an important role in agricultural crop production (Sobiech et al., 2022). The representation of individual weed species, as well as their diversity and distribution, depends on several factors, including region, crop type, seasonality and soil type (Hussein et al., 2024). The suppression of weed species in cereal crops is the result of several factors and interactions that influence weediness, including interactions between genotype, environment, and cereal

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crop management (Weiner Jaco, 2023). The interaction between weeds and cereals can also be significant in intercrops with legumes, where they contribute to the eradication of harmful weed species, as cereals provide support for legumes (Sutherland et al., 2025). This intercrop mixture can therefore contribute to more sustainable and effective weed control without the use of herbicides (Rácz et al., 2023). A broader crop rotation based on more diverse crop rotation helps regulate weed infestation by herbicides application with different mechanisms of action, thereby reducing the selection pressure on the development of resistant weed species (Sutherland et al., 2025). Monocotyledonous and dicotyledonous weed species represent one of the primary challenges faced by cereal growers. Their main negative impact is competition in cultivated crop stands (Al-Gburi et al., 2024). Weed resistance is also an important factor in weed control. Twenty-four species exhibiting resistance were observed in economically important crops. The most widespread were species from the Poaceae family, which had 54% resistant species, Brassicaceae with 17% and Asteraceae with 13% (Oreja et al., 2024). Resistance to pre-emergence herbicides was lower (10%) than to post-emergence herbicides (90%). Among crops, cereals (wheat and barley) ranked third in the number of resistant weed species (Oreja et al., 2024). Intensive primary agricultural production based on larger farms with narrow crop rotation and reduced crop rotation leads to a reduction in weed species (Kolářová et al., 2023). The weed composition on land is gradually changing in favour of herbicide-tolerant species and species that can easily adapt to the conditions applied in current plant production and crop protection (Kolářová et al., 2023). Effective method that can increase competition for resources is intercropping, which

promotes weed suppression in crops. This involves reducing the sensitivity of cropping systems by growing two or more crop species that can coexist on the land for a certain period (Hatt & Döring, 2024). Cover crops are increasingly used in farming systems as part of integrated plant protection against harmful weeds. These are crops that are planted between two main crop species and are not harvested, grazed or incorporated into the soil, but rather their presence on the soil surface is used during the cultivation of the next crop (Malaspina et al., 2024). White mustard (*Sinapis alba* L.) and white clover (*Trifolium repens* L.) used as cover crops reduce weediness, with studies showing 90% weed control for mustard and as much as 99% for clover, so these two species have considerable potential for use in weed control not only in cereal crops (Kadziene et al., 2019).

The emergence and spread of resistance in plant protection against dangerous weed species is a key challenge for global agriculture, with implications for food security and environmental sustainability. More than 530 cases of resistance discovered worldwide call for an urgent need for an integrated protection management strategy (Arasan et al., 2025). Weed resistance to active substances is often caused by the repeated use of the same active substances. Globally, there are 530 biotypes of weeds that are resistant to herbicides including 272 species of weeds, of which 155 are dicotyledons and 117 are monocotyledons (Xu et al., 2024). In field conditions, several resistance mechanisms are already present, which have spread to several active substances (Xu et al., 2024). Resistance to acetyl-CoA carboxylase (ACC), acetolactate synthase (ALS), hydroxyphenylpyruvate dioxygenase (HPPD) and auxin, and particularly dangerous in regulation

Table 1 The most dangerous weed species in winter wheat in Slovakia (Týr & Vereš, 2011). Plant nomenclature is according to Kliment et al. (2025)

	Production area		
	corn	sugar beet	potato
1.	<i>Stellaria media</i>	<i>Galium aparine</i>	<i>Anthemis</i> spp.
2.	<i>Galium aparine</i>	<i>Stellaria media</i>	<i>Tripleurospermum inodorum</i>
3.	<i>Apera spica-venti</i>	<i>Tripleurospermum inodorum</i>	<i>Cirsium arvense</i>
4.	<i>Anthemis</i> spp.	<i>Cirsium arvense</i>	<i>Elymus repens</i>
5.	<i>Tripleurospermum inodorum</i>	<i>Papaver rhoeas</i>	<i>Galium aparine</i>
6.	<i>Cirsium arvense</i>	<i>Thlaspi arvense</i>	<i>Apera spica-venti</i>
7.	<i>Avena fatua</i>	<i>Capsela bursa-pastoris</i>	<i>Brassica napus volunteers</i>
8.	<i>Elymus repens</i>	<i>Apera spica-venti</i>	<i>Persicaria</i> spp.
9.	<i>Brassica napus volunteers</i>	<i>Avena fatua</i>	<i>Stellaria media</i>
10.	<i>Bromus</i> spp.	<i>Brassica napus volunteers</i>	<i>Lamium</i> spp.
11.	<i>Papaver rhoeas</i>	<i>Bromus</i> spp.	<i>Brassica</i> spp.

Table 2 The most dangerous weed species in spring barley in Slovakia (Vereš & Týr, 2011). Plant nomenclature is according to Kliment et al. (2025)

	Production area		
	corn	sugar beet	potato
1.	<i>Cirsium arvense</i>	<i>Cirsium arvense</i>	<i>Chenopodium</i> spp.
2.	<i>Elymus repens</i>	<i>Tripleurospermum inodorum</i>	<i>Tripleurospermum inodorum</i>
3.	<i>Avena fatua</i>	<i>Anthemis</i> spp.	<i>Anthemis</i> spp.
4.	<i>Chenopodium</i> spp.	<i>Galium aparine</i>	<i>Elymus repens</i>
5.	<i>Galium aparine</i>	<i>Avena fatua</i>	<i>Galium aparine</i>
6.	<i>Helianthus annuus volunteers</i>	<i>Amaranthus</i> spp.	<i>Persicaria</i> spp.
7.	<i>Brassica napus volunteers</i>	<i>Chenopodium</i> spp.	<i>Avena fatua</i>
8.	<i>Tripleurospermum inodorum</i>	<i>Sinapis arvensis</i>	<i>Lamium</i> spp.
9.	<i>Anthemis arvensis</i>	<i>Atriplex</i> spp.	<i>Cirsium arvense</i>
10.	<i>Sinapis arvensis</i>	<i>Lamium</i> spp.	<i>Galeopsis tetrahit</i>

is the increasing resistance in *Avena fatua*, which is resistant to the combination of ACC + ALS, and in *Brassica rapa*, which is even resistant to ACC + ALS + auxin-based substances (Domínguez-Valenzuela et al., 2025). Weed control focused on specific locations can contribute to reducing herbicide use by identifying weed-infested areas and detecting areas with weeds in cultivation areas (Jensen et al., 2021). With the gradual development of agronomic practice, the growing importance of integrated weed control is increasingly emphasized, with various methods included in this control, mainly involving chemical, cultural and mechanical strategies as tools for sustainable weed population management (Hou et al., 2025). Given the increasing number of weeds resistant to the active ingredients contained in herbicides, mechanical treatment of crops is also becoming justified, when used correctly, it can reduce the use of herbicides while maintaining crop yields (Saile et al., 2022).

1.1 Occurrence of Herbicide Resistance in Agriculture

Over the course of several years, agricultural interventions and technologies used in agriculture have led to an intensification of food production worldwide (Ofosu et al., 2023). The introduction of herbicides has contributed to the difficult task of eliminating dangerous weed species. The growing trend of herbicide-resistant weed species is currently alarming (Ofosu et al., 2023). Weed resistance to herbicides has been studied for decades, but it appears that the biochemical and molecular basis of resistance is much more complex (Riechers et al., 2024). This process is the result of countless mechanisms of resistant weed species at target and non-target sites, with environmental influences and the timing of application of active substances also being important factors (Riechers et al., 2024). Intensive agricultural activity focuses on the use of herbicides for weed control, predominantly using active

substances from the same groups (Ofosu et al., 2023). Weeds have thus developed resistance in 21 of 31 known locations where herbicides are used in 165 types of herbicide preparations. Currently, resistance is known in 96 crops in 72 countries around the world (Ofosu et al., 2023). The use of synthetic herbicides over the past century has led to the development of resistance among various weed species to different active substances, which significantly impairs weed control (Ofosu et al., 2023). In contrast, in areas with lower agricultural intensity, where mechanical weed control methods are used, there is less reliance on chemical measures. Herbicide use is lower in these areas, and inaccurate doses of active substances are often used, which can also lead to resistance at lower doses. The influx of mislabel led or counterfeit products also increases the impact. In these areas, which may also be affected by the accidental introduction of invasive species, critical attention needs to be paid to the development of appropriate and correct regulations for the use of synthetic products (Ofosu et al., 2023).

1.2 Two Types of Resistance

Resistance in weed species is achieved through several mechanisms. Some mechanisms cause a change in the target site, which is probably due to a mutation in a single gene and is therefore monogenic resistance (target site resistance). These are specific to individual classes of herbicides (Renton et al., 2024). The second mode of action of resistance is based on off-target effects, caused by multiple mutations, and is polygenic (non-target site resistance). It is specific to a broader spectrum of herbicide classes (Renton et al., 2024). Advances in research suggest that monogenic herbicide resistance is simpler than polygenic resistance. This type of resistance is usually caused by dominant or semi-dominant alleles. It largely involves a change in

Table 3 Site of action in resistant weed in the world and year in which resistance was confirmed (Weedscience.org, 2026)

Weed species	Site of action	Country (first year of resistant)
<i>Apera spica-venti</i>	HRAC Group 2	Austria (2009), Belgium ((2019), Czech Republic (2005), Denmark (2011), Denmark (2016), France, Germany, Latvia, Lithuania, Poland (2010), Poland (2011), Sweden (2010)
	HRAC Group 1	Denmark (2016), Germany (2009), Poland (2010)
	HRAC Group 5	Austria (2009), Czech Republic (2009), Germany (1997), Germany (2009), Poland (2012), Sweden (2006)
<i>Tripleurospermum inodorum</i>	HRAC Group 2	Czech Republic (2021), Denmark (2010), France (2010), Germany (2009), Norway (2006), Poland (2014), Sweden (2015), United Kingdom (2002)
<i>Papaver rhoeas</i>	HRAC Group 2	Belgium (2014), Denmark (2003), France (2007,2015,2016), Germany (2012), Greece (1998, 2002), Italy (1998), Marocco (2025), Poland (2014), Portugal (2018), Spain (1993), Sweden (2011), Tunisia (2025), United Kingdom (2001)
	HRAC Group 4	France (2015, 2016), Greece (2002), Italy (1998), Marocco (2025), Portugal (2018), Spain (1993), Tunisia (2025)
<i>Bromus sterilis</i>	HRAC Group 1	Germany (2012)
	HRAC Group 2	Czech Republic (2017), France (2009), Germany (2012), Germany (2017), United Kingdom (2020)
<i>Amaranthus retroflexus</i>	HRAC Group 2	Brazil (2011, 2012), Canada (1998), Canada (2002, 2009, 2010), China (2017), Germany (2012), Israe (1991), Italy (2003), Serbia (2002), Ukraine (2002), United States (2005, 1998, 1999, 2010, 2020, 2022)
	HRAC Group 5	Brazil (2011), Bulgaria (1984), Canada (1980, 2001, 2003), China (1990), Czech republic (1985), France (1980), Germany (1980), Greece (2000), Italy (1999), Poland (1991), Spain (1986), Switzerland (1982), United States (1980, 1982, 1984, 1985, 1991, 1993, 1994, 1995, 1998, 2001, 2005, 2010)
	HRAC Group 14	Brazil (2014), China (2017), United States (2020, 2022)
	HRAC Group 9	United States (2022)
	HRAC Group 27	United States (2022)
<i>Ambrosia artemisiifolia</i>	HRAC Group 2	Canada (2000, 2007, 2012), France (2013), Serbia (2019), Ukraine (2023), United States (1998, 2005, 2006, 2010, 2013, 2015, 2016,
	HRAC Group 5	Canada 1976, 1999, 1999, 2023), United States (1990, 1993)
	HRAC Group 9	Canada (2012), United States (2004, 2006, 2007, 2008, 2010, 2013, 2014, 2015, 2016, 2017)
	HRAC Group 14	Ukraine (2013), United States (2015, 2006, 2016)
	HRAC Group 4	United States (2022)

the 3D structure of the herbicide target protein and in the distribution of polar groups in positions that are key to the stability of the herbicide-protein bond. Structural changes are caused by amino acid substitution in one of several possible positions on the herbicide target protein. It is true that in each key codon, there is the possibility of multiple substitutions that contribute to resistance to a given active substance. This change in the target protein can lead to high or medium resistance or may indicate higher sensitivity to herbicides (Délye et al., 2013). It is a modification of the herbicide target site or an increase in the number of copies of the target gene. This results in higher levels of the target enzyme, thereby reducing the negative impact of herbicide on the plant species (Pokhrel Raksha, 2025). The second type of resistance – polygenic resistance – is currently

considered to be the predominant mode of action resistance (Délye et al., 2013). Which includes the resistant efficacy of glyphosate, but also acetyl-CoA carboxylase inhibitors. In this case, it is cross-resistance, which is unpredictable and not specific to the mode of action of selective herbicide. Its mechanism manifests itself in a specific herbicide and can lead to cross-resistance to herbicides that have a different mechanism of action. This mechanism is often presented as a response to monogenic resistance and to a certain extent, it is also a subset of the response of plants to abiotic stresses occurring in field conditions, whereby the response of weeds will vary and differ between species and within species (Délye et al., 2013).

1.3 Most Common Herbicide Resistant Weed Species

A lower spectrum of herbicide products and reduced doses of active ingredients in herbicides predict easier development of resistance, especially in dangerous and resistance-prone weed species. High dependence on these chemical treatments results in intense selection pressure and contributes to the development of resistant weeds (Seng et al., 2024). Weeds with developing resistance not only affect crop yield but also threaten ecosystem services by disrupting biodiversity, reducing soil health, and other direct impacts on the ecosystem (Kodali et al., 2024). Silky wind grass (*Apera spica-venti*) is a dangerous weed species in winter cereals, oilseed rape, fodder crops and spring cereals (Papapanagiotou et al., 2022). Among the species with the highest resistance is certainly scentless mayweed (*Tripleurospermum inodorum*), which poses a challenge sustainable cereal production. Resistant populations of this weed can exploit different thermal niches, which affect the timing of their emergence and competitiveness in cereal crops (Marcinkowska et al., 2025). In this type of weed, resistance is probably based outside the target site of the active substance, and increased metabolism probably contributes to effective resistance. *A. spica-venti* also shows resistance when using pre-emergent herbicides such as diflufenican and pendimethalin (Petersen et al., 2012). In the case of dangerous weed species *Bromus* spp., resistance is also economically significant, particularly to the sulfonylurea mesosulfuron-methyl (Broster et al., 2023). These species exhibit multiple evolutionary origins of resistance to ACCase-inhibiting active substance's (Ribeiro et al., 2023).

1.4 Alternative Methods

Weed control in cereal crops is a common method in organic farming as an alternative to the use of chemical protection in weed control (Berge et al., 2023). Inter-row cultivation is also used to control weeds and is highly effective. This method of weed control can be used from crop emergence until the extension growth of cereals (Melander and McCollough, 2020). However, it can also be used in conventional crop cultivation, particularly because of the European Commission's efforts to reduce the use of hazardous chemicals by 50% (Berge et al., 2023). Weeding crops with harrows can be considered a relatively inexpensive alternative, especially given the size and width of the harrows provided that this tool consists of a series of straight or curved tines, which are usually spaced 50 or 25 mm. Apart, while protecting the crop against the weeds using a hoe can be carried out in two phases, as with chemical control either before or after emergence (BBCH 13-25). Combination of these methods (before and after emergence) can reduce

weed infestation in spring cereal crops by 75% (Berge et al., 2023). Harrowing contributes to a reduction in weed infestation of up to 50% with double harrowing. With single harrowing, the proportion of weeds can be reduced by 40% in crop stand. These methods, especially when repeated mechanical treatment is used, represent a potential way of controlling weeds in cereals (Salonen et al., 2022). This method of controlling dangerous weed species is particularly useful for cereals, which can be highly resistant to harrowing. A single harrowing treatment reduces weed density and biomass in cereals with one true leaf (Sobkowicz & Tendziagolska, 2022). In trials, harrowing the crop three times has proven to be most effective. The first mechanical treatment with harrowing should be carried out when the barley emerges, followed by a second treatment at the 2-leaf stage and a final treatment at the tillering stage. These dates were most effective in reducing weed infestation in spring barley crops (Sobkowicz et al., 2025).

2 Conclusions

Grain cultivation is part of a large proportion of agricultural businesses. Cultivation objectives vary, whatever it is for food or feed purposes, as is the case with many growers focusing on animal production. The biggest challenge in crop protection is protecting crops from harmful weeds. As shown in Table 1 and Table 2, depending on the production area, a wide range of dicotyledonous and monocotyledonous weed species occur in wheat and barley crops, which compete directly with cultivated cereals as they grow. As mentioned in the section describing the most common herbicide-resistant weed species, the use of a range of active substances with the same mechanism of action leads to the development and strengthening of existing resistance in cereal crops. This is a complex resistance outside the target site of action of the active substance, and therefore in many cases there is a high level of resistance to the active substance used. The mechanism of action consists in a change in the target site and is caused by a mutation of a single gene, but in the first case it is a polygenic mutation. Table 3 documents the development of resistance in European countries for the most dangerous weed species in cereals, which include silky wind grass (*Apera spica-venti*), scentless chamomile (*Tripleurospermum inodorum*), common poppy (*Papaver rhoeas*), poverty brome (*Bromus sterilis*), redroot pigweed (*Amaranthus retroflexus*), common ragweed (*Ambrosia artemisiifolia*). Table 3 also describes the location of resistance in the form of the HRAC group. The article also describes mechanical cultivation in the form of harrowing or weeding of crops in wide rows as an alternative to chemical treatment. Harrowing involves

the use of tins spaced 50 or 25 millimetres' apart, which disrupt emerging or already emerging weed species. Weeding crops is the most effective when repeated twice during the BBCH 13-25 growth stage, when it can reduce weed infestation by up to 75%. We consider these methods of mechanical cultivation suitable for practical application and recommend their gradual and careful introduction into the protection of cereal crops against dangerous weed species. Based on our analyses, we recommend this protocol as a starting point for studying resistance in dangerous weed species. Observation of the effect of treating crops with active substances with the same mechanism of action and their possible impact on weeds. Monitoring the effect of these groups of active substances on new weed species. We also lean towards the opinion that the procedures described in our manuscript, such as hoeing or harrowing, should be tested in semi-operational or operational field trials to evaluate the effectiveness, agronomic and economic aspects of these procedures, so that growers can gradually apply the results of these trials directly in primary production.

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Conflict of Interest

The authors declare that there is no conflict of interest.

Author Contributions

Conceptualization, Š.T. and A.Š.; data curation, A.Š. and Š.T.; formal analysis, Š.T. and A.Š.; funding acquisition, Š.T. and A.Š.; investigation, Š.T. and A.Š.; resources, Š.T. and A.Š.; supervision, Š.T.; validation, Š.T. and A.Š.; writing – original draft, A.Š. and Š.T.; writing – review & editing, Š.T. and A.Š. Both authors have read and agreed to the published version of the manuscript.

AI and AI-Assisted Technologies use Declaration

No generative AI tools/AI-assisted technologies were used during the preparation of the manuscript.

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