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Review

Weed Management in Maize

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Weed control in maize (*Zea mays* L.) is a key factor in achieving high and stable yields, as weeds compete with crops for nutrients, water, space and light, thereby reducing productivity and production quality. Traditional practices, based mainly on synthetic herbicides, remain dominant in intensive farming systems. Growing concerns about weed resistance, environmental impacts, and legislative restrictions are driving the search for alternative solutions. Currently, integrated weed management (IWM) is being promoted, combining chemical, mechanical, cultural, and biological methods. Promising trends include the use of precision farming, which allows for the targeted application of herbicides using sensors and drones (only in countries where this is legal), thereby reducing pesticide consumption and the risk of soil contamination. Another direction is biological weed control using allelopathic plants or microbial preparations that suppress weed seed germination. Mulching with organic materials and intercropping, which limit the formation of weed seed reserves, also play an important role. Modern research focuses on the use of artificial intelligence to predict the critical period of weed competition for the cultivated crop. These innovations are aimed at sustainable maize cultivation systems that minimize negative environmental impacts while ensuring economic efficiency of production. Currently, the most commonly used herbicide active ingredients in maize are, for example: dicamba, nicosulfuron, rimsulfuron, dimethenamid, and pendimethalin. These (and other) active ingredients are used in combination as a pre-emergence application followed by one or two post-emergence applications. Pre-emergence application immediately after sowing the soil is intended to control the so-called first wave of weeds; however this type of herbicide requires sufficient rainfall to activate. Therefore, the integration of diversified agronomic practices with well-timed herbicide use remains essential for achieving effective and sustainable weed control.

Keywords: maize, weed control, integrated weed management, herbicides, resistance

1 Introduction

Maize (*Zea mays* L.) is one of the most important cereals in the world and is a staple food for both humans and livestock. It originates from Central America, where it was domesticated more than 7,000 years ago. Botanically, it is an annual plant of the grass family (Poaceae) withC4 carbon fixation. It grows to a height of 1.5 to 3 meters, has a massive root system, and characteristic male (tassels) and female (ears) inflorescences. Maize kernels are rich in carbohydrates, especially starch, and also contain protein and small amounts of fat. Interestingly, maize does not have the ability to spread its seeds independently – its ears are tightly closed, which is a result of domestication (Hetta et al., 2022). In Slovakia, maize is grown annually on more than 200,000 hectares, which is approximately 8.5% of arable land (Statistical Yearbook, 2024). Maize is extremely versatile – it is used in the production of food, feed, starch, bioethanol, and even bioplastics. Thanks to its high production potential, it has become the basis of intensive agriculture. In recent decades, new trends have emerged in its cultivation: precision farming using GPS, drones, and sensors to optimize sowing and fertilization; biotechnology, including genetically modified varieties resistant to pests and herbicides; and sustainable practices such as intercropping and minimizing tillage to reduce erosion. In addition, maize has become an important source of renewable energy as it is used to produce bioethanol, making it a strategic crop for the future (Narmadha et al., 2023).

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1.1 Conditions for Growing Maize for Maximum Yield

Maize (*Zea mays* L.) is a thermophilic crop with high production potential, but it requires optimal agroecological conditions to achieve maximum yield. The most important factor is temperature – maize germinates at a minimum soil temperature of 8–10 °C, with optimal temperatures for growth ranging between 20–30 °C. Kawsar et al. (2013) mentioned it is sensitive to frost, so it is sown only after the frost has passed. Another key factor is sufficient water, especially during germination, tasseling, and grain filling. Maize consumes approximately 450–650 mm of precipitation during vegetation, with the most critical period being the flowering stage. Irrigation is essential in drier areas. The soil should be deep, fertile, well aerated, with a neutral to slightly acidic reaction (pH 6–7). Maize is demanding in terms of nutrients, especially nitrogen, phosphorus, and potassium (Kawsar et al., 2013). For high yields, the application of organic and mineral fertilizers is recommended based on the results of agrochemical soil analysis. Growth stimulation techniques, including targeted fertilization and biostimulants, can further enhance maize vitality and stress tolerance, especially under increasingly variable climatic conditions (VÚRV, 2020). Light is another limiting factor – maize requires full sunlight, so it is grown in wide rows to minimize shading. Sowing density depends on the variety and intended use, but for grain varieties it ranges from 65,000 to 75,000 plants per hectare, in 0,75 m row width(Kraska et al., 2020). Modern trends include the use of precision farming, which optimizes sowing, fertilization, and irrigation using GPS and sensors. Another trend is the cultivation of cover crops, which improve soil structure and reduce weed pressure. Adhering to these principles makes it possible to achieve stable and high maize yields while reducing environmental risks (Zong et al., 2021). Based on the analysis of available agronomic practices in Slovakia and globally, it is evident that crop management strategies must use different methods according to the final purpose of maize production. In grain maize, emphasis is placed on optimizing plant density (50 to 75 thousands of corn plant individuals), nutrient uptake, and protection of the assimilation area during critical growth stages (up to 6th leaf stage for both), whereas silage maize production requires practices that promote rapid biomass accumulation, uniform stand development, and high digestibility of plant material (FAO, 2018). The analysis further shows that a wide range of agrotechnical interventions including soil preparation, sowing date optimization, nutrient management, and cultivation practices significantly influence yield formation and weed competitiveness (FAO, 2021). These measures must be adapted to local soil and climatic conditions and production objectives. In terms of crop protection, integrated weed and pest management approaches are increasingly important (Šarapatka et al., 2019).

1.2 Weed Spectrum in Maize

Maize (*Zea mays* L.) is one of the world most important crops, cultivated on millions of hectares across a wide range of agroecological conditions. However, the high production potential of this crop is dependent on effective weed management, as weeds pose one of the greatest threats to its yield. Weeds compete with maize for water, nutrients, space, and light, significantly reducing its growth and productivity. Yield losses can reach up to 90% if weeds are not controlled during the critical competition period, which occurs from maize emergence to the 8–10 leaf stage (Agrawal et al., 2025). In addition to direct competition, weeds serve as hosts for pests (Elateridae, *Ostrinia nubilalis*, *Diabrotica virgifera* etc.) and diseases (*Pythium debaryanum*, *Ustiago maydis*, *Fusarium* spp., etc.), increasing the risk of secondary infections and further losses. Weed control in maize has changed significantly in recent decades. Traditional methods based on chemical herbicides are still dominant, but growing concerns about weed resistance, environmental impacts, and legislative restrictions are driving the search for alternative solutions (Lindsay et al., 2017). Modern

Table 1 Most common weed species in maize

Monocotyledonous weeds (grasses)	Dicotyledonous weeds
Echinochloa crus-galli (L.) P. Beauv. – very aggressive, grows quickly and competes with maize	*Amaranthus retroflexus* L. – highly competitive, ability to produce seeds quickly
Setaria spp. – common problem on lighter soils	*Chenopodium album* L. – adaptable to various soils
Digitaria sanguinalis (L.) Scop. – prefers warm conditions	*Polygonum* spp. – a problem especially on moist soils
Sorghum halepense (L.) Pers. – perennial grass, difficult to eliminate	*Ambrosia artemisiifolia* L. – allergenic plant, significant problem in Europe
–	*Datura stramonium* L. – poisonous weed, strong competition in later stages of growth
–	*Abutilon theophrasti* Med. Gaertner – strong competition in later stages of growth

approaches include integrated weed management (IWM), precision agriculture, biological methods, and the use of artificial intelligence. The spectrum of weeds in maize depends on climatic conditions, soil type, tillage method, and previous crop. Maize is a wide-row crop with slower initial growth, which creates ideal conditions for weed germination (Ameena et al., 2025). According to Tang et al. (2022), the following weed species are most commonly found in maize (in Table 1).

Globally problematic species include *Amaranthus palmeri* L. and *Amaranthus rudis* L., which are extremely invasive and resistant to several herbicide groups. *Amaranthus* spp. is dominant in specific regions, but they are spreading to others regions very fast. Other significant species are *Ambrosia trifida* L., *Ipomea hederacea* L., *Chenopodium album* L., and *Sorghum halepense* L. These weeds are dangerous not only as competitors but also as hosts for pathogens (Uddin et al., 2020).

1.3 Methods of Weed Control in Maize

Weed control in maize involves a combination of chemical, mechanical, cultural, and biological methods. Each has its advantages and limitations. Chemical methods remain the basis of weed control in intensive maize cultivation systems. Pre-emergence (before weeds emerge) and post-emergence (after weeds emerge) herbicides are used (Bidira, Dechassa, 2024):Pre-emergence herbicides: pendimethalin, dimethenamid, terbuthylazine, flufenacet.

Post-emergence herbicides: nicosulfuron, mesotrione, rimsulfuron, dicamba, 2,4-D, isoxaflutole, fluroxypyr, pethoxamid, bentazone, foramsulfuron, iodosulfuron, thiencarbazone-methyl, pyridate.

Mechanical and cultural methods: Inter-row cultivation – effective especially in the early stages of maize growth. Mulching – organic (straw, cover crops) or synthetic mulches reduce weed germination. Cover crops – reduce seed supply in the soil and improve soil structure. Optimization of sowing density – faster soil shading limits weed growth.

Integrated weed management combines more combination methods. According to the Table 2, the most efficient is to use all of interventions to gain highest yield per hectare. Research shows that the combination of herbicides with weeding or mulching significantly reduces weed density and increases yields. New approaches also include hybrid maize varieties, which reduce the need for herbicides by up to 25% while maintaining yields, and biological methods, which use allelopathic plants and microorganisms to suppress weeds (Kumar et al., 2022). Current trends in weed control: Precision farming: Drones, GPS, and sensors enable targeted application of herbicides, reducing pesticide consumption and the risk of soil contamination. Reducing herbicide doses: Combining lower doses with other measures (mulch, hybrid varieties) reduces the environmental impact. AI and digital platforms: Systems use machine learning to identify weeds and optimize spraying. Ecological practices: Crop rotation, minimising tillage and using biological products are part of sustainable strategies.

The biggest challenge is weed resistance to herbicides. In recent years, weed populations resistant to several groups (ALS inhibitors, Inhibitor of ACC, Auxin simulants) of active substances have emerged, complicating weed control. Another problem is environmental restrictions and pressure to reduce pesticide use. The future of weed control lies in a combination of technologies – precision agriculture, biological methods, genetic innovations, and digital tools. Weed control in maize is a complex process that requires a combination of traditional and modern practices (Mrudul et al., 2025). Chemical methods remain the basis, but the growing problem of resistance and environmental restrictions are forcing farmers to look for alternatives. Integrated management, precision technologies, biological methods, and the use of artificial intelligence represent the future of effective and sustainable weed control in maize (Mohammadi et al., 2023). It is recommended a differentiated cultivation and crop protection protocol for maize, tailored to production purpose (grain and silage), site-specific conditions, and integrated pest and weed management methods. This practical protocol should be validated under experimental station conditions as well as in semi-operational and operational field trials, in order to assess its agronomic effectiveness, economic viability, and environmental sustainability under practical farming conditions (Zadina et al., 2018).

1.4 Impact of Weed Control in Maize on the Agroecosystem

In addition to direct competition, they are hosts to pests and diseases, thereby increasing the risk of secondary infections. However, the methods used to control weeds have a significant impact on soil quality and the functioning of the agroecosystem. Traditional methods based on chemical herbicides are effective, but their long-term use poses environmental risks that cannot be ignored (Malik, 2015). Herbicides are highly effective, but many of them decompose slowly in the soil, increasing the risk of groundwater contamination. Herbicide residues can affect soil microbiota, reduce soil enzyme activity, and disrupt the nutrient cycle (Allmendinger et al., 2022). Research shows that repeated applications of herbicides lead to a decline in microbial biodiversity, which has a negative impact on organic matter decomposition and humus formation. These changes can reduce soil fertility and water retention capacity in the long term. In addition, excessive use of herbicides promotes the development of resistant weed populations, forcing farmers to increase doses or use new active ingredients, thereby exacerbating the problem (Singh et al., 2023). An alternative to a one-sided chemical approach is integrated weed management. Mechanical interventions, such as inter-row cultivation, improve soil aeration and promote soil structure. Cultural measures, such as optimizing sowing density, reduce weed germination by shading the soil more quickly (Nuru, 2021). Cover crops and mulching play an important role. Cover crops, especially legumes (*Vicia faba* L., *Pisum sativum* var. *arvense* L., *Phacelia tanacetifolia* Benth.), enrich the soil with nitrogen and increase its organic matter, thereby promoting soil microbial activity. In addition, they reduce the weed seed bank and improve soil structure. Mulching with organic materials such as straw or compost reduces weed germination, protects the soil surface from erosion, and improves water management. These practices are part of ecological strategies that reduce dependence on chemical herbicides and contribute to the sustainability of the agroecosystem (Gage, Schwartz-Lazaro, 2019). Future trends in weed control are moving towards precision agriculture. Modern technologies such as GPS, sensors, and drones enable targeted application of herbicides, minimizing chemical stress on the soil and reducing cultivation costs. Similarly, the use of artificial intelligence to predict weed pressure and optimize interventions is also developing. Digital platforms can analyze image data from fields and identify weeds with high accuracy, allowing herbicides to be applied only where they are really needed. Biological methods, such as the use of microbial preparations and allelopathic plants, are gaining importance in the context of growing environmental constraints and demands for reduced chemical inputs (Pooja, Ameena, 2021). Herbicide-tolerant (HT) crops, such ase Duo System maize tolerant to cycloxydim, as well as genetically modified (GMO) crops like Bt maize, are not cultivated in Slovakia. From an agroecosystem perspective, it is important to emphasize that weed control affects not only the crop itself, but also soil biodiversity and the stability of the entire system. Sustainable practices that combine different methods contribute to the preservation of soil structure, reduce the risk of erosion, and promote soil biological activity. This increases its ability to retain water and nutrients, which is crucial in the context of climate change (Müller-Schärer et al., 2018). It can be concluded that weed control in maize is a complex process that affects not only the yield but also soil quality and the functioning of the agroecosystem. Chemical methods remain the basis, but their negative impacts on soil and the environment require the search for alternatives. Integrated weed management, cover crops, mulching, and modern technologies are promising solutions that combine efficiency with sustainability. The future of weed control lies in a combination of innovative approaches that minimize environmental risks and ensure stable maize production (Mahaut et al., 2019). Agrochemical methods such as selective herbicides remain effective, particularly in early growth stages. However, their use should be complemented by mechanical and biological control, and preventive measures to reduce environmental impact and delay the development of resistance against herbicides active substances (Holt et al., 2017).

1.5 Economic Aspects of Weed Control in Maize

Weed control in maize crops is not only an agronomic challenge, but also an economic one. Weeds can cause crop losses of up to 90% if they are not controlled during the critical competition period, which has a direct impact on the profitability of cultivation (Braz et al., 2022). The costs of weed control consist of direct and indirect items. Direct costs include expenses for herbicides, their application, fuel, and labor. The price of pre-emergence herbicides ranges from several tens of euros per hectare, with post-emergence treatments further increasing costs. Mechanical methods, such as inter-row cultivation, require investment in equipment and higher fuel consumption, which increases overall costs (Sălceanu et al., 2022). Indirect costs are related to crop losses due to inadequate weed control, increased pest and disease pressure, and soil quality deterioration. If weeds reduce yields by 20–30%, the economic impact can be greater than the cost of herbicides alone. From this perspective, effective weed control is an investment that

Table 2 The impact of using individual methods on grain and silage corn yields

Methods	Yield difference (%, grain)	Yield (t/ha, grain)	Yield difference (%, silage)	Yield (t/ha, silage)
No interventions	0%	6,0	0%	35
Only mechanical interventions	+5 to +15%	6,3–6,9	+7 to +18%	37–41
Only biological interventions	+3 to +10%	6,2–6,6	+5 to +12%	37–39
Only chemical interventions	+15 to +30%	6,9–7,8	+18 to +35%	41–47
Combination of all interventions (IPM)	+30 to +50%	7,8–9,0	+35 to +60%	47–56

will result in stable production and higher profitability (Cimmyt, 2009). Although the combination of chemical, mechanical, and cultural methods requires greater initial coordination, it reduces the risk of weed resistance, eliminating the need for more expensive herbicides in the future. Sustainable practices such as intercropping and mulching bring long-term benefits in the form of improved soil fertility and reduced fertilizer requirements, which lowers costs in subsequent seasons (Lanker et al., 2019). Modern technologies, such as precision farming, enable targeted application of herbicides, saving inputs and reducing costs per hectare. Although the investment in sensors and digital systems can be high, the return on investment is ensured by savings on chemicals and higher cultivation efficiency. Economic analysis therefore clearly shows that weed control is a key factor in the profitability of maize cultivation, with the trend moving towards integrated and technologically advanced solutions (Alptekin et al., 2023).

2 Conclusion

Maize is a very significant and important crop, globally and for Slovakia. Every year, more than 200,000 hectares of maize (both, grain and silage) are sown in our country, which is why it is very important to know the principles of its effective cultivation, weed control, and, of course, new trends. With the right combination of chemical, mechanical, and biological methods, we can achieve high yields with above-average grain quality. Based on the analysis of available agronomic practices in Slovakia and globally, it is evident that crop management strategies must use different methods according to the final purpose of maize production. In grain maize, emphasis is placed on optimizing plant density (50 to 75 thousand of corn plant individuals), nutrient uptake, and protection of the assimilation area during critical growth stages (up to 6th leaf stage for both), whereas silage maize production requires practices that promote rapid biomass accumulation, uniform stand development, and high digestibility of plant material. The analysis further shows that a wide range of agrotechnical interventions including soil preparation, sowing date optimization, nutrient management, and cultivation practices significantly influence yield formation and weed competitiveness. These measures must be adapted to local soil and climatic conditions and production objectives. In terms of crop protection, integrated weed and pest management approaches are increasingly important. Agrochemical methods such as selective herbicides remain effective, particularly in early growth stages. However, their use should be complemented by mechanical and biological control, and preventive measures to reduce environmental impact and delay the development of resistance against herbicides active substances. Growth stimulation techniques, including targeted fertilization and biostimulants, can further enhance maize vitality and stress tolerance, especially under increasingly variable climatic conditions. Based on this analysis, it is recommended that a differentiated cultivation and crop protection protocol for maize, tailored to production purpose (grain and silage), site-specific conditions, and integrated pest and weed management methods. This protocol should be validated under experimental station conditions as well as in semi-operational and operational field trials, in order to assess its agronomic effectiveness, economic viability, and environmental sustainability under practical farming conditions.

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Conflict of Interest

The authors declare that there is no conflict of interest.

Author Contributions

Conceptualization, Š.T. and D.O.; data curation, D.O. and Š.T.; formal analysis, Š.T. and D.O.; funding acquisition, Š.T. and D.O.; investigation, D.O. and Š.T.; methodology, Š.T. and D.O.; software, Š.T. and D.O.; resources, Š.T. and D.O.; supervision, Š.T. and D.O.; validation, Š.T. and D.O.; visualization, D.O. and Š.T.; writing – original draft, D.O. and Š.T.; writing – review & editing, Š.T. and D.O. All 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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