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# Global and local trends in weed management under conventional and conservation agriculture

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**Abstract.** Weeds pose a persistent and multifaceted challenge to global agricultural systems, causing significant yield losses and undermining agroecological sustainability. This review explores contemporary trends in weed management across both conventional and conservation agriculture frameworks. Under intensive farming, chemical control remains predominant but faces growing limitations due to herbicide resistance, environmental contamination, and disruptions of soil biota. The emergence of multiple-resistant weed biotypes worldwide highlights the urgency of transitioning to integrated weed management (IWM) strategies that combine herbicides with mechanical, biological, and agronomic measures. By contrast, conservation agriculture – founded on minimal soil disturbance, permanent soil cover, and diversified crop rotations – offers a more sustainable pathway but introduces new challenges for weed control due to reduced tillage and limited chemical use. The paper examines recent innovations, such as site-specific herbicide applications, cover cropping, and the use of drones and AI for precision weed detection. Special attention is given to the role of weed seed bank management, allelopathic cover crops, and biological control agents in enhancing long-term control effectiveness. The Ukrainian experience is contextualised within global patterns, identifying constraints to conservation adoption such as limited infrastructure, knowledge gaps, and insufficient policy support. The review also identifies critical research gaps, including the lack of long-term field data and insufficient interdisciplinary collaboration. Emerging technologies – robotics, sensor-based systems, digital modelling, and the breeding of competitive crop cultivars – are discussed as potential breakthroughs in sustainable weed management. Ultimately, this synthesis underscores the need for a paradigm shift from single-method approaches to holistic, climate-resilient systems that integrate ecological principles with technological innovation. Future progress depends on policy incentives, stakeholder education, and international research cooperation.

**Keywords:** integrated weed management; herbicide resistance; cover crops; minimum tillage; precision agriculture; soil seed bank.

## Introduction

Weeds represent one of the principal threats to the stability and productivity of agroecosystems globally. According to scientific estimates, annual crop yield losses caused by weeds can reach up to 34% worldwide, surpassing the combined damage caused by pests and diseases (Ofosu et al., 2023; Shevchenko et al., 2024). This issue is becoming increasingly acute under climate change conditions, where disruptions in natural seasonal patterns facilitate the expansion of the ranges of invasive and quarantine weed species such as *Ambrosia artemisiifolia* L., *Amaranthus palmeri* S. Watson, and *Conyza canadensis* (L.) Cronquist (Roberts & Florentine, 2022; Umkulzhum et al., 2024).

In countries with advanced agricultural sectors, the effectiveness of chemical weed control is diminishing rapidly due to the spread of herbicide-resistant biotypes. As of 2024, over 500 cases of herbicide resistance across various weed species have been recorded in more than 70 countries (Tataridas et al., 2022; Priyadarshini, et al., 2024). This alarming trend highlights the crisis of the prevailing chemical protection paradigm and underscores the urgent need to implement integrated weed management (IWM) strategies. In Ukraine and other Eastern European countries, weed control presents specific challenges. Perennial weeds such as *Cirsium arvense* (L.) Scop. and *Elytrigia repens* (L.) Nevski have become widespread, alongside alien invasive species with a high capacity for forming persistent soil seed banks. The intensive use of herbicides within high-input farming systems has led to a decline in the efficacy of conventional control schemes and has disrupted crop rotations, thereby exacerbating weed pressure (Shevchenko et al., 2023; Priyadarshini et al., 2024). Beyond economic damage, weeds undermine agroecological sustainability by competing with crops for water, light, and nutrients, hindering mechanised harvesting, and acting as reservoirs for pests and pathogens (Boutagayout et al., 2023). Within the broader context of transitioning to sustainable and environmentally responsible agriculture, weed management requires a fundamental rethinking – from exclusively chemical methods towards ecologically adaptive agronomic approaches.

Weeds are among the most aggressive competitors of cultivated plants, capable of significantly reducing yields, causing economic losses, and disturbing the ecological balance of agroecosystems. They compete with crops for light, water, nutrients, and space, particularly during early developmental stages when crops are most vulnerable (Altieri et al., 2024). Uncontrolled weed infestation may result in average yield losses of up to 50–60% in cereals (Akhter et al., 2023), over 70% in row crops such as maize and sunflower (Mokgolo et al., 2024), and even complete crop failure in cases of invasion by noxious species such as *Striga* spp. in Africa or *Amaranthus palmeri* in the United States (Mou et al., 2025). Weed control is among the most expensive components in the crop production cost structure. In developed countries, herbicides and associated technologies account for up to 40% of crop protection expenditures (Heitkämper et al., 2023). In the USA alone, annual farmer expenditures on weed control exceed $11 billion, a substantial portion of which targets resistant populations (Day et al., 2023). In low-mechanised systems or areas with limited access to plant protection products, yield losses can be critical – especially for smallholder farms. Additionally, weeds can reduce produce quality, complicate harvesting, increase post-harvest processing costs, and lower market value. Despite their short-term efficiency, conventional herbicide-based methods have serious environmental implications: the evolution of resistant weed biotypes due to repeated herbicide use; contamination of groundwater with herbicides and their metabolites; suppression of non-target flora and microbiota, resulting in reduced biodiversity; and detrimental impacts on pollinators and soil fauna (Elhamalawy et al., 2024).

In conservation agriculture systems, the challenge of weed control becomes even more complex, as reduced or excluded tillage and limited chemical use necessitate alternative strategies – such as mulching, cover cropping, and diversified rotations. When these strategies fail, weeds not only reduce yields but may accelerate agroecosystem degradation, including losses in soil organic matter, increased erosion, and reduced microbial activity. Therefore, weed management carries not only agronomic but also socio-economic and environmental significance, and must be considered a cornerstone of sustainable farming. In response to soil degradation, biodiversity loss, agrochemical contamination, and climate change, the global agricultural community is increasingly turning to the concept of conservation agriculture (CA). This system is based on three core principles: minimal soil disturbance, permanent soil cover with plant residues, and diverse crop rotations or cover crops (FAO, 2021). As of 2023, more than 205 million hectares across over 80 countries are under CA practices – approximately 15% of the world's arable land. The largest areas are reported in South America (Brazil, Argentina), North America (USA, Canada), and Australia. While adoption in Europe and Asia is slower, the trend is steadily rising (Mitchell et al., 2025).

Conservation agriculture provides multiple agroecological benefits: improved soil structure and reduced compaction and erosion; enhanced water retention and reduced moisture loss; increased organic matter content and stimulated soil biota (Raza et al., 2023); reduced greenhouse gas emissions and enhanced soil carbon sequestration (Bhattacharyya et al., 2022); and strengthened ecosystem services, including natural control of weeds, pests, and diseases (Pokharel et al., 2023). Since CA largely excludes traditional mechanical weed control methods, there is an urgent need to adapt weed management strategies. This shift has prompted the search for alternative or combined approaches: mulching, cover crops, regulated rotations, selective herbicide use, and biological control mechanisms (Bhaskar et al., 2021). In the broader transition towards sustainable agrosystems, conservation agriculture is emerging not only as a technological alternative but also as a holistic paradigm encompassing economic, ecological, and social dimensions. Its adoption is supported by international institutions (FAO, CGIAR, World Bank) and is embedded in strategic frameworks such as the EU's Green Deal and Farm to Fork Strategy (Cotta, 2025).

In Ukraine, conservation agriculture is gaining momentum, particularly in the Steppe zone, where challenges such as moisture deficits, soil degradation, and declining biological activity are especially pressing. Many farms are gradually adopting CA elements such as no-till, reduced tillage, stubble mulching, and diversified rotations including legumes and cover crops. However, large-scale implementation remains constrained by the lack of systemic state support, limited access to expert consultation, insufficient technical resources, and poor farmer awareness. Moreover, the increased dependence on herbicides during the transition period introduces additional ecological risks that require comprehensive solutions. Despite these challenges, the prospects for CA in Ukraine are significant: improved moisture conservation, restoration of soil potential, reduced tillage and agrochemical costs, and enhanced climate resilience (Onopriienko et al., 2024; Shevchenko et al., 2024; Kharytonov et al., 2025). In this context, conservation agriculture is increasingly viewed as a key instrument for the sustainable development of the agricultural sector, both nationally and globally.

The objective of this review article was to summarise contemporary, scientifically substantiated approaches to weed control under both conventional (intensive) and conservation farming systems. It aimed to assess the effectiveness of various weed management methods in the context of sustainable agroecosystem development, and to outline the prospects of integrated weed management strategies based on ecological and economic feasibility.

## Conventional agriculture and weed management

*Chemical control: advantages, risks, and resistance.* Chemical weed control remains one of the most widespread and effective methods within conventional agricultural systems, offering rapid suppression of a broad spectrum of unwanted vegetation. Its key advantages include high selectivity, efficacy, and scalability across large agricultural areas, which significantly enhances crop yields (Gao et al., 2024).

In recent years, increasing attention has been paid to the interactions between herbicides and the soil or rhizosphere microbiome. Studies suggest that herbicide pressure can alter microbial community structure, reducing the abundance and activity of beneficial bacteria and fungi involved in nitrogen fixation, organic matter decomposition, and induction of plant stress resistance (Wei et al., 2024). This concern is particularly pertinent to sustainable farming systems, where the microbiome plays a crucial role in soil fertility and crop health. A promising direction lies in combining chemical control with probiotic preparations based on plant growth-promoting rhizobacteria (PGPR) and biological agents that can simultaneously suppress weed growth while maintaining microbial balance in agroecosystems.

One of the contemporary trends in chemical weed management is the growing interest in herbicides with novel modes of action. According to the Herbicide Resistance Action Committee (HRAC), only a few new classes of active substances have been proposed in the past decade, none of which have yet achieved wide-scale commercial use. This raises concerns over the future efficacy of chemical control, especially in light of the global spread of multiple herbicide-resistant biotypes such as *Amaranthus palmeri* S. Watson and *Lolium rigidum* Gaudin, which exhibit cross-resistance to several herbicide groups (Braz & Takano, 2022).

In modern agricultural systems of Ukraine and leading global producers, herbicides with diverse modes of action are actively implemented to suppress the development of weed resistance and ensure effective control even under increasingly complex phytosanitary conditions. In maize cultivation, herbicide formulations based on dicamba (HRAC Group 4 – synthetic auxins) are widely used due to their high efficacy against broadleaf weeds, including *Amaranthus retroflexus* L. biotypes resistant to ALS inhibitors. Dicamba is often combined with halauxifen-methyl, an innovative compound from the arylpicolinate class, also classified as a synthetic auxin. This combination exhibits a broad spectrum of activity against problematic dicotyledonous species. When applied in tank mixtures with ALS inhibitors, such as nicosulfuron or saflufenacil (HRAC Group 2), these combinations provide extended weed control in maize with a reduced risk of cross-resistance (Papapanagiotou et al., 2025).

Among emerging trends in the USA and EU, glufosinate ammonium (HRAC Group 10 – glutamine synthetase inhibitor) is gaining attention as a more environmentally acceptable alternative to glyphosate, especially in light of increasing regulatory restrictions on the latter in the European Union. Glufosinate demonstrates high efficacy in genetically modified cropping systems and is particularly suited for spot applications in zones of intense infestation, such as vegetable production and orchards (Muranaka et al., 2024).

Another promising innovation is florpyrauxifen-benzyl, a representative of the arylpicolinate class (HRAC Group 4), which also acts as a synthetic auxin but lacks cross-resistance with traditional growth regulators such as dicamba or 2,4-D. This active substance is already incorporated into new-generation combination herbicides designed to manage difficult-to-control broadleaf weeds, including *Ambrosia artemisiifolia* L. and *Chenopodium album* L. (Prusinska et al., 2023).

The combination of mesotrione (HRAC Group 27 – HPPD inhibitor) and terbuthylazine (HRAC Group 5 – photosystem II inhibitor) forms an effective strategy for controlling both broadleaf and grass weeds in maize. These formulations provide both pre-emergence and post-emergence activity and are particularly efficient under conditions of mixed weed infestations. Additionally, tembotrione and topramezone (also HRAC Group 27) further enhance the selectivity and flexibility of weed management during active crop growth stages (Goddard et al., 2021).

In specialised crops and inter-row treatments, herbicides based on pyridate (HRAC Group 6 – photosystem II inhibitor) are increasingly adopted, particularly in vegetable systems, due to their high selectivity and suitability for precision applications. Overall, the adoption of herbicides with varied modes of action, coupled with their rational integration based on current best practices, contributes to the prolonged efficacy of crop protection systems and mitigates the risk of adaptive weed species (Dhanda et al., 2025).

Promising results have also been achieved with new herbicide combinations, such as mesotrione (HRAC F2, an HPPD inhibitor) combined with terbuthylazine (HRAC C1), which ensures robust control of resistant weeds in maize and sunflower. On the global scale, there is a growing adoption of substances such as rimsulfuron, topramezone, and florpyrauxifen-benzyl – the latter being a novel arylpicolinate acting as a synthetic auxin but without cross-resistance to dicamba or 2,4-D (Moreno-Serrano et al., 2024).

In 2024, a US-based collaboration between chemical companies and university researchers announced the development of a new active ingredient with a completely novel mode of action – the first in over 30 years. The compound, currently under a provisional name, does not belong to any existing HRAC classification. Preliminary studies have shown its high efficacy against resistant forms of *Amaranthus palmeri* S. Watson, *Chenopodium album* L., *Echinochloa crus-galli* (L.) P.Beauv., even among biotypes resistant to glyphosate, ALS, and HPPD inhibitors (Li et al., 2025). Remarkably, this herbicide also demonstrates the ability to modulate stress responses in crops, enhancing antioxidant activity during herbicide-induced stress. If confirmed, this would represent a paradigm shift from conventional weed suppression to agroecosystem physiology modulation – an innovation aligning with the emerging framework of "smart" agriculture. Market introduction is expected between 2026 and 2028 in the USA and subsequently in the EU. Ukrainian research institutions under the National Academy of Agrarian Sciences have already expressed interest in participating in international field trials (Schwartau et al., 2023).

The expansion of the herbicide range through the development of active ingredients targeting distinct metabolic sites in weeds allows for more efficient control programmes. When combined with crop rotation and precision agriculture technologies, such strategies reduce herbicide load and support the long-term protection of agroecosystems. However, excessive and unregulated herbicide use carries notable risks, including soil and water contamination, negative impacts on biodiversity, and potential human health hazards (Parven et al., 2025). A particularly pressing issue is the evolution of herbicide resistance in weeds, which complicates control efforts and results in substantial economic losses. The incidence of resistance has increased in recent years, necessitating the adoption of more integrated and holistic approaches (Endale et al., 2023).

Research indicates that resistance often emerges due to repeated applications of herbicides with identical mechanisms of action. Therefore, effective resistance management requires herbicide rotation, integration with non-chemical control methods, and the implementation of integrated weed management (IWM) systems (Pavlović et al., 2022). Innovative solutions, such as the use of biopesticides and precision chemical application, also offer opportunities to reduce environmental impact and slow the development of resistance.

Climate change – including rising mean annual temperatures, shifts in growing seasons, and more frequent droughts – is already affecting the efficacy of chemical weed control in various regions. Studies have shown that under heat and moisture stress, weeds may activate alternative detoxification pathways, reducing herbicide efficacy, particularly for systemic products (Anwar et al., 2021). For instance, glyphosate and ALS inhibitors are significantly less effective during extreme drought due to reduced transpiration and slower uptake of active substances. Moreover, warming climates are increasing the invasion potential of subtropical weeds such as Ambrosia trifida and Sorghum halepense, which exhibit extended vegetative periods and rapid adaptive responses. These species frequently develop resistance quickly, with cases of cross-resistant populations to multiple herbicide groups already reported in the USA, Italy, and Southern Ukraine (Schantz et al., 2021; Kato-Noguchi & Kato, 2024).

Therefore, adapting chemical weed control programmes to new climatic realities requires greater consideration of environmental conditions when selecting active ingredients, the use of highly bioactive herbicides under stress scenarios, and the integration of agronomic and biological practices. This opens new avenues for research into climate-adaptive herbicide protection models tailored to specific agroecological zones.

*Mechanical methods: Tillage, cultivation, and inter-row management.* Mechanical weed control methods remain among the oldest and most widely used practices in conventional agriculture. These include ploughing, cultivation, and inter-row tillage, which physically remove or bury weed biomass, disrupt root systems, and reduce the soil seed bank (Cordeau, 2022).

Ploughing ensures deep inversion of the soil profile, effectively destroying both aboveground and underground parts of weeds. However, frequent and intensive ploughing is often associated with the degradation of soil structure, increased erosion, and loss of organic matter (Varnagirytė-Kabašinskienė et al., 2021). As a result, current best practices recommend combining ploughing with other weed management methods or limiting its frequency to avoid long-term ecological harm. Despite the growing popularity of reduced- or zero-tillage systems, ploughing still retains its strategic importance, particularly in cases of severe infestation by overwintered or perennial weed species that are less responsive to chemical or shallow mechanical control. Recent innovations have introduced targeted (zonal) or differentiated tillage, where the depth and intensity of soil disturbance are adapted based on soil type, crop rotation history, moisture conditions, or phytosanitary status. For instance, in the Forest-Steppe zone of Ukraine, deep subsoiling every second year has been shown to reduce the soil weed seed bank by 35–45% (Tarariko et al., 2023; Fedoniuk et al., 2024). In several EU countries, including Austria, France, and Poland, there is a resurgence of regulated ploughing within organic farming systems, where ploughing is used once per crop rotation to deplete the weed seed bank, often in conjunction with green manures or mulching practices. This integrated approach combines mechanical and biological strategies, such as the use of cover crops to suppress weed emergence, enabling ecological balance while maintaining effective control of aggressive species. Recent research indicates that occasional deep ploughing, when alternated with no-till or strip-till systems, can break resistance cycles in weed populations.

Cultivation and inter-row hoeing are less intensive than deep tillage and are mainly used to manage weeds in the upper soil layers while preserving soil structure and maintaining biological activity. These techniques are especially effective in wide-row crops such as maize and sunflower. Nevertheless, mechanical methods often require considerable labour and energy inputs, which may limit their application in large-scale or highly mechanised agricultural systems. Furthermore, repeated cultivation can accelerate soil erosion and reduce humus content (Lin et al., 2022).

Intensive ploughing, although traditionally considered an effective weed control and seedbed preparation method, is also linked to significant losses of soil organic carbon. Frequent deep inversion accelerates the decomposition of organic residues, increasing carbon dioxide ($CO_2$) emissions into the atmosphere and thereby degrading soil quality (Lal, 2020).

Given the global challenges of climate change, reducing tillage intensity and implementing minimum tillage practices have become increasingly important. Conservation tillage helps preserve greater amounts of stabilised carbon within the soil, functioning as a natural sink for greenhouse gases. Maintaining soil organic matter improves water retention, enhances soil structure and nutrient cycling, and supports the sustainability of agroecosystems. However, the scientific community highlights the need for further long-term studies to evaluate the agronomic and environmental consequences of reduced tillage. It is essential to consider regional climatic conditions, soil types, crop species, and preceding crops, as under certain circumstances, insufficient tillage may lead to the accumulation of weed seeds, reduced yields, and deterioration of phytosanitary conditions (Kumar et al., 2024).

Thus, striking a balance between the efficacy of mechanical weed control and the conservation of soil carbon stocks represents a critical goal for modern sustainable farming systems – one that simultaneously addresses agronomic productivity and environmental stewardship.

*Biological methods: limited but growing application.* Biological weed control methods in conventional agriculture are aimed at reducing reliance on chemical herbicides while minimising environmental harm. These approaches include the use of natural enemies of weeds – such as phytopathogens and insect herbivores – biopesticides, and agronomic practices that enhance natural plant competition (Merfield, 2023). Although biological control has the potential to serve as a component of integrated weed management (IWM) systems, its use remains limited due to several constraints. These include the high specificity of biological agents, the need for continuous monitoring, dependence on climatic conditions, and a relatively slow onset of control efficacy (Lahlali et al., 2022). Furthermore, compared with herbicides, biological methods are generally less predictable in their effects and require complex integration with other control strategies.

Recent research has focused on identifying more effective microorganisms and insect biocontrol agents, as well as developing bioproducts with improved stability and field performance (Villavicencio-Vásquez et al., 2025). However, large-scale implementation remains challenging due to difficulties in the mass production, formulation, and storage of biological agents. Despite these limitations, biological control is increasingly recognised as a valuable strategy for reducing chemical input loads – especially within conservation agriculture systems, where the integration of biological, agronomic, and chemical methods contributes to the long-term resilience of agroecosystems (Cárceles Rodríguez et al., 2023).

Modern biotechnological approaches are opening new avenues for improving the efficacy of biological weed control. Genetically modified microorganisms and synthetic consortia of beneficial bacteria and fungi are being actively investigated for their ability to suppress weed growth synergistically, while simultaneously enhancing crop resilience to biotic and abiotic stresses (Wong et al., 2024). In the United States and parts of Europe, the adoption of such bioinoculants is increasingly supported by government programmes promoting sustainable agriculture.

In Ukraine, interest is growing in the use of local entomophagous species, particularly insects that parasitise common weeds in maize and sunflower systems. For example, Ukrainian studies have demonstrated the efficacy of *Zygogramma bicolorata* in controlling *Ambrosia artemisi-*

*ifolia* L. – one of the most aggressive invasive weeds in the steppe zone (Afaq et al., 2023). These methods could be integrated into weed management programmes to reduce herbicide use and ecological impact.

Overall, biological weed control is gaining strategic importance in the context of the global transition towards environmentally sustainable farming systems – a trend that is increasingly relevant both in Ukraine and in leading agricultural nations worldwide.

*Short-term efficacy and long-term impacts on soil and the environment.* Traditional weed control practices – particularly the intensive use of chemical herbicides and deep tillage – demonstrate high short-term efficacy, enabling rapid and effective reduction of weed pressure and enhancing crop yields. Chemical control offers broad-spectrum activity and operational simplicity, while mechanical soil tillage physically removes weeds, making it particularly relevant in arid regions. However, the long-term consequences of such practices can be detrimental to soil health and agroecosystem sustainability. Frequent and intensive tillage contributes to the degradation of soil structure, loss of organic matter, increased erosion, and compaction, which collectively reduce water retention capacity and soil fertility. Overuse of herbicides leads to contamination of soil and water resources, disruption of microbial communities, and the emergence of herbicide-resistant weed populations (Gao & Su, 2024).

Long-term ecological consequences also include the decline of biodiversity both within agroecosystems and the surrounding environment, negatively affecting ecosystem services such as natural pest regulation and erosion control (Ekka et al., 2022). These concerns underscore the urgent need to transition from single-method intensive weed control towards integrated systems that combine diverse control strategies with an emphasis on sustainability and soil resource conservation.

Mechanical soil tillage – especially deep ploughing – can significantly reduce the weed seedbank and disrupt weed root systems, thus lowering weed infestation levels. However, it simultaneously leads to soil structure degradation, humus depletion, and intensified erosion processes (Aušra et al., 2025). Repeated soil inversion accelerates mineralisation of organic matter, reducing the soil's capacity to retain water and nutrients. This is especially critical in dry regions, where structural soil damage can result in substantial productivity losses.

Chemical weed control, despite its high selectivity and rapid action, carries risks of toxic residue accumulation, negative impacts on beneficial soil organisms and microbiota, and accelerated development of weed resistance (Mohd Ghazi et al., 2023). Herbicide use without strategic planning may increase agrosystem dependency on chemical inputs and diminish long-term resilience.

By contrast, biological and agronomic methods, although slower in action, contribute to maintaining or restoring soil health, lowering chemical input loads, and supporting the development of more resilient agroecosystems (Shahane & Shivay, 2022). Their efficacy is significantly enhanced when combined with other weed control approaches, allowing for a reduction in environmental impacts.

Modern agronomic practice increasingly seeks to balance short-term productivity with long-term ecological sustainability by applying principles of integrated weed management (IWM), which combines mechanical, chemical, biological, and agronomic methods to create diversified, adaptive, and context-specific strategies. This approach is key to addressing current agricultural challenges, including climate change, soil degradation, and biodiversity loss (Leguizamón et al., 2022).

### Conservation agriculture and weed control innovations

*Minimum tillage and mulching in conservation agriculture.* Minimum tillage is a fundamental principle of conservation agriculture, aiming to preserve soil structure and enhance biological activity by reducing or eliminating traditional plough-based operations. This approach helps prevent erosion, improves water retention, and facilitates the accumulation of organic matter, contributing positively to agroecosystem health (Amami et al., 2023). A central component of conservation agriculture is the no-till system, which focuses on long-term soil fertility preservation, erosion control, and increased organic matter content. No-till practices support soil biota and improve soil physico-chemical properties, significantly enhancing agroecosystem resilience to climate stressors such as drought and heavy rainfall. By minimizing disturbance to the soil profile, no-till also reduces the formation of compacted layers or plough pans – common issues under conventional tillage.

One key feature of no-till is the formation of a mulch layer from crop residues left on the soil surface, which performs multiple ecological functions. First, it acts as a physical barrier, impeding weed germination and reducing reliance on herbicides. Second, mulch helps retain soil moisture by reducing evaporation – critical in dryland agriculture. Third, decomposing plant residues provide a steady input of organic matter, feeding soil microorganisms and enhancing biological activity (Zhao et al., 2024). Together, these effects increase the overall productivity of agroecosystems and buffer against climate fluctuations. However, a major challenge during the early years of no-till adoption is increased weed pressure, especially from perennial and herbicide-resistant species that thrive in the absence of intensive mechanical control. To address this, an integrated strategy combining biological, agronomic, and chemical methods is recommended. For instance, cover crops with allelopathic properties can suppress weed germination, and spot applications of herbicides can reduce chemical loads while maintaining weed control efficacy (Pavlović et al., 2022). Such integration helps reduce pesticide dependency and fosters more resilient agroecosystems.

In North America, no-till is widely implemented in the production of maize, soybean, wheat, and other crops, where it has proven effective in improving soil fertility, reducing erosion, and increasing yields, particularly in arid climates (Licht & Al-Kaisi, 2021). Similar results have been documented in EU countries, where no-till is often integrated with digital precision agriculture systems, optimizing resource use and management efficiency (Müller et al., 2023). In this context, no-till is not just a practice but part of an innovative approach to sustainable farming.

In Ukraine, no-till is gaining momentum, particularly in the steppe zone, where climate change has led to frequent droughts and moisture shortages. Studies by the Institute of Grain Crops of NAAS show that combining no-till with mulching and cover crops reduces erosion, conserves productive soil moisture, and decreases weed infestation by 20–30% compared to conventional tillage (Shevchenko et al., 2024). These benefits are critical for improving yield stability under risky farming conditions. When combined with adaptive crop rotations and precision fertilization, no-till shows strong potential as a foundation of sustainable agricultural technologies in Ukraine.

No-till also plays a critical role in carbon sequestration, increasing the amount of stabilized organic matter in soil. This helps improve soil physical properties, water retention capacity, and crop root development, while simultaneously reducing greenhouse gas emissions. For optimal results, tillage practices, crop rotations, fertilization systems, and weed control must be tailored to local climatic and edaphic conditions. An alternative to conventional ploughing is strip-till, a practice that combines targeted mechanical disturbance in the seed row with residue preservation in the inter-row. This approach helps reduce erosion, conserve moisture, and simultaneously control weeds in the seeding zone (Jaskulski et al., 2022). When paired with cover crops, strip-till can effectively suppress weeds without excessive soil disturbance, making it suitable under conditions of climate variability.

In EU countries, roller crimpers are increasingly used for mechanical mulching. These tools flatten cover crops onto the soil surface, forming a dense organic mulch layer that inhibits weed growth and reduces the need for ploughing. This technique is especially prevalent in organic farming systems in France, Italy, and Poland.

In the Ukrainian Steppe, where spring and summer droughts are common, strip-till is expanding, especially for maize and sunflower. It combines narrow-zone soil loosening with mulch conservation in the inter-rows, reducing evaporation and weed pressure. Research by the Institute of Grain Crops NAAS (2021–2023) indicates that strip-till, combined with mulching after crops like wheat or rapeseed, can reduce weed infestation by 25–30% and conserve 18–22 mm of productive moisture in the 0–30 cm soil layer during critical growth stages of maize. Strip-till also enables localized nutrient and micronutrient application, reducing resource competition with weeds. It is increasingly integrated into precision agriculture technologies, making it a scalable strategy for dryland regions and high-risk farming systems. Experience from southern and central Ukraine highlights its potential as part of a sustainable mechanical weed control framework (Shevchenko et al., 2024).

Another promising approach is vertical tillage (Verti-Till), which involves shallow soil loosening without inversion of the soil profile. This technique preserves soil structure, organic matter, and moisture, while mechanically disrupting weed seedlings and breaking compaction channels. Unlike ploughing, vertical tillage does not create a plough pan, thus improving water infiltration and root development. In the U.S. and Canada, Verti-Till is widely used in conservation systems, especially after maize and soybean harvests. Crop residues are shredded and partially incorporated into the soil, forming a mulch layer that suppresses weeds. In central and southern Ukraine, especially in light and medium-textured soils, this method is being tested as an alternative to ploughing for spring cereals and oilseed crops (Nikonchuk et al., 2023).

Mulching, either with crop residues or cover crops, plays a critical role in weed suppression. It creates a physical barrier that inhibits weed seed germination, lowers soil temperature, and improves water retention. Studies show that mulching can substantially reduce herbicide dependence, contributing to more environmentally friendly weed management systems. The use of minimum tillage and mulching requires adaptive integration of agronomic, biological, and chemical weed control methods. For example, mulch can reduce herbicide penetration into the soil, necessitating adjustments in application timing and methods. Nevertheless, these practices enhance system resilience and support the restoration of natural agroecological processes.

Challenges to adopting minimum tillage and mulching include the need to revise traditional farming practices and secure adequate amounts of plant residues, especially in high-input systems (Cordeau, 2022). However, their soil conservation benefits and potential to reduce environmental impact make them highly promising tools for advancing sustainable agriculture.

*Crop rotations and cover crops in conservation agriculture.* Crop rotations and the use of cover crops are among the most effective agronomic practices in conservation agriculture. They play a vital role in reducing weed infestation, improving soil structure, and enhancing soil fertility. Crop rotation creates direct competitive pressure for weeds, limiting their development and reproduction while also reducing the weed seed bank in the soil. By interrupting weed life cycles, crop rotation lowers weed resilience and increases the effectiveness of other weed control measures (Boutagayout et al., 2023). Integrating broadleaf and narrow-leaf crops in rotation significantly alters agroecological conditions, enhancing biodiversity and suppressing weed emergence.

Cover crops, particularly legumes (e.g., peas, clover) and grasses (e.g., rye, oats), contribute to the formation of a mulch layer from plant residues. This layer creates a physical barrier that inhibits weed germination, reduces weed competitiveness, and helps retain soil moisture. In addition, cover crops stimulate soil biological activity by promoting the development of beneficial microorganisms and atmospheric nitrogen fixation, which enriches soil nutrient content and strengthens agroecosystem resilience (Koudahe et al., 2024). This is especially important in regions with depleted or eroded soils, where cover crops can restore soil fertility without the need for synthetic fertilizers.

Innovative approaches to crop rotation management now emphasize optimizing crop sequences based on agroecological requirements and integrating cover crops with targeted herbicide applications and biological weed control. This combination significantly enhances weed suppression while reducing chemical loads on the environment (Tataridas et al., 2022). Climatic conditions and soil types must be considered when designing rotation schemes, as they determine the competitive ability and productivity of crops. In the European Union, support systems have been introduced to incentivize the use of diverse crop rotations and cover crops as part of climate-smart agriculture.

Beyond their traditional functions, recent studies highlight the role of crop rotations and cover crops in increasing climate resilience. Cover crops improve the physical and biochemical properties of soil and help regulate microclimatic conditions by buffering against temperature extremes and moisture fluctuations (Smith et al., 2024). They enhance rainfall infiltration in the upper soil layers, reduce nutrient loss and erosion risks, and stabilize nutrient cycling. Cover crops also influence soil biota dynamics, stimulating beneficial microbial communities that improve plant immunity and suppress soil-borne diseases and pests.

A promising innovation is the use of multifunctional cover crops that combine weed suppression with biomass production for livestock feed or bioenergy. These crops improve overall farm system efficiency, reduce reliance on external inputs, and support ecological balance (Garcia & Lee, 2025). The development of new cover crop cultivars with enhanced allelopathic properties and adaptability to various climate zones opens new possibilities for targeted weed control.

Weed species composition in agroecosystems depends not only on the preceding crop but also on the allelopathic profile of the crops within the rotation. Studies by leading Ukrainian researchers demonstrate that, in many cases, weed pressure is largely driven by a small group of dominant weed species. These include *Ambrosia artemisiifolia* L., *Amaranthus retroflexus* L., *Chenopodium album* L., *Echinochloa crus-galli* L., *Setaria glauca* L., and *Polygonum convolvulus* L., which are responsible for most yield losses. Thus, weed management should focus on targeting these most harmful species within the rotation. Additionally, primary tillage practices and the use of organic and mineral fertilizers strongly influence weed infestation levels and weed community structure (Valiño, 2025).

In this context, the proper planning of crop rotations and the integration of cover crops are key components of successful conservation agriculture and sustainable weed management strategies.

*Targeted herbicide application in precision agriculture.* Targeted or site-specific herbicide application is one of the key innovations in conservation agriculture, aiming to increase the efficiency of weed control while reducing agrochemical load on the environment. The use of GPS technologies, drones, sensors, and artificial intelligence (AI) systems enables real-time weed detection and localized pesticide application only in necessary zones. This approach allows for a significant reduction in herbicide use, which not only decreases input costs for farmers but also minimizes the risk of herbicide-resistant weed populations and contamination of soil and water resources. For example, multispectral vegetation sensing enables precise weed mapping and real-time adjustment of herbicide application rates. A major advantage of targeted herbicide application is its integration with automated machinery. Modern tractors and sprayers equipped with high-precision GPS modules and motion control systems can adjust speed and dosage based on the degree of weed infestation in specific field areas. This minimizes overlapping of treated zones and prevents excessive chemical use. These systems also enable data collection and analysis, facilitating more effective planning of subsequent agronomic measures (Upadhyay et al., 2024). The development of Internet of Things (IoT) technologies and mobile applications further expands the capacity for remote crop monitoring and management in hard-to-access regions.

An innovative direction in targeted weed control is the use of robotics and autonomous treatment systems, which can operate without human involvement, with high precision and minimal environmental impact. Spraying robots equipped with cameras and sensors recognize weeds based on morphological features or spectral signatures and apply herbicides selectively or remove weeds mechanically. This drastically reduces herbicide input and enhances environmental sustainability (Oliveira et al., 2024). These technologies are being actively adopted in the USA, Canada, and Europe, and are gradually spreading in Ukraine, particularly in the high-tech farming sector.

In parallel with the development of site-specific herbicide application, increasing attention is being paid to its role in managing herbicide resistance. Localized application of active ingredients tailored to the weed species spectrum allows more efficient use of different modes of action, slowing down the development of resistance (Islam & Monjardino, 2025). Moreover, combining targeted herbicide use with integrated weed management – including crop rotations, cover crops, and biological agents – creates multifactorial pressure on weed populations, reducing their adaptability and long-term impact. This integrated approach is considered one of the most promising strategies for sustainable agricultural production under growing environmental and economic pressures.

However, the widespread adoption of precision herbicide application faces constraints such as high equipment costs, the need for specialized personnel, and dependence on high-quality data. Further research is required to adapt these technologies to diverse agro-climatic conditions and crop-specific needs (Barbosa et al., 2023).

In the long term, the integration of targeted herbicide application with other weed management practices – such as crop rotation, cover cropping, and biological control – has the potential to greatly enhance the resilience and ecological sustainability of agricultural systems.

*Agronomic practices for reducing the weed seed bank in soil.* Reducing the weed seed bank in soil is a fundamental objective for achieving long-term weed control in conservation agriculture. Effective management of this seed reservoir allows a gradual reduction in overall weed density, thereby decreasing the reliance on chemical and mechanical control methods. Modern agronomic practices focus not only on directly eliminating weed seedlings and mature plants but also on strategically disrupting weed life cycles to prevent replenishment of the soil seed bank (Choudhary, 2023). This approach plays a strategic role in maintaining ecological balance and improving the productivity of agroecosystems.

Incorporating highly competitive crops into crop rotations is of particular value. Species with dense canopies and rapid early growth can effectively shade the soil surface and limit light availability for weed seed germination. Simultaneously, cover crops provide a permanent mulch layer from plant residues, which physically suppresses weed emergence, moderates soil temperature fluctuations, and helps maintain optimal moisture in the upper soil layers. Early and repeated inter-row cultivation, even within minimum tillage systems, can disrupt young weed root systems and improve soil aeration, promoting stronger crop development. Timely mechanical removal of weeds before seed formation is critically important, as it prevents the accumulation of viable seeds in the soil. An innovative approach involves combining agronomic practices with biological interventions, such as the application of saprophytic and pathogenic fungi that specifically infect weed seeds, reducing their viability and germination. This method is promising because it does not harm crops and supports the restoration of soil microbial biodiversity. Additionally, the implementation of monitoring systems to detect weed development stages enables optimal timing of control measures. Regional climatic conditions, soil types, and biodiversity must be taken into account when adapting agronomic strategies to enhance their effectiveness in reducing the seed bank.

Fundamental aspects of weed seed bank dynamics in response to deep plowing, minimum, and no-till systems with surface mulch cover have been examined by Lundgren et al. (2023), who emphasize the importance of vertical seed distribution within the soil profile. However, the latter does not consider complementary agronomic measures that are part of conventional tillage systems and may enhance its efficacy. The study by Alagbo et al. (2022) highlight the role of tillage methods in suppressing weed seed germination and mitigating yield losses in cereals and legumes.

An analysis of experimental data shows that weed seed bank size varies widely across soil types, making accurate interpretation of infestation levels based on seed count challenging. According to the research by Shevchenko et al. (2023), the total seed bank in a 0–10 cm soil layer in the Ukrainian Steppe can reach 570 million seeds/ha. Other studies indicate seed reserves ranging 6 million seeds/ha in fallow lands to 133 million seeds/ha in agroecosystems. Nevertheless, it is evident that substantial yield losses occur under both low and high weed seed densities. Therefore, reducing weed seed presence in the topsoil is critical for decreasing the cost of weed management in agricultural systems.

In conclusion, a comprehensive strategy that integrates crop rotation, cover crops, mechanical and biological control methods is essential for sustainable reduction of the weed seed bank. This integration not only lowers ecological pressure but also enhances economic viability, making such practices highly promising for broad adoption in modern agroecosystems across Ukraine, Europe, and North America.

*Challenges and benefits of sustainable practices in conservation agriculture.* Conservation agriculture offers a number of significant benefits for weed control, including the preservation of soil structure, reduced erosion, improved water management, and enhanced biodiversity. The application of minimum tillage, mulching, and crop rotation within conservation systems promotes weed suppression through natural mechanisms, thereby reducing the need for chemical herbicides and enhancing the ecological safety of agroecosystems. Furthermore, conservation practices improve the microbiological composition of soils, increasing biological activity and facilitating natural weed suppression through competition with crops (Francaviglia et al., 2023).

At the same time, the implementation of conservation agriculture is accompanied by several challenges. First, a lack of knowledge and skills among farmers regarding weed management under reduced tillage systems may lead to increased weed pressure during the initial transition period, particularly in systems relying on monoculture. Second, an increased dependence on herbicides during the adaptation phase can contribute to the emergence of herbicide-resistant weed populations, a global issue in modern agriculture. Third, limited access to modern equipment for precision application of crop protection products, along with insufficient funding and government support, hinders the widespread adoption of innovations such as drones, sensors, and autonomous systems (Rai et al., 2023).

Despite these challenges, the sustainable approach of conservation agriculture shows considerable potential for long-term productivity and ecological resilience. The integration of agronomic, biological, and chemical methods within an integrated weed management framework helps to reduce environmental impacts, improve soil quality, and limit economic losses due to resistance. Particularly promising is the development of digital technologies, which enable weed control strategies to be adapted to local conditions, thus enhancing the efficiency and sustainability of agricultural systems. In the face of global climate challenges, conservation agriculture is emerging as a key strategy for ensuring food security and preserving ecosystems at the international level (Jayaraman et al., 2021).

By incorporating reduced tillage, mulching, crop rotation, and innovative precision technologies, conservation agriculture demonstrates strong potential for effective and environmentally safe weed control. While certain challenges remain – such as the need for farmer training, the risk of herbicide resistance, and limited access to modern machinery – this sustainable approach contributes to soil preservation, biodiversity enhancement, and increased soil fertility. The integration of agronomic, biological, and digital weed management tools opens new pathways for sustainable agricultural development worldwide, which is especially important under the pressures of climate change and growing demands on natural resources. Continued research and the development of locally adapted technologies will further maximize the environmental and economic benefits of conservation agriculture.

**Global trends in weed management**

*Leading countries in the implementation of conservation-based weed management.* Conservation agriculture, as a system of sustainable agroecosystem management, is rapidly gaining global traction – particularly in the context of weed control, reducing agrochemical use, and adapting to climate change. The largest areas under conservation agriculture are located in South America, especially in Brazil and Argentina, where this practice covers over 50 million hectares. In these countries, a wide range of agronomic methods is integrated with weed management systems, significantly reducing the reliance on chemical inputs (Swaminathan et al., 2022).

In North America, particularly the United States and Canada, advanced precision agriculture technologies are being actively implemented to complement conservation practices. These technologies enable the adaptation of weed control strategies to local conditions, optimizing the use of herbicides and mechanical measures (Novak et al., 2021).

The European Union is also making consistent progress in adopting conservation agriculture, driven by policy initiatives such as the Green Deal and the Farm to Fork strategy, which emphasize reducing pesticide use and enhancing biodiversity (Klebl et al., 2024). These policies provide incentives and regulatory frameworks that support farmers in adopting more sustainable weed management practices.

In Asia and Africa, the spread of conservation-based weed control is proceeding more slowly due to limited resources, insufficient technical support, and the specific characteristics of regional farming systems. Nevertheless, the number of pilot projects and international programs is increasing, aiming to adapt these practices to local conditions and farmer needs (Kaur et al., 2021).

In conclusion, the leading countries in implementing conservation-based weed management combine long-standing experience in traditional farming with cutting-edge technologies, enabling them to strike a balance between productivity and ecological sustainability.

*Development of principles of integrated weed management (IWM).* Integrated Weed Management (IWM) has become a key approach in modern agriculture, aimed at combining diverse control methods to reduce environmental impact and enhance weed control efficiency. Integrated weed management involves a balanced application of agronomic practices, biological methods, chemical control, and cutting-edge technologies, which helps to mitigate the risk of weed resistance development. In recent years, there has been growing recognition of the need to adapt IWM to specific regional conditions, considering weed species diversity, agroclimatic features, and socio-economic factors. This adaptation increases system resilience and promotes more sustainable resource use. The development of digital tools, including platforms for weed monitoring and growth forecasting, significantly improves decision-making processes within IWM frameworks (Riemens et al., 2022).

At the same time, the implementation of IWM faces challenges related to increasing farmer awareness and training, as well as optimizing costs associated with applying integrated measures. The lack of long-term data complicates the economic evaluation of various IWM components, necessitating further research (Zheng et al., 2024).

Thus, the establishment of IWM as a standard for sustainable weed management represents an important advancement in the agricultural sector, combining scientific innovation and practical solutions to maintain productivity and environmental safety.

*Impact of climate change on weed distribution and control effectiveness.* Climate change significantly affects the dynamics of weed distribution across different regions worldwide, altering their biological cycles, adaptability, and competitiveness relative to cultivated crops. Rising average annual temperatures, changing precipitation patterns, and the increasing frequency of extreme weather events contribute to the spread of new weed species into traditionally unfavorable zones and increase the aggressiveness of existing populations. These changes complicate the effectiveness of traditional control methods, as weeds may recover more rapidly after treatments or adapt to commonly used herbicides. For example, increased temperatures affect plant metabolism and can reduce the sensitivity of certain weed species to chemical agents (Vilà et al., 2021). Additionally, climate change shifts vegetation periods, necessitating a revision of the timing for agronomic interventions.

To adapt weed management systems to new climatic realities, increasing attention is being given to developing integrated approaches that combine resilient agronomic practices, precision herbicide application, and digital monitoring technologies (Clements & Jones, 2021). The implementation of climate-oriented predictive models for weed spread is also crucial for timely management decisions.

Despite significant progress, the lack of localized long-term studies across diverse agroclimatic zones remains a serious obstacle to fully understanding and adapting weed control methods to climate challenges.

**Local and regional aspects**

*Ukrainian experience in weed control and adoption of conservation agriculture.* In Ukraine, weed management remains a critical issue for agriculture, as weeds significantly reduce crop yields and complicate technological processes (Shevchenko et al., 2023). The dominant weeds in cereals, industrial crops, and vegetables include highly competitive and fast-spreading species such as *Ambrosia artemisiifolia*, *Amaranthus retroflexus*, *Chenopodium album*, *Setaria viridis*, and *Echinochloa crus-galli*, many of which exhibit frequent herbicide resistance. Traditionally, intensive methods of chemical control have been employed in Ukraine, with widespread use of herbicides from the sulfonylurea, imidazolinone, and phenoxy acids (Moldavan et al., 2022). However, growing awareness of the need to reduce chemical loads on ecosystems is driving interest in conservation technologies. In recent years, Ukraine has seen a gradual adoption of conservation agriculture principles – minimal tillage, cover cropping, and crop rotation systems. According to the Ministry of Economy, lands managed under conservation agriculture cover approximately 5–7% of the total cereal crop area, with the greatest prevalence in southern and central regions (Moldavan et al., 2022).

The main challenges to wider adoption include insufficient technical infrastructure on farms, a shortage of qualified agronomic personnel, and limited governmental support for innovative technologies (Shevchenko et al., 2023). Nonetheless, international technical assistance projects and scientific research contribute positively to the advancement of conservation-based weed management and sustainable agriculture in general (FAO Ukraine, 2023).

*Examples from other regions: EU, USA, Latin America, Asia.* European Union countries are progressively implementing integrated weed control approaches that combine traditional methods with conservation practices. Notably, the "Farm to Fork" strategy aims to reduce pesticide use by 50% by 2030, encouraging farmers to adopt integrated weed management (IWM) with emphasis on mechanical and agronomic methods. In Northern Europe (e.g., Sweden, Denmark), precision herbicide applications using GPS technology are widely employed, significantly reducing chemical inputs (Loddo et al., 2021). In the United States, conservation agriculture covers over 70 million hectares, mainly in the prairie states (USDA, 2023). Practices commonly combine minimal soil disturbance, mulching, and rotations with cover crops to reduce erosion and suppress weeds. The spread of herbicide-resistant weeds such as Palmer amaranth and Waterhemp stimulates the use of digital technologies for precision herbicide application and biological control methods (Fiore et al., 2022).

Latin America shows rapid growth in conservation agriculture, especially in Brazil and Argentina, where no-till areas have increased by more than 40% over the past decade. Herbicides are traditionally combined with agronomic measures and innovations such as crop rotations with cover crops to reduce weed pressure (Jacquet et al., 2022).

In Asia, conservation practices develop more slowly due to challenging climatic conditions and predominance of smallholder farms. However, in China, India, and Vietnam, interest in minimum tillage and crop rotations is rising to preserve soil fertility and control weeds. China conducts extensive research on adapting conservation agriculture to monoculture rice and wheat systems, while India implements digital platforms for weed monitoring and precision agrochemical application (Xuan et al., 2025).

*Role of government policy and scientific programmes.* Government policy plays a pivotal role in creating favorable conditions for adopting modern weed control methods, particularly within conservation agriculture frameworks. Many countries, including EU member states, the USA, and Ukraine, have government programmes promoting sustainable agriculture through support for integrated weed management systems and reduction of agrochemical reliance (Vulchi et al., 2022; Mytsyk, et al., 2024).

The EU's "Farm to Fork" strategy targets a 50% reduction in pesticide use by 2030, accompanied by subsidies and technical assistance to farmers for implementing conservation technologies and biological weed control. Similarly, U.S. NRCS programmes provide financial and advisory support for minimal tillage, cover cropping, and other conservation practices (Silva et al., 2022).

In Ukraine, the development of conservation agriculture is supported by state and international scientific initiatives, including projects involving FAO, the European Bank for Reconstruction and Development (EBRD), and others that facilitate training, technology adoption, and the adaptation of international experience. Programmes focus on advancing agronomic methods, assisting farmers in transitioning to conservation farming, and researching herbicide resistance control. Recent scientific programmes increasingly emphasize integrating multi-component weed management approaches that combine chemical, mechanical, biological, and digital technologies, with special attention to adapting strategies to climate change and regional specificities (Silva et al., 2022). Ukrainian research institutions, such as the Institute of Agriculture of the Steppe Zone of the National Academy of Agrarian Sciences, implement projects optimising plant protection systems considering agroecological conditions (Shevchenko et al., 2024).

Thus, government policies and scientific programmes act as catalysts for the development of sustainable and effective weed management, enhancing agroecosystem productivity and environmental preservation.

**Research gaps and future perspectives**

*The necessity of interdisciplinary research.* Contemporary challenges in weed management within agroecosystems necessitate a comprehensive approach that transcends traditional agronomic and chemical methods. Interdisciplinary research, integrating agronomy, ecology, molecular biology, informatics, and social sciences, has the potential to substantially enhance the effectiveness and sustainability of weed management systems. In particular, understanding genetic mechanisms of resistance combined with the development of digital monitoring technologies enables the creation of predictive models for adaptive management (Jiang et al., 2022).

One of the major scientific gaps lies in the insufficient integration of data regarding climate change, agroecological regional specificities, and socioeconomic factors influencing the adoption of new technologies. This integration is especially critical for adapting conservation agriculture systems to variable conditions and the diversity of farming enterprises worldwide. The lack of interdisciplinary studies hampers the development of comprehensive strategies that balance ecological safety with economic feasibility. Furthermore, the combined effects of biological, mechanical, and chemical methods within Integrated Weed Management (IWM), considering regional soil, climate, and crop particularities, remain insufficiently explored (Rusmayadi et al., 2023). Research on the impact of various agrotechnologies on soil microbiomes is urgently needed, as the microbiome plays a key role in agroecosystem stability and weed suppression.

Innovative prospects lie in the advancement of digital agricultural technologies – machine vision, artificial intelligence, and drone-based monitoring and targeted application of plant protection products – which require close collaboration among agronomists, engineers, IT specialists, and ecologists (Nahiyoon et al., 2024). The further development of interdisciplinary approaches will not only optimise weed control but also enhance the overall resilience of agricultural systems to external stresses.

In foundational works, Baliuk et al., (2023) substantiated a sustainable soil resource management strategy for Ukraine from an interdisciplinary perspective. This strategy involves the improvement of legislative and regulatory frameworks; enhancement of informational, institutional, technological, and financial support for soil resource management; effective international cooperation; and outlined projected economic, ecological, and social benefits from addressing these challenges.

*Insufficiency of long-term data.* One of the key scientific gaps in weed management, both in conventional and conservation agriculture, is the lack of long-term studies reflecting the temporal impact of various control methods on agroecosystems. Most existing research focuses on short-term effects of herbicide application or agronomic practices, which complicates the prediction of system sustainability, resistance development, and impacts on soil environments. Long-term experiments allow for the assessment of cumulative effects of chemical use, shifts in weed community composition, and effects on soil fertility and biodiversity. Particularly in conservation agriculture systems, the absence of prolonged studies hinders the analysis of the economic efficiency of transitioning to reduced tillage and cover crop utilisation across diverse regions with varying agroclimatic conditions (Mutuku et al., 2021).

Moreover, long-term monitoring is essential for adequate evaluation of environmental risks, including the impact of chemical agents on soil microorganisms, accumulation of toxic substances in soils and water bodies, and the adaptation of weeds to climate change (Wittwer et al., 2023). Without such data, it is challenging to develop sustainable weed management strategies effective over decadal time scales.

Therefore, there is an urgent need to initiate and maintain long-term agroecological research programmes integrating the monitoring of biotic and abiotic factors, socioeconomic aspects, and technological innovations for a comprehensive assessment of weed control systems. Expansion of such studies will contribute to more reliable decision-making in policy, agronomy, and scientific programming.

*Potential of new technologies for weed control.* Innovative technologies, including drones, artificial intelligence (AI), and sensor systems, open new perspectives for effective and sustainable weed management in agroecosystems. The use of unmanned aerial vehicles enables rapid monitoring of crop conditions, early detection of weeds, and precise localisation of herbicide application, significantly reducing pesticide use and environmental impact/ Artificial intelligence and machine learning allow for the analysis of large data sets from images, sensors, and meteorological data, facilitating weed species recognition and forecasting their dynamics, which enables adaptive and integrated management approaches. Sensor technologies, including multispectral and hyperspectral cameras, provide detailed assessments of plant cover status, enabling the detection of stress associated with weed competition and evaluation of control measures' effectiveness (Roslim et al., 2021).

Despite their considerable potential, the implementation of these technologies faces challenges such as high initial investment costs, the need for qualified personnel, adaptation of algorithms to regional conditions, and integration with existing agronomic systems. Currently, there is a lack of long-term studies assessing the economic feasibility and environmental consequences of large-scale deployment of these technologies. The development of interdisciplinary research projects that unite agronomists, engineers, IT specialists, and ecologists is essential for creating integrated solutions that account for the specifics of regions, crops, and production scales. It is expected that in the coming years, the use of drones, AI, and sensors will become key components of sustainable weed management strategies, enhancing agricultural productivity and environmental safety (Esposito et al., 2021).

A novel direction involves the development of autonomous robotic systems for mechanical weed removal, currently actively tested in the USA, Germany, and the Netherlands. These robot agents, equipped with computer vision and manipulators, can selectively remove weeds without damaging crops, allowing for complete avoidance of chemical intervention in targeted areas. For example, the FarmDroid FD20 robot performs autonomous seeding and inter-row weeding using GPS navigation without the need for herbicides. Although such technologies are at an early implementation stage, they have the potential to radically transform weed control approaches in highly specialized organic farming systems (Barreto et al., 2025).

Another innovative approach is laser and plasma weed destruction, which uses thermal energy to destroy weed tissues. Studies conducted in Israel and Canada demonstrate that these methods have high selectivity and efficacy against a wide spectrum of weeds without negative impacts on soil or crops. Laser units integrated into robotic complexes allow real-time operation, minimising contact with non-target objects. Although energy consumption remains a limiting factor, this technology shows significant potential for ecological agriculture.

Finally, a promising yet underexplored area is the application of blockchain technology for verification and tracking of weed control measures in sustainable agro-systems. With the growing demand for environmentally certified products, blockchain can ensure transparency in managing agro-technological operations by recording the origin, cultivation methods, and applied control measures. This is particularly relevant within the EU, where sustainable agriculture certification is part of the Green Deal framework. Thus, digital verification of weed management practices can not only enhance consumer trust but also incentivise farmers to adopt less invasive and more sustainable practices.

*Synthesis of traditional and innovative methods.* Contemporary challenges in weed management necessitate the integration of traditional agronomic practices with cutting-edge technologies to enhance the effectiveness and resilience of weed control systems. Combining mechanical, chemical, and biological methods with digital tools such as artificial intelligence, drones, and sensor technologies opens new avenues for adaptive and targeted weed management. However, such synthesis requires a profound understanding of the ecological, economic, and social aspects associated with the application of diverse approaches. For instance, integrating reduced tillage with precision herbicide application via drones can decrease chemical load while maintaining productivity, but this demands adequate farmer training and adaptation of technologies to local conditions. Similarly, the use of cover crops in conjunction with biological agents and agronomic measures calls for interdisciplinary research to develop comprehensive management protocols. A significant scientific gap exists in developing integrated weed management models that account for variability in climatic conditions, soil types, crop and weed species, as well as socioeconomic factors. The absence of such models complicates the scaling of successful practices across diverse regions (Garcia et al., 2023). Enhancing the efficiency of method synthesis depends on access to high-quality data and active collaboration among scientists, agricultural producers, and technology developers (Zawada et al., 2023).

An emerging research direction in weed management involves digital agroecosystem modeling, particularly the application of dynamic cropping system models (e.g., DSSAT, APSIM) to simulate weed development influenced by climatic, agronomic, and biotic factors. These models enable not only the planning of effective crop rotations but also the assessment of germination probabilities for specific weed species and their potential impact on yield under varying weather scenarios (Kushal et al., 2024). Implementing these models in practice can significantly strengthen farmers' adaptive decision-making under climate change but requires supplementation with localized phytosanitary data, which currently represents a critical deficiency in many regions.

Another promising yet underexplored area is the genetic improvement of crops aimed at reducing weed competition. This includes breeding varieties with enhanced allelopathic activity or more developed root systems that naturally suppress weed emergence in the rhizosphere (Bertholdsson et al., 2023). Such approaches offer potential for biological weed suppression without additional chemical inputs; however, widespread adoption necessitates comprehensive genomic research and evaluation of agroecological risks associated with introducing highly competitive cultivars into the environment. Simultaneously, the development of open international data-sharing platforms on weeds and control efficacy based on FAIR principles (Findable, Accessible, Interoperable, Reusable) is a promising vector. Initiatives such as the Global Weed Atlas and WeedID.AI are advancing within the EU and North America but require active engagement of researchers from Central and Eastern Europe as well as the Global South. Expanding global monitoring will accelerate invasive species identification, risk mapping, and coordination of research through shared access to real-world field data (Hussain et al., 2021).

Thus, the integration of traditional and innovative weed control approaches unveils new horizons for creating effective, adaptive, and sustainable agroecosystems. Further development of digital modeling, breeding technologies, and global information platforms is key to overcoming the existing research gaps and promoting innovation across regions. Successful implementation of these directions is contingent upon interdisciplinary collaboration among scientists, farmers, and technology companies.

## Conclusions

Traditional weed control methods, particularly chemical and mechanical approaches, provide high short-term efficacy and constitute the foundation of modern agriculture. However, their intensive use leads to negative long-term consequences such as soil structure degradation, environmental pollution, and the development of weed resistance. Conservation-oriented and integrated approaches that combine various control methods demonstrate greater ecological sustainability and hold promise for ensuring the long-term viability of agroecosystems. Implementing comprehensive weed management strategies is essential to balance control effectiveness with the protection of soil resources and the environment.

Chemical and mechanical methods are characterised by rapid weed suppression and ease of application, enabling stable yields that are crucial in commercial farming. Nonetheless, prolonged and intensive use of these methods results in adverse ecological effects, including soil degradation, biodiversity loss, and the accumulation of herbicide-resistant weed populations.

Conservation and integrated strategies, while exhibiting slower weed control dynamics, contribute to the preservation of soil resources, reduce ecosystem impacts, and promote the long-term stability of agroecosystems. The combination of agronomic, biological, and chemical methods within integrated weed management (IWM) frameworks enhances control efficiency and ensures ecological resilience.

Thus, in the long run, systems that synthesise traditional and innovative methods prove more sustainable by balancing productivity and environmental stewardship.

For practitioners, it is recommended to adopt integrated weed management systems that combine chemical, mechanical, and biological methods tailored to local agroclimatic conditions. The use of precision application technologies and regular crop monitoring can improve control efficiency while minimising environmental impacts.

Researchers should focus on developing adaptive and sustainable weed control strategies that integrate traditional methods with innovative technologies, including artificial intelligence, drones, and sensor systems for early detection and localised weed control.

Policymakers are encouraged to support research and implementation of conservation technologies through funding scientific programs, creating incentives for farmers, and enacting appropriate legislation. The advancement of educational initiatives will further raise awareness of sustainable weed management and the conservation of agroecosystems.

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