

BIOTECHNOLOGICAL WEED CONTROL METHODS IN FIELD CROPS (REVIEW)

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Abstract. Climate change, manifested through increased frequency and intensity of drought as well as rising temperature regimes, significantly influences weed dynamics in field crops in southern Romania. In this context, the effectiveness of conventional weed control methods, predominantly based on herbicides, is limited both by the emergence of resistance to active substances and by European restrictions on the use of plant protection products. This paper analyzes and systematizes the main biotechnological methods of weed control, with emphasis on cover crops, allelopathy, the use of biological agents, genetic improvement for enhancing crop competitiveness, and the application of bioinputs (beneficial microorganisms). The methodology consists of a critical review of recent scientific literature, correlated with the pedoclimatic characteristics of southern Romania. The results highlight that biotechnological methods contribute to reducing weed pressure through complex ecological mechanisms, such as resource competition, chemical inhibition, and optimization of rhizosphere interactions. At the same time, their effectiveness is strongly dependent on climatic conditions, particularly water availability and soil temperature. It is concluded that the implementation of integrated weed management, based on the combination of biotechnological strategies and their adaptation to local conditions, represents an essential direction for developing sustainable and climate-resilient agricultural systems. However, practical implementation remains constrained by economic and knowledge barriers.

Keywords: biological control, weeds, climate change, cover crops

INTRODUCTION

The instability of agroclimatic conditions under climate change significantly alters weed ecology and crop–weed interactions in field systems.

In southern Romania, increased drought frequency, irregular precipitation, and higher temperatures favor stress-tolerant and thermophilic weed species. These shifts affect emergence, phenology, and competitiveness, reducing the reliability of herbicide-based control (POWLES ET AL., 2010; IPCC, 2021; MIRCOV ET AL., 2025). At the same time, repeated herbicide use has accelerated the evolution of resistant weed biotypes (DÉLYE ET AL., 2013; HEAP, 2023).

Regulatory restrictions within the EU further limit available chemical control options. This combined biological and legislative pressure necessitates sustainable alternatives. Biotechnological approaches within Integrated Weed Management include cover crops, allelopathy, biological control, and beneficial microorganisms. These strategies act through ecological mechanisms such as resource competition and rhizosphere interactions. Their effectiveness depends strongly on pedoclimatic conditions and management practices. In water-limited regions like southern Romania, careful adaptation is required for consistent performance (OLESEN ET AL., 2011; MIHUȚ ET AL., 2024).

MATERIAL AND METHODS

A systematic literature review was conducted targeting studies published between 2015 and 2025, complemented by representative foundational works. The databases consulted included Scopus, PubMed, Web of Science, and Google Scholar. The search strategy employed keywords such as: “herbicide resistance weeds,” “herbicide efficacy climate change,” “integrated weed management,” “non-chemical weed control,” “allelopathy weed suppression,” and “biological control of weeds.” Both experimental studies and review articles were considered to ensure comprehensive coverage of current knowledge and methodological approaches in herbicide use and alternative weed management strategies.

RESULTS AND DISCUSSIONS

1. Weed dynamics under climate change in field crops

Climate change exerts a multifactorial influence on weed communities, altering species composition, spatial distribution, phenology, and competitive interactions within agroecosystems. Rising temperatures, elevated atmospheric CO₂ concentrations, and increasing frequency of drought events contribute to shifts in weed flora toward more thermophilic, C₄-type, and stress-tolerant species, which often display enhanced growth rates and resource-use efficiency compared to C₃ crops (OLESEN ET AL., 2011; POWLES ET AL., 2010). Elevated CO₂ levels can differentially stimulate photosynthesis and biomass accumulation, frequently favoring weeds over crops due to their higher phenotypic plasticity and adaptive capacity.

Phenological shifts represent another critical aspect, with earlier germination, accelerated growth cycles, and extended reproductive periods observed in many weed species. These changes increase the complexity of weed management by disrupting the synchrony between crop development and control interventions. In addition, altered precipitation regimes, characterized by irregular rainfall distribution and prolonged dry intervals, affect seed dormancy, germination patterns, and soil seed bank dynamics.

In southern Romania, these processes are particularly relevant due to the region’s susceptibility to drought and high summer temperatures. Under such conditions, species such as *Sorghum halepense*, *Amaranthus retroflexus*, and *Setaria spp.* tend to proliferate, intensifying crop–weed competition for limited water and nutrients. The interaction between elevated temperature and CO₂ further enhances weed competitiveness by increasing water-use efficiency and modifying root system architecture, thereby amplifying belowground competition (OLESEN ET AL., 2011).

2. Limitations of Conventional Weed Control Methods

Conventional weed control in field crops has been predominantly based on the application of synthetic herbicides. While initially effective, the extensive and repeated use of herbicides has led to the widespread evolution of resistant weed populations. Herbicide resistance is an evolutionary process driven by selection pressure, resulting in the survival and proliferation of resistant biotypes. This phenomenon has been extensively documented across multiple modes of action and is considered a major threat to sustainable crop production (DÉLYE ET AL., 2013; HEAP, 2023).

In parallel, environmental and toxicological concerns associated with herbicide use have intensified. Issues such as soil and water contamination, negative impacts on non-target organisms, and potential risks to human health have prompted stricter regulatory measures. Within the European Union, policies such as the European Green Deal and the Farm to Fork Strategy aim to significantly reduce pesticide use and associated risks, leading to the withdrawal or restriction of several active substances.

Climatic factors further constrain herbicide efficacy. High temperatures and drought conditions can reduce herbicide absorption, translocation, and overall effectiveness, particularly for systemic compounds. Water stress may also induce physiological changes in weeds, such as thicker cuticles and reduced metabolic activity, which diminish herbicide sensitivity. Additionally, erratic rainfall patterns complicate the timing of herbicide applications, increasing the risk of suboptimal control.

These combined limitations highlight the vulnerability of herbicide-dependent systems and underscore the need for alternative or complementary approaches that are more resilient to environmental variability and regulatory constraints.

3. Conceptual Framework of Integrated Weed Management

Integrated Weed Management (IWM) represents a holistic approach that combines multiple control strategies to achieve effective, economically viable, and environmentally sustainable weed suppression. The conceptual foundation of IWM is rooted in ecological principles, particularly those related to competition, disturbance, and biodiversity within agroecosystems.

IWM emphasizes the integration of cultural, mechanical, biological, and biotechnological methods, reducing reliance on any single control measure. Key principles include diversification of cropping systems, optimization of crop rotation, manipulation of sowing dates and densities, and enhancement of crop competitiveness. These practices aim to create unfavorable conditions for weed establishment while promoting crop dominance.

Biotechnological tools play a central role within this framework by exploiting natural processes such as allelopathy, microbial interactions, and genetic variability. For example, the use of cover crops contributes to weed suppression through resource competition and physical soil coverage (TEASDALE ET AL., 2007), while allelopathic crops release secondary metabolites that inhibit weed germination and growth (RICE, 1974). Similarly, biological control agents, including plant pathogens, can selectively target weed species without affecting crops (CHARUDATTAN, 2001).

The effectiveness of IWM depends on the synergistic interaction among its components. Rather than aiming for complete weed eradication, the objective is to maintain weed populations below economic thresholds while preserving ecosystem functionality. This requires site-specific adaptation, continuous monitoring, and a systems-based perspective that accounts for climatic variability, soil conditions, and crop management practices.

In the context of southern Romania, the implementation of IWM is particularly relevant due to increasing climatic constraints and regulatory pressures. By integrating biotechnological methods with traditional practices, it is possible to enhance system resilience, reduce chemical inputs, and support the transition toward sustainable agricultural systems.

4. Biotechnological weed control methods

Biotechnological weed control encompasses a heterogeneous suite of ecologically grounded and biologically mediated strategies that collectively aim to regulate weed populations through system-level processes rather than through direct eradication, thereby shifting the conceptual framework of weed management from chemically deterministic interventions toward functionally integrated agroecosystem regulation. These approaches are fundamentally dependent on the manipulation of interspecific plant interactions, rhizosphere-mediated processes, and biologically active compounds, all of which operate within dynamic environmental constraints that modulate their efficacy and stability.

4.1 Cover crops and functional suppression systems

Cover crops constitute one of the most structurally and functionally significant components within biotechnological weed suppression systems, their mode of action being inherently multifactorial, as they simultaneously impose constraints on weed emergence through rapid canopy closure, aboveground light interception, and belowground competitive exclusion for water and mineral nutrients, while also inducing longer-term alterations in soil microclimatic conditions that collectively reduce the probability of successful weed establishment.

Empirical evidence indicates that the integration of cover crops within intercropping or rotational systems can substantially enhance agroecosystem productivity while concurrently diminishing weed pressure, particularly when species are selected based on complementary phenological development, growth rate, and resource acquisition strategies, as demonstrated in diversified maize–legume systems (AYIL YOGISHWAR GOUD, 2025). The functional efficiency of these systems is further amplified when biomass production is sufficient to generate persistent soil coverage after termination, thereby creating a physical mulch layer that modifies temperature gradients, reduces light availability at the soil surface, and impedes seed germination processes.

The effectiveness of cover crop-based suppression is strongly contingent upon environmental conditions, particularly water availability and seasonal precipitation distribution, such that under drought-prone environments their performance becomes increasingly dependent on species-specific drought tolerance and physiological plasticity (WEZEL ET AL., 2014). Long-term experimental observations further suggest that repeated incorporation of cover crops contributes to a gradual but measurable reduction in soil weed seed banks, primarily through cumulative effects on seed germination inhibition, altered dormancy cycling, and increased biotic seed mortality within biologically active soils (BLANCO-CANQUI, 2021).

4.2 Allelopathy and biochemical weed suppression

Allelopathy represents a chemically mediated ecological mechanism whereby plants release a diverse spectrum of secondary metabolites into their surrounding environment, thereby exerting inhibitory or regulatory effects on neighboring plant species through interference with germination, cellular division, hormonal signaling, and nutrient uptake pathways, all of which contribute to suppression of weed establishment at early developmental stages.

Recent syntheses emphasize that allelopathic interactions constitute a functionally relevant component of sustainable weed management systems, particularly when embedded within rotational or cover cropping frameworks that allow for cumulative biochemical effects over time (BAŞDEMİR & ÖZKAN, 2026). The ecological expression of allelopathy is mediated through multiple release pathways, including root exudation during active growth phases, volatilization from aerial tissues, and leaching or decomposition of plant residues, each of which contributes differently depending on plant phenology and environmental context.

However, the field-level expression of allelopathic activity is inherently variable, as it is strongly modulated by edaphic and climatic factors such as soil moisture regimes, microbial degradation dynamics, organic matter content, and temperature fluctuations, which collectively determine both the persistence and bioavailability of allelochemicals within the soil matrix (BARAIBAR, ET AL., 2017). This environmental sensitivity has increasingly directed research toward the integration of allelopathic systems within precision-oriented agricultural frameworks, where spatial and temporal management can partially compensate for inherent variability in biochemical expression.

4.3 Bioherbicides and plant-based weed control agents

Bioherbicides represent a rapidly evolving class of biologically derived weed control agents that originate from microbial organisms, plant extracts, or naturally occurring secondary metabolites, and which exert their effects through diverse physiological and biochemical pathways, often involving multi-target modes of action that significantly reduce the likelihood of resistance evolution relative to conventional synthetic herbicides.

Contemporary research indicates that plant-based bioherbicides offer promising avenues for environmentally compatible weed management, although their practical deployment is frequently constrained by instability under field conditions, inconsistent efficacy across environmental gradients, and formulation-related limitations that affect persistence and bioavailability (ROSSKOPF, 2017; ROUTH ET AL., 2025). These constraints are primarily associated with rapid degradation processes induced by ultraviolet radiation, thermal fluctuations, and microbial catabolism in soil systems.

To address these limitations, recent technological developments have focused on advanced formulation strategies, including nanoencapsulation, emulsification systems, and controlled-release matrices, which collectively aim to stabilize active compounds and extend their functional persistence in agronomic environments (BRATOVCIC, 2025). At the mechanistic level, bioherbicides have been shown to disrupt membrane integrity, induce oxidative stress cascades, and inhibit key enzymatic pathways, thereby producing cumulative physiological stress responses in target weed species (ZHANG ET AL., 2025).

More recently, symbiotic formulations combining microbial agents with plant-derived metabolites have been proposed as next-generation bioherbicidal systems, capable of generating synergistic interactions that enhance efficacy while simultaneously improving ecological compatibility and reducing environmental risk profiles (RAZAFINDRALAMBO ET AL., 2026).

4.4 Microbial inoculants and rhizosphere engineering

Microbial inoculants, including plant growth-promoting rhizobacteria and mycorrhizal fungi, constitute an essential component of biotechnological weed management systems, not through direct weed suppression, but rather via the modulation of plant physiological performance and resource acquisition efficiency, which collectively enhance crop competitiveness within shared ecological niches. (SANTOYO ET AL., 2021).

These microorganisms influence plant growth through multiple mechanisms, including enhanced nutrient solubilization, phytohormone modulation, and improved water uptake efficiency, thereby indirectly reducing weed competitiveness by strengthening crop dominance under resource-limited conditions. Recent studies further demonstrate that such microbial interactions become particularly significant under abiotic stress conditions, where symbiotic relationships contribute to improved drought tolerance and physiological stability in crops (PINTILIA ET AL., 2025).

The rhizosphere, therefore, functions as a highly dynamic and interactive biological interface in which microbial community composition exerts a decisive influence on plant-plant competition outcomes, mediated through changes in nutrient cycling, root architecture, and soil biochemical signaling pathways.

4.5 Genetic and crop-based competitive strategies

Genetic improvement strategies aimed at enhancing crop competitiveness constitute a foundational pillar of biotechnological weed management, with particular emphasis on traits such as early vigor, rapid canopy development, optimized root system architecture, and improved resource-

use efficiency, all of which contribute to the suppression of weed emergence and establishment through pre-emptive resource capture (LEMERLE ET AL., 2006).

Evidence indicates that cultivar selection significantly influences the intensity and outcome of crop–weed interactions, particularly under environmental stress conditions associated with climate variability, where competitive crop genotypes can maintain yield stability while simultaneously reducing weed biomass accumulation (KORRES ET AL., 2016). In intercropping systems, genetic complementarity between species further enhances spatial and temporal resource partitioning, thereby minimizing direct competition and improving overall system productivity (SAVIC, 2025).

4.6 Bioinputs and integrated biotechnological systems

Bioinputs, encompassing biofertilizers, biostimulants, and microbial consortia, function primarily as indirect regulators of weed dynamics by enhancing crop physiological performance, improving soil fertility, and stabilizing soil microbial communities, thereby reinforcing crop dominance within competitive agroecosystems (SHAHZAD ET AL., 2025).

Recent experimental evidence demonstrates that combined applications of microbial inoculants and organic amendments can significantly improve soil chemical properties, enhance plant growth under drought stress, and indirectly reduce weed competitiveness through improved crop vigor and resource acquisition efficiency (ROUPHAEL & COLLA, 2020). These synergistic interactions are particularly relevant in environments characterized by water limitation and climatic instability.

The integration of bioinputs within broader agronomic systems is most effective when they are deployed in conjunction with other biotechnological strategies such as cover cropping, allelopathic crop selection, and reduced tillage systems, thereby generating multilayered suppression effects that operate across different temporal and spatial scales.

5. Ecological mechanisms underlying biotechnological weed control

Biotechnological weed control relies on complex ecological processes that regulate weed populations through interactions within agroecosystems rather than direct elimination. A fundamental mechanism is resource competition, where crops and associated plant species limit weed access to light, water, nutrients, and space. These interactions occur simultaneously aboveground (light interception, canopy closure) and belowground (root competition), and are strongly influenced by species traits and environmental variability (LIEBMAN ET AL., 2001; KORRES ET AL., 2016).

A key advancement in recent research is the recognition that ecological weed suppression is enhanced by functional diversity and system complexity, which reduce ecological niches available to weeds and disrupt their life cycles (MACLAREN ET AL., 2020). Diversified systems increase resilience and reduce reliance on chemical inputs.

Allelopathy represents a central biochemical mechanism in biotechnological weed control. Recent studies confirm that allelochemicals, such as phenolics, terpenoids, and alkaloids, interfere with germination, root development, and physiological processes of weeds (MURTHY ET AL., 2025). These compounds are released through root exudation, volatilization, residue decomposition, or leaching, providing multiple pathways for weed suppression (DANG ET AL., 2025).

Moreover, integrating allelopathic crops into rotations or cover cropping systems significantly reduces herbicide dependence while improving soil health and biodiversity.

Recent advances highlight the increasing role of bioherbicides, which consist of plant-derived compounds, microorganisms, or their metabolites. These products often exhibit multiple modes of action, acting at cellular and physiological levels, which reduces the likelihood of resistance development (ZHANG ET AL., 2025).

In addition, soil microbiome interactions play a critical role. Beneficial microorganisms enhance crop vigor, nutrient uptake, and stress tolerance, indirectly suppressing weeds by improving crop competitiveness. These rhizosphere-mediated effects are increasingly recognized as essential components of sustainable weed management systems (ARORA, 2025).

6. Influence of pedoclimatic conditions in southern Romania

Pedoclimatic conditions strongly influence both weed dynamics and the effectiveness of biotechnological control strategies.

Weed communities tend to shift toward xerophytic and thermophilic species, which exhibit high physiological plasticity and resource-use efficiency. These species often outcompete crops under water-limited conditions, increasing weed pressure and yield losses (OLESEN ET AL., 2011; KORRES ET AL., 2016).

Recent studies emphasize that climate change modifies not only species composition but also weed phenology and emergence patterns, leading to asynchronous crop–weed interactions and increased management complexity. Water stress conditions favor deep-rooted and drought-tolerant weeds, intensifying belowground competition (ANDERT, 2021).

Soil characteristics further modulate these processes. In southern Romania, chernozem soils provide high fertility but may experience reduced water availability under drought stress. This limits the biomass production of cover crops, reducing their weed suppression capacity. The effectiveness of allelopathic interactions is also influenced by soil moisture and temperature, which regulate the release and degradation of allelochemicals.

Recent literature highlights that allelopathy and bioherbicide efficacy are strongly environment-dependent, with climatic factors affecting both persistence and biological activity of active compounds (JIANG ET AL., 2026).

Similarly, microbial-based strategies depend on soil biological activity, which is highly sensitive to temperature and moisture conditions.

In conservation and reduced-tillage systems, weed control increasingly relies on ecological processes rather than mechanical disturbance. These systems alter weed emergence patterns and favor species adapted to undisturbed soils, requiring adaptive management approaches.

Thus, the success of biotechnological weed control in southern Romania depends on precise adaptation to local pedoclimatic conditions, emphasizing the need for site-specific and climate-resilient strategies.

7. Practical implementation

The effective implementation of biotechnological weed control requires integration within a systems-based framework such as Integrated Weed Management. This approach combines ecological, biological, and technological methods to achieve sustainable weed suppression.

A central principle is diversification, which reduces weed adaptation by altering selection pressures over time. Crop rotation, intercropping, and cover cropping disrupt weed

life cycles and reduce population buildup. These practices are fundamental to ecological weed management and are increasingly supported by recent research (MACLAREN ET AL., 2020).

Recent advances emphasize the role of bioherbicides and plant-based compounds as key components of integrated systems. These alternatives reduce environmental risks and support sustainable agriculture, although their adoption is still limited by technical and regulatory challenges (ISLAM ET AL., 2024).

Another important development is the integration of precision agriculture technologies, including sensor-based weed detection and site-specific management. These tools enable targeted interventions, reducing input use and increasing efficiency. Sensor-based systems can identify weed species and growth stages in real time, improving control accuracy and supporting decision-making (VIGNESH ET AL., 2025).

Similarly, advances in AI and robotics allow automated weed detection and selective control, significantly reducing herbicide use while maintaining effectiveness. High-accuracy models for weed identification across growth stages support real-time management and precision interventions (AHMADI ET AL., 2024). Autonomous systems for spot spraying further enhance efficiency and reduce environmental impact.

The integration of biological, ecological, and digital approaches represents a major paradigm shift in weed management. Rather than relying on single-method control, modern systems combine multiple strategies that act at different stages of the weed life cycle.

However, practical implementation remains constrained by economic and knowledge barriers. Biotechnological systems require higher management complexity and a deeper understanding of ecological processes. Despite this, long-term benefits include improved soil health, reduced chemical dependency, and increased resilience to climate variability.

Adaptive management is therefore essential. Continuous monitoring, combined with flexible decision-making and predictive tools, enables optimization of weed control strategies under dynamic environmental conditions.

CONCLUSIONS

Biotechnological weed management represents an evolving paradigm in which weed suppression is achieved through the coordinated exploitation of ecological interactions, biological agents, and system-level agronomic design, rather than through exclusive reliance on synthetic herbicides. The synthesis of current literature indicates that cover crops, allelopathic interactions, bioherbicides, microbial inoculants, and genetically improved competitive cultivars function not as isolated tools, but as interconnected components of a broader agroecological framework that regulates weed populations through competition, biochemical interference, and rhizosphere-mediated processes.

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